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Slope Stability Of Laterite Soil Embankments

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SLOPE STABILITY ANALYSIS OF LATERITE SOIL EMBANKMENTS

by

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ABSTRACT

Embankments are key elements in the infrastructural development of structures such as dams, bridges, and roads. Residual soils are generally used as fills in the construction of embankments in areas were residual soils such as laterite is the dominant soil types. Laterite soils have the characteristics of losing its shear strength with time and in fully saturated conditions and its properties varies from region to region. The soil property is influenced by the chemical composition and the environment. The binding agent iron oxide in such soils changes its composition with time and in the presence of moisture. Sudden failures of embankments founded of laterite soils which were, otherwise, checked and found to be safe with high factor of safety, have been observed. This study is performed to investigate the stability of embankments with sudden loss of strength with time and when it is fully saturated.

The research includes an investigation of the properties of laterite soils around the world, with particular emphasis on Nigeria. Initially, information is gathered from different sources about the strength-based properties of such soils. Previous research in Nigeria is used as a basis for obtaining real-world soil data. Next, stability analyses are performed using SLOPE/W with shear strength parameters for total stress (short-term), effective stress (long-term), and fully saturated soil conditions. A probability analysis is conducted for the fully saturated conditions because of the variability in the input parameters. Three slope configurations (1:1, 2:1, and 3:1) are considered. The study revealed that the laterite soils embankments lose most of its stability over time period and in full saturation soil conditions. Both these conditions significantly compromise the

strength of the soil and the related stability of slopes. To consolidate all information, a database of the properties of laterite soils in some localities of Nigeria was created on the geographic information system (GIS), in order provide a quick access to information on laterite soils in Nigeria. In addition, To Bolou, my wife

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CHAPTER ONE: INTRODUCTION

1.1 Background

The response of geotechnical engineers to the growth in developmental projects, the difficulty in understanding soil conditions and the failures associated with tropical soils, and the need to address these failures and the related problems in the tropics, has led to the apparent increase in research on the tropical soil types and their engineering properties. The importance of these laterite soils cannot be more emphasized as they are being used as construction and engineering material for roads and airfield sub-bases and sub-grades; fills and embankments for bridges and dams; and other engineering uses as may require soil materials in the tropics. It is the dominant soil type in the region. In some instances, it is used also as burnt-bricks for building blocks in the construction of residential houses.

Another factor that has led to the increase in research involving this soil type is the strong intention of geotechnical engineers in adopting the soil classification and testing methods developed and recommended for temperate regions in classifying the laterite soils of the tropics. Temperate region soil classification and testing methods have been reported to have often failed to predict the field performance of laterite or lateritic soils. This is because the index tests upon which the classifications are based are not always reproducible for lateritic soils (Tuncer and Lohnes, 1977). In addition to this is the fact that soils are geological materials in a natural geological environment. Thus, the environment in which the soil is located influences to a great extent the development of soil texture, structure, and mineralogy (Skempton, 1953; Nnadi, 1987; and Gidigasu and Kuma, 1987).

The soil type in the tropics is generally called Laterite, or, Residual soil. This soil was first described by Buchanan in 1807 as *"... reddish in color, vesicular and unstratified in structure; a mantle of ferruginous (red to brown color) rock covering large areas in southern India. In the natural state the material is soft enough to be cut into blocks with iron instruments but could rapidly harden on exposure to air to be fairly resistant to the weathering effect of climate*". Consequently, there have been several definitions of the laterite soil or residual red soil by various researchers. Laterite has been defined as *"... a mass that may be vesicular, concretionary, vermicular, pistolistic, or more or less massive, consisting essentially of iron oxide with or without clastic quartz, and containing small amount of manganese*" (Du Perez, 1949). Describing its state and constituents, laterite has been defined as *"... a reddish, poorly cemented rock, composed of kaolinite, halloysite, and iron oxides; and further describes it as lacking in montmorillonite, hidromicas, sulphates, carbonates, and other soluble salts, and forms in tropical zones with variable humidity as a result of chemical disintegration and decomposition of clay and igneous rock*" (Geological Monument, 2005). Furthermore, laterite is defined as a ferruginous soil of clayey texture and which has concretionary appearance (Tomlinson, 1976).

There have been varied definitions for laterite soils. However, most researchers agree with the definition of Cady (1962) that laterite is *"... 'highly weathered materials rich in secondary oxides of iron, aluminum, or both'; and describes it further as nearly void of bases and primary rock-forming minerals (silicates) but may contain large* *amount of quartz and kaolinite; and either hard or capable of hardening*". Furthermore, there is the intent of differentiating between laterite and lateritic soils, the latter being described as "… *all products of tropical weathering with red, reddish brown or dark brown color, with or without nodules or concretion and generally (but not exclusively) found below hardened ferruginous crusts or hard pan*" (Ola, 1977).

Others have used the silica/sesquioxide ratio in conjunction with other criteria for the definition of lateritic soils (Maignien, 1966 and Madu, 1975). The suggested ratios are:

$$\frac{SiO_2}{R_2O_3} = \frac{SiO_2}{Fe_2O_3 + Al_2O_3}$$

When the ratio is less than 1.33, the soil is described as laterite, between 1.33 and 2.00 – lateritic soil, and greater than 2.00 – non-lateritic soil.

The variability in the definition of the laterite soil is an indication of the variability of its nature and properties. Hence, there is an increase in the interest in studying in the various localities where the soil is found. The inconsistency in the nature and properties of laterite soils and the need to better understand each local condition prompted the study of laterite soils around the world. In response to the unpredictability of laterite soil nature and properties, research studies have been published by several researchers in journals and presented in seminars and conferences of Soil Mechanics and Foundation Engineering Conference for Africa 1987, United States Agency for International Development among other independent publications. Other such publications are ASCE Geotechnical Engineering Division Specialty Conference, 1982 "Engineering and Construction in Tropical and Residual Soils"; 1st International Conference on Geomechanics in Tropical Lateritic and Saprolitic Soils, 1985; and Regional Conferences of ISSMFE in Africa, South America and Asia.

These studies are conducted with the knowledge that the findings are limited to the areas where the soil samples were obtained. However, some researchers imply that the results of these findings could be assumed to have similar properties and behavior at other locations, especially where the laterite soils are from the same parent rock or of similar geological formation. There is the need to limit the present study to particular locality of Nigeria so as to achieve a focused and in-depth knowledge of the laterite soil of the chosen locality.

1.2 Research Objective and Scope

The primary objective of this study is to investigate the effect of the variable nature and properties of compacted laterite soil embankment with time and in fully saturated state within Nigeria. The characteristics of laterite soil, unlike other soil types, vary from region to region. This is attributed to the formation and constituent mineralogy of the soil, which is influenced by the climatic and environmental conditions of its locality. Thus, the shear strength varies with time and location because of the difference in the mineralogy of the laterite soil. In addition, the strength of compacted laterite soils vary with time, as it loses its cohesion and increases its internal angle of friction. This is as a result of the ineffectiveness of the iron oxide (binding agent) to coalesce because of the loss of moisture with time. There is also the issue of loss of strength due to fully saturated soil condition. In a fully saturated state, the iron oxide, which is the fines of the compacted laterite soil, is removed by a light current of water. This also results in the loss of cohesion and increase in the internal friction angle, thus a reduction in the shear strength of the compacted laterite soil.

This study further develops a geographic information system (GIS) data base of the nature and engineering properties of laterite soils in Nigeria. The research focuses on obtaining published experimental results on the properties of laterite soils of Nigeria and establishing a database of these properties on the web for easy accessibility. In addition, a sensitivity analysis of laterite soils to varying cohesion, internal angle of friction, and density in slope failure within Nigeria is performed to provide knowledge of the behavior of laterite soils. It also looks at the combinations of these properties that are suitable for the stability of the slopes used in embankments.

In order to achieve this objective, different models of embankments using various laterite soils properties are studied using the SLOPE/W software (Geo-Slope Manual, 2000). The SLOPE/W software program models and analyses unsaturated laterite soils for both total and effective stress parameters, and a fully saturated laterite soil condition for different embankment geometry. In the SLOPE/W slope stability analysis program uses the Ordinary (Fellenius), Bishop Simplified, Janbu Simplified, and Morgenstern-Price methods of analysis of slope embankments. The model is intended to create an understanding of the effect of time and/or saturation of laterite soil embankments on the shear strength and invariably the stability of slopes, specifically in Nigeria.

1.3 Research Approach

This thesis consists of five chapters. The first chapter, Introduction, presents an overview of the thesis topic, laterite soil, and the scope of the research material. The next chapter reviews some published materials on laterite or residual soil, its nature, properties and geotechnical parameters required to predict the behavior in varying conditions. The review was done for tropical regions around the world. However, emphasis was placed on literature on laterite soils in Nigeria. Chapter three dwells on the slope analysis methods and the geographic information system (GIS) adopted in providing the data base of laterite soils in Nigeria. Chapter four presents the results obtained from the slope stability analyses and results of the sensitivity analysis of the different combinations of the geotechnical parameters. This chapter also contains charts and tables of these analyses, and the discussions of the charts and results. Chapter five consists of the conclusions and findings of the slope stability analyses, and offers recommendations for future studies on laterite soils.

CHAPTER TWO: LITERATURE REVIEW

2.1 Soil Formation Process

Residual soils, otherwise called laterite or lateritic soils are the dominant soil type in the tropics and subtropics of the world. The tropical residual red soil forms the major surface deposit of engineering material in this part of the world. The geographic and geomorphic features of laterite soils are generally summed up as a.) Tropical rainforest and savanna; b.) Deep residual soil profile; and c.) Shield and sedimentary cover outside shield in South and Central America, Central and West Africa, Southeast Asia and other parts of the world (NAVFAC DM- 7.01, 1986). Its distribution around the world is vividly shown in the Figure1 below.

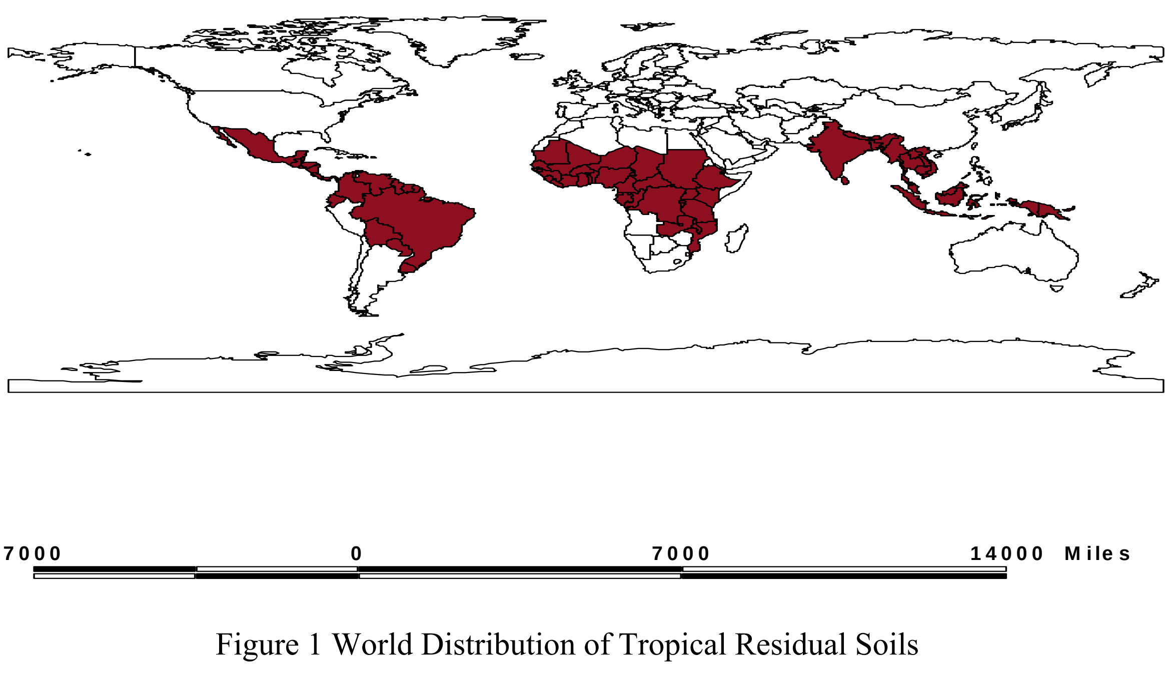


Figure 1 World Distribution of Tropical Residual Soils

The presence of the residual soils, mainly in the tropical and subtropical regions of the world, suggests that there are certain characteristics required for the formation and its abundance. There are several mechanisms attributable to its formation which is centered on the climatic conditions of these regions. The climate shapes the stratigraphy of the soil with regards to the depth of deposition of salts, the degree of surface desiccation and/or saturation (Gidigasu, 1988). Persons, (1956) describes the climatic requirements for the formation of residual soils in a region as having an average annual rainfall of at least 1200 mm (47.24 inches) and a daily temperature in excess of 25º Celsius (77º Fahrenheit). In addition, it is portrayed to occur mostly in humid tropical climate within 30ºN and 30ºS of the equator (Madu, 1976).

Laterite is described as a product of in situ weathering of igneous, sedimentary, and metamorphic rocks commonly found under unsaturated conditions (Rahardjo, et al, 2004) or by the ferruginization of existing soils (D'Hoore, 1954). Laterite needs the high rainfall and temperature of the tropics to form. The disintegration of these underlying rocks occurs as the water washes out the soil minerals such as sodium, potassium, calcium, magnesium, and other metals, and enriches the soil with aluminum, phyllo-silicates, aluminum oxides, iron (III) oxides, and hydroxides (Brainy Encyclopedia 2005). The particular presence of iron gives the soil the typical red color associated with it, thus it is described as residual red soil.

There is the modification to the climate requirement, which is the physical feature of the region. The environment extensively shapes the mode of deposition and development of the soil, and the type of clay minerals present (Gidigasu, 1988).

Consequently, an online encyclopedia (*LoveToKnow*, 2003, 2004) describes the conditions under which residual soils are formed as:

- First, a high seasonal temperature, for it occurs only in tropical districts and in plains or mountains up to about 5000 feet in height;
- Secondly, a heavy rainfall with well-marked alternation of wet and dry seasons (in arid countries laterite is seldom seen, and where the rainfall is moderate the laterite is often calcareous);
- Thirdly, the presence of rocks containing aluminous minerals such as feldspar, augite, hornblende and mica. On pure limestone such as coral rocks and on quartzite laterite deposits do not originate except where the material has been transported.

In addition, Gidigasu, (1972) and Novais, (1985) characterize the conditions which must be prevalent for the weathering process of laterization to occur as:

- Chemical and mineralogical composition of parent rock having appreciable amount of ferric and aluminous compounds;
- Permeable profile permitting good circulation of water;
- Tropical climate with heavy rainfall and dry season;
- High atmospheric temperature during the day;
- Flattish topography of sufficient elevation;
- Fluctuating water table; and
- Vegetation for tropical and savannah.

Furthermore, Tuncer, et al, (1977), described the genesis of laterite as the weathering process which involves leaching of silica, formation of colloidal sesquioxides, and precipitation of the oxides with increasing crystallinity and dehydration as the soil is weathered. Primary minerals in the parent rock such as feldspar, quartz, and ferromagnesian minerals are transformed to a porous clayey system containing kaolinite, sesquioxides, and some residual quartz. The primary feldspars are further transformed to kaolinite and subsequent gibbsite. Primary ferromagnesian minerals are converted to diffuse goethite, then to well-crystallized goethite, and finally hematite. In highly developed stages weathering crystallization leads to the formation of iron and/or aluminum oxide concretions (Malomo, 1989), followed by coalescence of concretions and their cementation; eventually the entire system becomes a continuous cemented crust (LoveToKnow, 2003, 2004).

Evidently, factors for the weathering of the tropical soil involve the evolution of the soil system, the type of mobile salts, the process of deposition and leaching, and the type of clay mineral. Field and laboratory studies have shown that residual soils consist of different zones of weathering with differing morphological, physical, and geotechnical characteristics; and vary for different locations due to the heterogeneous nature and highly variable degree of weathering (Adekoya, 1987 and Rahardjo, 2004). The differences in characteristics of laterite soil is associated with the climatic and topographic conditions, which involves the weathering front, translocation of materials through groundwater and percolating rainwater, alternating wet and dry climatic conditions, and biological factors including both faunal and floral activities in the soils (Norton 1973, Faniran 1978, Schorin 1981, Leprun 1981). In addition, differences in textural and mineralogical characteristics of parent rocks could be responsible for significant differences in the engineering properties of the derived soils (Adeyemi 1995)

2.2 Soil Structure of Laterite Soils

Soil structure, generally, refers to both the geometric arrangement of the soil particles and the inter-particle forces which may act between these particles (Day, 1999). Accordingly, the structure of soil provides for soil integrity and its response to externally applied and internally induced forces (Yong and Warkentin, 1975). There are varying hypotheses of particle arrangement in natural soils (Lambe, 1958). However, observations have established the fact that there is no exact singular arrangement of particle grouping characteristic of any soil type. Only sedimentary soil formations may have similarity in its arrangement and some are more prevalent in certain soils than others (Collins and McGowan, 1974). The assumptions that soil properties are dependent on the initial structure and porosity as deposited and on its subsequent stress history (Nnadi, 1987) cannot be true for soils in the tropics. The actions of weathering and erosion in the tropics steadily alter the properties of residual soils, thus making it difficult to relate the soil structure to the stress history (Vaughan and Kwan, 1984). Therefore, the origin of the soil determines the micro fabric of the clay soils (Osipov and Sokolov, 1978), and the microstructure is strongly related to its environment of formation and consequent transformation during compaction (Malomo, 1989).

Lateritic weathering products derived from different rock types in the tropics varies in different locations. Consequently, the soil structure differs for the diverse rock types. Residual soil formation involves some form of a complex weathering process which is likely to cause the variability in the intermediate and final structures. Accordingly, studies in some lateritic soils reveal that they posses a porous granular structure consisting of iron impregnated clayey material in minute spherical aggregations (Hamilton, 1964). The aggregations derive its strength from the thin film found within the micro-joints of the elementary clay particles, which in addition coats the particles (Gidigasu, 1988). Thus, the thin film found within the micro joints of the elementary clay particles and as coatings over particles provides the strength of the aggregation.

Further studies by Malomo (1989) reveal that under the microscope, laterite soils show strongly cemented surfaces covered by iron oxides, which initially exist as a semi-gelatinous coating and thus follow these steps:

- Becoming denser through the loss of moisture but retaining its non-crystalline structure, and
- Crystallizing slowly into forms such as goethite or hematite.

The microstructure of soils tends to influence the engineering properties of tropical residual soils (Terzaghi, 1958), and there exist a wide variety of microstructures of the residual soils (Nnadi, 1988). The examination of the microstructure reveals two major micro structural arrangements, namely matrix and skeletal, which are resultants of different stages in the laterization (Malomo, 1989).

Matrix microstructure (dense region) is characterized by a strongly cemented and coated with iron oxide, while the skeletal microstructure (porous region) has its surfaces and voids coated in similar manner like the matrix microstructure but the extent of filling is minor (Sergeyev et al., 1978). These microstructures development is based on the deposition of iron oxides at different stages of the weathering process. Skeletal microstructure (porous region) develops at the early stages of weathering with fewer deposition of iron oxide when compared to the matrix microstructure (dense region) which occurs at an advanced stage (Malomo, 1989). The influence of the microstructure of soils has been identified as a leading factor responsible for the unique properties. The soil microstructure consists of the micro fabrics, composition and the inter-particle forces, (Collins and McGowan, 1974, Wallace, 1973, Mitchell and Sitar, 1982, and Collins 1985). Hence, there is an increasing interest in relating the microstructure of the soil to its engineering properties (Tuncer et al., 1977, Gidigasu et al., 1988, and Rahardjo et al., 2004). This is evidently seen in the effect of the granular structure of the soil to the engineering properties (Townsend et al., 1973).

Laterite soils consist of hard masses, nodules, and bands with a superficial layers often indurated (made harden by extremes of climate) and smooth black or dark brown crusts where its constituent clay has long been exposed to dry atmosphere. In other cases, the soft clays of laterite are full of hard nodules, and are generally, perforated by tubules, sometimes with veins of different composition and appearance from the main mass. Tropical residual soils consist of an accumulation of particles ranging from larger granular constituents to clay-size materials as well as sesquioxides which are present as cementing materials (Nnadi, 1988). In situ laterite possesses a granular structure due to the presence of sesquioxides, which coat and knit the indigenous soil particles into tiny spherical aggregations (Alexander and Cady, 1962).

2.3 Laterite Soil Characterization

Laterite soils, depleted of most of its elements except iron and aluminum oxides, are derived from the weathering of parent rocks. The loss of the soil elements is as a result of the residual soil exposure to high rainfall which washes out these elements (sodium, potassium, magnesium, and calcium) and other metals from the soil. In substitution, the soil is enriched with aluminum phyllosillicate, aluminum oxide, iron oxides and hydroxides. Concern for the effect of these elements to the geotechnical properties is indicative of the interest in the research of characterization of this soil type. Soil characterization is intended to identify the soil properties, its predictability, and responses to varying loading conditions.

In response to need for characterization of laterite soils, temperate region soil classification techniques and methods are widely used. However, research shows that these temperate region classification methods do not adequately predict tropical soil behavior (Tuncer and Lohnes, 1977, Nnadi, 1988, Gidigasu and Kuma, 1988, and Rahardjo et al., 2004). The failure of these methods to predict the field behavior is attributed to the variation in plasticity and particle-size frequency characteristics of lateritic soils resulting from sample preparation and handling which disrupt the natural structure of the soils (Lohnes et al., 1971, Foote et al., 1972). Thus, it is suggested to base the engineering characterization of the laterite soils on the parent material and degree of weathering (Gidigasu, 1971, Adekoya, 1987, Rahardjo et al., 2004). Accordingly, studies have been performed in various regions of the tropics to adequately characterize the residual soils and their engineering properties, which are greatly influenced by the formation process, climatic and environmental conditions of the varying localities, and types of parent rocks.

An understanding of the engineering characteristics of lateritic soils, from bed rock to totally weathered soil, is necessary for engineers in the tropics, for the proper application of this soil to engineering works. It is thus, required that a proper characterization of the residual soils be based on these facts:

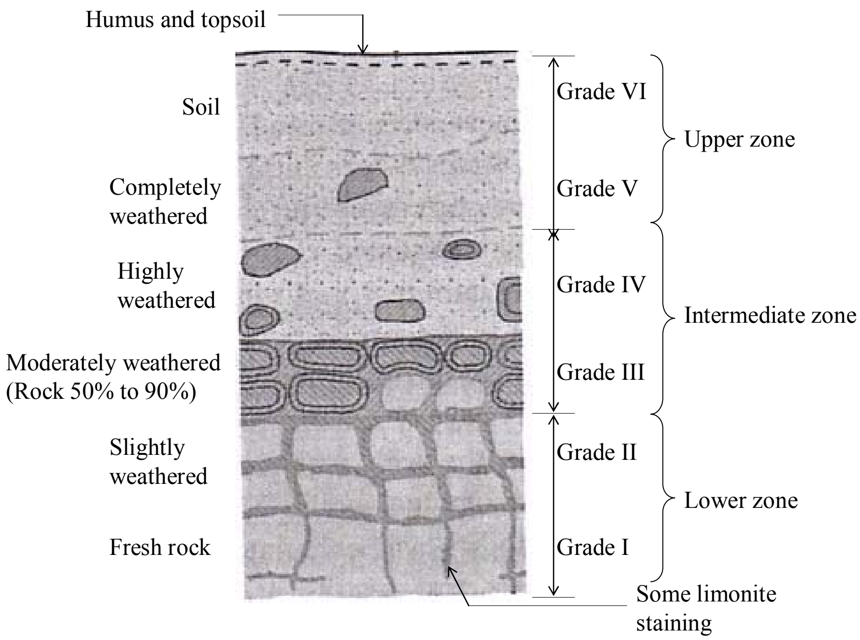
- the material is the most common, naturally occurring;
- there is a wide variation in weathering environments and resulting soil profiles;
- the soil exhibit wide variation in its engineering characteristics; and
- it is the most economic engineering material for use in diverse developmental projects.

The consistency of laterite soils generally yields readily to pressure and disaggregates by the remolding of the soil. Remolding of the soil greatly influences the textural characteristics and plasticity. Laterite soil characteristics is dependent on the factors mention above, and these influence the type of mineralogy, clay type and content, grain size, and degree of dehydration (Nnadi, 1987). A description that involves the soil profile horizons and the constituent particles, such as the color, soil texture, soil structure, mineralogy, and organic content is necessary to adequately state the engineering properties.

2.3.1 Soil Profile

Laterite soil profile characteristics is defined as that in which lateritic horizon exists or capable of developing under favorable conditions (Gidigasu 1988). It is generally agreed that there exists three major profiles below the humus stained top soil (Little 1969, Gidigasu 1988, Adekoya 1987, and Rahardjo et al. 2004). These are partitioned into upper, intermediate and lower zones, see Figure 2. Adekoya (1987) recognized three variants of laterites in the field observations as:

- A mixture of fine-grained black and reddish iron oxide, clay matrix, and quartz in variable proportions within a horizon;
- Fine-grained iron oxide layer with subordinate quartz (ferricrete); and
- Stony siliceous layer with minor oxide (silcrete).



Source: Rahardjo et al. (2004)

Figure 2 Typical weathering profiles of residual soils.

In the study of the engineering significance of laterization and profile development process, Gidigasu and Kuma (1987) described the three laterite horizon profiles as:

- The sesquioxide rich so-called laterite horizon (sometimes gravelly and/or hardened in situ as crust);
- The so-called mottled zone with evidence of enrichment of sesquioxides; and

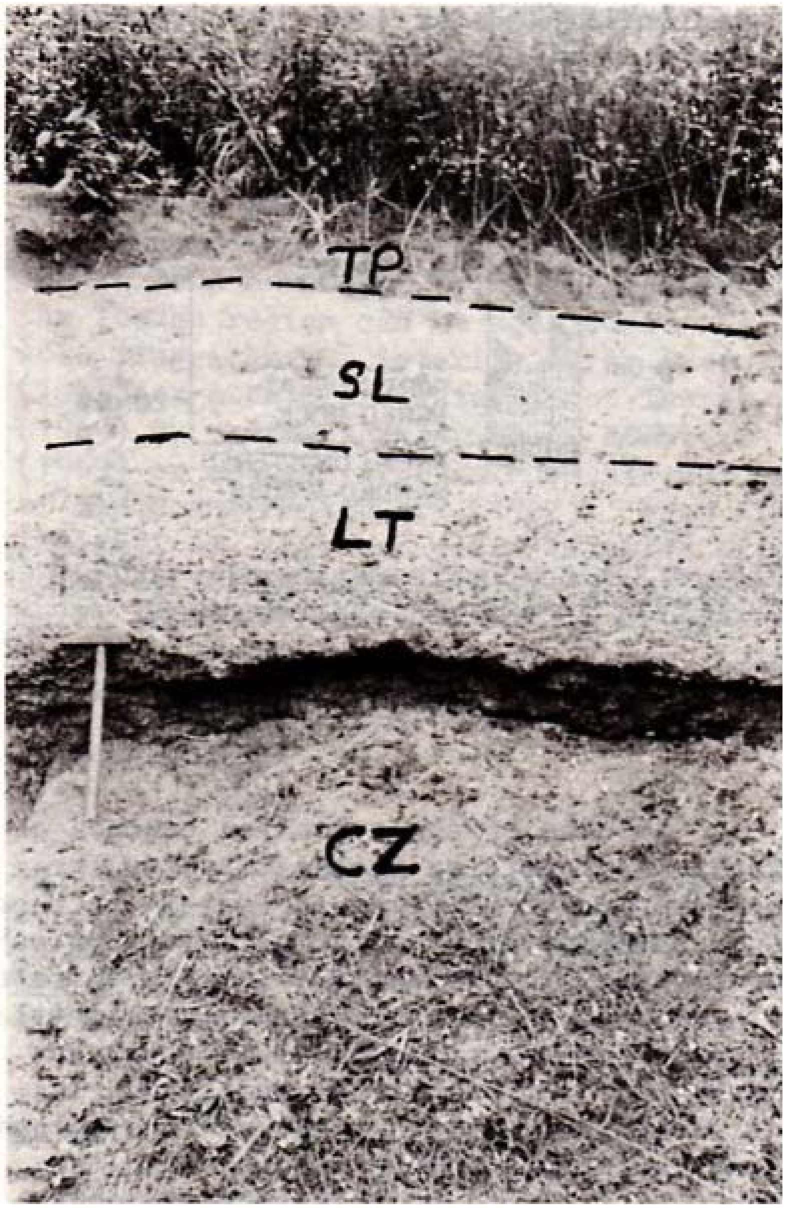
- The pallid or leached zone (rock suffering chemical and mineralogical changes, retaining physical appearance) overlying the parent rock.

The morphological, chemical, and mineralogical properties of the materials in the three horizons vary vertically and horizontally; and their thicknesses vary in relation to the degree of weathering of the parent rock, the intensity of lateritization processes as well as the physiographical characteristics of the terrain reflecting the drainage condition, Hamilton (1964). The soil profile is further partitioned into two: namely, zoned and unzoned profiles, described as duricrust and kaolinized, respectively (Adekoya 1987). The duricrust is composed of the following six soil layers as shown in Figure 3:

1. Top soil (termite soil)
2. Stone layer (gravelly soil layer)
3. Laterite (iron crust)
4. Clay zone (mottled zone)
5. Saprolite (pallid zone)
6. Partly weathered rock (weathering rock)

And the kaolinized profiles consist of:

1. Top soil (organic matter)
2. Undifferentiated clayey soil or latosol (brown or reddish brown with white patches)
3. Partly weathered rock



Source: Adekoya (1987)
TP=Top soil, SL=Stone layer, LT=Laterite, CZ=Clay zone

Figure 3 Zoned profile

2.3.2 Soil Chemical Composition and Mineralogy

The chemical composition and mineralogy of laterite soils is derived from the constituents of the parent rocks through the formation process. The constituent clay minerals are bound together by the oxides and hydroxides of iron and aluminum. The cementation forms a coating for the clayey constituents of the soil and further bound them into coarser aggregations which suppress the normal behavior of clay (Townsend et al., 1973), and determines the resistance to degradation of the soil grains (Malomo, 1989). Laterite soil chemistry and mineralogy is shown by studies to greatly influence the geotechnical properties, and in certain circumstances, significantly affects the economic potential in the construction industry (Ogunsanwo, 1995). Townsend (1973) describes the amorphous allophonic constituents as largely responsible for the exhibited physicochemical behavior of the soil, because of the large specific surfaces and high moisture-retention capabilities characteristic of these materials. This is confirmed by the crystallization of accumulated sesquioxides in the pore spaces which leads to bonding of soil elements and the formation of concretionary structure (Malomo, 1989). Studies reveal that mineralogy has very good correlation with the degree of weathering, as kaolinite content is high in early stages of weathering and decreases with increasing weathering; whereas the amount of sesquioxides increases (Tuncer and Lohnes, 1977). Furthermore, the silica/sesquioxide (SiO_2/R_2O_3) ratio provides a possible means of predicting the engineering characteristics of lateritic soils (Townsend et al., 1973), and the presence of iron gives it the reddish color.

Generally, residual soils are composed of silica (SiO_2), aluminum oxide (Al_2O_3), iron-III-oxide (Fe_2O_3), tin oxide (TiO_2), Magnesium oxide (MgO), calcium oxide (CaO), sodium oxide (Na_2O), potassium oxide (K_2O), and copper (Cu). Others are feldspar, quartz, kaolinite, muscovite, goethite, montmorillonite and traces of other clay minerals as may be found in the parent rock underlining the laterite soil formation. However, the proportions of these elements vary vertically and horizontally in any given formation, as while as, from region to region. An example of the influence of weathering on the chemical composition is the iron-oxide content, which is low in the lateritic shale (skeletal arrangement) but comparatively high in the sandstone (matrix arrangement) laterites (Madu, 1976 and Malomo, 1989). Specific composition of the mineral constituents in some laterite soils in Nigeria are shown Table 1 through Table 4 below.

Table 1: Mineralogy of the Bulk Samples

Locality	*Feldspar*	*Quartz*	*Kaolinite*	*Muscovite*	*Goethite*	*Others*
Ife-Ondo Rd.	-	40	25	30	Traces	Sillimanite 5
Ife-Akure Rd.	Traces	60	35	-	15	-
Unife	50	30	10	-	10	-
Ife-Ifewara Rd	30	Traces	55	5	10	-
Maryland	-	50	35	-	15	-

Source: Ogunsanwo 1995 (Western Nigerian Laterite Soils)

Table 2: Mineralogy (%) of the Clay Size Fraction (after removal of iron oxide)

Locality	*Feldspar*	*Quartz*	*Kaolinite*	*Muscovite*	*Montmorillonite*
Ife-Ondo Rd.	-	30	60	10	-
Ife-Akure Rd.	-	75	15	10	-
Unife	5	30	60	5	-
Ife-Ifewara Rd	5	5	90	Traces	Traces
Maryland	-	-	100	Traces	-

Source: Ogunsanwo 1995 (Western Nigerian Laterite Soils)

Table 3: Chemical Analysis (%) of the Bulk Samples

Elements	*Ife-Ondo Rd.*	*Ife-Akure Rd.*	*Maryland*	*Unife*	*Ife-Ifewara Rd.*
SiO_2	62.59	68.83	67.11	62.37	51.41
Al_2O_3	25.40	19.30	21.21	23.93	25.82
Fe_2O_3	3.87	2.36	5.87	5.30	12.52
TiO_2	0.47	0.64	0.90	0.64	0.81
MgO	-	-	-	-	0.19
CaO	0.49	0.62	0.32	0.17	0.57
Na_2O	-	-	-	0.11	0.13
K_2O	0.43	2.62	0.22	1.63	4.10
Cu	-	-	-	-	0.01
H_2O+	5.30	4.08	3.47	4.72	3.85
H_2O-	0.70	0.38	0.57	1.01	0.37
Total	99.25	98.83	99.67	99.88	99.78
Molecular					
(S)/(R)	3.85	5.75	4.68	4.00	2.61
SO^{2-}	-	-	-	-	500 ppm
Cl^-	-	-	-	-	-

Source: Ogunsanwo 1995 (Western Nigerian Laterite Soils)

Table 4: Chemical Composition of the Bulk Samples

Elements	*Onitsha*	*Imo Airport*	*Okigwe*
SiO_2	56.8	49.5	54.7
Fe_2O_3	6.45	5.98	4.75
Al_2O_3	17.6	12.3	11.5
CaO	0.01	0.01	0.01
MgO	0.106	0.059	0.054
MnO	0.017	0.015	0.010
TiO_2	1.27	0.801	0.754
K_2O	0.148	0.069	0.07
Na_2O	0.12	0.16	0.075
P_2O_5	0.13	0.20	0.10
LoI	4.44	5.29	5.14

Source: Nnadi 1988 (Eastern Nigerian Laterite Soils)

Chemical and microscopic investigations have shown that "lateritic clay differs from those commonly found in temperate regions. It does not contain of hydrous silicate of alumina, but is a mechanical mixture of fine grains of quartz with minute scales of hydrates of alumina. The latter are easily soluble in acid while clay is not, and after treating laterite with acids the alumina and iron leave the silica as a residue in the form of quartz. The alumina seems to be combined with variable proportions of water, probably as the minerals hydrargillite, diaspore and gibbsite, while the iron occurs as goethite, turgite, limonite, and hematite. There is a tendency for the superficial layers to become hard, probably by a loss of the water contained in these aluminous minerals. These chemical changes may be the cause of the frequent concretionary structure and veining in the laterite. The great abundance of alumina in some varieties of laterite is a consequence of the removal of the fine particles of gibbsite, hydrargillite, and diaspore from the quartz by the action of gentle currents of water.

2.3.3 Soil Physical Properties

The physical properties of residual soil vary from region to region due to the heterogeneous nature and highly variable degree of weathering controlled by regional climatic and topographic conditions, and the nature of bedrock, (Nnadi, 1988, Rahardjo et al., 2004). Studies have revealed that the variation in the properties of lateritic soils is greatly influenced by large amount of tropical rainfall combined with hot and climatic conditions which penetrates deep into the bedrock to a varying degree. Consequently, the physical properties of laterite soil vary vertically and horizontally with depth and from region to region. Research, (Tuncer et al., 1977 and Rahardjo et al., 2004), conducted on the effect of weathering on the physical properties of laterite soils reveal the followings:

1. Pore-size distribution varies with the degree of weathering.
2. Higher pore volume and larger range of pore-size distribution indicates advancement in the weathering stage.
3. Soil classification and Atterberg limits do not show any correlation to weathering.

4. High specific gravity is a good indication of advanced degree of weathering.
5. Soil aggregation increases with increasing weathering.

The composition of chemicals found in laterite soils tends to have varying effects. The iron oxide does not correlate with the physical properties but sesquioxides does, and consequently indicates that a decrease of the specific gravity is a result of decrease in sesquioxide content (Madu 1976). Tables 5 to 8 show some of the physical properties of laterite soils in different parts of the world with tropical climates.

Table 5: Physical Properties of Laterite Soils in Eastern Nigeria

Property	*Onitsha*	*Imo Airport*	*Okigwe*
HRB Classification	A-2-4	A-2-4	A-2-4
Unified System	SC-SM	SC-SM	SC
Sand %	63	75	65
Silt %	20	13	15
Clay %	17	12	20
Liquid Limit %	33.7	44.2	32.8
Plastic Limit %	16.4	23.2	17.6
Specific Gravity	2.65	2.64	2.74
Moisture Content %	8	7	6

Source: Nnadi 1988 (Eastern Nigerian Laterite Soils)

Table 6: Physical Properties of Laterite Soils in Hawaii

Property	*Unremolded*	*Remolded*	*Sesquioxide-Free*
Liquid Limit %	57.8	69.0	51.3
Plastic Limit %	39.5	40.1	32.1
Plasticity Index %	18.3	28.9	19.2
Specific Gravity	2.8	2.8	2.67
Proctor Density (pcf)	84.5	83.0	88.0
Optimum Moisture Content %	35.0	34.5	29.5

Source: Townsend and Manke 1971

Table 7: Physical and Geotechnical Characteristics of the Weathering Profile at Alapako, Nigeria

Weathering Zone	*Depth/ Thickness (cm)*	*Natural Moisture Content %*	*Atterbergs Limits (%)*			*Flow Index*	*Tough-ness Index*	*Linear Shrink-age*	*Specific Gravity*	*% Passing #200 mesh*	*% Gravel (> 200mm)*	*Optimum moisture content*	*Max. Dry Density tons/m³*	*CBR (unsoaked)*
			LL	*PL*	*PI*									
Top Soil	0 – 69	1.4	24	-	-	0.14	-	1.4	2.6	25.4	3.8	12.2	1.89	29
Stone layer	69 – 113	1.4	36	23	13	0.35	37	7.9	2.5	19.0	27.7	11.0	2.03	32
Laterite	113 – 155	0.9	41	25	16	0.03	533	8.6	2.5	28.1	20.0	12.2	2.00	47
Clay zone (upper part)	155 – 178	1.2	42	25	17	0.09	189	9.3	2.6	32.1	13.5	13.8	1.89	29
Clay zone (lower part)	178 – 195	1.0	41	24	17	0.27	63	9.3	2.5	42.1	7.8	13.6	1.84	31
Saprolite	195 – 236	6.7	44	24	20	0.21	95	7.9	2.6	54.1	4.5	7.6	2.12	27

Table 8: Physical and Geotechnical Characteristics of the Weathering Profile at Alomaja, Nigeria

Weathering Zone	*Depth/ Thickness (cm)*	*Natural Moisture Content %*	*Atterbergs Limits (%)*			*Flow Index*	*Tough-ness Index*	*Linear Shrink-Age*	*Specific Gravity*	*% Passing #200 mesh*	*% Gravel (> 200mm)*	*Optimum moisture content*	*Max. Dry Density tons/m³*	*CBR (unsoaked)*
			LL	*PL*	*PI*									
Top Soil	0 – 40	1.8	24	20	20	0.39	51	16	2.6	20.7	39.1	9.6	2.02	22
Stone layer	40 – 80	2.4	46	21	25	0.26	96	10	2.7	32.1	11.6	11.6	1.92	24
Laterite (clayey)	80 – 120	2.8	52	25	27	0.44	61	12	2.7	19.7	49.7	11.2	2.00	44
Clay zone	120 – 160	2.8	65	30	35	0.33	106	14	2.6	44.6	9.9	14.1	1.90	18
Saprolite	160 – 200	4.8	61	29	32	0.25	126	11	2.7	47.4	7.7	16.8	1.74	25

Source: Adekoya 1987 (Southwest Nigeria).

2.4 Geotechnical Properties of Laterite Soils

The effect of weathering on laterite soils is of paramount importance to the geotechnical engineer, as the engineering properties are significantly affected by various constituents of laterite soils and their response to the climate. Research has shown that laterite soils possess very favorable geotechnical properties, and this is evident in the widespread use of the material in the construction industry. Most of the engineering structures such as earth dams, embankments, roads, and high-rise structures are made or founded on this soil type. However, there exist some problems which need to be identified and adequate responses in order to taken avert any catastrophic failure. In particular, the role of effective stress and high degree of saturation needs to be investigated. An overview of the responses of the different engineering properties and the significant contributions made is presented.

2.4.1 Density

Laterite soils tend to increase in density as the void ratio decreases with depth reflecting the degree of weathering (Rahardjo et al., 2004). The leaching of minerals from the soil leads to a porous structure that traps water and air in the porous micro-aggregations created by weathering. As a result, the upper layers have higher void ratio and porosity combining to produce a lower density. However, with increase in depth, porosity decreases resulting in a higher density. Thus, the low density is attributable to the granular nature, and with increasing depth laterite soils tend to have finer particles because of the breakdown of the granular structure by the removal of the sesquioxides cementing agents (Townsend et al., 1973). In addition, the soft and friable nature of the laterite soil allows the granular particles to breakdown, thus increases the percentage of finer particles. This is readily achievable in remolded soils, as remolding significantly affects the textural characteristics and plasticity of the soil (Townsend et al., 1973). Table 6 shows the effect of remolded, unremolded, and sesquioxide-free laterite soils. The dry density of the remolded soils is only slightly smaller than their Proctor maximum dry densities (Ogunsanwo, 1993).

2.4.2 Compressibility

Laterite soils in an undisturbed state exhibits macro-structure which is destroyed on compaction. The compacted laterite soil have appreciable improvements in the unit weight, void ratio, compression index, coefficient of permeability, and cohesion (Ogunsanwo, 1990). The compressibility of compacted residual soils is generally low and the settlement is within the elastic zone. Therefore, collapse occurs after saturation at high applied pressure in soils compacted dry of optimum indicating probable loss of suction (Nnadi, 1988). Laterite soils compacted dry of optimum deform gradually up to a pressure equivalent to that induced by compaction. Beyond this critical pressure, rapid deformation occurs. However, when laterite soils are compacted wet of optimum to the same density it shows a steady deformation, but at high pressure both behave comparably indicating similarity in microstructure (Nnadi, 1988).

2.4.3 Permeability

Soil structure, in the form of pore-sizes, is regarded as the notable single variable influencing permeability. This is because of the interconnected voids through which water flows. Permeability is an important factor necessary to determine the suitability of various soil types to engineering works. Field permeability of laterite soils is usually high due to the cemented particle aggregates and clusters, and other microstructures. However, the reality is different as the leaching of fines combined with the effect of weathering with depth fills up the pores (Nnadi, 1988). The permeability becomes lower with increase in depth. This is an example of the influence of weathering. Also, laterite soils with matrix microstructure are dense and expected to have lower permeability (Malomo, 1989). Furthermore, when compacted, laterite soils have very low permeability and possess medium to low compressibility (Ogunsanwo, 1989). Tropical residual soils compacted dry generally presents a higher permeability with the least at the optimum water content. In effect, there is a gradually reduction in the permeability as the saturation of the compacted soil increases, but at degree of saturation of 90 percent and beyond, the reduction is abrupt (Nnadi, 1988). Table 9 shows the permeability of some in situ and compacted laterite soils.

Table 9: In-situ and Compacted Permeability of Some Tropical Laterite Soils

Soil Type	*Location*	*Clay Content (%)*	*Permeability (cm/sec)*		*Reference*
			Compacted	*In situ*	
Red Residual soil	Kenya	78 -90	10^{-7}	10^{-4}	Foss, 1973
Lateritic Soil	Nigeria	N.A	10^{-6} to 10^{-10}	N.A	Ola, 1980
Granitic Laterite	Venezuela	N.A	10^{-6}	10^{-4}	Prusza, 1983
Cenozoic	Brazil	10 – 40	N.A	10^{-3} - 10^{-4}	Villar, 1985
Amphibolites	Nigeria	60	*1.17 x 10^{-9}	1.7 x 10^{-6} - 1.3 x 10^{-6}	Ogunsanwo, 1985 & 1989
Latosol	Brazil	68	6.2-1.3 x 10^{-8}	1.5 x 10^{-5}	Dias & Gonzales 1985
Lateritic Soil	Nigeria	15 – 20	10^{-7} – 10^{-8}	N.A	Nnadi, 1987
* Bukit Timah & Jurong	Singapore		N.A	7 – 0.3 x 10^{-9}	Rahardjo, 2004

Source: Nnadi 1988. *Not reported in Nnadi 1988. N.A – Not available.

2.4.4 Shear Strength

Shear strength parameters, such as cohesion and internal friction angle of laterite soils have systematic trends with increasing degree of weathering. Cohesion increases with decreasing void ratio, and internal friction angle increases as the specific gravity increases (Tuncer and Lohnes, 1977). Thus, weathering and shear strength parameters of laterite soils have an inverse relationship. That is, the shear strength parameters tend to increase with depth as weathering decreases with depth (Rahardjo et al., 2004). However, the effective cohesion decreases as the degree of weathering decreases with depth due to decrease in fines content. Conversely, the effective internal friction angle increases with depth as the coarse particles increases.

It can be concluded that the magnitude of the effective internal friction angle is subject to the texture, size, and distribution of soil particles (Rahardjo et al., 2004), which in turn are related to the degree of weathering and depth of soil profile. Figure 10 shows the shear strength parameters of compacted laterite soils. It could be observed that the effective cohesion reduces and the effective internal friction angle increases for the different laterite soils.

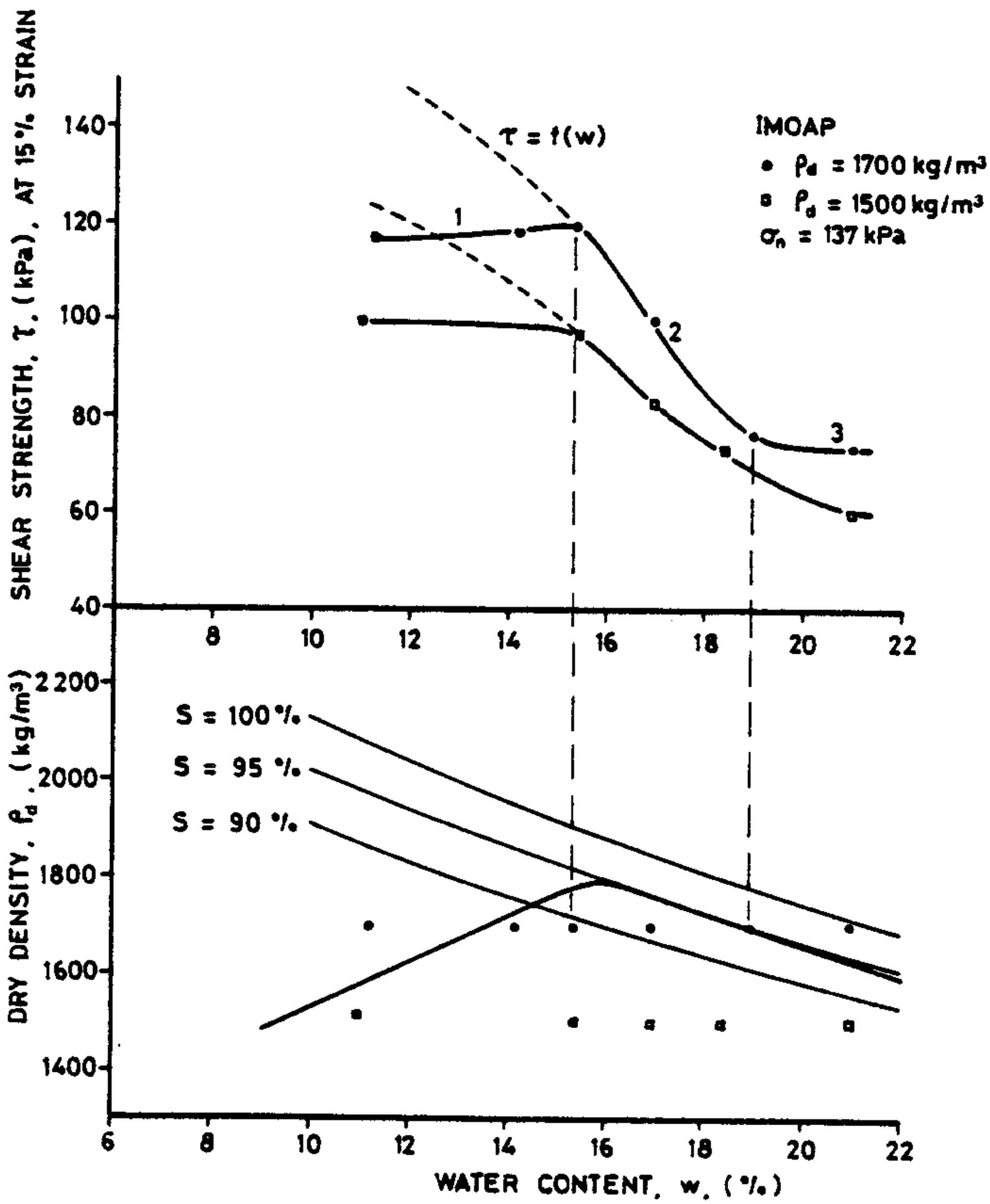
Table 10: Shear Strength Parameters of Compacted Laterite Soils

Parent Material	*ϕ (deg)*	*c (kPa)*	*ϕ' (deg)*	*c' (kPa)*
Quartz schist	22	43	31	15
Mica schist	26	70	31	35
Granite gneiss	22	28	30	15
Amphibolites	17	92	27	45
Benin sand	17	58	26	26

ϕ, ϕ' = Friction angle under total, effective stress conditions.
c, c′ = Cohesion under total, effective stress conditions. Source: Ogunsanwo 1989

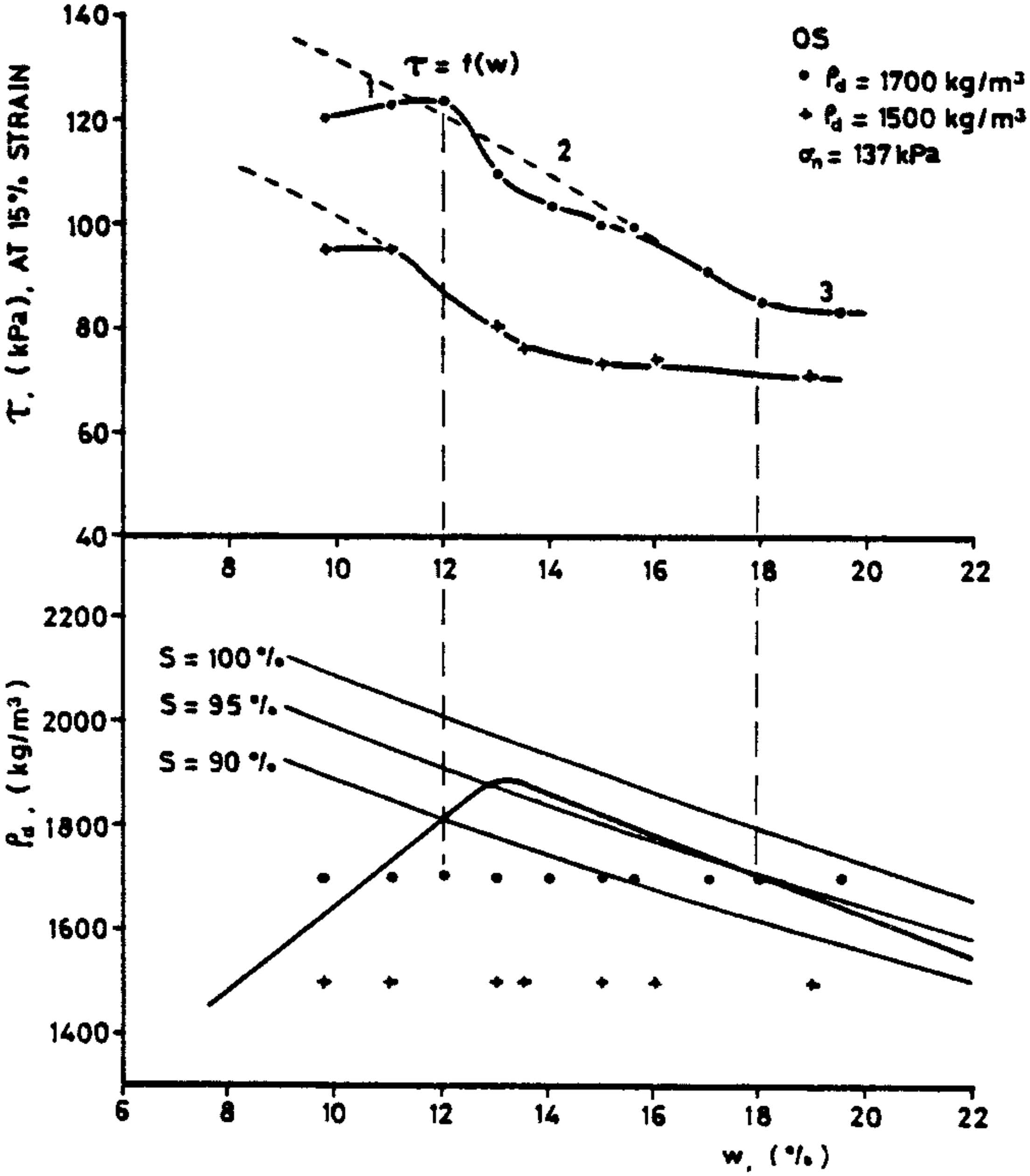
Shear strength parameters are also influenced by the mineralogy and chemical composition of the laterite soil. Cohesion increases with increasing kaolinite content, and the internal friction angle increases with increasing sesquioxides content. The high angles of internal friction reflect a greater amount of interlocking than is normally found in soils having such a proportion of platy minerals (Townsend et al., 1973). Furthermore, the shear strength of laterite soils decreases with water content. The shear strength is a function of water content, nature of particles, normal effective stress, and composition of dissolved salt, but at 95 percent degree of saturation it becomes a function of degree of orientation and the angle of friction (Nnadi, 1988).

The shear strength of laterite soils reduces on inundation and has led to drastic reduction of stability capacity, thus resulted in failure of embankments and foundations. The influence of water on the shear strength of laterite soil studied at 15 percent strain is shown in Figures 4 (a) and (b).



(Source: Nnadi, 1988)

(a)

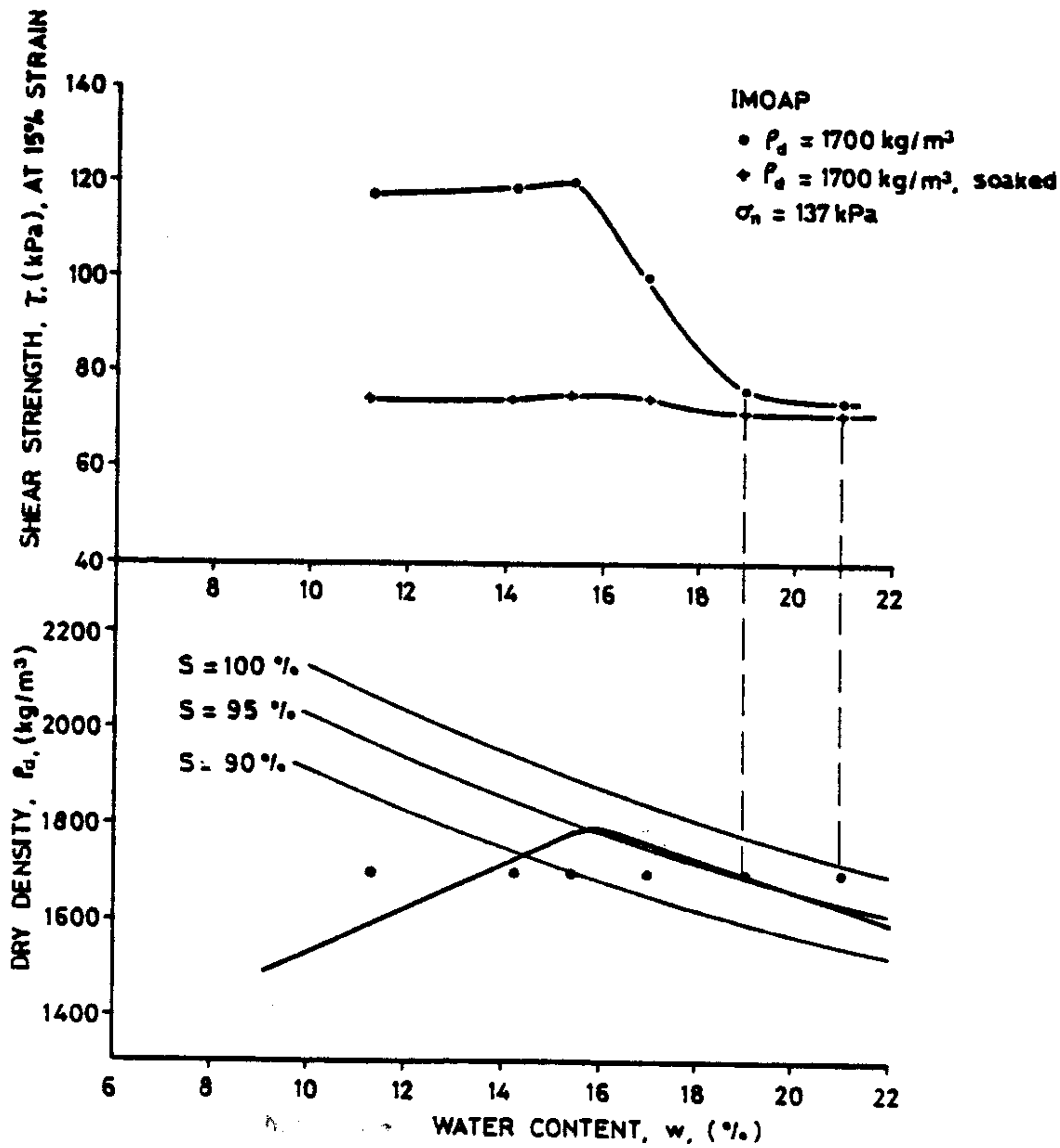


(Source: Nnadi 1988)

(b)

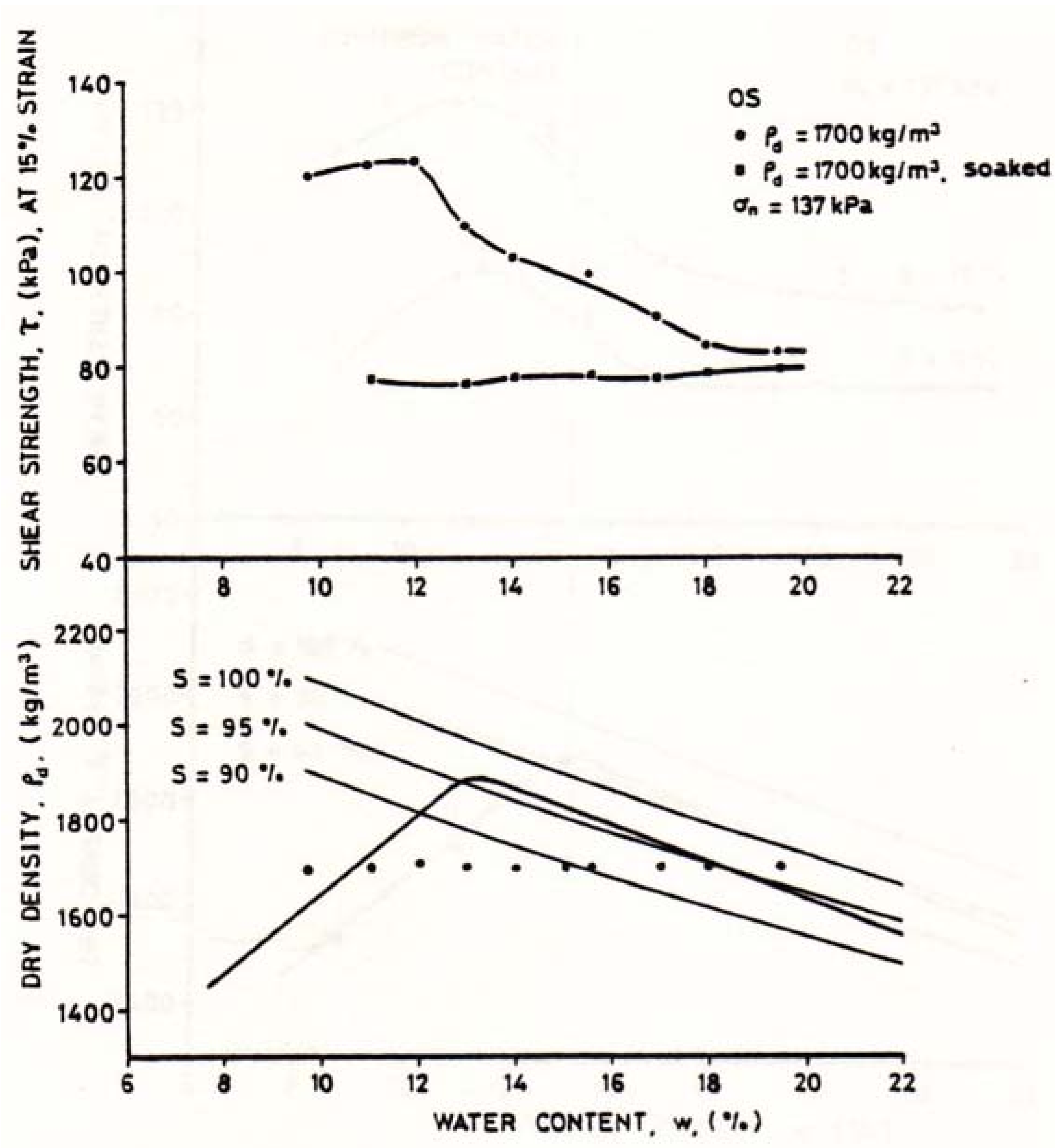
Figure 4: Influence of water content on shear strength at constant density

The plots in the Figures are for two separate samples obtained from different locations in eastern Nigeria. Plots of shear strength against water content for constant densities of 1500 kg/m^3 and 1700 kg/m^3, and normal stress kept constant at 137 kPa reveal that shear strength is higher in laterite soils compacted dry of optimum water content. The dashed curve means decrease in the shear strength as the water content increases. Further increase of the water content alters the structure of the compacted soil along the shear zone from random to parallel arrangement. This study holds for soils between 90 to 95 percent degree of saturation. Under this critical range of degree of saturation, factors such as the nature of particles, normal effective stress, and composition of dissolved salts compensate for the effect of water content (Nnadi, 1988). Above this critical range, the compacted soil assumes a parallel structural arrangement and the shear strength does not depend on water content but on the degree of orientation and angle of internal friction of the soil. This is clearly shown in Figures 5a and 5b as the shear strength of the compacted laterite soil sample submerged is not affected by the water content.



(Source: Nnadi 1988)

(a)

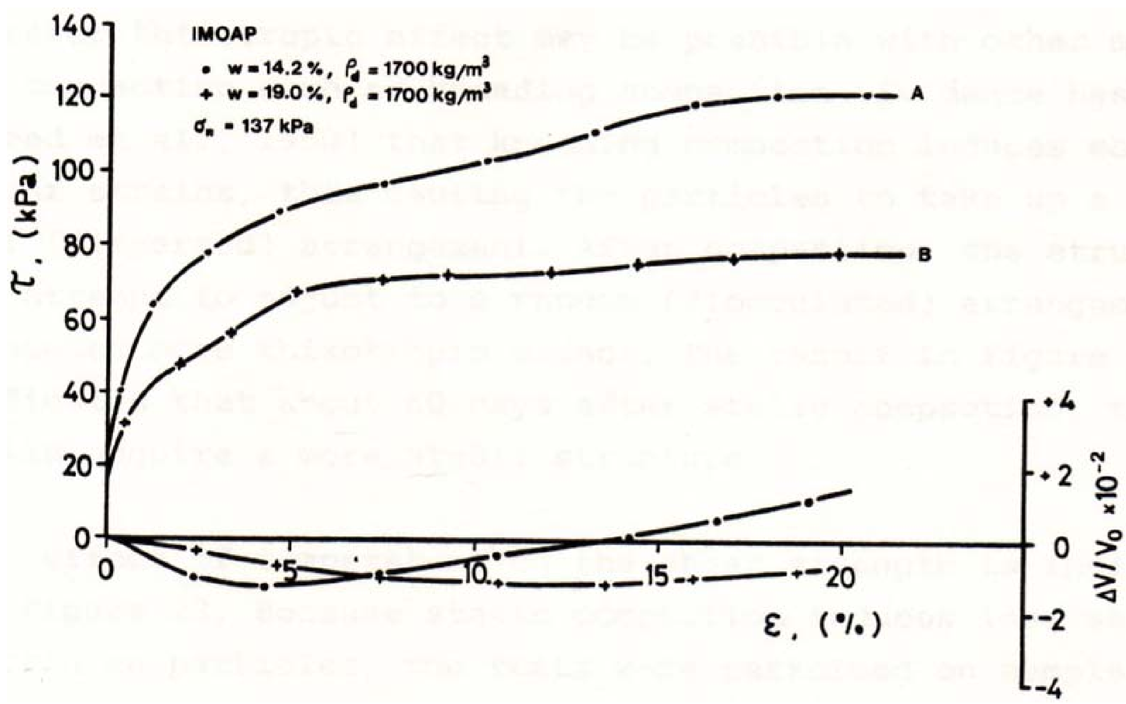


(Source: Nnadi 1988)

(b)

Figure 5: Effects of water contents on soaked samples at constant density

Temperature also affects the shear strength of laterite soils at lower strain. However, the effect is negligible as the strain increases (Nnadi, 1988). It is important to note that the laterite soil has two limiting microstructure conditions, namely the random and parallel arrangements, which are independent of the nature and amount of compaction (Nnadi, 1985). However, the effect of saturation on these limiting arrangements is profound, as it is evident that an increase in saturation tends to change the microstructure from random to parallel arrangement, which reduces the shear strength of the laterite soil (Nnadi, 1988). Figure 6 shows the influence of soil structure on the shear strength and volume change characteristics of two samples compacted dry of the optimum water content on the same density.



(Source: Nnadi 1988).

Figure 6 Influence of microstructure on shear strength and volume change characteristics

Sample *A* represents soil with random structure arrangement and sample *B* represents a soil with parallel structure arrangement. Both samples increase in strength as the strain increases, however, the rate of plastic strain hardening is higher in soil *A*. Above 15 percent strain value, both *A* and *B* maintain the same rate of plastic strain hardening. This suggest that the particles are oriented in the direction of motion, and consequently, the structure in the shear zone gradually changes from random to parallel arrangement as strain increases.

These studies reveal that the structure of the laterite soil, more than anything else, significantly affects the shear strength. The laterite soil readily changes its structure from random to parallel arrangement thus loses its cohesiveness and increases the internal friction angle. The change in structure with the resultant reduction of its strength could be attributed to the unpredictable nature of laterite soil in the long-term and at full saturation. Thus, this thesis aims to investigate the effect of microstructure change of compacted laterite soil embankments.

2.5 Geographic Information System

ArcView is a powerful, easy-to-use tool that brings geographic information to our desktop, and provides the enablement to visualize, explore, query and analyze data spatially (ArcView Guide Manual, 1995). ArcView is made by Environmental Systems Research Institute (ESRI), the makers of ARC/INFO, the leading geographic information system (GIS) software. Geography is a framework for organizing global knowledge, and GIS is a technology that

- Allows for the creation, management, publication, and dissemination of this knowledge for all of society.
- Manages, analyzes, and disseminates geographic knowledge.
- Used to view and analyze data from a geographic perspective.

- Links location to information (such as people to addresses, buildings to parcels, or streets within a network) and layers that information to give a better understanding of how it all interrelates.

Geographic information systems are most often used extensively in various applications like land-use, transportation, and natural resource assessment. The three ways GIS can be used to work with geographic information are:

1. *Database View*: A GIS is a unique kind of database of the world—a geographic database (geodatabase). It is an "Information System for Geography." Fundamentally, a GIS is based on a structured database that describes the world in geographic terms.
2. *Map View*: A GIS is a set of intelligent maps and other views that show features and feature relationships on the earth's surface. Maps of the underlying geographic information can be constructed and used as "windows into the database" to support queries, analysis, and editing of the information. This is called geovisualization.
3. *Model View*: A GIS is a set of information transformation tools that derive new geographic datasets from existing datasets. These geoprocessing functions take information from existing datasets, apply analytic functions, and write results into new derived datasets.

The combinations of these three views constitute a critical part of an intelligent geographic information system and are used at varying levels in all its applications.

The fundamental process of geographic information system involves the application of the tool to answer questions and make decisions. Therefore, it is important to know what you want to ask and follow a disciplined process for getting the answer. This could be achieved by framing the question, selecting the data, choosing an analysis method, processing the data, and looking for the results. It serves as a reservoir of world database for all kinds of information.

Most planning information has spatial orientation. The spatial feature of planning information is essential for acquiring knowledge necessary for public use. The geographic information systems (GIS) will be employed in this thesis to answer to spatial queries using the latitude and longitude data of localities within Nigeria where laterite soil properties have been obtained to manage and link the different data sets. The GIS will be used to integrate map (digital) data with attribute (tabular) data using different matching methods. Thus, the GIS will be used to create a database of geotechnical properties of laterite soils in Nigeria linked to the geographic location of the region where the soil samples were obtained.

2.6 Slope/W Computer Program

SLOPE/W is one of the powerful software products for slope stability analysis, using limit equilibrium theory to compute the factor of safety of earth and rock slopes. SLOPE/W is a 32-bit, graphic software product that operates under Microsoft Windows, and is comprehensively formulated to easily analyze both simple and complex slope stability problems using a variety of methods to calculate the factor of safety. It is equipped to model heterogeneous soil types, complex stratigraphic and slip surface geometry, and variable pore-water pressure conditions using a large selection of soil models. Furthermore, it is designed to handle almost any slope stability analysis, using either the deterministic or probabilistic input parameters.

The SLOPE/W software is capable of analyzing the following models of embankment slope, listed for clarity:

- Heterogeneous Slope Overlying Bedrock (Figure 7)
- Block Failure Analysis
- External Loads and Reinforcements
- Complex Pore-Water Pressure Condition
- Stability Analysis Using Finite Element Stress
- Dynamic Stability Analysis Using QUAKE Stress
- Probabilistic Stability Analysis (Figure 8)

Figure 7 shows a typical output of the SLOPE/W slope stability analysis software displaying a multilayer soil profile, water table, slip surface and grid, and the minimum factor of safety of an embankment analyzed.

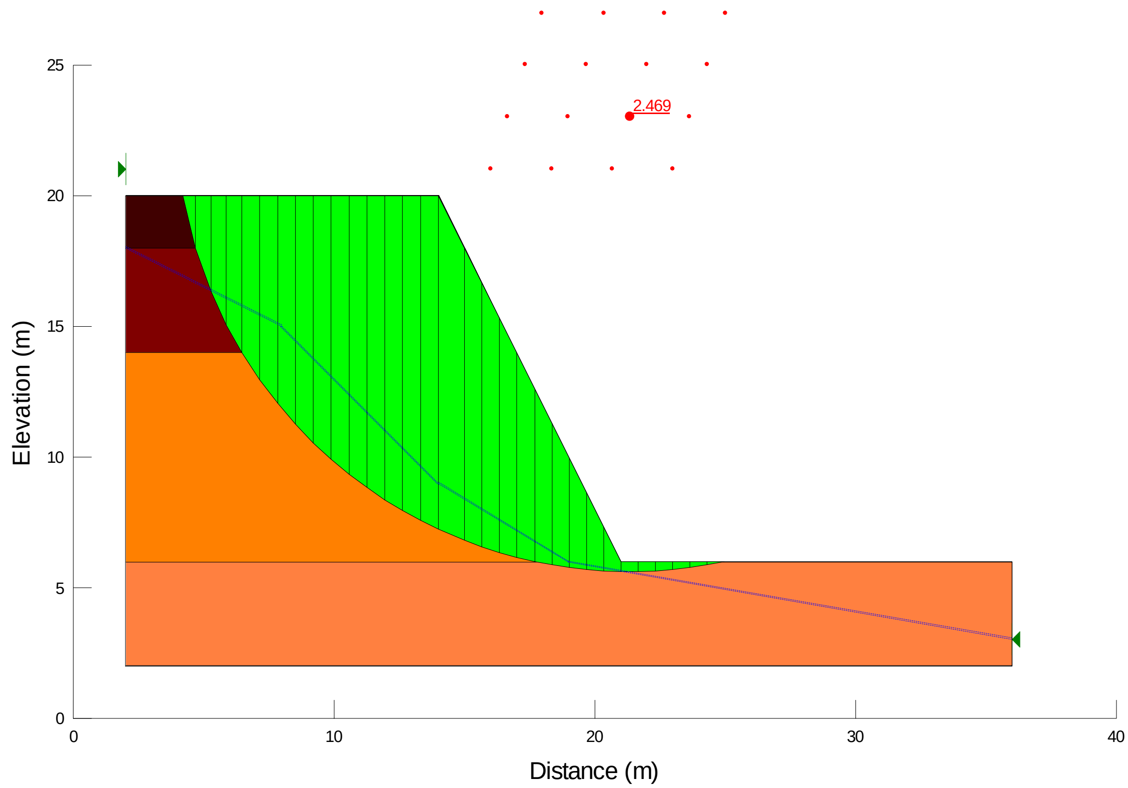


Figure 7 Heterogeneous Slope Overlying Bedrock

The features and capabilities of the SLOPE/W slope stability analysis software includes:

- Definition of the problem using CAD-like functionality on a graphical interface, which include sketch graphics, text and import pictures, graphical problem definition and editing, and graphical and keyboard editing of functions.
- Computation of the factor of safety for all specified trial slips surfaces; for probabilistic analyses, the Monte Carlos techniques applied.
- Graphical view of the results, which include the factor of safety and the associated critical surface, contour factor of safety values, slice forces, probability distributions, and export computed data and plots.

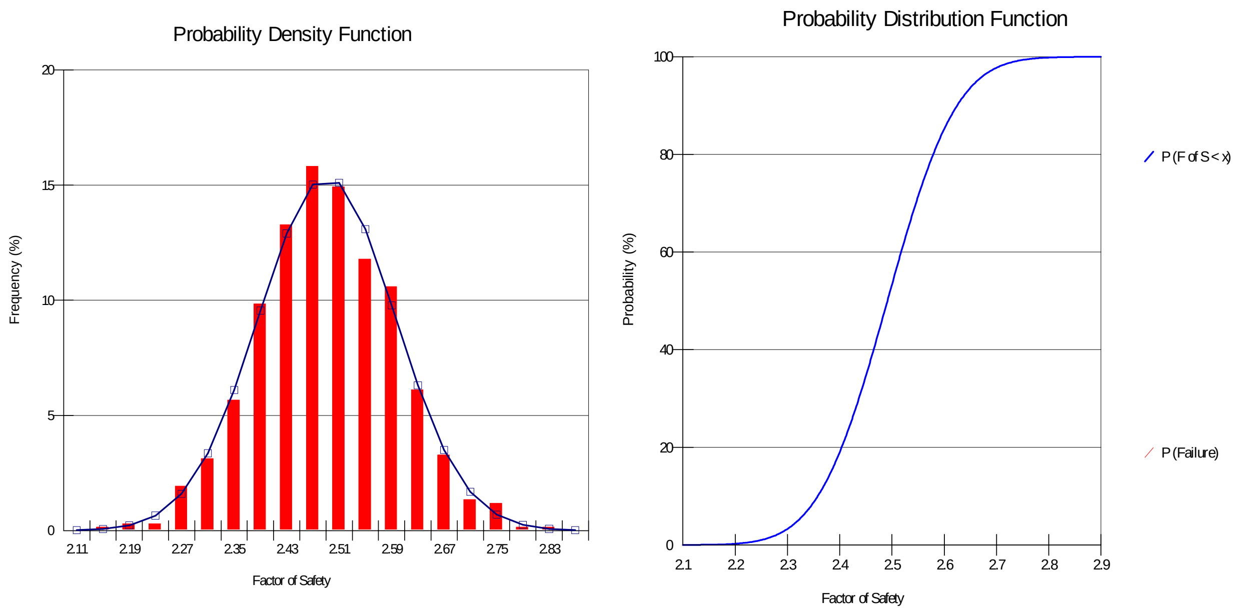


Figure 8: Probability Density and Distribution Functions

The following analysis methods are employed by the SLOPE/W for stability analysis: Ordinary (or Fellenius) method, Bishop Simplified method, Janbu Simplified method, Spencer method, Morgenstern-Price method, Corps of Engineers method, Lowe-Karafiath method, generalized limit equilibrium (GLE) method, and the Finite element stress method. In addition, a probabilistic slope stability analyses (Monte Carlos technique) is incorporated in the software to account for variability and uncertainty associated with the input parameters. Furthermore, an array of slope geometry and stratigraphy can be modeled with this software. These are multiple soil types, partial submergence in water, variable thickness and discontinuous soil strata, impenetrable soil layers, and tension cracks. The reliability of the functionality of the software could be confirmed by hand calculations, and the software accurately predicts the factor of safety for the various analysis methods in SLOPE/W.

The SLOPE/W slope stability analysis provides for the modeling of different properties of the laterite soil. Such properties as the unit weight, cohesion, and internal friction angle, and variable groundwater level will be modeled to simulate the soil properties and their responses. In addition, the SLOPE/W software program models laterite soil conditions in unsaturated for both total and effective stress parameters, and in saturated state for different embankment geometry. SLOPE/W computes the factors of safety for any geometry of embankment using these methods of analyses, Ordinary (Fellenius) method, Bishop Simplified method, Janbu Simplified method, and Morgenstern-Price method. The minimum factor of safety for each set of shear parameters is computed and the mean factor of safety for the variable water table level obtained.

CHAPTER THREE: METHODOLOGY

3.1 Modeling Concept

This chapter will provide an overview of the strategy which was employed to conduct the research and the procedures required in achieving the research goals. The research is intended to develop a database within a geographic information system (GIS) of the nature and engineering properties of laterite soils, followed by a parametric study of slope failure criteria in Nigeria.

The primary objective of this study is to create a database with spatial data (geotechnical properties) linked to location and a parametric study of the stability of embankments made of compacted laterite soils in Nigeria. The essence is to provide an access database of the geotechnical properties of laterite soils in Nigeria to all would-be users in the future and also provide a basis for a better understanding of the Nigerian laterite soil. It is intended to equip the geotechnical engineers with quick information guide to the actual properties, such as soil types. These properties vary vertically and horizontally in the different regions. Consequently, this will aid in future knowledge availability, accessibility, and usability.

The process of developing the geographic information system involved the following questions:

1. What geotechnical properties of laterite soils were needed to establish the database?
2. Where the laterite soils could be found?
3. How could the needed data be collected?

4. What analysis method best suited the desired objective?
5. How could the data be processed with the available information?
6. How best to create a database containing all needed information, and makes it easily accessible?

Each step is necessary for the success of the overall research goal, and needs to be properly and conscientiously executed.

On the other hand, the parametric study on slope stability based on the available shear strength parameters was intended to give a general overview of the stability of slopes exposed to varying severe but acceptable conditions. This is also very important to the geotechnical engineer as it gives a quick guide to the likely problems expected in the designing, constructing, and maintaining of embankments in Nigeria, based on the shear strength parameters. The results of the parametric study were intended to be provided on the database for easy accessibility and referencing.

This research was not modeled to erode other studies of their information on the geotechnical properties of laterite soils in Nigeria or anywhere else, but conceived to have a collection of the different research findings in the geographic information systems and provide internet accessible piece of geotechnical properties of laterite soils in Nigeria. The centerpiece of all the findings for the different regions within Nigeria would be made available to all around the world with full acknowledgement and references to the original researchers of the information in the geographic information system (GIS).

3.2 Modeling Approach

Fundamentally, this is a research conceived to build on past research findings. It explores the possibility of presenting the properties of laterite soils in Nigeria as a web-base tool for engineering usage. The research is important to geotechnical engineers as spatial features of planning information is essential for acquiring knowledge necessary for public participation in the planning and designing process. The study uses the conclusions of a distinct group of research publications limited to the Nigerian laterite soil and to specific locations within the country to establish the database of information. Secondly, the variable nature of the published soil parameters requires the use of probabilistic analysis approach to conduct the parametric study on the slope stability analysis.

This study was conducted in three stages and involved an in-depth review of the geotechnical properties identifiable in laterite soils. The first stage involves a detailed review of published literature on laterite (residual) soils around the world on issues prevalent and relevant to this soil type. These are pertinent issues worth the interest of geotechnical engineering in establishing adequate information, as there is the dearth of detailed data on the laterite soil. The research focused on identification of the laterite soil location around the world, what constitute a laterite soil, its formation process, the properties (both physical and geotechnical), the responses of these soils, and identifiable problems associated with the laterite soils. Specific attention was placed on the laterite soil types found in Nigeria, as these are among the least studied by researchers. The information garnered from this portion of the study is reflected in the literature review.

Stage two consisted of the creation of a geographic information system (GIS) database of the geotechnical properties of laterite soils in Nigeria. The information derived from the reviewed literature were adapted and used in the creation of the GIS database. These data were linked to geographic locations of samples identifiable by the longitude and latitude of the towns. The first stage provided the necessary background information to develop the GIS database of stage two and the framework for the parametric study in stage three.

The third stage was developed from the information derived from stages one and two. These were adapted for the parametric study on the factor of safety of embankments made of compacted laterite soils in Nigeria. The collected information were analyzed and finally added to the GIS database.

The overall research design for this study were both descriptive, in that it made use of publications on researches on laterite, and analytic, in that a parametric analysis of the stability of the slope was conducted. The literature review sought to identify the properties of the laterite soils with regard to its implementation in the GIS database and analyses.

3.2.1 Geographic Information System (GIS) Models

The Geographic Information System (GIS) model consisted mainly of the design of a database for the laterite soils in Nigeria. It is employed as a technological tool to organize available information and mapping of laterite soils in Nigeria. The application of this tool was categorized into five interconnected stages to provide a detail information and mapping.

The first category involves the framing of the question, which in this study was the research goal – provide a database that is accessible in today's technology based world (Information Technology). The need to provide the database inspired the search for a tool that is relevant, usable, and adaptable. The tool that suits this need was the ArcView GIS created by Environmental Systems Research Institute (ESRI). The features and interfaces have already been listed in the literature review.

In response to the question in category one, the investigation was geared at obtaining the relevant data needed to achieve the purpose of the research. The information needed is the data type and the features required to establish the data. The initial data for this category were derived from the review of the literature pertaining to laterite soils in Nigeria, including but not limited to the chemical composition and mineralogy, physical and geotechnical properties, and the exact locations of where the soil tests and results were obtained. An overview of the literature can be found in chapter two of this study.

As a follow up to the data type – category two – an analysis method requiring the selection and sorting of the available data was applied. This involves the identification of reliable geotechnical and physical properties, the regions and parent materials, and the mineralogy and chemical compositions of the laterite soil in Nigeria. This was necessitated by the fact that some of the required information was not clearly tabulated for easy referencing, but needed to be plotted out from their concealed graphical sources. On the other hand, in order for the data processed to be functional the GIS require explicit data (longitude and latitude). The detailed information related to the locations of the towns and cities were obtained from internet records of United State Geological

Survey (USGS) sites. With these obtained, georeferencing of the different features needed were clearly tabulated for a meaningful combinations of the relationships and the spatial data organized thematically into different layers, or themes. A theme represents one set of geographic features or phenomena for which information are recorded.

The results were displayed both in digital map for easy accessibility and printed as a paper map for the record of the research. In addition, the results of the geotechnical properties of laterite soils in Nigeria were tabulated and could be viewed each time.

3.2.2 Slope Stability Analysis by Computer Program

This stage of the research provided a key bridge between the initial gathering of information with regards to geographic information systems and the final analysis applying the information garnered. At this stage, key geotechnical properties of the laterite soils in the different parts of Nigeria were obtained and modeled in the slope stability analyses. The soil properties studied include cohesion, internal friction angle, density, and the effect of water to these properties processed. These were then modeled into the SLOPE/W software for a probabilistic analysis, using the Monte Carlos technique. The Monte Carlos technique was adopted because of the variability of the test results and the need to estimate rather than pinpoint a specific factor of safety for any of the given combination of factors.

Modeling involves the simulation of the geotechnical properties and inputting them in the SLOPE/W software to evaluate actual responses. The SLOPE/W software provided a powerful design tool with the aid of the Computer Aided Drafting, CAD-like functionality to graphically represent the real-world soil conditions and properties of the laterite soil in different parts of Nigeria. The steps required for the modeled embankments were as follows.

Definition of the Problem

This included the followings steps:

- An initial set up of the working area, scale, and grid spacing were specified, and the files were saved.
- The embankment geometry, such as slopes of 1:1, 2:1, and 3:1, respectively, were sketched and later drawn on the graphic interface of SLOPE/W.
- Analysis methods and options were selected. In this section, Ordinary, Bishop, Janbu, and Morgenstern-Price analysis method, pore-water pressure with piezometric lines, probabilistic analysis and Monte Carlos trial number, grid and radius surface option, and left to right direction of movement were selected.
- The soil properties were defined for the Mohr-Coulomb strength model chosen. These were the input parameters for cohesion, unit weight, internal friction angle, and the standard deviation values for the basic parameters.
- The piezometric lines were drawn for the analysis with water tables.
- Slip surface radius and grid lines were then specified and drawn.

A view of typical section is shown in Figure 9.

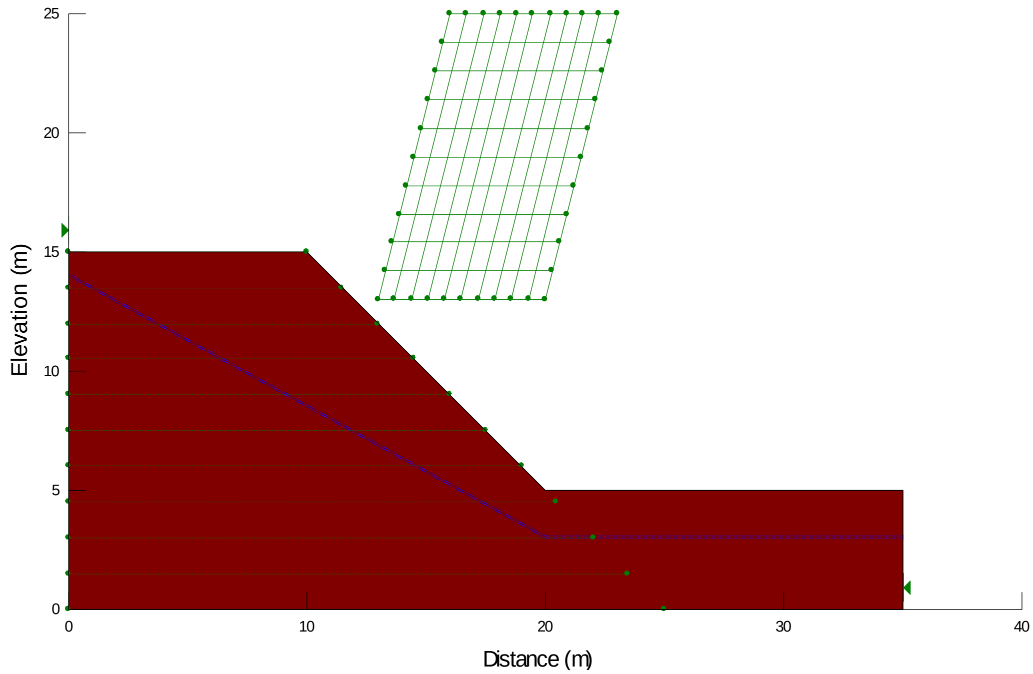


Figure 9: View of the Slip, Surface and Grid, Pore-water Pressure line and Slope Section

Solving the Problem

This section of the analysis was used to compute the minimum factor of safety for the different analyses methods displayed. SLOPE/W software computes a network of safety factors based on an initially specified mesh of probe locations. It then provides the value of the minimum factor of safety, as shown in Figure 10.

Viewing the Results

At this stage of the analysis, the resulting analyzed slip surface associated with the minimum factor of safety was displayed in Figure 10.

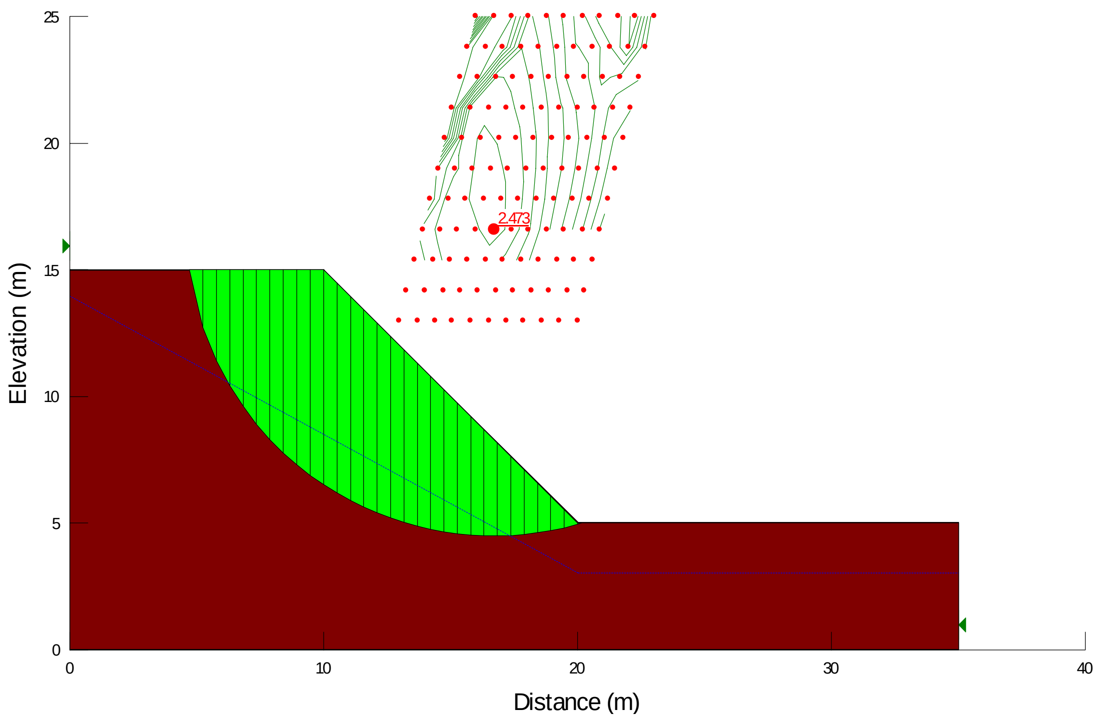


Figure 10: View of the slip surface, contour, and factor of safety of a typical section

For the probabilistic analysis, the probability density and distribution function charts were employed in analyzing the distribution of the factor of safety as regards the standard deviation values for the parameters varied.

3.2.3 Data Management

The final stage of this study consisted of a parametric study for determining the factor of safety of embankments for different geometric configurations. The shear strength parameters for the parametric study were varied for total and effective stress methods, and for saturated and unsaturated soil conditions. The factors of safety calculated are presented as a function of against the different parameters used and plots of these are created and discussed. It is necessary to conduct this parametric study to investigate the stability of embankments for both short and long term soil stress conditions, and the effect of saturation on embankments of laterite soils. The shear strength parameters used were obtained from the various investigations on laterite soils.

The study is conducted in two parts – actual investigation of the stability of embankments with total and effective shear stress parameter on the factor of safety and the parametric investigation on the effect of saturation. In the first part, the results calculated are plotted against factor of safety and the response to different embankment geometry configurations are investigated and discussed. In the second part, the cohesion value for given shear strength are determined by back calculation for different internal friction angles. These are inputted and the factor safety calculated plotted against the internal friction angles to check the sensitivity to saturated soil conditions. Consequently, the change in the factor of safety for both the unsaturated and saturated soil conditions are compared to identify the response of laterite soils to inundation and the stability of slope saturated due to flooding or rise in groundwater table.

CHAPTER FOUR: FINDINGS

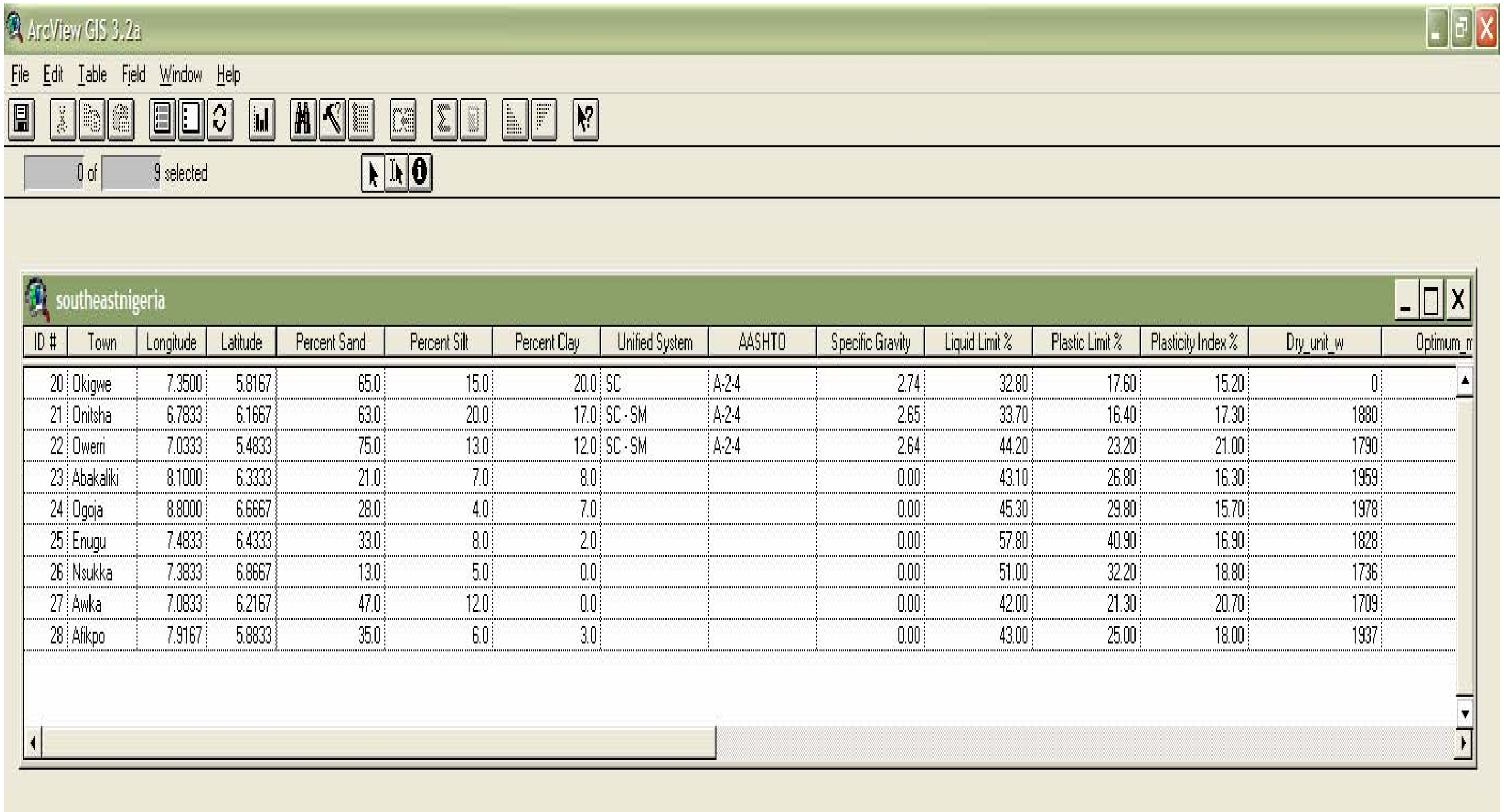
This chapter presents the results of the spatial data, digital images, and views of the geographic information system (GIS) database. In addition, it also presents the results of the slope stability analyses conducted as the basis for the parametric study and the plots of these comparative investigations. Analysis of the results obtained from the parametric study is provided to study the variation of shear strength parameters and the findings are discussed. Detailed description of the methods and procedures explored in chapter three will be presented and discussion on these will follow each presentation.

4.1 Geographic Information System (GIS) Database and Outputs

Geographic Information Systems (GIS) are "... computer-based information systems that attempt to capture, store, manipulate, analyze and display geographically referenced and associated tabular attribute data, for solving complex research, planning and management problems" (Fischer and Nijkamp, 1993). A GIS was used extensively in this study to present digital mapping of laterite soil properties in Nigeria. It allowed for a flexible storage, display, and exchange of spatial data garnered from the review of literature and the parametric study conducted during the course of the research. The output from the GIS technology is presented in a systematic manner. Starting with how the information was obtained, the formulation of tabular data, the themes of the view, and finally the image mapping.

The information gathering process was performed first, and details of how these where garnered for the study were presented previously in chapter three. This information was sorted according to geographic locations within Nigeria and stored in a tabular manner. The stored information was geocoded by linking the sample locations to the longitude and latitude coordinates. With this done, the soil properties were added to the map in the GIS environment to precise positions. Furthermore, the data can be symbolized, queried, and analyzed like any theme in the GIS program.

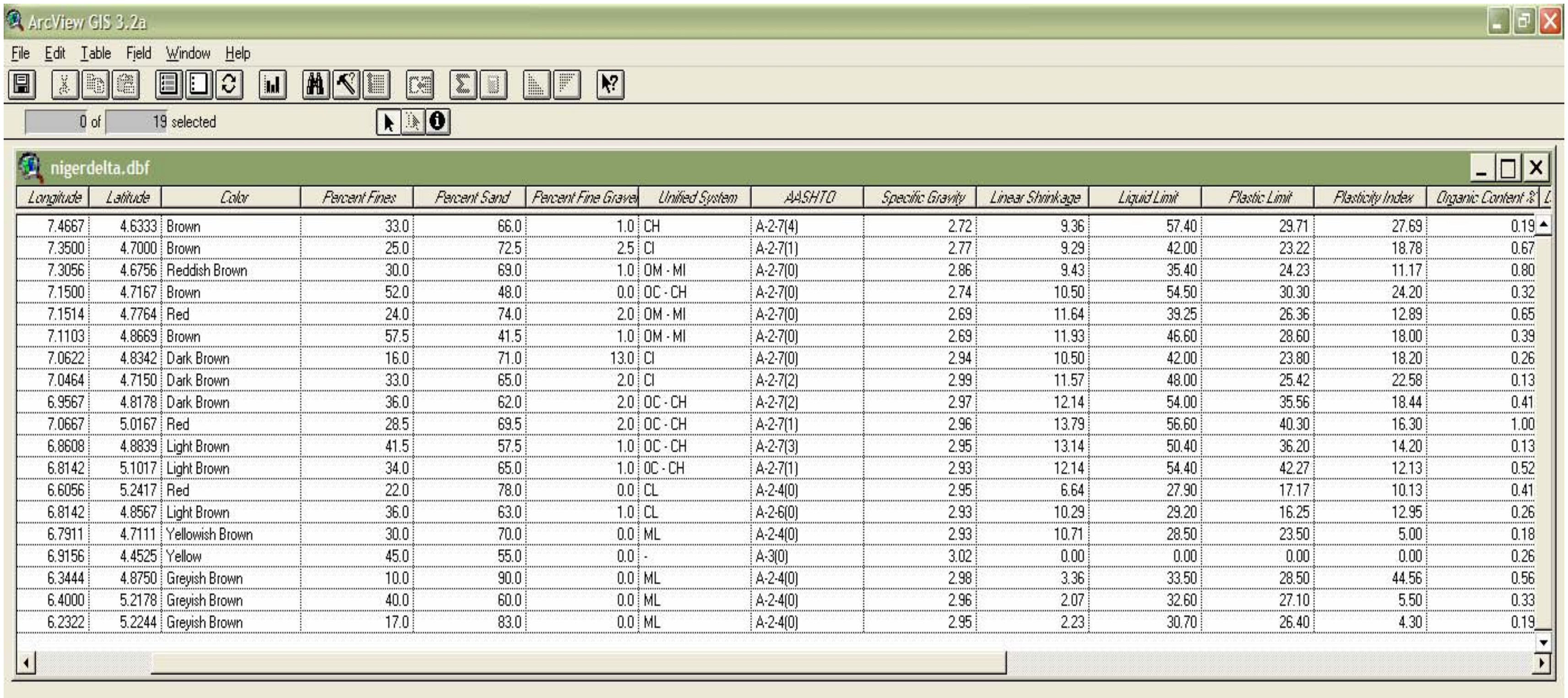
Below are the tabular presentations for the various regions where information was obtained. There is a limitation in presenting these tabular data from the geographic information systems (GIS). This is because the GIS-based file format is not supported by Microsoft Word. Thus, these are presented in the print screen format, accordingly. Figure 11, 12, 13, and 14 shows attribute tables of the engineering properties of laterite soils in Southeast, Southwest, Northern, and Niger Delta regions of Nigeria.



ID #	Town	Longitude	Latitude	Percent Sand	Percent Silt	Percent Clay	Unified System	AASHTO	Specific Gravity	Liquid Limit %	Plastic Limit %	Plasticity Index %	Dry_unit_w
20	Okigwe	7.3500	5.8167	65.0	15.0	20.0	SC	A-2-4	2.74	32.80	17.60	15.20	0
21	Onitsha	6.7833	6.1667	63.0	20.0	17.0	SC - SM	A-2-4	2.65	33.70	16.40	17.30	1880
22	Owerri	7.0333	5.4833	75.0	13.0	12.0	SC - SM	A-2-4	2.64	44.20	23.20	21.00	1790
23	Abakaliki	8.1000	6.3333	21.0	7.0	8.0			0.00	43.10	26.80	16.30	1959
24	Ogoja	8.8000	6.6667	28.0	4.0	7.0			0.00	45.30	29.80	15.70	1978
25	Enugu	7.4833	6.4333	33.0	8.0	2.0			0.00	57.80	40.90	16.90	1828
26	Nsukka	7.3833	6.8667	13.0	5.0	0.0			0.00	51.00	32.20	18.80	1736
27	Awka	7.0833	6.2167	47.0	12.0	0.0			0.00	42.00	21.30	20.70	1709
28	Afikpo	7.9167	5.8833	35.0	6.0	3.0			0.00	43.00	25.00	18.00	1937

Sources: Madu, 1977 and Nnadi, 1988. (Modified)

Figure 11: Attributes of Soil Samples in Southeast Nigeria



Longitude	Latitude	Color	Percent Fines	Percent Sand	Percent Fine Gravel	Unified System	AASHTO	Specific Gravity	Linear Shrinkage	Liquid Limit	Plastic Limit	Plasticity Index	Organic Content %
7.4667	4.6333	Brown	33.0	66.0	1.0	CH	A-2-7(4)	2.72	9.36	57.40	29.71	27.69	0.19
7.3500	4.7000	Brown	25.0	72.5	2.5	CI	A-2-7(1)	2.77	9.29	42.00	23.22	18.78	0.67
7.3056	4.6756	Reddish Brown	30.0	69.0	1.0	OM - MI	A-2-7(0)	2.86	9.43	35.40	24.23	11.17	0.80
7.1500	4.7167	Brown	52.0	48.0	0.0	OC - CH	A-2-7(0)	2.74	10.50	54.50	30.30	24.20	0.32
7.1514	4.7764	Red	24.0	74.0	2.0	OM - MI	A-2-7(0)	2.69	11.64	39.25	26.36	12.89	0.65
7.1103	4.8669	Brown	57.5	41.5	1.0	OM - MI	A-2-7(0)	2.69	11.93	46.60	28.60	18.00	0.39
7.0622	4.8342	Dark Brown	16.0	71.0	13.0	CI	A-2-7(0)	2.94	10.50	42.00	23.80	18.20	0.26
7.0464	4.7150	Dark Brown	33.0	65.0	2.0	CI	A-2-7(2)	2.99	11.57	48.00	25.42	22.58	0.13
6.9567	4.8178	Dark Brown	36.0	62.0	2.0	OC - CH	A-2-7(2)	2.97	12.14	54.00	35.56	18.44	0.41
7.0667	5.0167	Red	28.5	69.5	2.0	OC - CH	A-2-7(1)	2.96	13.79	56.60	40.30	16.30	1.00
6.8608	4.8839	Light Brown	41.5	57.5	1.0	OC - CH	A-2-7(3)	2.95	13.14	50.40	36.20	14.20	0.13
6.8142	5.1017	Light Brown	34.0	65.0	1.0	OC - CH	A-2-7(1)	2.93	12.14	54.40	42.27	12.13	0.52
6.6056	5.2417	Red	22.0	78.0	0.0	CL	A-2-4(0)	2.95	6.64	27.90	17.17	10.13	0.41
6.8142	4.8567	Light Brown	36.0	63.0	1.0	CL	A-2-6(0)	2.93	10.29	29.20	16.25	12.95	0.26
6.7911	4.7111	Yellowish Brown	30.0	70.0	0.0	ML	A-2-4(0)	2.93	10.71	28.50	23.50	5.00	0.18
6.9156	4.4525	Yellow	45.0	55.0	0.0	-	A-3(0)	3.02	0.00	0.00	0.00	0.00	0.26
6.3444	4.8750	Greyish Brown	10.0	90.0	0.0	ML	A-2-4(0)	2.98	3.36	33.50	28.50	44.56	0.56
6.4000	5.2178	Greyish Brown	40.0	60.0	0.0	ML	A-2-4(0)	2.96	2.07	32.60	27.10	5.50	0.33
6.2322	5.2244	Greyish Brown	17.0	83.0	0.0	ML	A-2-4(0)	2.95	2.23	30.70	26.40	4.30	0.19

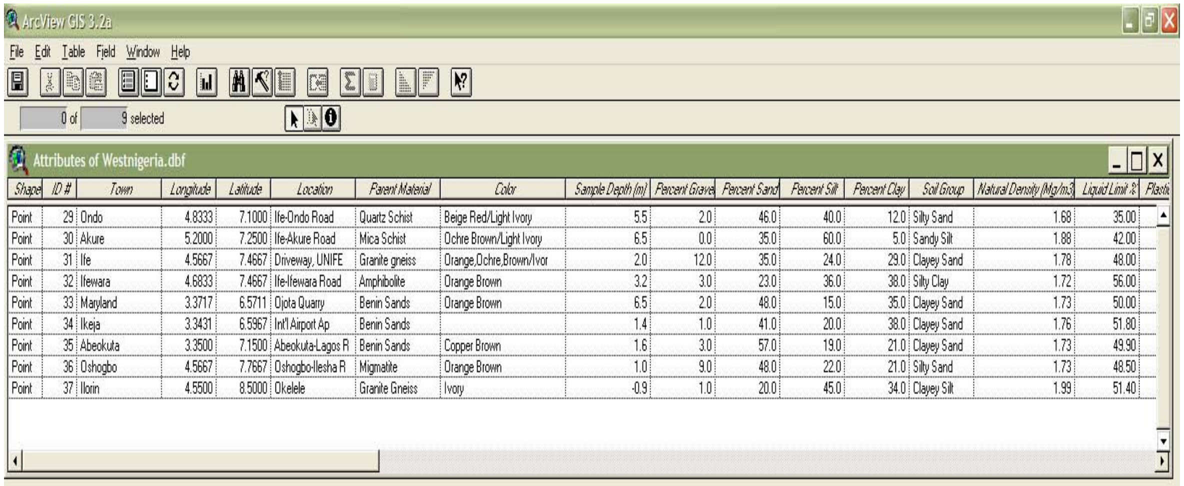
Source: Alabo and Pandey, 1988 (Modified)

Figure 12: Attributes of Soil Samples in Niger Delta, Nigeria

ID #	Town	Longitude	Latitude	Location	Parent Material	Color	Liquid Limit %	Plastic Limit %	Plasticity Index %	Linear Shrinkage %	Specific Gravity	% Passing BS #200	% Passing 2u	Group Index	Optimum Mois
38	Bakura	5.8667	12.7167	Bakura Soil	Sandstone Coal Shale		42.0	8.0	34.0	0.0	2.54	77.00	32.0	16.4	
39	Akure	5.2000	7.2500	Concretionary Laterite			0.0	0.0	0.0	0.0	2.88	1.60	0.0	0.0	
40	Zaria	7.7000	11.0667	Concretionary Laterite			0.0	0.0	0.0	0.0	2.77	0.88	0.0	0.0	
41	Zaria	7.7000	11.0667	Institute of Administration			34.0	10.0	24.0	0.0	2.69	85.00	31.0	13.6	
42	Kaduna	7.4403	10.5231	Kaduna Textile Industry			0.0	0.0	0.0	0.0	2.51	20.00	1.0	0.0	
43	Maiduguri	13.1500	11.8500	Maiduguri	Black Cotton Soil		78.0	31.0	47.0	0.0	2.56	90.00	47.0	20.0	
44	Wase	9.9667	9.1000	Wase-Yelwa Road	Pre-Turonian		51.0	20.0	31.0	0.0	0.00	88.00	48.0	18.2	
45	Zaria	7.7000	11.0667	Ahmado Bello Hospital		Reddish Brown	46.0	28.0	18.0	12.1	2.69	53.00	0.0	7.2	
46	Sokoto	5.2500	13.0667	House of Assembly	Soft Clay Shale	Mottled Grey Yel	180.0	47.0	133.0	22.1	2.43	98.00	0.0	20.0	
47	Gambaru	14.2167	12.3667	Maiduguri-Gambaru Road	Black Cotton Soil	Black	70.0	27.0	43.0	20.7	2.56	92.00	0.0	20.0	

Source: Ola, 1979 (Modified)

Figure 13: Attributes of Soil Samples in Northern Nigeria



Shape	ID #	Town	Longitude	Latitude	Location	Parent Material	Color	Sample Depth (m)	Percent Gravel	Percent Sand	Percent Silt	Percent Clay	Soil Group	Natural Density (Mg/m3)	Liquid Limit %	Plasti
Point	29	Ondo	4.8333	7.1000	Ife-Ondo Road	Quartz Schist	Beige Red/Light Ivory	5.5	2.0	46.0	40.0	12.0	Silty Sand	1.68	35.00	
Point	30	Akure	5.2000	7.2500	Ife-Akure Road	Mica Schist	Ochre Brown/Light Ivory	6.5	0.0	35.0	60.0	5.0	Sandy Silt	1.88	42.00	
Point	31	Ife	4.5667	7.4667	Driveway, UNIFE	Granite gneiss	Orange,Ochre,Brown/Ivor	2.0	12.0	35.0	24.0	29.0	Clayey Sand	1.78	48.00	
Point	32	Ifewara	4.6833	7.4667	Ife-Ifewara Road	Amphibolite	Orange Brown	3.2	3.0	23.0	36.0	38.0	Silty Clay	1.72	56.00	
Point	33	Maryland	3.3717	6.5711	Ojota Quarry	Benin Sands	Orange Brown	6.5	2.0	48.0	15.0	35.0	Clayey Sand	1.73	50.00	
Point	34	Ikeja	3.3431	6.5967	Int'l Airport Ap	Benin Sands		1.4	1.0	41.0	20.0	38.0	Clayey Sand	1.76	51.80	
Point	35	Abeokuta	3.3500	7.1500	Abeokuta-Lagos R	Benin Sands	Copper Brown	1.6	3.0	57.0	19.0	21.0	Clayey Sand	1.73	49.90	
Point	36	Oshogbo	4.5667	7.7667	Oshogbo-Ilesha R	Migmatite	Orange Brown	1.0	9.0	48.0	22.0	21.0	Silty Sand	1.73	48.50	
Point	37	Ilorin	4.5500	8.5000	Okelele	Granite Gneiss	Ivory	-0.9	1.0	20.0	45.0	34.0	Clayey Silt	1.99	51.40	

Source: Ogunsanwo, 1995, 1996. (Modified)

Figure 14: Attributes of Soil Samples in Southwest Nigeria

Following the creation of the tabular data with regional information views for the area of interest were created. The simplified geological map of Nigeria was created with the geological features as themes. In the geographic information systems, themes are the layers of geographic features. In this study, a reproduction of a simplified geologic map of Nigeria was also presented in the GIS as shown in Figure 15.

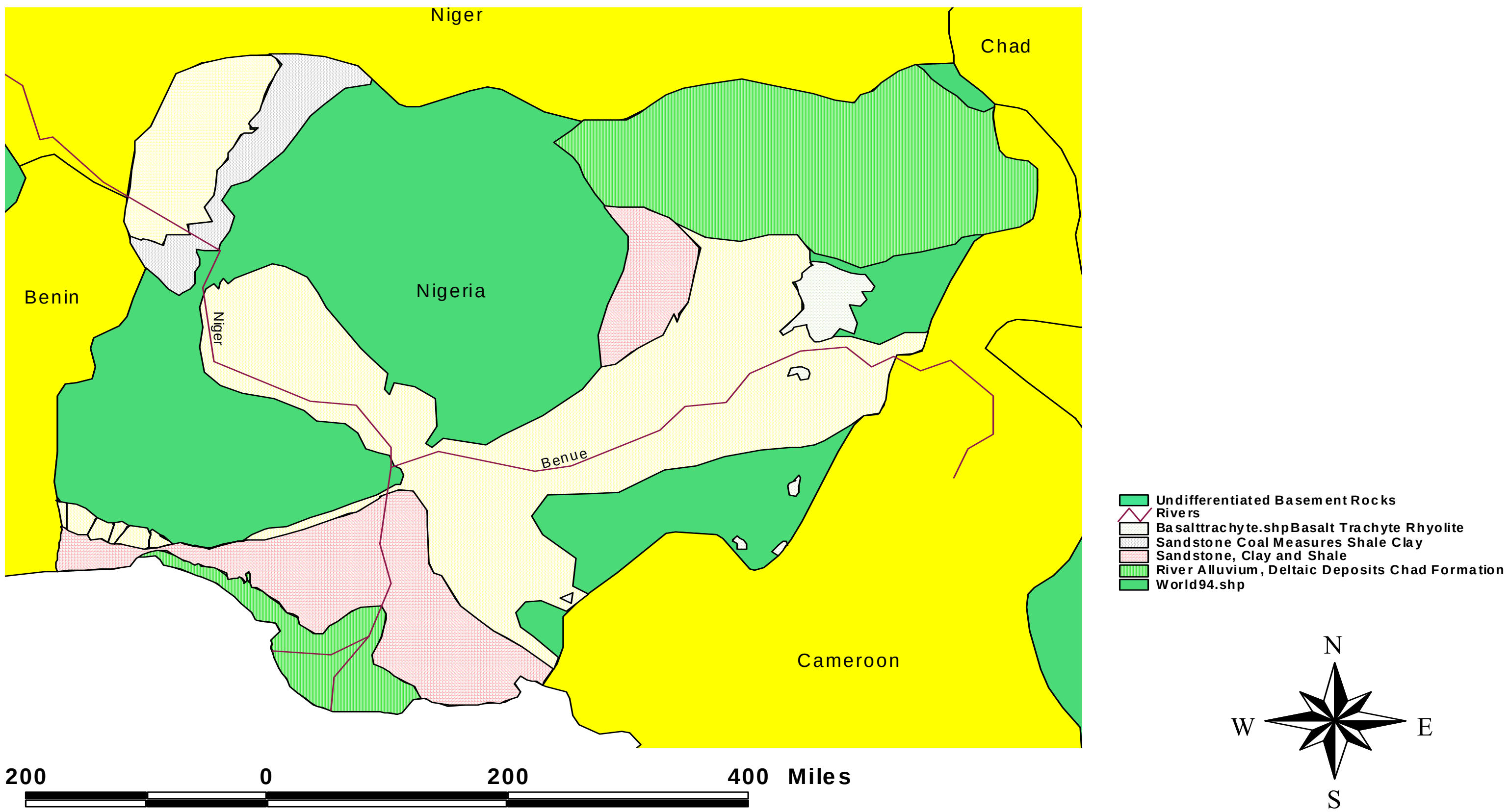


Figure 15: Simplified Geologic Map of Nigeria

Subsequent views of Nigeria and the location of towns and cities were created. This process involved the mapping of the data and the creation of the themes of these locations. Subsequently, the names of these cities were labeled on the map using the "label" tool in the GIS. The identity tool is used to label each feature in the theme one-by-one in the view on GIS display. The view of Nigeria with its 36 State capital cities and view of the towns and cities where information about the soil data was collected and for which attributes of the geotechnical properties have been created are shown in Figures 16 and 17, respectively. Further views of the Northern, Southwest, Southeast, and Niger-Delta regions of Nigeria are shown in Figure 18 through Figure 20.

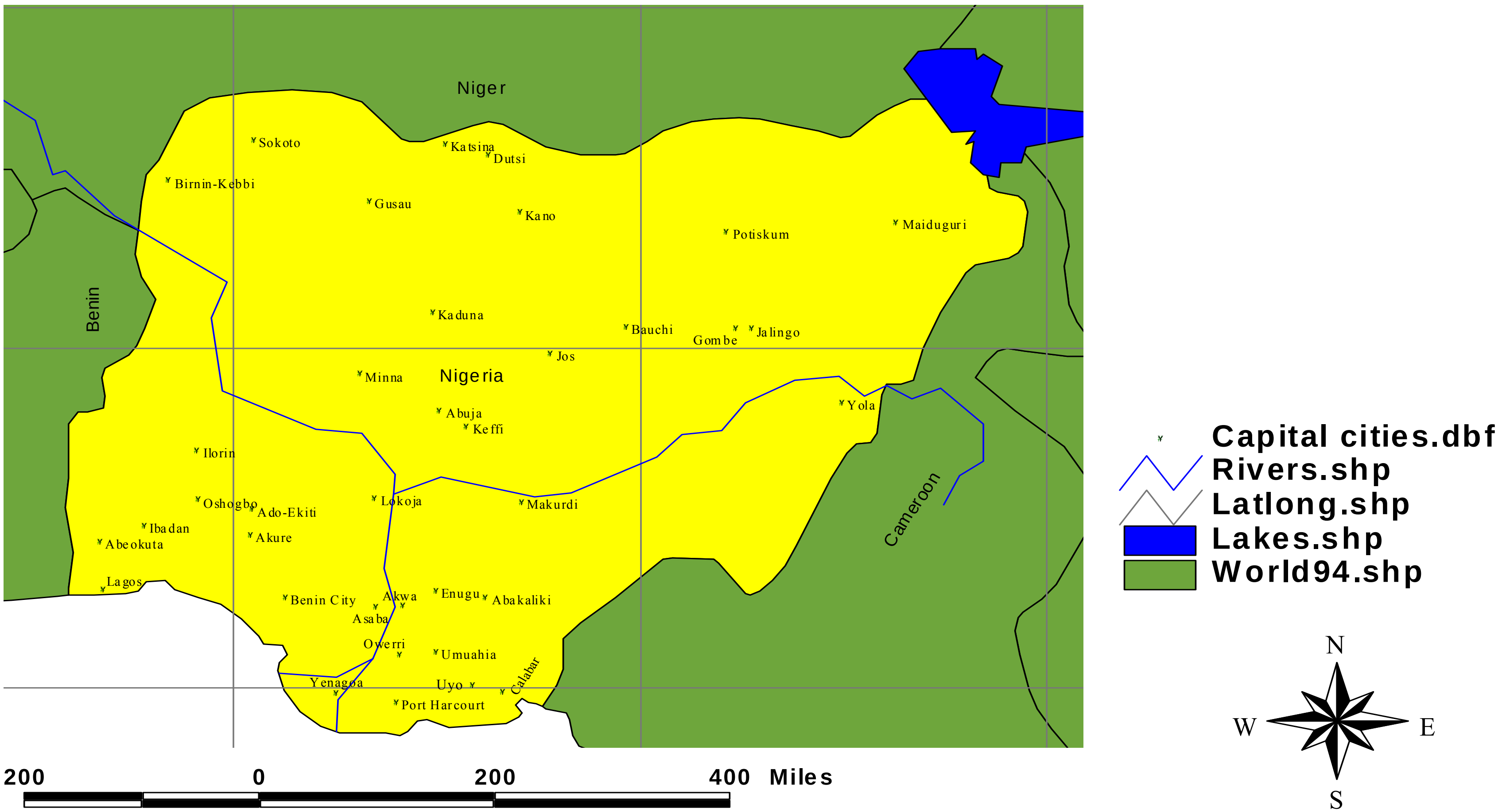


Figure 16: Map of Nigeria and the State Capital Cities.

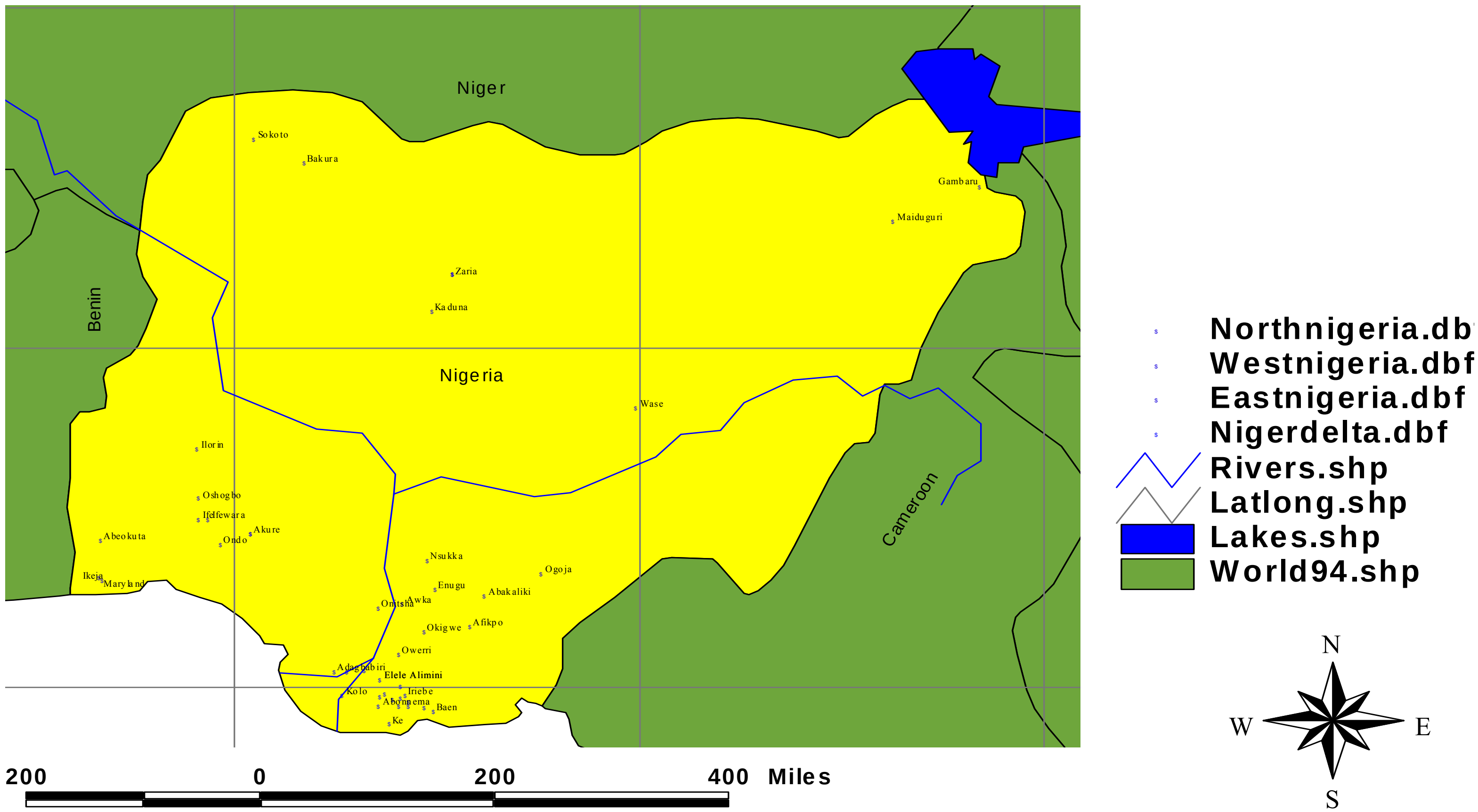


Figure 17: Views of Sample Locations.

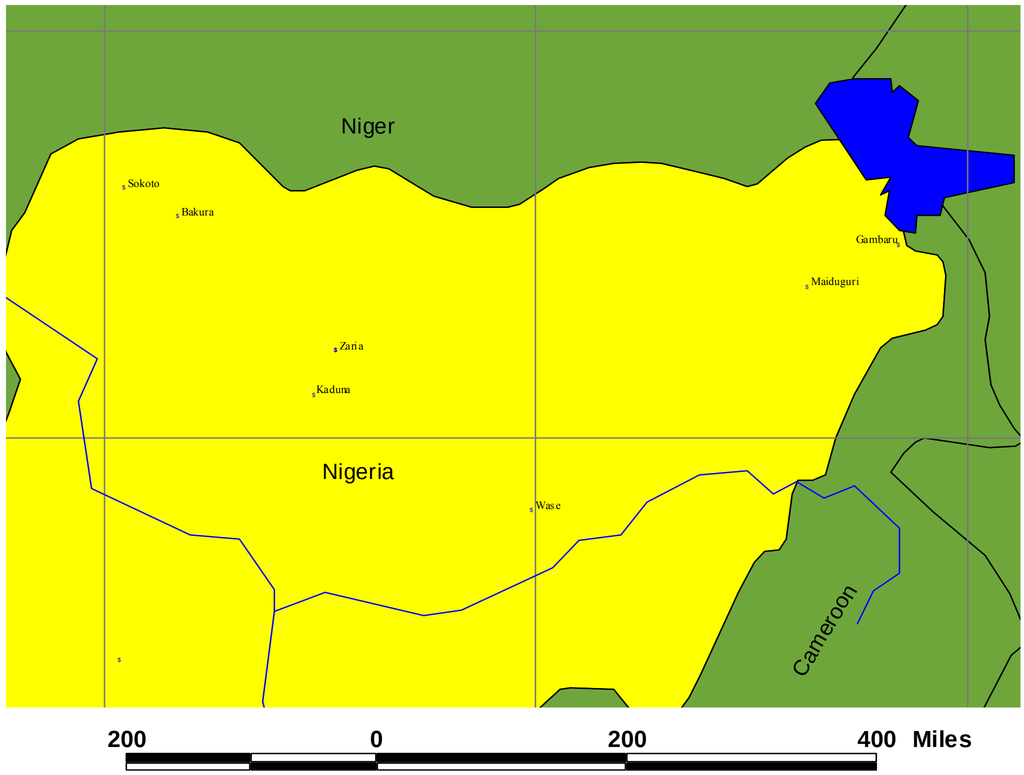


Figure 18: View of Northern Nigeria Locations

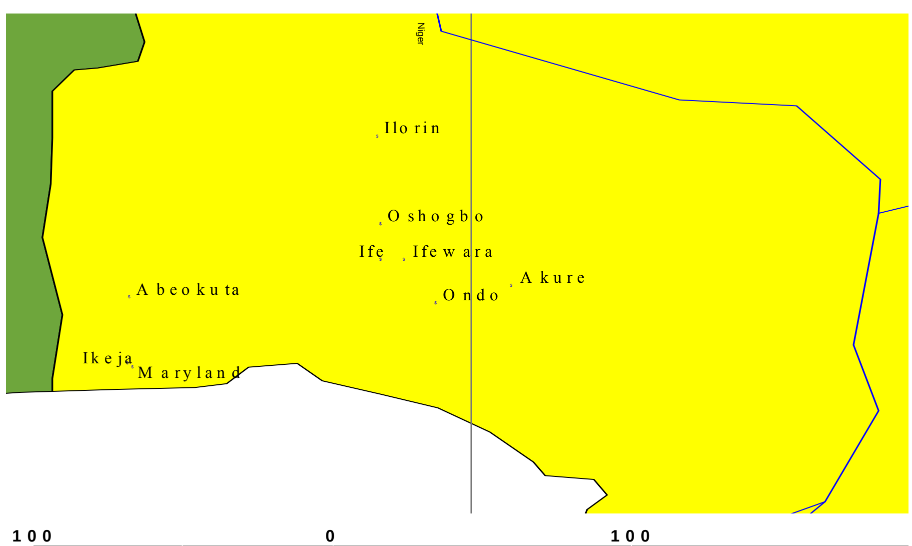


Figure 19: View of Southwest Nigeria Locations

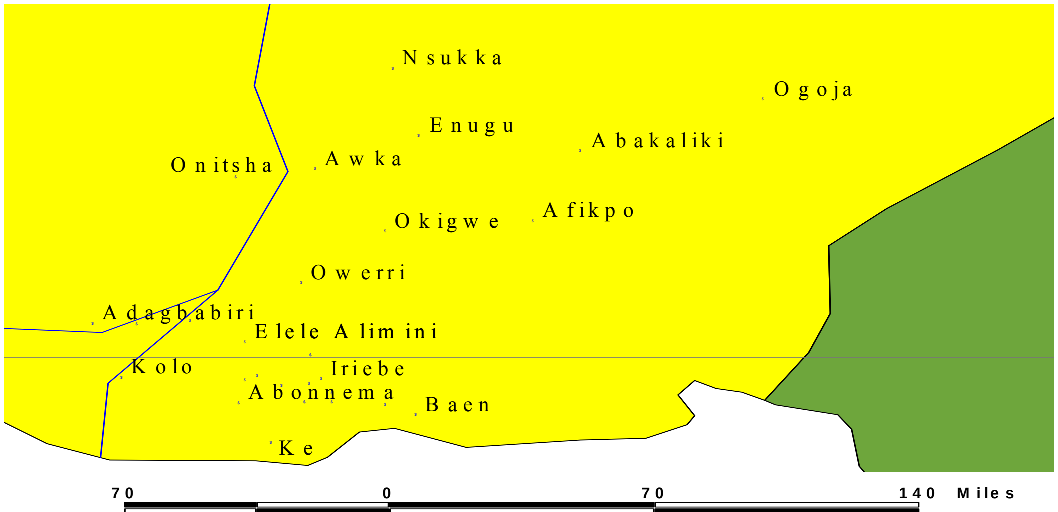


Figure 20: View of Southern Nigeria Locations

Furthermore, a detailed view of the themes and identity of the towns, showing all the internal attributes, which in this case are the geotechnical properties of the laterite soils at the location, is presented in Figure 21. More of the detailed views for all the regions in Nigeria are shown in the Appendix. The tool "identify" within the GIS environment presents a table of the attributes assigned to the feature whenever it is selected.

This information database can be easily exported and made available to geotechnical engineers in Nigeria

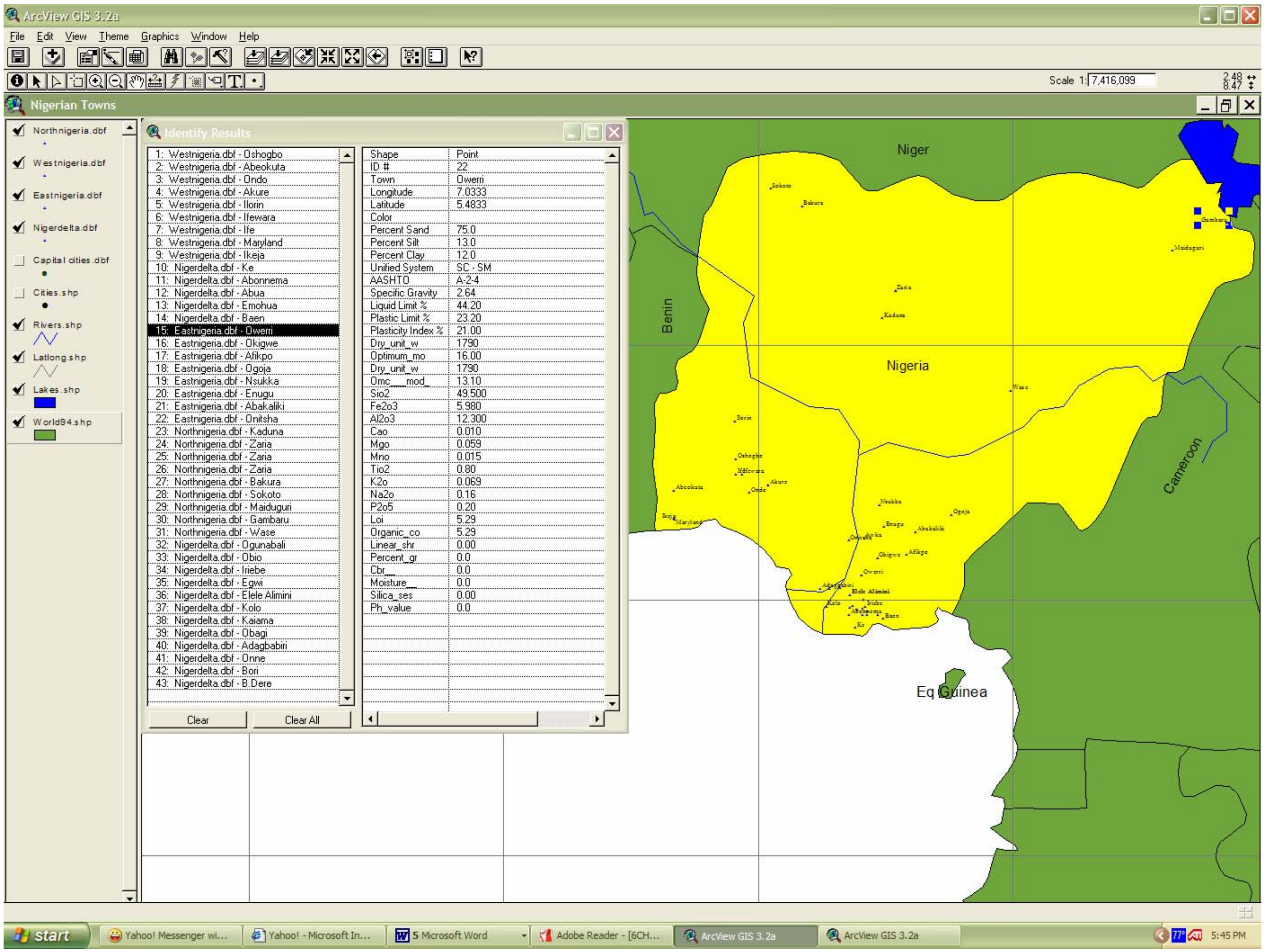


Figure 21: View of the Identify Table, Themes, and Map

4.2 Slope/W Outputs

Following the creation of the GIS database, slope stability analyses were conducted for both saturated and unsaturated laterite soils used in embankment construction. Slopes of 1:1, 2:1, and 3:1 are studied in order to investigate the safety of embankments in Nigeria using laterite soils. The SLOPE/W for slope stability analysis program was used to perform these analyses. The Slope/W slope stability program permits the analysis of slope stability by means of different established methods and probabilistic analysis methods, involving the Ordinary, Bishop, Janbu, and Morgenstern-Price techniques. The slip surface was considered to be either circular or elliptical. The various cross sections with the slip surface radius and grid of the slopes are presented in Figure 22 through 25 corresponding to slopes of 1:1, 2:1, 3:1, and zero, respectively.

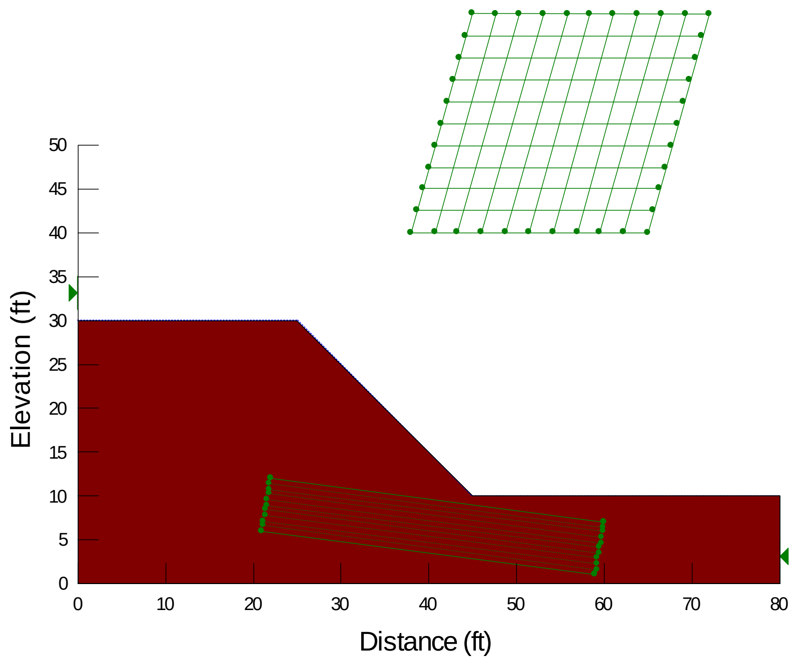


Figure 22: Typical Cross section of a 1:1 Slope

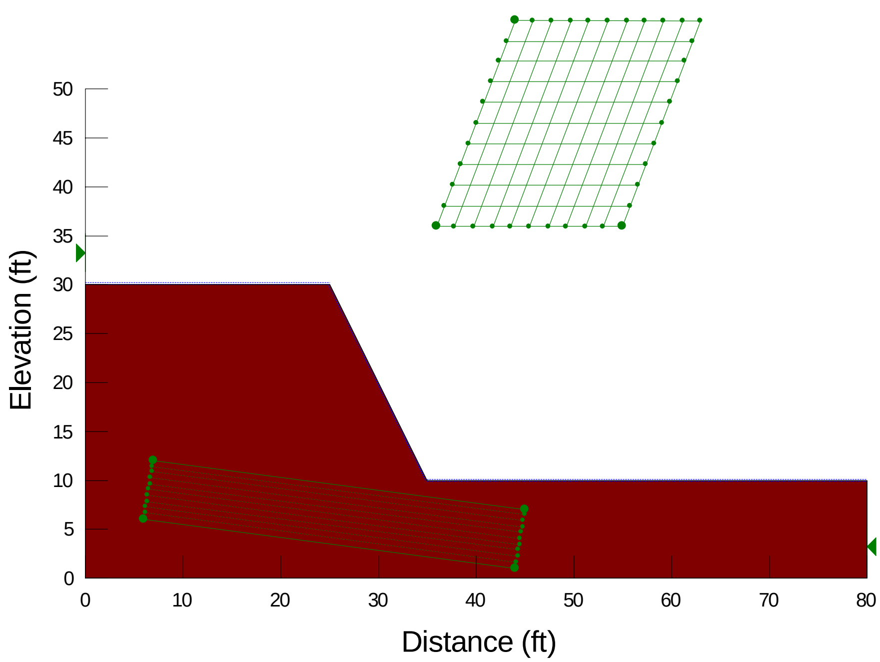


Figure 23: Typical Cross section of a 2:1 Slope

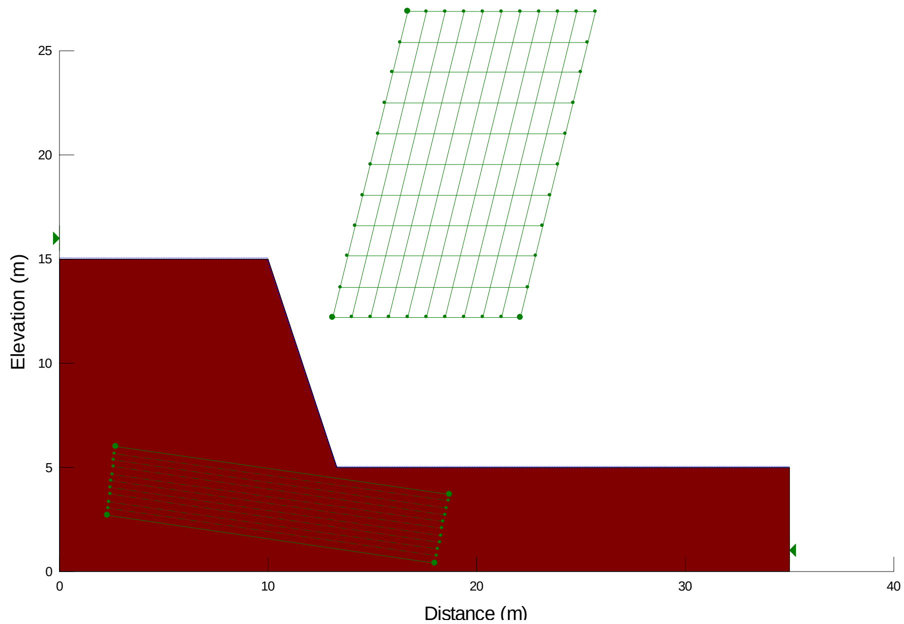


Figure 24: Typical Cross Section of a 3:1 Slope

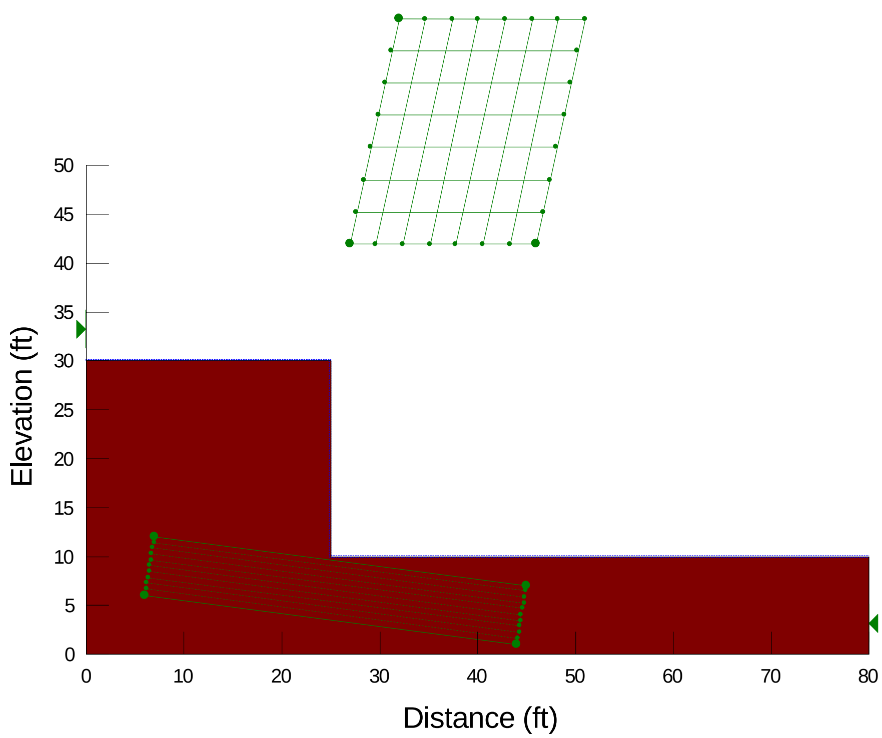


Figure 25: Typical Cross Section of a Zero Slope

At this juncture, it is necessary to mention that no experiments were conducted for the shear strength parameters used for the slope stability analyses. This was due to the logistics of having the soil imported from Nigeria and tested in United States of America. However, the shear strength parameters used for the analyses were based on data collected from published studies on laterite soils in different parts of Nigeria. This has been already discussed in the reviewed literature in chapter two.

Figure 26 shows a representative or typical cross section of the SLOPE/W output showing the minimum factor of safety, contours and labels of other factors of safety, most critical and some trial slip surfaces. This graphically reveals the extent of the trial slip surfaces with the most critical displayed with its resulting mass colored green.

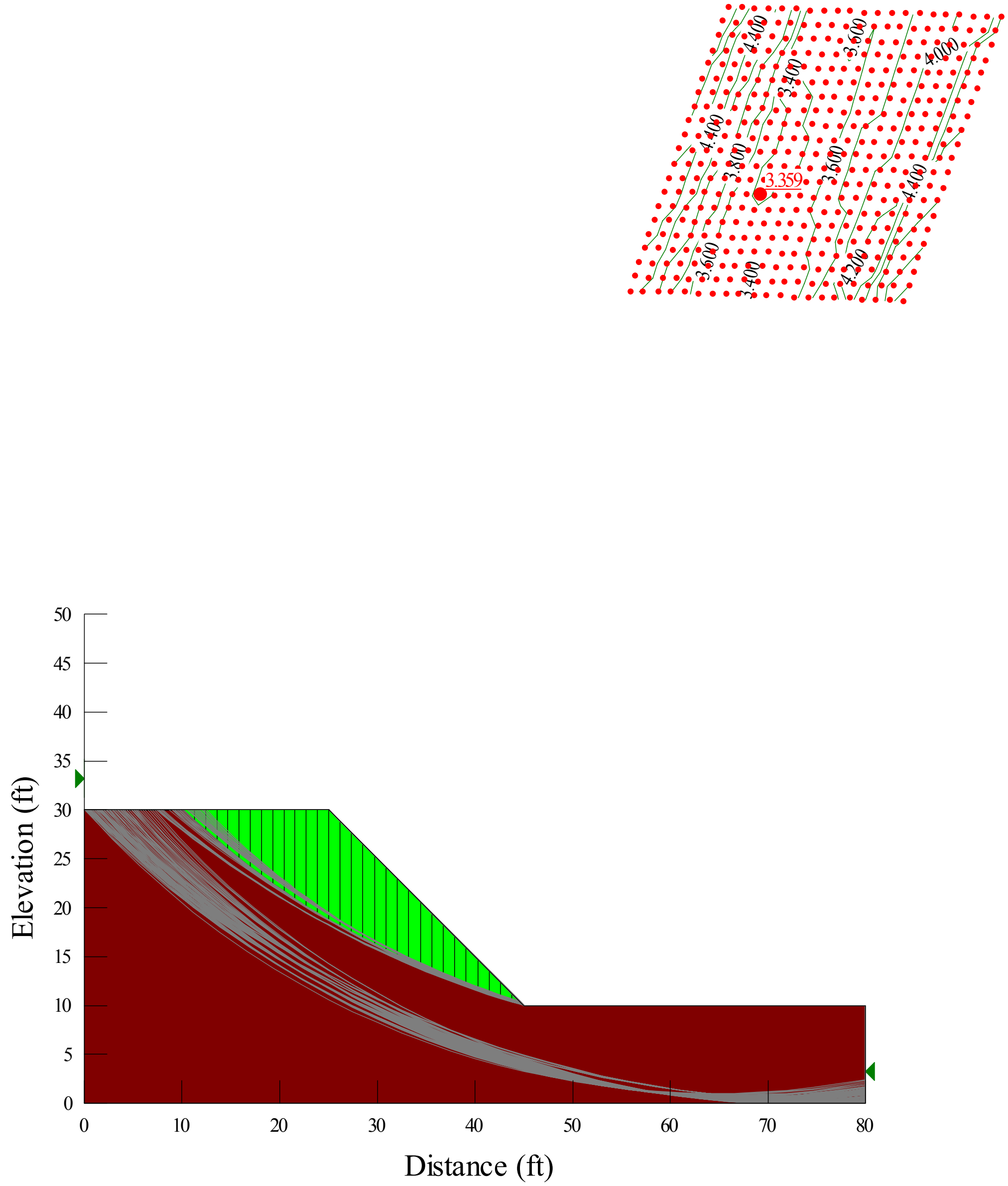


Figure 26: View of Typical Cross Section, Showing the Slip Surfaces, Factors of Safety, Contours of Factor of Safety

4.2.1 Total Stress Method

Table 11 through Table 14 present the results of the slope stability analyses of the actual soil parameters (unsaturated) available in the reviewed literature and the corresponding calculated factor of safety based on each stability model within SLOPE/W, and slopes of 1:1, 2:1, 3:1, and 0, respectively.

Table 11: Total Stress Analysis of 20 feet Laterite Soil Slope of 1: 1

Sample Locality	*Parent Material*	*Soil Group Name/Symbol (Unified System)*	*Internal Friction Angle*	*Unit Weight (pcf)*	*Cohesion C (psf)*	*Minimum Factor of Safety*				
						Moment			*Force*	
						Morgenstern Price	*Ordinary*	*Bishop*	*Janbu*	*Morgenstern Price*
Abeokuta/Lagos	Benin Sand	Clayey SAND (SC)	32	115.35	898.07	4.134	4.124	4.135	4.118	4.130
Ojota Quarry, Maryland	Benin Sand	Silty clayey SAND (SC-SM)	17	108.38	1211.35	4.699	4.656	4.702	4.534	4.697
Int'l Airport, Ikeja	Benin Sand	Sandy elastic SILT (ML)	12	111.55	563.91	2.340	2.320	2.341	2.263	2.341
Oshogbo/Ilesha	Migmatite	Silty clayey SAND (SC-SM)	34	113.01	647.45	3.425	3.413	3.425	3.407	3.418
Ife/Ifewara	Amphibolites	Elastic SILT with sand (MH)	17	95.07	1921.46	7.747	7.705	7.750	7.487	7.748
Unife	Granite gneiss	Sandy SILT (ML)	22	108.38	584.79	2.813	2.807	2.814	2.803	2.811
Okelele, Ilorin	Granite	Elastic SILT with sand (MH)	21	108.57	772.76	3.446	3.440	3.446	3.422	3.445
Ife/Ondo	Quartz schist	Silty SAND (ML)	22	114.09	898.07	3.774	3.769	3.775	3.728	3.773
Ife/Akure	Mica schist	Sandy SILT (ML)	26	106.48	1461.98	6.113	6.045	6.117	5.893	6.111

Table 12: Total Stress Analysis of a 20 feet Laterite Soil Slope of 2:1

Sample Locality	*Parent Material*	*Soil Group Name/Symbol (Unified System)*	*Internal Friction Angle*	*Unit Weight (pcf)*	*Cohesion C (psf)*	*Minimum Factor of Safety*				
						Moment			*Force*	
						Morgenstern Price	*Ordinary*	*Bishop*	*Janbu*	*Morgenstern Price*
Abeokuta/Lagos	Benin Sand	Clayey SAND (SC)	32	115.35	898.07	3.052	2.982	2.965	3.031	3.061
Ojota Quarry, Maryland	Benin Sand	Silty clayey SAND (SC-SM)	17	108.38	1211.35	3.583	3.484	3.577	3.577	3.590
Int'l Airport, Ikeja	Benin Sand	Sandy elastic SILT (ML)	12	111.55	563.91	1.693	1.670	1.663	1.706	1.700
Oshogbo/Ilesha	Migmatite	Silty clayey SAND (SC-SM)	34	113.01	647.45	2.486	2.428	2.414	2.462	2.494
Ife/Ifewara	Amphibolites	Elastic SILT with sand (MH)	17	95.07	1921.46	6.082	5.988	5.973	6.169	6.080
Unife	Granite gneiss	Sandy SILT (ML)	22	108.38	584.79	2.059	2.034	2.023	2.069	2.066
Okelele, Ilorin	Granite	Elastic SILT with sand (MH)	21	108.57	772.76	2.534	2.503	2.496	2.535	2.541
Ife/Ondo	Quartz schist	Silty SAND (ML)	22	114.09	898.07	2.777	2.739	2.731	2.775	2.782
Ife/Akure	Mica schist	Sandy SILT (ML)	26	106.48	1461.98	4.522	4.463	4.450	4.531	4.527

Table 13: Total Stress Analysis of a 20 feet Laterite Soil Slope of 3:1

Sample Locality	*Parent Material*	*Soil Group Name/Symbol (Unified System)*	*Internal Friction Angle*	*Unit Weight (pcf)*	*Cohesion C (psf)*	*Minimum Factor of Safety*				
						Moment			*Force*	
						Morgenstern Price	*Ordinary*	*Bishop*	*Janbu*	*Morgenstern Price*
Abeokuta/Lagos	Benin Sand	Clayey SAND (SC)	32	115.35	898.07	2.735	2.678	2.644	2.742	2.741
Ojota Quarry, Maryland	Benin Sand	Silty clayey SAND (SC-SM)	17	108.38	1211.35	3.223	3.120	3.096	3.255	3.233
Int'l Airport, Ikeja	Benin Sand	Sandy elastic SILT (ML)	12	111.55	563.91	1.545	1.507	1.493	1.560	1.550
Oshogbo/Ilesha	Migmatite	Silty clayey SAND (SC-SM)	34	113.01	647.45	2.239	2.188	2.156	2.231	2.249
Ife/Ifewara	Amphibolites	Elastic SILT with sand (MH)	17	95.07	1921.46	5.542	5.324	5.296	5.597	5.539
Unife	Granite gneiss	Sandy SILT (ML)	22	108.38	584.79	1.846	1.825	1.803	1.868	1.853
Okelele, Ilorin	Granite	Elastic SILT with sand (MH)	21	108.57	772.76	2.257	2.230	2.209	2.294	2.264
Ife/Ondo	Quartz schist	Silty SAND (ML)	22	114.09	898.07	2.484	2.440	2.417	2.513	2.491
Ife/Akure	Mica schist	Sandy SILT (ML)	26	106.48	1461.98	4.109	3.977	3.943	4.129	4.111

Table 14: Total Stress Analysis of a 20 feet Laterite Soil Slope of 0 (zero)

Sample Locality	*Parent Material*	*Soil Group Name/Symbol (Unified System)*	*Internal Friction Angle*	*Unit Weight (pcf)*	*Cohesion C (psf)*	*Minimum Factor of Safety*				
						Moment			*Force*	
						Morgenstern Price	*Ordinary*	*Bishop*	*Janbu*	*Morgenstern Price*
Abeokuta/Lagos	Benin Sand	Clayey SAND (SC)	32	115.35	898.07	2.189	2.096	1.994	2.213	2.199
Ojota Quarry, Maryland	Benin Sand	Silty clayey SAND (SC-SM)	17	108.38	1211.35	2.574	2.463	2.420	2.636	2.583
Int'l Airport, Ikeja	Benin Sand	Sandy elastic SILT (ML)	12	111.55	563.91	1.238	1.190	1.160	1.272	1.235
Oshogbo/Ilesha	Migmatite	Silty clayey SAND (SC-SM)	34	113.01	647.45	1.742	1.727	1.626	1.812	1.750
Ife/Ifewara	Amphibolites	Elastic SILT with sand (MH)	17	95.07	1921.46	4.416	4.203	4.179	4.545	4.424
Unife	Granite gneiss	Sandy SILT (ML)	22	108.38	584.79	1.472	1.427	1.358	1.501	1.479
Okelele, Ilorin	Granite	Elastic SILT with sand (MH)	21	108.57	772.76	1.832	1.755	1.705	1.851	1.839
Ife/Ondo	Quartz schist	Silty SAND (ML)	22	114.09	898.07	2.003	1.923	1.868	2.028	2.012
Ife/Akure	Mica schist	Sandy SILT (ML)	26	106.48	1461.98	3.287	3.140	3.072	3.374	3.290

The factors of safety were found to be above 1.0 (minimum safe value) for all geometry of slopes, even in the case of zero inclination. This could be attributed to the high cohesive values for the different soil types. The factors of safety obtained from the calculation of slope stability were plotted against the slope geometry. The resultant plots reveal a rapid change in the factors of safety for geometry of 1:1 and 2:1, and a rather nearly straight line between slopes of 2:1 and 3:1, as shown in Figure 27 through Figure 31 with the corresponding values in Table 15 through Table 19.

Table 15 Factors of safety versus slope geometry for Maryland, Lagos

Sample Locality	*Parent Material*	*Soil Group Name/Symbol (Unified System)*	*Internal Friction Angle*	*Unit Weight (pcf)*	*Cohesion C (psf)*
Ojota Quarry, Maryland	Benin Sand	Silty clayey SAND (SC-SM)	26º	108.38	543.02
Slope Geometry	*Minimum Factor of Safety (Unsaturated)*				
	Moment			*Force*	
	Morgenstern Price	*Ordinary*	*Bishop*	*Janbu*	*Morgenstern Price*
0.000	1.477	1.421	1.335	1.492	1.474
3.000	1.834	1.825	1.804	1.856	1.843
2.000	2.037	2.041	2.035	2.059	2.047
1.000	2.785	2.775	2.786	2.769	2.778

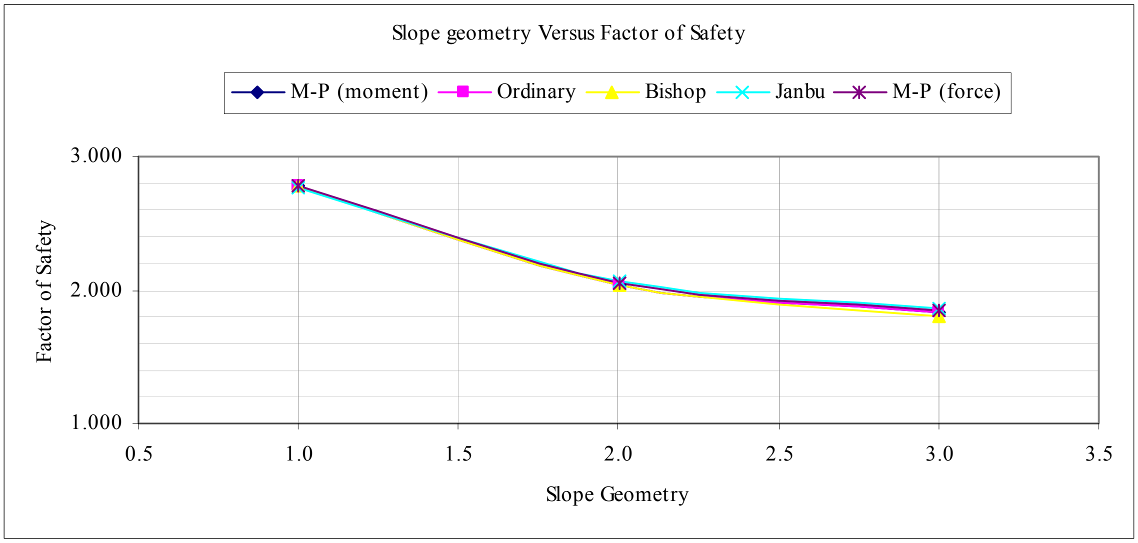


Figure 27: Plot of Factor of safety versus slope geometry, Maryland, Lagos

Table 16 Factors of safety versus slope geometry for Ife-Ifewara Road

Sample Locality	*Parent Material*	*Soil Group Name/Symbol (Unified System)*	*Internal Friction Angle*	*Unit Weight (pcf)*	*Cohesion C (psf)*
Ife/Ifewara	Amphiolite	Elastic SILT with sand (MH)	27	95.07	939.84
Slope Geometry	*Minimum Factor of Safety*				
	Moment			*Force*	
	Morgenstern Price	*Ordinary*	*Bishop*	*Janbu*	*Morgenstern Price*
0.000	2.480	2.413	2.331	2.573	2.490
3.000	3.117	3.050	3.015	3.164	3.122
2.000	3.493	3.419	3.408	3.466	3.492
1.000	4.742	4.732	4.742	4.690	4.737

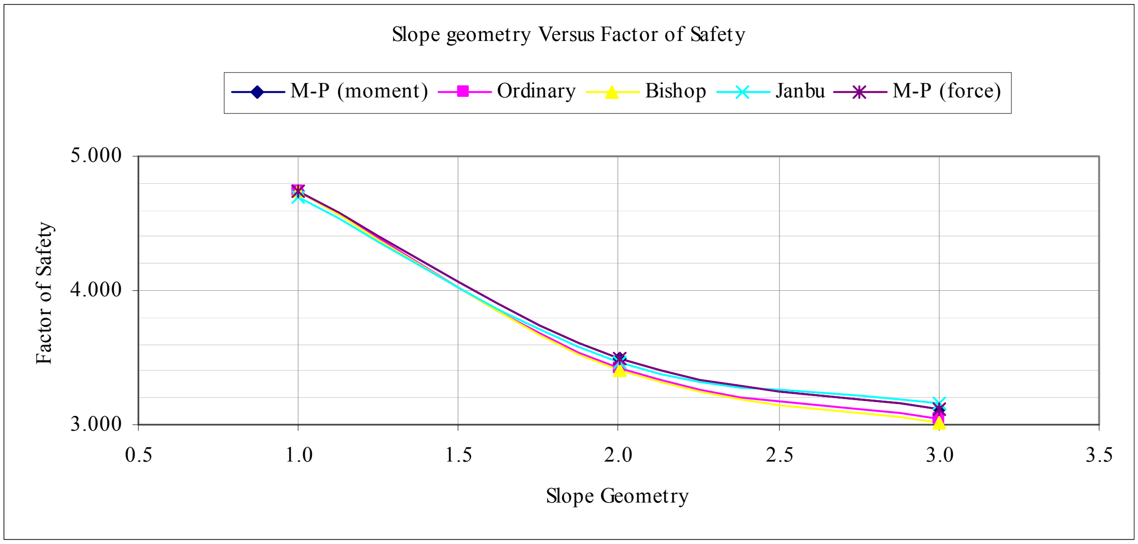


Figure 28: Plot of Factor of safety versus slope geometry, Ife-Ifewara Road

Table 17 Factors of safety versus slope geometry for UNIFE, Ife

Sample Locality	*Parent Material*	*Soil Group Name/Symbol (Unified System)*	*Internal Friction Angle*	*Unit Weight (pcf)*	*Cohesion C (psf)*
Unife	Granite gneiss	Sandy SILT (ML)	30	108.38	313.28
Slope Geometry	*Minimum Factor of Safety*				
	Moment			*Force*	
	Morgenstern Price	*Ordinary*	*Bishop*	*Janbu*	*Morgenstern Price*
0.000	1.051	1.048	0.946	1.092	1.058
3.000	1.337	1.332	1.309	1.345	1.345
2.000	1.485	1.476	1.474	1.484	1.494
1.000	2.069	2.054	2.071	2.046	2.069

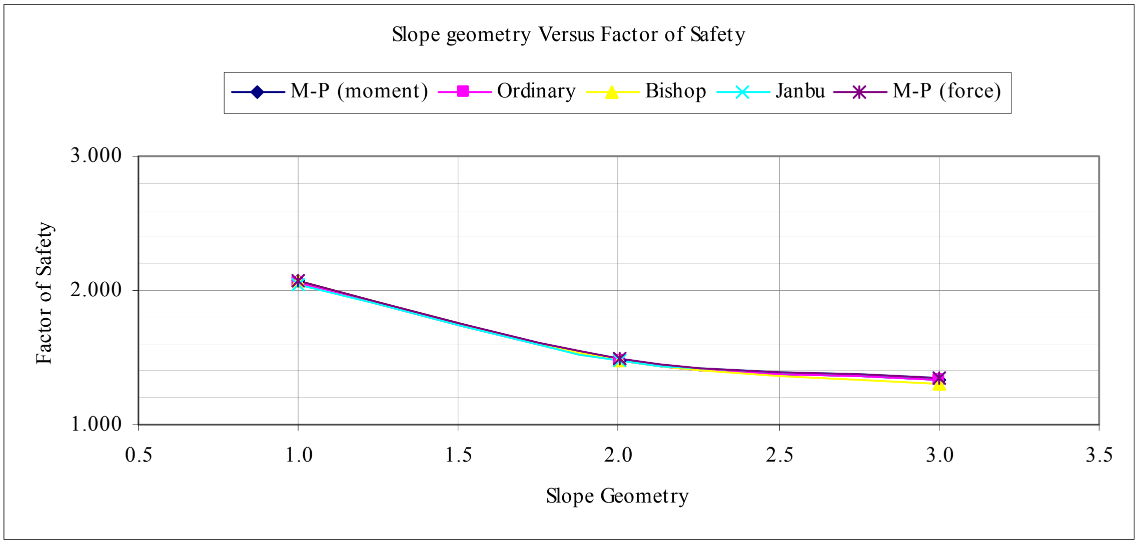


Figure 29: Plot of Factor of safety versus slope geometry, UNIFE, Ife

Table 18 Factors of safety versus slope geometry for Ife-Ondo Road

Sample Locality	*Parent Material*	*Soil Group Name/Symbol (Unified System)*	*Internal Friction Angle*	*Unit Weight (pcf)*	*Cohesion C (psf)*
Ife/Ondo	Quartz schist	Silty SAND (ML)	31	114.09	313.28
Slope Geometry	*Minimum Factor of Safety*				
	Moment			*Force*	
	Morgenstern Price	*Ordinary*	*Bishop*	*Janbu*	*Morgenstern Price*
0.000	1.044	1.030	0.914	1.075	1.047
3.000	1.306	1.310	1.287	1.325	1.314
2.000	1.463	1.457	1.457	1.465	1.470
1.000	2.046	2.030	2.048	2.022	2.045

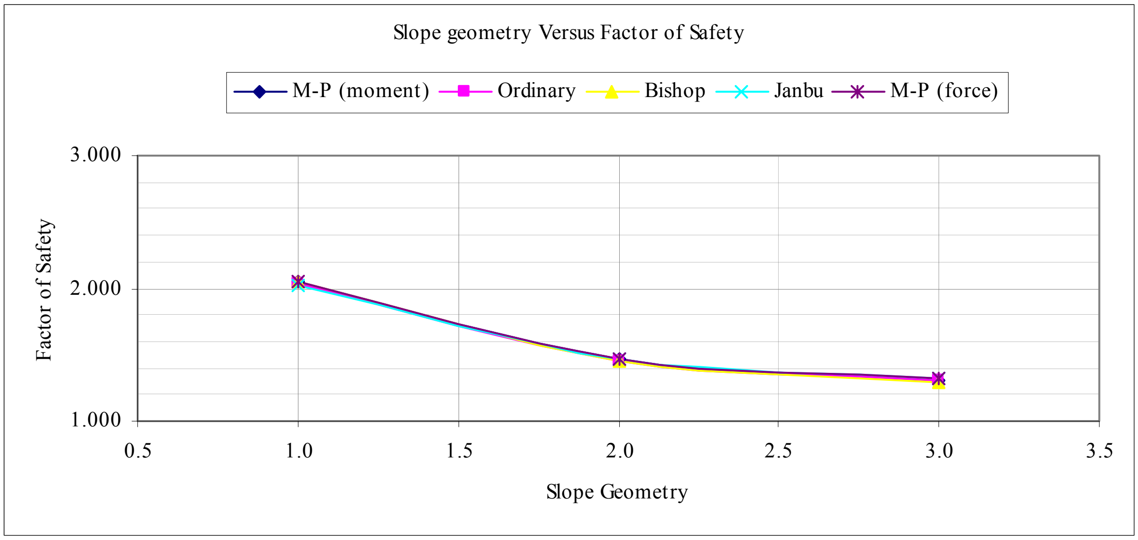


Figure 30: Plot of Factor of safety versus slope geometry, Ife-Ondo Road

Table 19 Factors of safety versus slope geometry for Ife-Akure Road

Sample Locality	*Parent Material*	*Soil Group Name/Symbol (Unified System)*	*Internal Friction Angle*	*Unit Weight (pcf)*	*Cohesion C (psf)*
Ife/Akure	Mica schist	Sandy SILT (ML)	31	106.48	730.99
Slope Geometry	*Minimum Factor of Safety*				
	Moment			*Force*	
	Morgenstern Price	*Ordinary*	*Bishop*	*Janbu*	*Morgenstern Price*
0.000	1.960	1.893	1.801	1.983	1.970
3.000	2.444	2.409	2.358	2.479	2.453
2.000	2.753	2.645	2.633	2.691	2.761
1.000	3.712	3.699	3.712	3.684	3.706

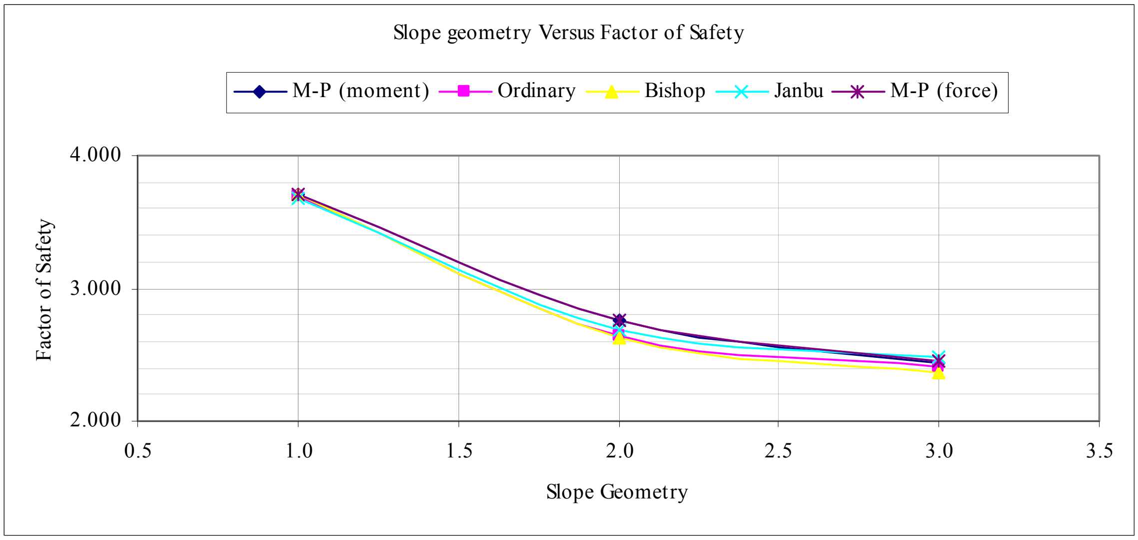


Figure 31: Plot of Factor of safety versus slope geometry, Ife-Akure Road

Table 20 presents the variation in slope for the 1:1 to 2:1 slopes versus the 2:1 to 3:1 slopes for the different laterite soils. It can be observed from this that there is a little change in the factor of safety between a 3:1 and 2:1 embankment.

Table 20: Variation in Factor of Safety with the Slope Geometry (Total Stress).

Sample Locality	*Parent Material*	*Soil Group Name/Symbol (Unified System)*	*Internal Friction Angle*	*Unit Weight (pcf)*	*Cohesion C (psf)*	*Slope*		*Difference %*
						1:1 and 2:1	*2:1 and 3:1*	
Abeokuta/Lagos	Benin Sand	Clayey SAND (SC)	32	115.35	898.07	0.924	3.155	29.3
Ojota Quarry, Maryland	Benin Sand	Silty clayey SAND (SC-SM)	17	108.38	1211.35	0.896	2.778	32.3
Int'l Airport, Ikeja	Benin Sand	Sandy elastic SILT (ML)	12	111.55	563.91	1.546	6.757	22.9
Oshogbo/Ilesha	Migmatite	Silty clayey SAND (SC-SM)	34	113.01	647.45	1.065	4.049	26.3
Ife/Ifewara	Amphibolites	Elastic SILT with sand (MH)	17	95.07	1921.46	0.601	1.852	32.4
Unife	Granite gneiss	Sandy SILT (ML)	22	108.38	584.79	1.326	4.695	28.2
Okelele, Ilorin	Granite	Elastic SILT with sand (MH)	21	108.57	772.76	1.096	3.610	30.4
Ife/Ondo	Quartz schist	Silty SAND (ML)	22	114.09	898.07	1.003	3.413	29.4
Ife/Akure	Mica schist	Sandy SILT (ML)	26	106.48	1461.98	0.629	2.421	26.0

4.2.2 Effective Stress Method

The shear strength in soils is governed by effective stresses in laterite soils. Thus, the effective cohesion and internal friction angles for the soils were next used in the SLOPE/W for slope stability analysis. In addition, compacted laterite soils are placed at the optimum moisture content with 90 percent saturation and 10 percent air void. The initial stability needs to be analyzed again by the effective stress parameters (Ogunsanwo, 1989). This is necessary since the long term stability is of importance. This case shows a lower factor of safety.

According to Ogunsanwo (2002), remolding reduces the cohesive values drastically, which implies that the water content at remolding and the iron oxide (agent of binding fines in Laterite soils) has been reduced. The increase in the value of the internal friction angle of the soils implies that the non-cohesive grains remain intact. Also, a comparison of the factors of safety between the total and effective stress analyses methods confirms the theory that the effective stress method should govern the stability of slopes, as it results in significantly lower factors of safety. It also represents the long term response of the soil. Presented in Tables 21 through Table 24, are the results of the slope stability analyses based on effective shear stress method and the effective soil parameters, and Figure 32 to 35 showing the plots of effective stress and total stress analyses. The plots show the best fit lines as the density varies for the different soil samples investigated.

Table 21: Effective Stress Analysis for a 20 feet Laterite Soil Slope of 1:1

Sample Locality	*Parent Material*	*Soil Group Name/Symbol (Unified System)*	*Effective Internal Friction Angle*	*Unit Weight (pcf)*	*Effective Cohesion C' (psf)*	*Minimum Factor of Safety*				
						Moment			*Force*	
						Morgenstern Price	*Ordinary*	*Bishop*	*Janbu*	*Morgenstern Price*
Ojota Quarry, Maryland	Benin Sand	Silty clayey SAND (SC-SM)	26	108.38	543.02	2.785	2.775	2.786	2.769	2.778
Ife/Ifewara	Amphibolites	Elastic SILT with sand (MH)	27	95.07	939.84	4.742	4.732	4.742	4.690	4.737
Unife	Granite gneiss	Sandy SILT (ML)	30	108.38	313.28	2.069	2.054	2.071	2.046	2.069
Ife/Ondo	Quartz schist	Silty SAND (ML)	31	114.09	313.28	2.046	2.030	2.048	2.022	2.045
Ife/Akure	Mica schist	Sandy SILT (ML)	31	106.48	730.99	3.712	3.699	3.712	3.684	3.706

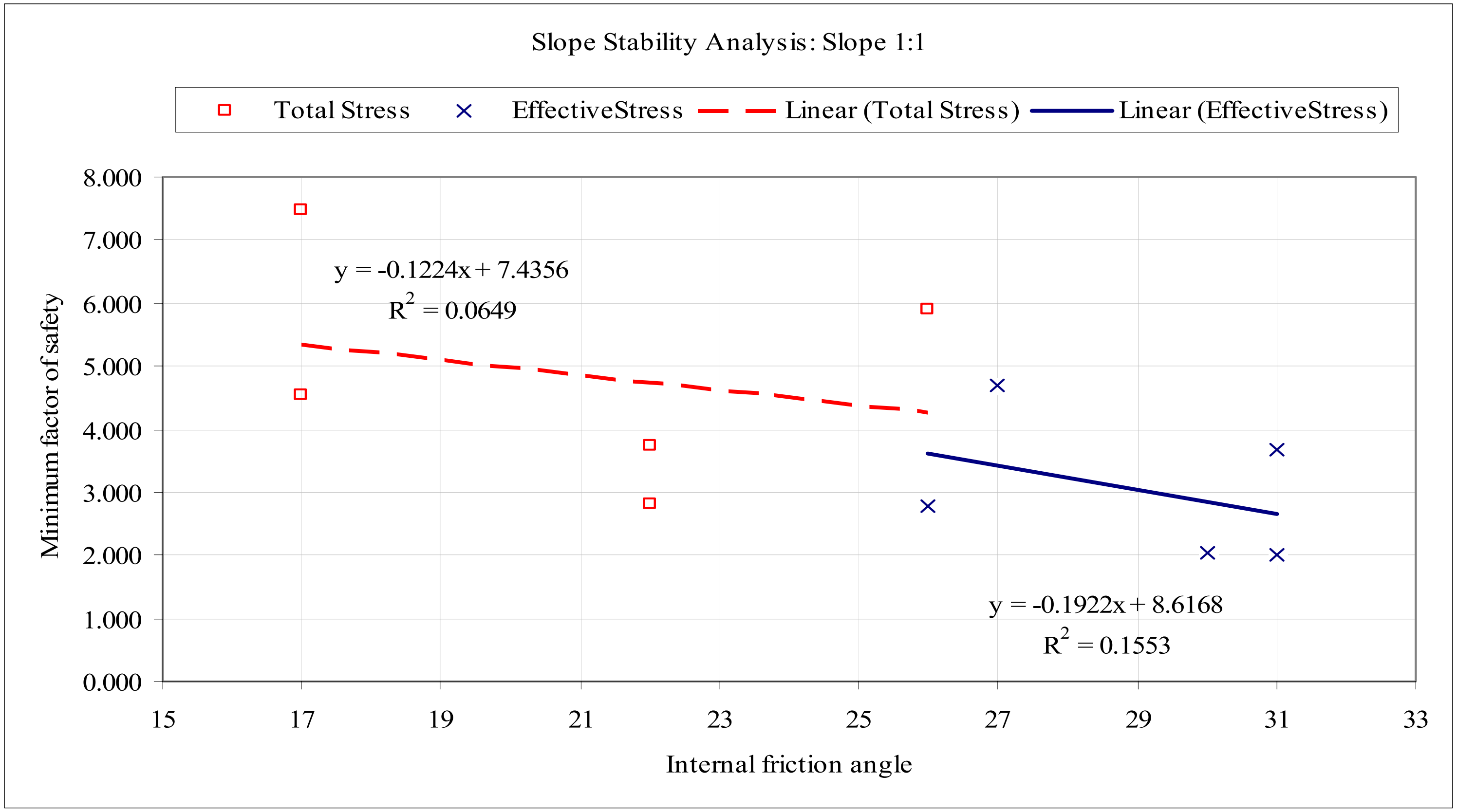


Figure 32: Plot of Factor of Safety versus Internal Friction Angle for Total and Effective stress Analysis (Slope 1:1)

Table 22: Effective Stress Analysis for a 20 feet Laterite Soil Slope of 2:1

Sample Locality	*Parent Material*	*Soil Group Name/Symbol (Unified System)*	*Effective Internal Friction Angle*	*Unit Weight (pcf)*	*Effective Cohesion C' (psf)*	*Minimum Factor of Safety*				
						Moment			*Force*	
						Morgenstern Price	*Ordinary*	*Bishop*	*Janbu*	*Morgenstern Price*
Ojota Quarry, Maryland	Benin Sand	Silty clayey SAND (SC-SM)	26	108.38	543.02	2.037	2.041	2.035	2.059	2.047
Ife/Ifewara	Amphibolites	Elastic SILT with sand (MH)	27	95.07	939.84	3.493	3.419	3.408	3.466	3.492
Unife	Granite gneiss	Sandy SILT (ML)	30	108.38	313.28	1.485	1.476	1.474	1.484	1.494
Ife/Ondo	Quartz schist	Silty SAND (ML)	31	114.09	313.28	1.463	1.457	1.457	1.465	1.470
Ife/Akure	Mica schist	Sandy SILT (ML)	31	106.48	730.99	2.753	2.645	2.633	2.691	2.761

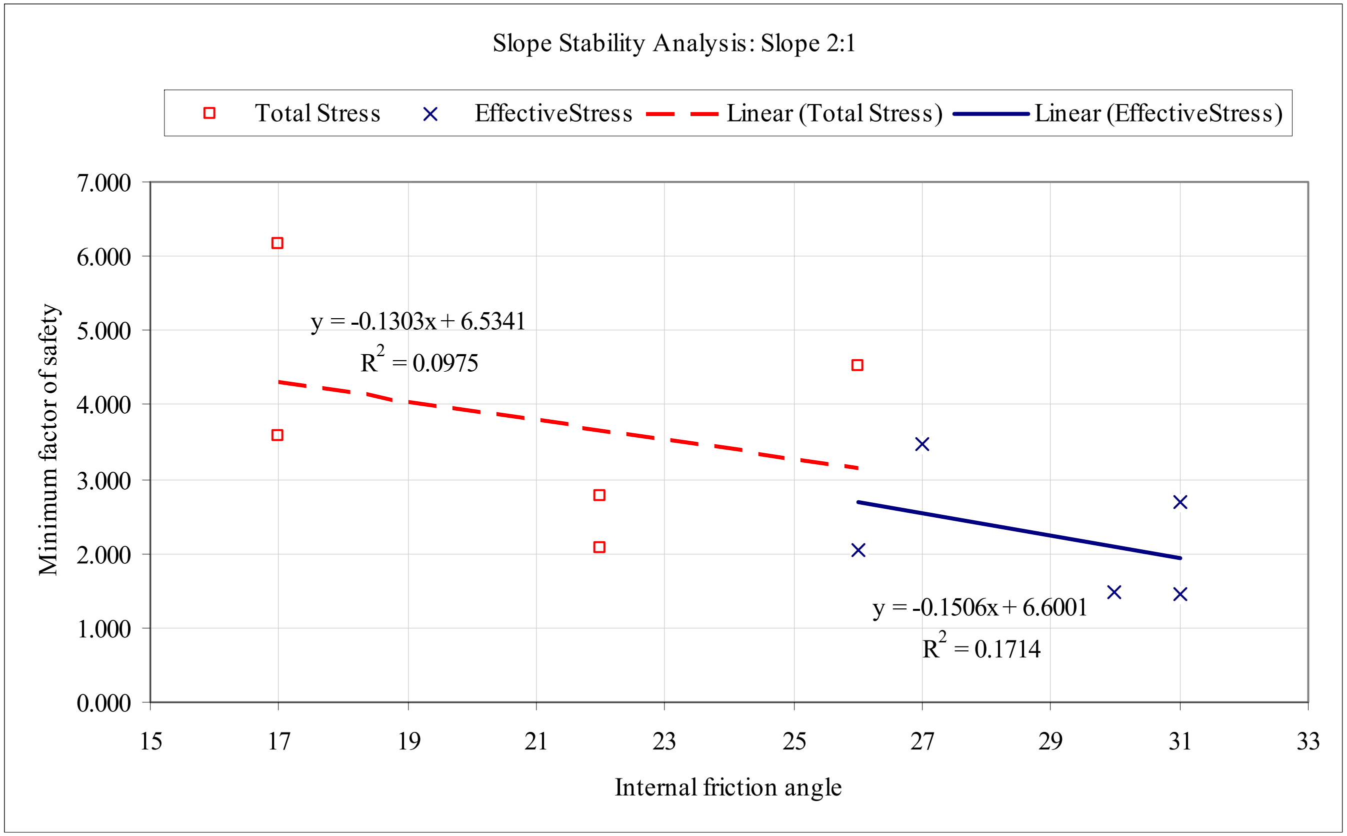


Figure 33: Plot of Factor of Safety versus Internal Friction Angle for Total and Effective stress Analysis (Slope 2:1)

Table 23: Effective Stress Analysis for a 20 feet Laterite Soil Slope of 3:1

Sample Locality	*Parent Material*	*Soil Group Name/Symbol (Unified System)*	*Effective Internal Friction Angle*	*Unit Weight (pcf)*	*Effective Cohesion C' (psf)*	*Minimum Factor of Safety*				
						Moment			*Force*	
						Morgenstern Price	*Ordinary*	*Bishop*	*Janbu*	*Morgenstern Price*
Ojota Quarry, Maryland	Benin Sand	Silty clayey SAND (SC-SM)	26	108.38	543.02	1.834	1.825	1.804	1.856	1.843
Ife/Ifewara	Amphibolites	Elastic SILT with sand (MH)	27	95.07	939.84	3.117	3.050	3.015	3.164	3.122
Unife	Granite gneiss	Sandy SILT (ML)	30	108.38	313.28	1.337	1.332	1.309	1.345	1.345
Ife/Ondo	Quartz schist	Silty SAND (ML)	31	114.09	313.28	1.306	1.310	1.287	1.325	1.314
Ife/Akure	Mica schist	Sandy SILT (ML)	31	106.48	730.99	2.444	2.409	2.358	2.479	2.453

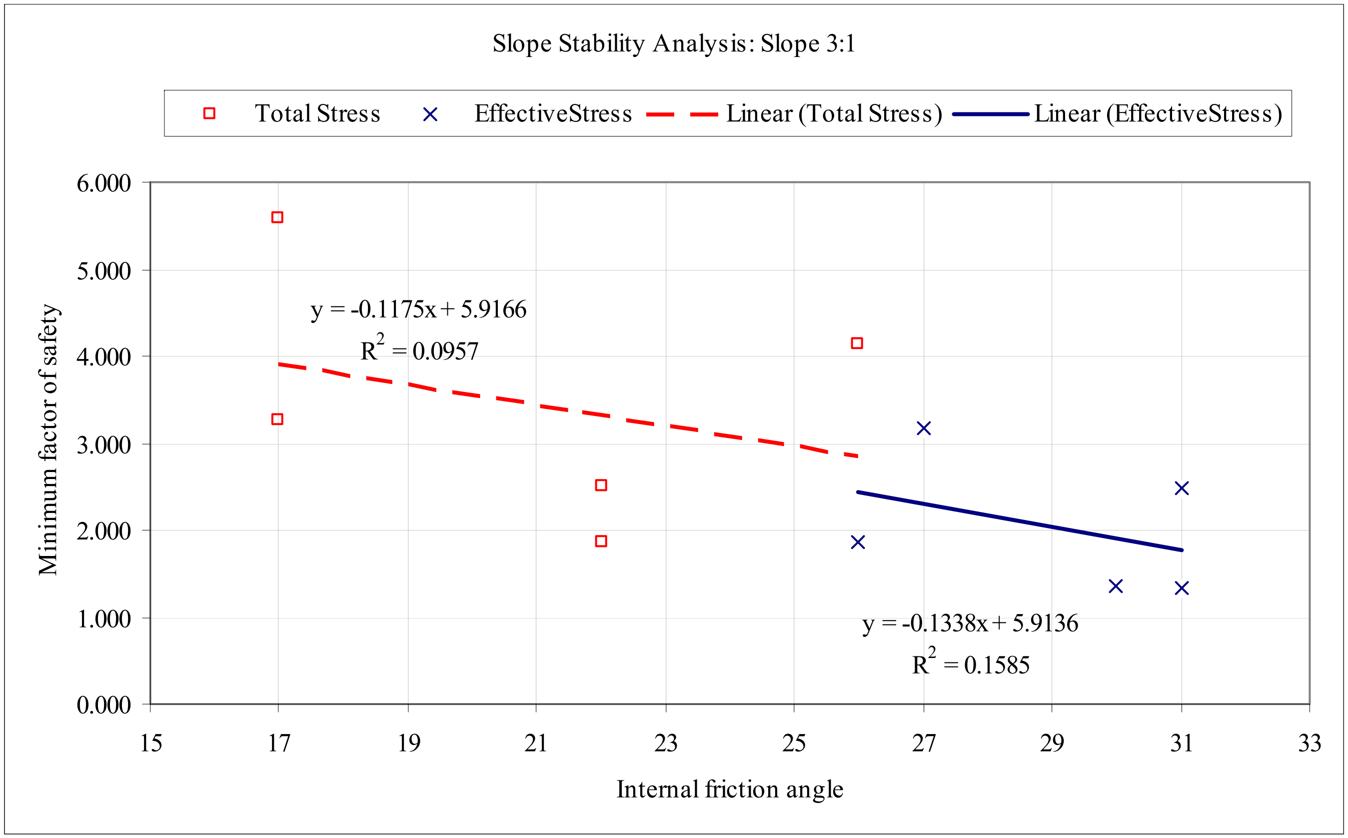


Figure 34: Plot of Factor of Safety versus Internal Friction Angle for Total and Effective stress Analysis (Slope 3:1)

Table 24: Effective Stress Analysis of a 20 feet Laterite Soil Slope of 0 (zero)

Sample Locality	*Parent Material*	*Soil Group Name/Symbol (Unified System)*	*Effective Internal Friction Angle*	*Unit Weight (pcf)*	*Effective Cohesion C' (psf)*	*Minimum Factor of Safety*				
						Moment			*Force*	
						Morgenstern Price	*Ordinary*	*Bishop*	*Janbu*	*Morgenstern Price*
Ojota Quarry, Maryland	Benin Sand	Silty clayey SAND (SC-SM)	26	108.38	543.02	1.477	1.421	1.335	1.492	1.474
Ife/Ifewara	Amphibolites	Elastic SILT with sand (MH)	27	95.07	939.84	2.480	2.413	2.331	2.573	2.490
Unife	Granite gneiss	Sandy SILT (ML)	30	108.38	313.28	1.051	1.048	0.946	1.092	1.058
Ife/Ondo	Quartz schist	Silty SAND (ML)	31	114.09	313.28	1.044	1.030	0.914	1.075	1.047
Ife/Akure	Mica schist	Sandy SILT (ML)	31	106.48	730.99	1.960	1.893	1.801	1.983	1.970

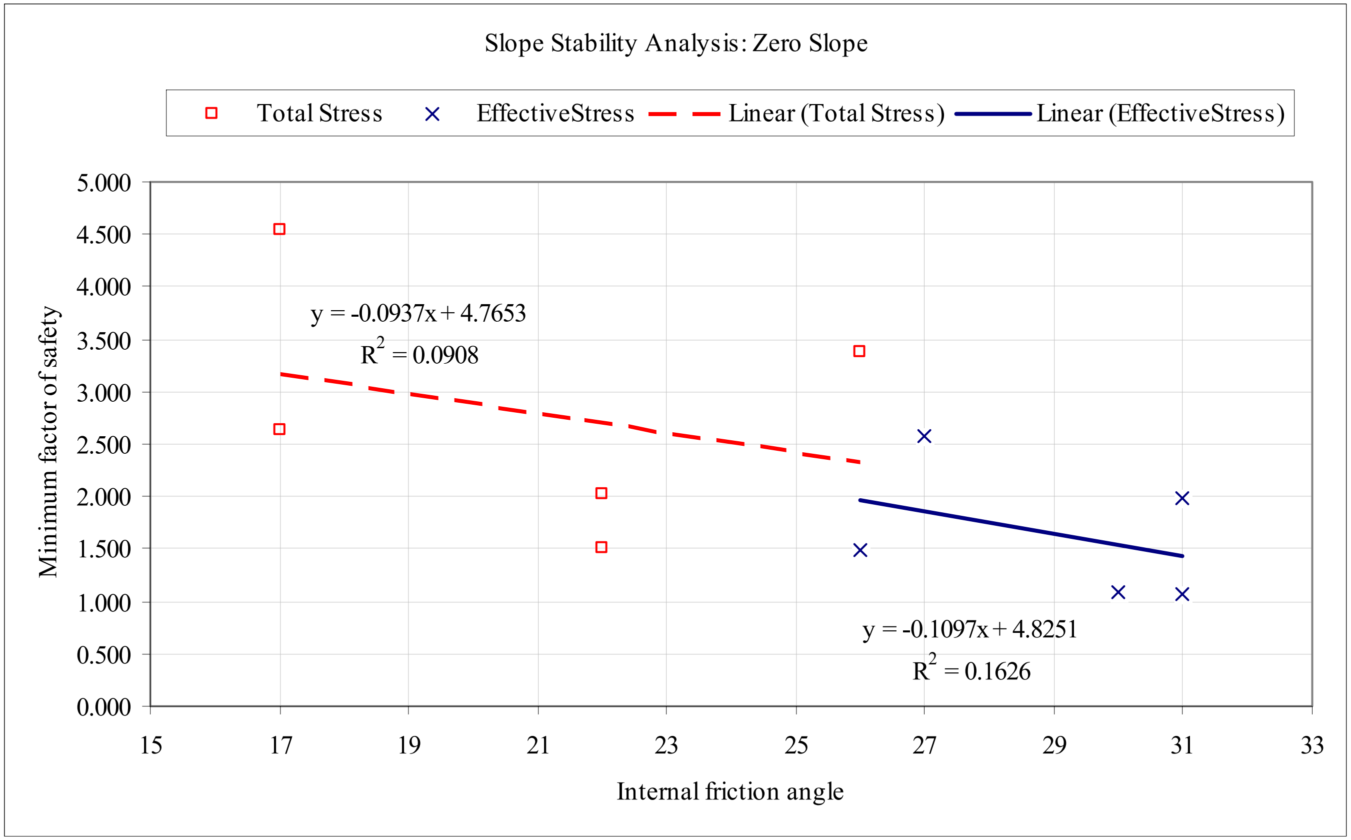


Figure 35: Plot of Factor of Safety versus Internal Friction Angle for Total and Effective stress Analysis (zero Slopes)

Similarly, like the total stress method, the effective stress method shows a rapid change in the factors of safety values of slope geometry between 1:1 and 2:1, and a nearly no changes for those between slope geometry of 2:1 and 3:1 as is evident from Table 25. From such a response, it can be deduced that there is very little difference in designing the slopes for stability of the slope between the geometry of 2:1 and 3:1.

Table 25: Factor of Safety with the Slope Geometry (Effective Stress).

Sample Locality	*Parent Material*	*Soil Group Name/Symbol (Unified System)*	*Effective Internal Friction Angle*	*Unit Weight (pcf)*	*Effective Cohesion C' (psf)*	*Slope*		*Difference %*
						1:1 and 2:1	*2:1 and 3:1*	
Ojota Quarry, Maryland	Benin Sand	Silty clayey SAND (SC-SM)	26	108.38	543.02	1.337	4.926	27.1
Ife/Ifewara	Amphibolites	Elastic SILT with sand (MH)	27	95.07	939.84	0.801	2.660	30.1
Unife	Granite gneiss	Sandy SILT (ML)	30	108.38	313.28	1.712	6.757	25.3
Ife/Ondo	Quartz schist	Silty SAND (ML)	31	114.09	313.28	1.715	6.369	26.9
Ife/Akure	Mica schist	Sandy SILT (ML)	31	106.48	730.99	1.043	3.236	32.2

The percent difference in values of the factor of safety obtained for both the total stress and effective stress analyses methods ranges between 48 to 74 percent for the computed values of slope geometry of 1:1, 2:1, 3:1 and 0. The significant reduction of the factor of safety between the total stress and effective stress methods for all slope configurations is attributed to the loss of cohesion and corresponding increase in the internal friction angle. In other words, for the overall evaluation of the stability of slopes, the effective stress methods would give safer prediction of the factor of safety than the total stress method which is only a short term stress analysis. As mentioned earlier, the reduction in the factor of safety is attributed to the loss of the fines (the binding agents – iron oxides) and water, and the rearrangement of the microstructure of the soil. The microstructure changes from a random arrangement to a parallel arrangement.

4.2.3 Shear Strength of Saturated Laterite Soil

In the review of literature, it was stated that the shear strength of laterite soils decreases with an increase in the degree of saturation (Nnadi, 1988). Plots showed that with all other parameters kept constant and if only the water content was varied, the shear strength of the laterite soil samples reduced from 100 kPa (2088.5 psf) to 60 kPa (1253.12 psf) at a degree of saturation of above 95 percent and soil density of 1500 kg/m^3 (93.57 pcf). For soil density of 1700 kg/m3 (106.5 pcf), the shear strength of the laterite soil reduced from 120 kPa (2506.25 psf) to 70 kPa (1461.12 psf). Using this information, back calculation analyses were performed to obtain the corresponding cohesion values of the laterite soils for a range of internal friction angles of between 10 to 40 degrees (reasonable assumption based of other published values) for a normal stress value of 137 kPa (2861.3 psf).

The shear strength for total stress method is given by the Mohr-Coulomb failure equation as follows:

$$\tau_f = c + \sigma_n \cdot \tan(\phi) \qquad (1)$$

where c is the cohesion, σ_n is the total normal stress, and ϕ is the internal friction angle in degrees.

Thus, cohesion c can be determined as:

$$c = \tau_f - \sigma_n \cdot \tan(\phi) \qquad (2)$$

The cohesion values for the unsaturated and fully saturated conditions of the laterite soil with the corresponding shear strength obtained by back calculation are presented in Tables 26 and 27 for soil density 1700 kg/m^3 and 1500 kg/m^3, respectively.

Table 26: Shear Strength Parameters for Unsaturated and Saturated Conditions and Soil

Unsaturated Laterite Soil (Density = 1700kg/m^3)				
τ_f *(psf)*	*c (psf)*	σ_n *(psf)*	ϕ^o	*c (kPa)*
2506.25	2506.25	2861.3	0	120.00
2506.25	2001.73	2861.3	10	95.84
2506.25	1739.57	2861.3	15	83.29
2506.25	1464.82	2861.3	20	70.14
2506.25	1172.00	2861.3	25	56.12
2506.25	854.28	2861.3	30	40.90
2506.25	502.75	2861.3	35	24.07
2506.25	105.33	2861.3	40	5.04

Saturated Laterite Soil (Density = 1700kg/m^3)				
τ_f *(psf)*	*c (psf)*	σ_n *(psf)*	ϕ^o	*C (kPa)*
1453.12	1453.12	2861.3	0	69.58
1453.12	948.60	2861.3	10	45.42
1453.12	686.44	2861.3	15	32.87
1453.12	411.69	2861.3	20	19.71
1453.12	118.87	2861.3	25	5.69

Table 27: Shear Strength Parameters for Unsaturated and Saturated Conditions, and Soil

Unsaturated Laterite Soil (Density = 1500 kg/m³)				
τ_f *(psf)*	*c (psf)*	σ_n *(psf)*	ϕ^o	*c (kPa)*
2088.54	2088.54	2861.3	0	100.00
2088.54	1584.02	2861.3	10	75.84
2088.54	1321.86	2861.3	15	63.29
2088.54	1047.11	2861.3	20	50.14
2088.54	754.29	2861.3	25	36.12
2088.54	436.57	2861.3	30	20.90
2088.54	85.04	2861.3	35	4.07

Saturated Laterite Soil (Density = 1500 kg/m³)				
τ_f *(psf)*	*c (psf)*	σ_n *(psf)*	ϕ^o	*C (kPa)*
1253.12	1253.12	2861.3	0	60.00
1253.12	748.60	2861.3	10	35.84
1253.12	486.44	2861.3	15	23.29
1253.12	211.69	2861.3	20	10.14

In both Tables 26 and 27 the cohesion required to obtain the shear strength value decreases as the internal friction angle increases, in the case of both unsaturated and saturated soil conditions. In addition, the table shows that the shear strength values decrease by about 60 percent from an unsaturated to saturated condition, showing a weakening of the soil strength by the rearrangement of the structure from random to parallel arrangements (Nnadi, 1988).

Based on these shear strength parameters a parametric study was conducted to determine the corresponding factors of safety for an embankment with geometry of 1:1, 2:1, and 3:1. For this study a probabilistic analysis was conducted because of the variability of the input parameters. The SLOPE/W software supports such a probabilistic study, in which the cohesion, internal friction angle, unit weight, and water level are inputted as the mean values and varies slightly as shown in Table 28.

Table 28 Table of soil properties and variance

Property	*Range of variation*	*Standard Deviation*	*Variance*
Cohesion	± 5 pcf	68.1	11
Internal Friction angle	± 2º	1.58	2.5
Unit weight	Constant	0	0
Water table	± 8 feet	5.05	22.67

For this probabilistic study the mean factors of safety are obtained, and the reliability and the distribution functions are plotted within SLOPE/W.

Tables 29 through 40 show the calculated factors of safety for the corresponding shear strength parameters, probability of failure percentage, and reliability index. The probability of failure reveals the percentage of slope failure if constructed randomly, and/or the level of confidence that can be placed on the slope. On the other hand, the reliability index describes the stability of a slope by the number of standard deviations separating the mean factor of safety from its defined failure value of 1.0, thus normalizes the factor of safety with respect to its certainty. Figure 36 through Figure 41 shows the variations of the factors of safety with changes in the internal friction angles. The probability density functions are shown in Appendix B1.

Table 29: Mean Factor of Safety a Slope of 1:1 and Unsaturated Soil

Density = 93.57 pcf		*Mean Factor of Safety (Slope 1:1, Unsaturated)*					*Number of Trials = 6000*				
Cohesion c psf	*Internal Friction Angle, ϕ*	*Moment*			*Force*		*Reliability Index*	*Probability of Failure (%)*	*Standard Deviation*	*Minimum Factor of Safety*	*Maximum Factor of Safety*
		Morgenstern Price	*Ordinary*	*Bishop*	*Janbu*	*Morgenstern Price*					
2088.54	0	6.542	6.542	6.542	6.640	6.543	89.436	0.000	0.063	6.454	6.900
1584.02	10	5.448	5.407	5.450	5.550	5.451	73.355	0.000	0.062	5.393	5.754
1321.86	15	4.745	4.721	4.746	4.788	4.747	48.314	0.000	0.078	4.453	5.037
1047.11	20	4.056	4.025	4.057	4.094	4.062	32.997	0.000	0.094	3.728	4.315
754.29	25	3.299	3.251	3.300	3.266	3.300	20.129	0.000	0.113	2.783	3.561
436.57	30	2.443	2.361	2.445	2.368	2.442	9.574	0.000	0.143	1.767	2.637
85.04	35	1.200	1.174	1.204	1.170	1.195	0.684	24.657	0.249	0.338	1.505

Table 30: Mean Factor of Safety a Slope of 1:1 and Saturated Soil

Density = 93.57 pcf		*Mean Factor of Safety (Slope 1:1, Saturated)*					*Number of Trials = 6000*				
Cohesion c psf	*Internal Friction Angle, ϕ*	*Moment*			*Force*		*Reliability Index*	*Probability of Failure (%)*	*Standard Deviation*	*Minimum Factor of Safety*	*Maximum Factor of Safety*
		Morgenstern Price	*Ordinary*	*Bishop*	*Janbu*	*Morgenstern Price*					
1253.12	0	3.928	3.924	3.928	3.999	3.929	133.29	0.000	0.022	3.8962	4.1141
748.60	10	2.476	2.451	2.476	2.517	2.479	17.518	0.000	0.087	2.4008	2.8904
486.44	15	1.667	1.660	1.671	1.728	1.671	6.421	0.000	0.113	1.620	2.314
211.69	20	0.895	0.799	0.893	0.836	0.896	-0.927	82.346	0.177	0.645	1.467

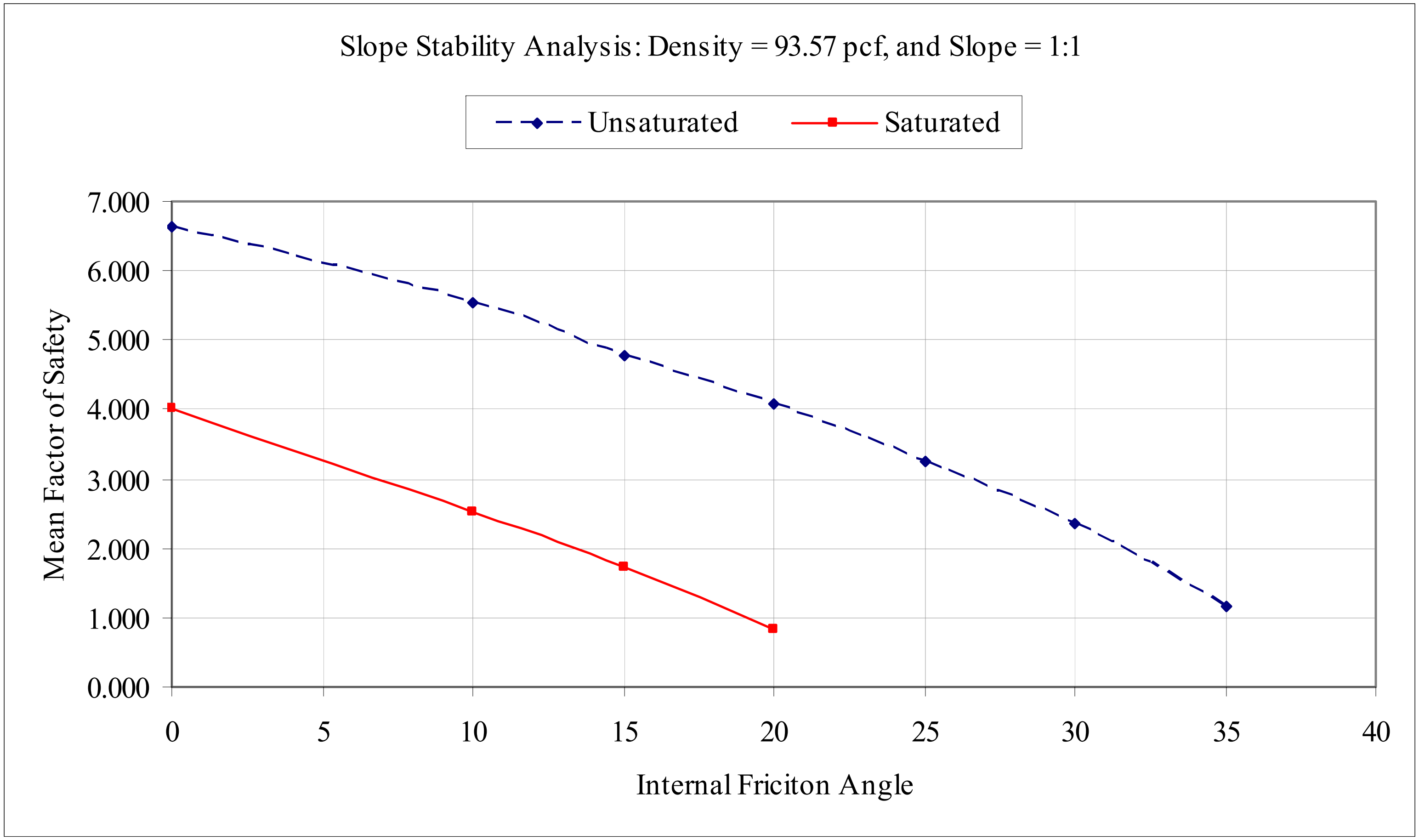


Figure 36: Plot of Factor of Safety versus Internal Friction Angle (Slope 1:1)

Table 31: Mean Factor of Safety a Slope of 1:1 and Unsaturated Soil

Density = 106.5 pcf		*Mean Factor of Safety (Slope 1:1, Unsaturated)*					*Number of Trials = 6000*				
		Moment			*Force*						
Cohesion c psf	*Internal Friction Angle, ϕ*	*Morgenstern Price*	*Ordinary*	*Bishop*	*Janbu*	*Morgenstern Price*	*Reliability Index*	*Probability of Failure (%)*	*Standard Deviation*	*Minimum Factor of Safety*	*Maximum Factor of Safety*
2506.25	0	6.906	6.896	6.906	7.043	6.908	120.970	0.000	0.050	6.933	7.242
2001.73	10	5.983	5.956	5.984	6.100	5.987	79.220	0.000	0.064	5.900	6.331
1739.57	15	5.425	5.400	5.426	5.489	5.428	65.190	0.000	0.069	5.203	5.709
1464.82	20	4.840	4.803	4.841	4.900	4.841	45.311	0.000	0.086	4.520	5.117
1172.00	25	4.208	4.168	4.208	4.221	4.208	31.658	0.000	0.102	3.734	4.478
854.28	30	3.498	3.433	3.498	3.467	3.498	19.464	0.000	0.127	2.890	3.721
502.75	35	2.729	2.622	2.735	2.606	2.733	11.348	0.000	0.142	1.874	2.886
105.33	40	1.673	1.452	1.675	1.445	1.671	2.291	1.094	0.194	0.622	1.750

Table 32: Mean Factor of Safety a Slope of 1:1 and Saturated Soil

Density = 106.5 pcf		*Mean Factor of Safety (Slope 1:1, Saturated)*					*Number of Trials = 6000*				
		Moment			*Force*						
Cohesion c psf	*Internal Friction Angle, ϕ*	*Morgenstern Price*	*Ordinary*	*Bishop*	*Janbu*	*Morgenstern Price*	*Reliability Index*	*Probability of Failure (%)*	*Standard Deviation*	*Minimum Factor of Safety*	*Maximum Factor of Safety*
1453.12	0	4.003	3.998	4.003	4.075	4.003	130.96	0.000	0.023	3.9838	4.1872
948.6	10	2.782	2.757	2.783	2.830	2.785	23.78	0.000	0.077	2.7254	3.2331
686.44	15	2.122	2.086	2.123	2.153	2.124	10.253	0.000	0.112	2.015	2.571
411.69	20	1.418	1.370	1.419	1.429	1.420	2.619	0.439	0.164	1.251	2.018
118.87	25	0.697	0.519	0.677	0.569	0.694	-2.265	98.830	0.190	0.383	1.202

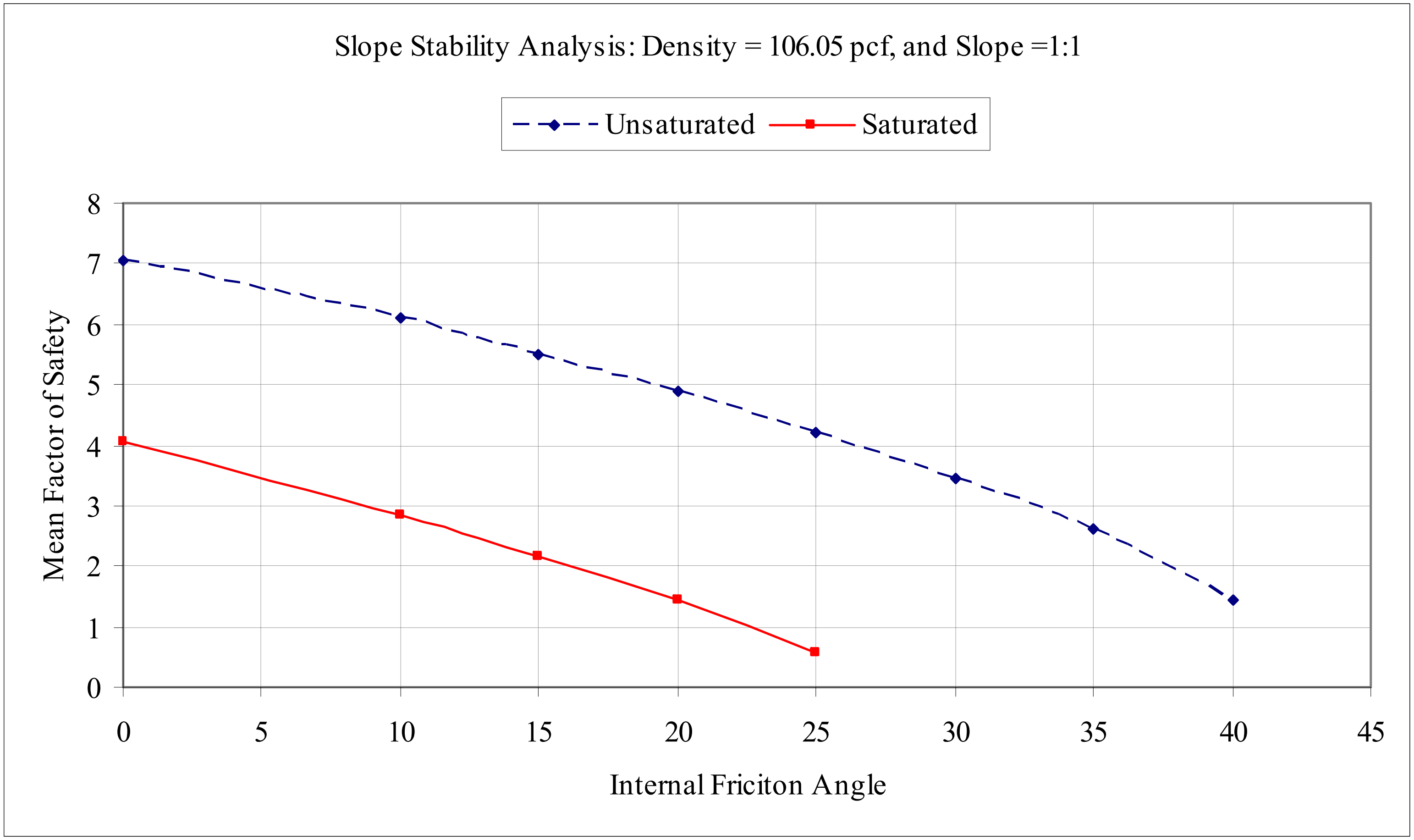


Figure 37: Plot of Factor of Safety versus Internal Friction Angle (Slope 1:1)

Table 33: Mean Factor of Safety a Slope of 2:1 and Unsaturated Soil

Density = 93.57 pcf		*Mean Factor of Safety (Slope 2:1, Unsaturated)*					*Number of Trials = 6000*				
Cohesion c psf	*Internal Friction Angle, ϕ*	*Moment*			*Force*		*Reliability Index*	*Probability of Failure (%)*	*Standard Deviation*	*Minimum Factor of Safety*	*Maximum Factor of Safety*
		Morgenstern Price	*Ordinary*	*Bishop*	*Janbu*	*Morgenstern Price*					
2088.54	0	6.120	6.118	6.120	6.258	6.129	146.260	0.000	0.036	6.123	6.402
1584.02	10	4.955	4.935	4.952	5.044	4.959	75.683	0.000	0.053	4.840	5.188
1321.86	15	4.256	4.265	4.253	4.330	4.263	51.011	0.000	0.065	4.109	4.486
1047.11	20	3.580	3.584	3.576	3.636	3.583	32.239	0.000	0.082	3.312	3.822
754.29	25	2.892	2.860	2.889	2.923	2.901	29.165	0.000	0.066	2.511	3.094
436.57	30	2.035	1.995	2.033	2.055	2.045	12.644	0.000	0.083	1.684	2.213
85.04	35	0.807	0.773	0.813	0.777	0.803	-1.269	89.817	0.175	0.130	1.011

Table 34: Mean Factor of Safety a Slope of 2:1 and Saturated Soil

Density = 93.57 pcf		*Mean Factor of Safety (Slope 2:1, Saturated)*					*Number of Trials = 6000*				
Cohesion c psf	*Internal Friction Angle, ϕ*	*Moment*			*Force*		*Reliability Index*	*Probability of Failure (%)*	*Standard Deviation*	*Minimum Factor of Safety*	*Maximum Factor of Safety*
		Morgenstern Price	*Ordinary*	*Bishop*	*Janbu*	*Morgenstern Price*					
1253.12	0	3.641	3.647	3.641	3.73	3.651	163.2	0.000	0.017	3.6715	3.8189
748.60	10	2.268	2.271	2.266	2.310	2.272	17.355	0.000	0.075	2.1934	2.6336
486.44	15	1.451	1.495	1.448	1.480	1.460	7.048	0.000	0.068	1.393	1.876
211.69	20	0.545	0.658	0.548	0.551	0.553	-14.167	100.000	0.032	0.491	0.984

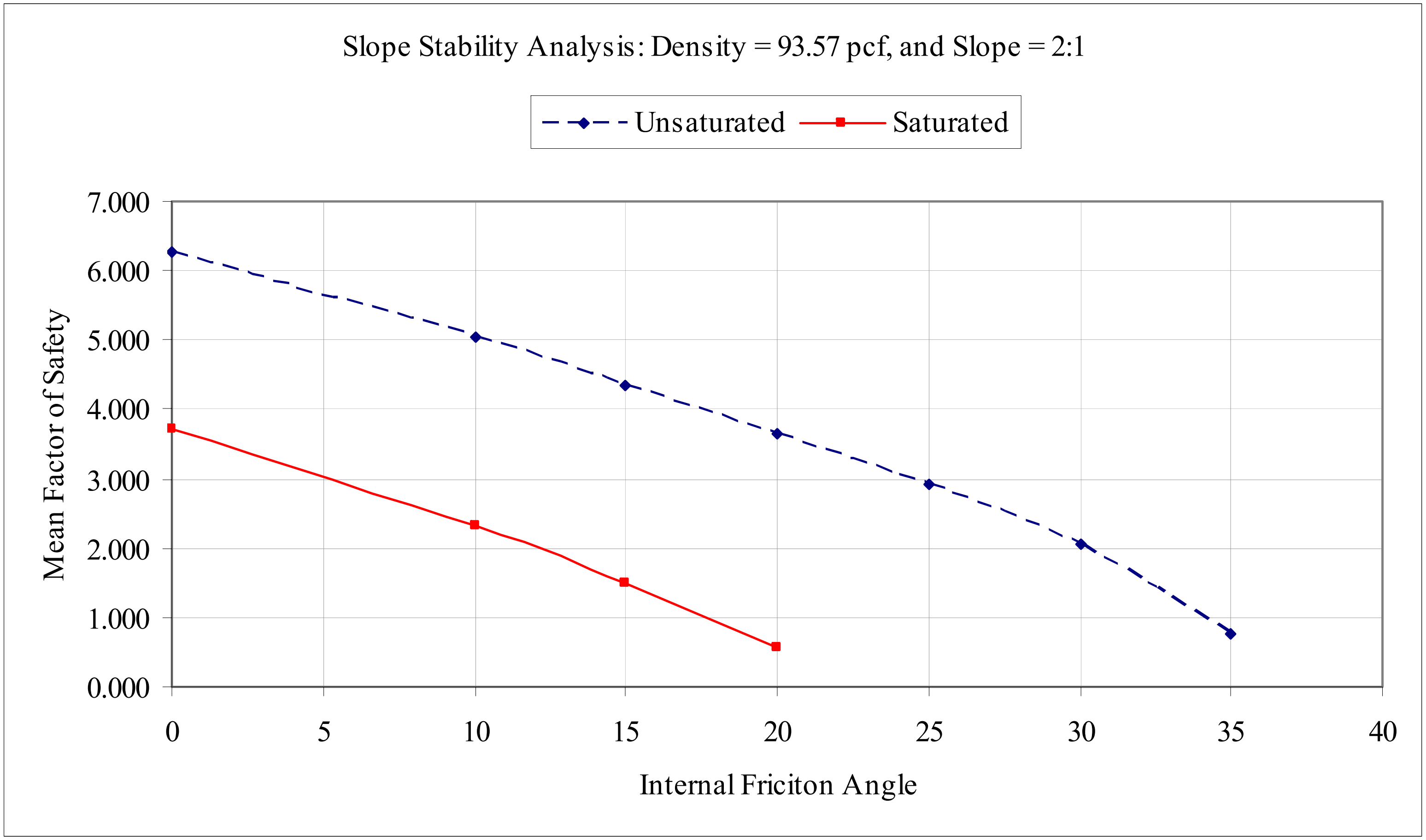


Figure 38: Plot of Factor of Safety versus Internal Friction Angle (Slope 2:1)

Table 35: Mean Factor of Safety a Slope of 2:1 and Unsaturated Soil

Density = 106.5 pcf		*Mean Factor of Safety (Slope 2:1, Unsaturated)*					*Number of Trials = 6000*				
		Moment			*Force*						
Cohesion c psf	*Internal Friction Angle, ϕ*	*Morgenstern Price*	*Ordinary*	*Bishop*	*Janbu*	*Morgenstern Price*	*Reliability Index*	*Probability of Failure (%)*	*Standard Deviation*	*Minimum Factor of Safety*	*Maximum Factor of Safety*
2506.25	0	6.557	6.55	6.557	6.690	6.564	162.230	0.000	0.035	6.513	6.785
2001.73	10	5.474	5.477	5.472	5.580	5.480	83.076	0.000	0.055	5.393	5.803
1739.57	15	4.890	4.903	4.887	4.981	4.898	74.879	0.000	0.053	4.759	5.152
1464.82	20	4.333	4.339	4.329	4.405	4.337	45.124	0.000	0.075	4.091	4.601
1172.00	25	3.681	3.695	3.676	3.734	3.690	30.835	0.000	0.089	3.395	3.929
854.28	30	3.061	3.018	3.058	3.089	3.070	49.148	0.000	0.043	2.866	3.262
502.75	35	2.115	2.120	2.113	2.132	2.125	7.250	0.000	0.156	1.551	2.304
105.33	40	0.912	0.884	0.919	0.885	0.907	-0.540	70.596	0.212	0.129	1.158

Table 36: Mean Factor of Safety a Slope of 2:1 and Saturated Soil

Density = 106.5 pcf		*Mean Factor of Safety (Slope 2:1, Saturated)*					*Number of Trials = 6000*				
		Moment			*Force*						
Cohesion c psf	*Internal Friction Angle, ϕ*	*Morgenstern Price*	*Ordinary*	*Bishop*	*Janbu*	*Morgenstern Price*	*Reliability Index*	*Probability of Failure (%)*	*Standard Deviation*	*Minimum Factor of Safety*	*Maximum Factor of Safety*
1453.12	0	3.743	3.742	3.743	3.828	3.748	134.640	0.000	0.021	3.728	3.940
948.6	10	2.532	2.527	2.530	2.586	2.534	21.605	0.000	0.073	2.483	2.867
686.44	15	1.842	1.868	1.838	1.876	1.849	11.643	0.000	0.075	1.788	2.220
411.69	20	1.178	1.193	1.175	1.196	1.187	1.450	7.328	0.135	1.066	1.600
118.87	25	0.389	0.342	0.379	0.364	0.387	-3.236	99.940	0.197	0.134	0.880

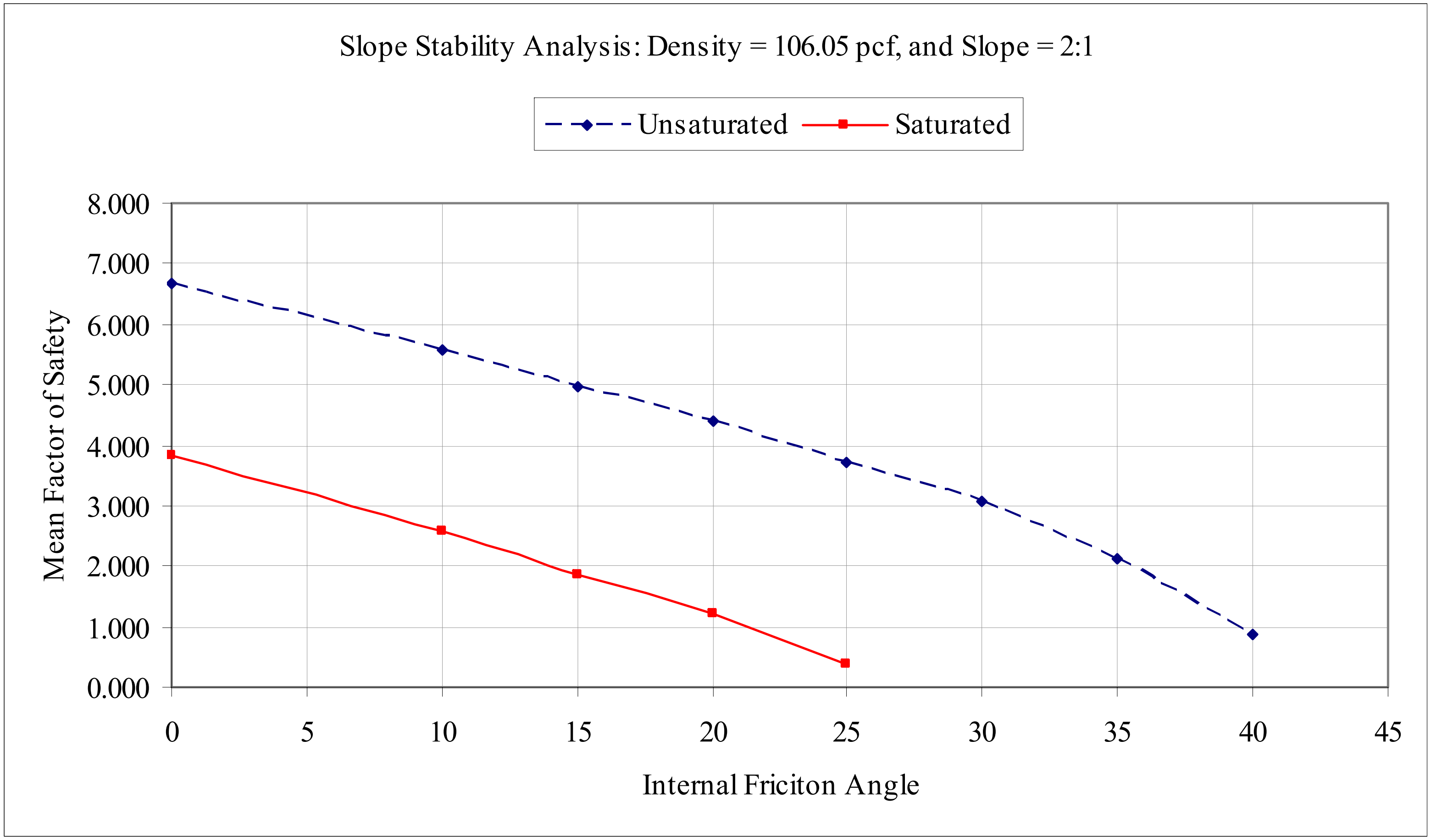


Figure 39: Plot of Factor of Safety versus Internal Friction Angle (Slope 2:1)

Table 37: Mean Factor of Safety a Slope of 3:1 and Unsaturated Soil

Density = 93.57 pcf		*Mean Factor of Safety (Slope 3:1, Unsaturated)*					*Number of Trials = 6000*				
		Moment			*Force*						
Cohesion c psf	*Internal Friction Angle, ϕ*	*Morgenstern Price*	*Ordinary*	*Bishop*	*Janbu*	*Morgenstern Price*	*Reliability Index*	*Probability of Failure (%)*	*Standard Deviation*	*Minimum Factor of Safety*	*Maximum Factor of Safety*
2088.54	0	5.592	5.598	5.592	5.781	5.598	136.530	0.000	0.035	5.661	5.941
1584.02	10	4.482	4.470	4.478	4.625	4.488	75.737	0.000	0.048	4.458	4.759
1321.86	15	3.878	3.881	3.873	3.980	3.884	50.691	0.000	0.059	3.731	4.125
1047.11	20	3.244	3.258	3.238	3.324	3.248	31.504	0.000	0.074	3.033	3.518
754.29	25	2.564	2.575	2.557	2.621	2.569	18.170	0.000	0.089	2.267	2.817
436.57	30	1.757	1.761	1.751	1.787	1.762	6.502	0.000	0.121	1.315	1.938
85.04	35	0.686	0.672	0.692	0.677	0.686	-1.871	96.944	0.173	0.111	0.888

Table 38: Mean Factor of Safety a Slope of 3:1 and Saturated Soil

Density = 93.57 pcf		*Mean Factor of Safety (Slope 3:1, Saturated)*					*Number of Trials = 6000*				
		Moment			*Force*						
Cohesion c psf	*Internal Friction Angle, ϕ*	*Morgenstern Price*	*Ordinary*	*Bishop*	*Janbu*	*Morgenstern Price*	*Reliability Index*	*Probability Of Failure (%)*	*Standard Deviation*	*Minimum Factor of Safety*	*Maximum Factor of Safety*
1253.12	0	3.328	3.325	3.327	3.449	3.332	141.9	0.000	0.017	3.3638	3.5217
748.60	10	1.998	2.013	1.993	2.071	2.004	17.415	0.000	0.061	1.9831	2.3214
486.44	15	1.317	1.339	1.311	1.357	1.319	4.087	0.002	0.087	1.257	1.768
211.69	20	0.529	0.572	0.532	0.544	0.536	-3.857	99.994	0.118	0.406	1.022

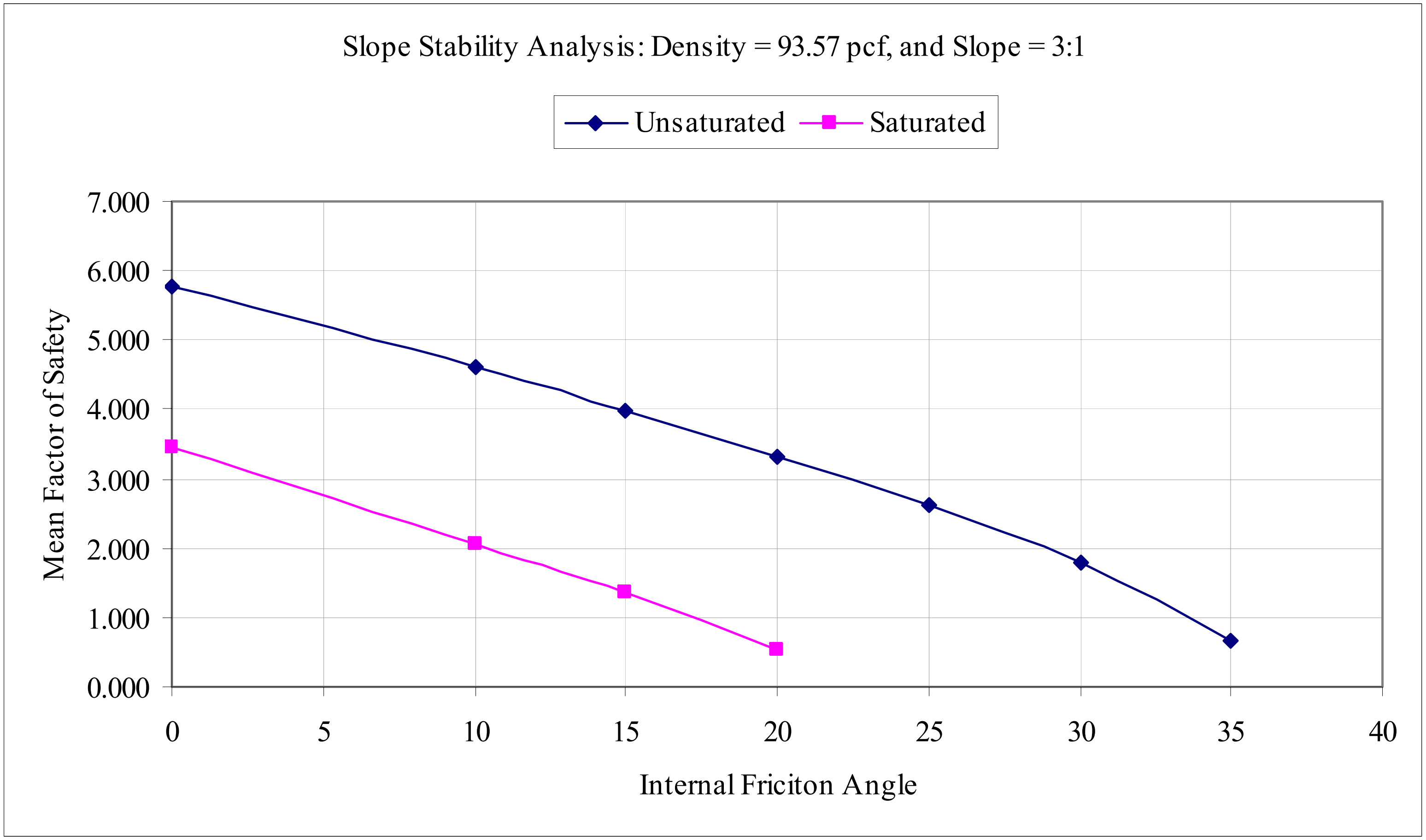


Figure 40: Plot of Factor of Safety versus Internal Friction Angle

Table 39: Mean Factor of Safety a Slope of 3:1 and Unsaturated Soil

Density = 106.5 pcf		*Mean Factor of Safety (Slope 3:1, Unsaturated)*					*Number of Trials = 6000*				
Cohesion c psf	*Internal Friction Angle, ϕ*	*Moment*			*Force*		*Reliability Index*	*Probability Of Failure (%)*	*Standard Deviation*	*Minimum Factor of Safety*	*Maximum Factor of Safety*
		Morgenstern Price	*Ordinary*	*Bishop*	*Janbu*	*Morgenstern Price*					
2506.25	0	5.909	5.911	5.909	6.094	5.912	126.580	0.000	0.040	5.959	6.254
2001.73	10	4.938	4.934	4.921	5.092	4.945	100.590	0.000	0.041	4.943	5.231
1739.57	15	4.458	4.460	4.451	4.596	4.462	64.627	0.000	0.056	4.364	4.754
1464.82	20	3.933	3.918	3.925	4.049	3.938	72.031	0.000	0.042	3.888	4.130
1172.00	25	3.315	3.322	3.307	3.396	3.320	28.120	0.000	0.085	3.064	3.584
854.28	30	2.699	2.675	2.691	2.762	2.709	26.259	0.000	0.067	2.317	2.863
502.75	35	1.911	1.903	1.905	1.942	1.918	8.855	0.000	0.106	1.443	2.116
105.33	40	0.790	0.770	0.796	0.777	0.789	-1.131	87.143	0.197	0.122	1.006

Table 40: Mean Factor of Safety a Slope of 3:1 and Saturated Soil

Density = 106.5 pcf		*Mean Factor of Safety (Slope 3:1, Saturated)*					*Number of Trials = 6000*				
Cohesion c psf	*Internal Friction Angle, ϕ*	*Moment*			*Force*		*Reliability Index*	*Probability Of Failure (%)*	*Standard Deviation*	*Minimum Factor of Safety*	*Maximum Factor of Safety*
		Morgenstern Price	*Ordinary*	*Bishop*	*Janbu*	*Morgenstern Price*					
1453.12	0	3.394	3.387	3.393	3.517	3.398	164.230	0.000	0.015	3.429	3.586
948.6	10	2.287	2.285	2.283	2.372	2.296	20.381	0.000	0.067	2.282	2.612
686.44	15	1.648	1.684	1.642	1.699	1.653	9.882	0.000	0.071	1.619	2.054
411.69	20	0.998	1.055	0.991	1.035	1.005	0.346	36.453	0.101	0.956	1.444
118.87	25	0.214	0.325	0.216	0.212	0.211	-7.068	100.000	0.112	0.106	0.783

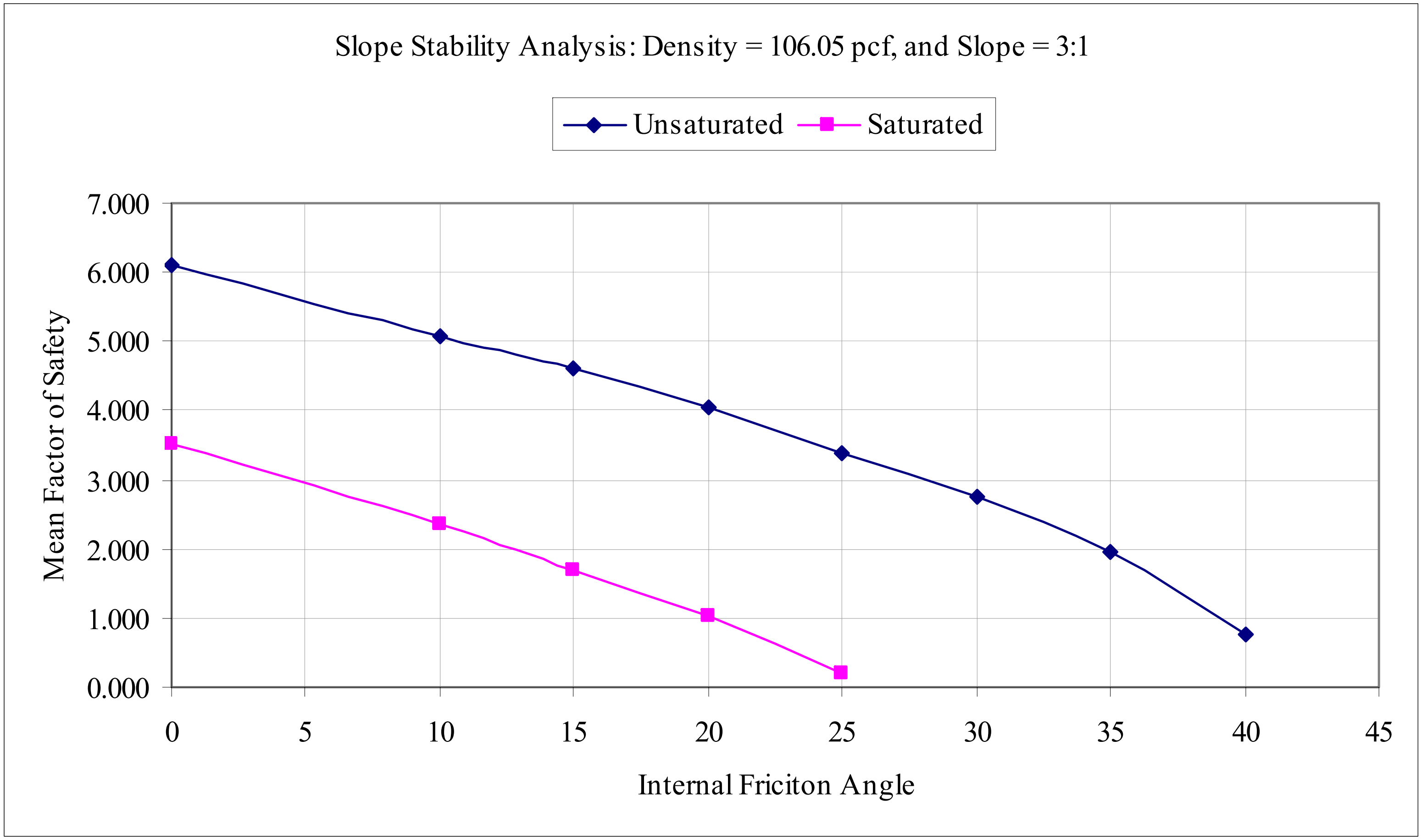


Figure 41: Plot of Factor of Safety versus Internal Friction Angle

Critical review of the probability analysis shows that there is a zero percentage of failure for both unsaturated and saturated conditions shear strength parameters. However, for the internal friction angles of 35º and 40º for the unsaturated soil conditions and 20º to 25º for the saturated conditions the probability of failure percentage increases as show in the Table 29 through Table 40. The factor of safety is shown as a probability density function in Appendix B to Appendix D. The probability density function shows the frequency of the distribution of the Monte Carlo trial factors of safety in terms of percentage.

The reliability index reveals a more meaningful measure of stability of the slopes than the factor of safety. It is sensitive to the amount of variability in the input parameters. At zero internal friction angles, all slope geometry show high values of reliability index in the range 89 to 162 for unsaturated conditions, and 131 to 163 for saturated conditions. It was also observed that the slope of 2:1 has higher reliability index than slopes of 1:1 and 3:1 for all degree of saturation, and the fully saturated conditions posses greater reliability index than the unsaturated conditions. However, as the soil decreases in cohesion strength and increases in the internal friction angles the reliability index of the saturated condition becomes significantly lower than the unsaturated condition.

This study reveals a significant reduction in the factor of safety between the unsaturated and saturated soil conditions. This could be attributed to the loss of the fines and the iron oxide, which acts as a binding agent in laterite soils, from the laterite soil, leaving intact the non-cohesive grains. This results in the reduction of the cohesive strength of the laterite soil. It also results in an increase in the internal friction angle, due to increased angularity of the soil grains. Finally, it is a less stable embankment, as the matrix microstructure of the laterite (dense regions with more concretion) changes to the skeletal microstructure (porous regions with more segregated particles). The laterite soil shows a reduction in strength with increase in the degree of saturation.

CHAPTER FIVE: CONCLUSIONS

The importance of the investigation of laterite soils with regards to slope stability of embankments is an important problem in tropical geological environments. It illustrates the changing ways in which scientific and engineering technology is shared across the globe for the benefit to society. The growth of developmental projects within the regions of tropics and subtropical areas of the world, where the laterite soil is the dominant soil type, has increased dramatically. There are some reported cases of failures of embankments constructed with laterite soils. Thus, a thorough research study on the strength of the laterite soils is undeniably important to accommodate both the economic and social problems associated with the soil.

There is the increasing awareness and usage of geographic information systems (GIS) as a planning tool for a wide range of applications. The GIS is a very useful tool that enables the storage and rapid analysis of enormous amount of information and creation of new records, in this case, a geotechnical database. It is therefore, necessary to have a database of the properties of laterite soils based on the location of origin. Although it is acknowledged that soil properties vary vertically and horizontally from region to region, such a database can be very useful to the geotechnical engineer. This will serve as a guide for engineers in the planning and design of earth structures in these regions.

This chapter summarizes the conclusions of the current study of embankment stability in Nigeria, due to the peculiar characteristics of laterite soils. In addition, the chapter also describes the results of the laterite soil stability using the total and effective stress methods. Finally, the effects of degree of saturation to the stability of embankments are summarized.

5.1 REVIEW OF FINDINGS

It is evident from the literature review that there is the need to compare the calculated factors of safety of the total and effective stress methods based on their respective shear strength parameters for laterite soils. This comparison was carried out in this thesis by comparing the predictions of the stability of embankments with the SLOPE/W slope stability analysis software program. The analysis included embankment profiles with different shear strength parameters, slope geometric configurations, and saturation conditions. Initial outputs of the slope stability analyses reveal that the factors of safety of laterite soil embankment are relatively high. The high factors of safety values were based on the total stress methods, which is only a short-term analysis of the laterite soil condition. In the total stress method, which is the initial state of the embankment construction, the laterite soil microstructure is likely to be random and dense. In this state, the laterite soil microstructure consists of a higher percentage of fines (iron oxides) that are properly coalesced with the non-cohesive grains, forming stronger aggregate concretion and firmer structure. This results in higher shear strengths as is evident in published literatures.

The studies conducted on the stability of laterite soil embankment brought to focus the need to perform an effective stress analysis and compare to the total stress method. This is necessitated by the concern for long-term effect of the shear strength of the laterite soil, and consequently, the final stability of laterite soil embankments.

Effective stress stability analysis is very sensitive to the value of effective cohesion used in calculation (Otoko 1988). A critical review of the literature reveals a drastic reduction in the cohesive strength of compacted laterite soil embankment analyzed by the effective stress method. The loss of cohesion of laterite soils may result from the loss of moisture and the binding agents for the fines (such as iron oxides) over longer time periods. The resultant effect is the significant reduction of the factor of safety, thereby compromising the stability of an otherwise stable embankment. The factor of safety predicted using the total stress method parameters is higher than the factor of safety predicted using the effective stress method, and it varies within the range of 40 percent to 90 percent higher.

This study also show that the shear strength of compacted laterite soils decreases with increasing water content. With water content above 95 percent, the shear strength becomes a function of degree of orientation and the angle of internal friction along the shear zone. A low current of water remove the fines (iron oxides) and reduces the cohesion of the compacted laterite soil. At very high degree of saturation, the compacted laterite soil alters its microstructure from a random to parallel arrangement, which causes a reduction in the shear strength significantly. The slope stability analysis performed on the compacted laterite soil embankment for fully saturated condition and using the shear strength parameters obtained for saturated conditions, shows a significant reduction of the factor of safety when compared to the initial state of the compacted laterite soil. This is due to the low cohesion and high internal friction angle.

The results obtained from the slope stability analysis performed within study show that the effective stress method and the degree of saturation influences the stability of compacted laterite soil embankments. This is because of the reduction of the shear strength with time and a change in the microstructure arrangement with the degree of saturation.

Pursuant to one of the objectives of this study, the geographic information systems (GIS) is developed to provide for the creation, management, publication, and dissemination of the properties of soils for some investigated urban locations in Nigeria with costal laterite soils. The creation of this database on laterite soil properties brings to the desktop of planners, designers, and managers in the geotechnical engineering field, the much needed preliminary knowledge of the conditions, and better perspective to the intricacies of characterizing the strength of the soil. It is intended to serve as starting block for organizing a global knowledge based on scientific data of the local soil strength and potential problems that may be encountered in laterite soils of Nigeria. The results of the GIS can be displayed digitally, viewed on paper maps with the spreadsheet-like tables and printed, or displayed as such. All this is being done to capture, store, display, and exchange spatial data, and allow for efficient and flexible information technology on laterite soils.

5.2 RECOMMENDATIONS

The study reveals that there is the need for geotechnical engineers to conduct more investigations on the effective stress parameters and the influence on the microstructure. In addition, more studies on the effect of degree of saturation and the response of the soil in the long term, and the effect on the shear strength need also be conducted. The implementation of these will provide better strength parameters for the prediction of the stability of laterite soil embankments and a more complete database for the geographic information systems. Further investigations aimed at improving the predictability of field compaction strength behavior from statistical examination of the magnitude and variation of the soaked strength of the laboratory compacted laterite need to be performed. A quantitative relationship may be established which will allow the prediction of properties as well as the determination of the compaction variables to produce desired behavior.

This study has identified the problems of slope stability in laterite soil embankments and thus, will suggest that some ground improvement methods need to be performed to stabilize failure potentials in slopes. Among such ground improvement methods to be considered is the reinforced earth used to reinforce backfills of retaining walls generally referred to as mechanically stabilized retaining walls such as metallic strips, geotextiles, and geogrids. In addition, vegetation on the slope surface could improve the stability of the embankment.

APPENDIX A: VIEWS OF SOIL PROPERTIES ON GIS

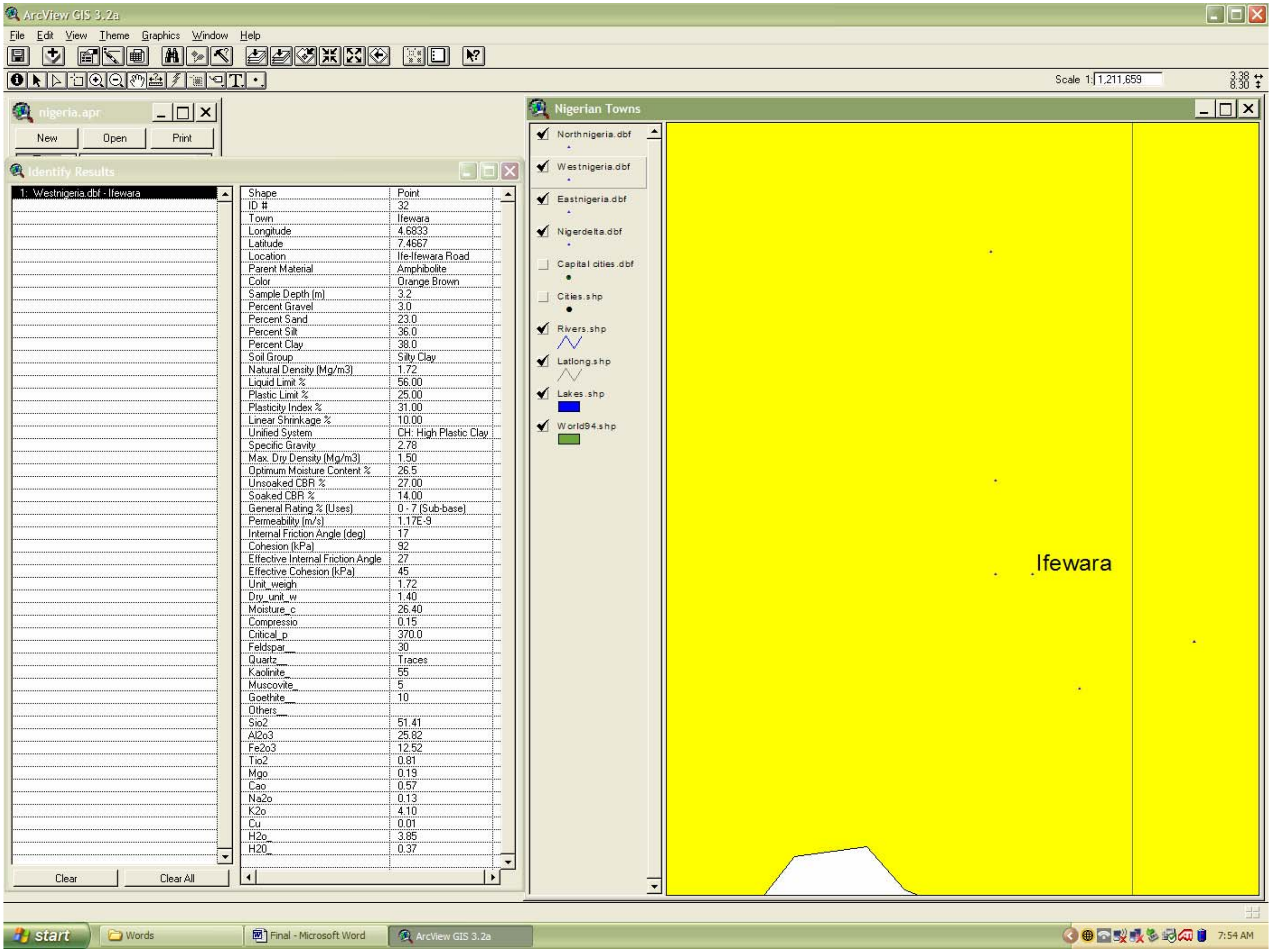


Figure 42: Soil properties of Ifewara

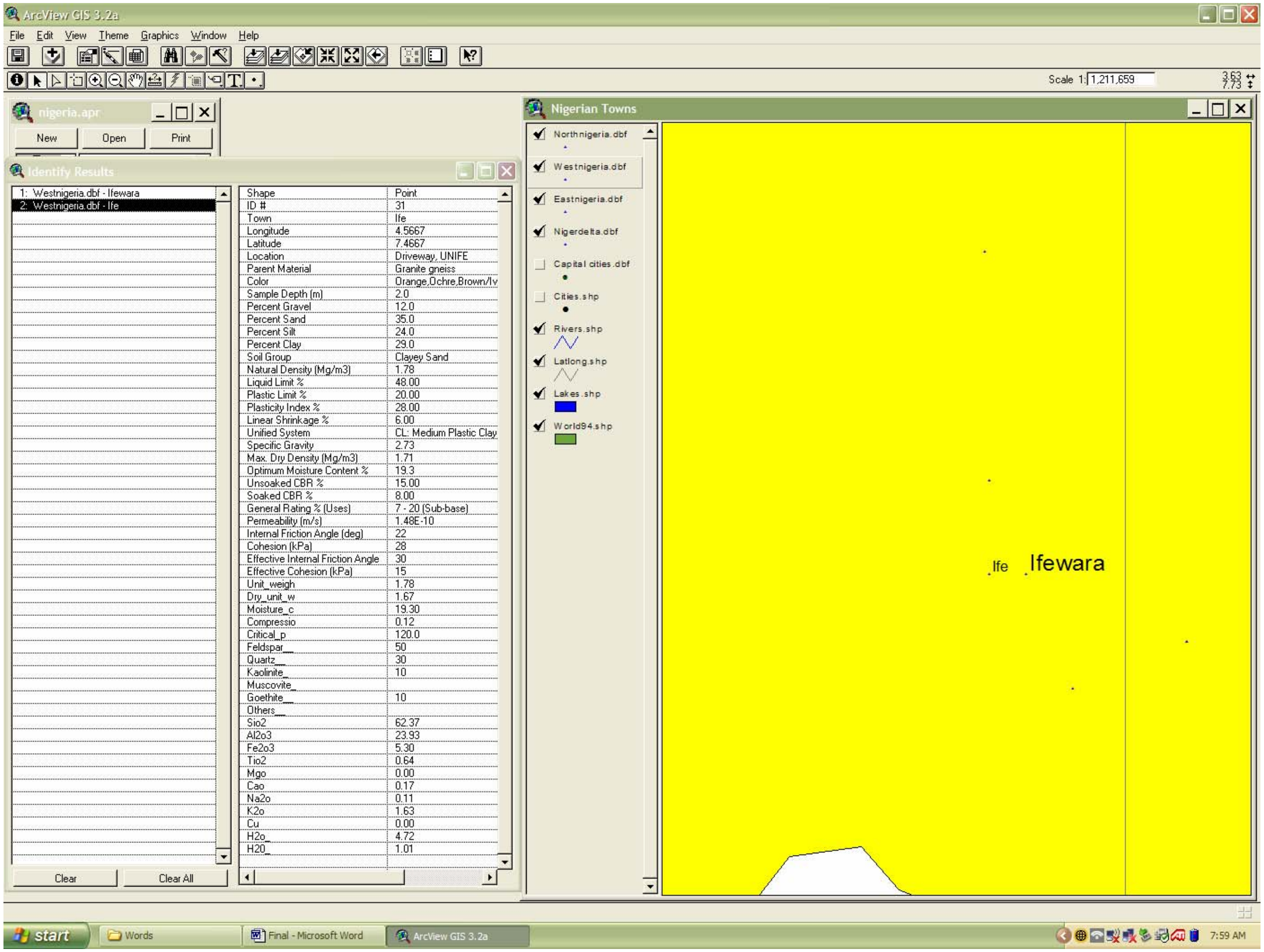


Figure 43: Soil properties of Ife

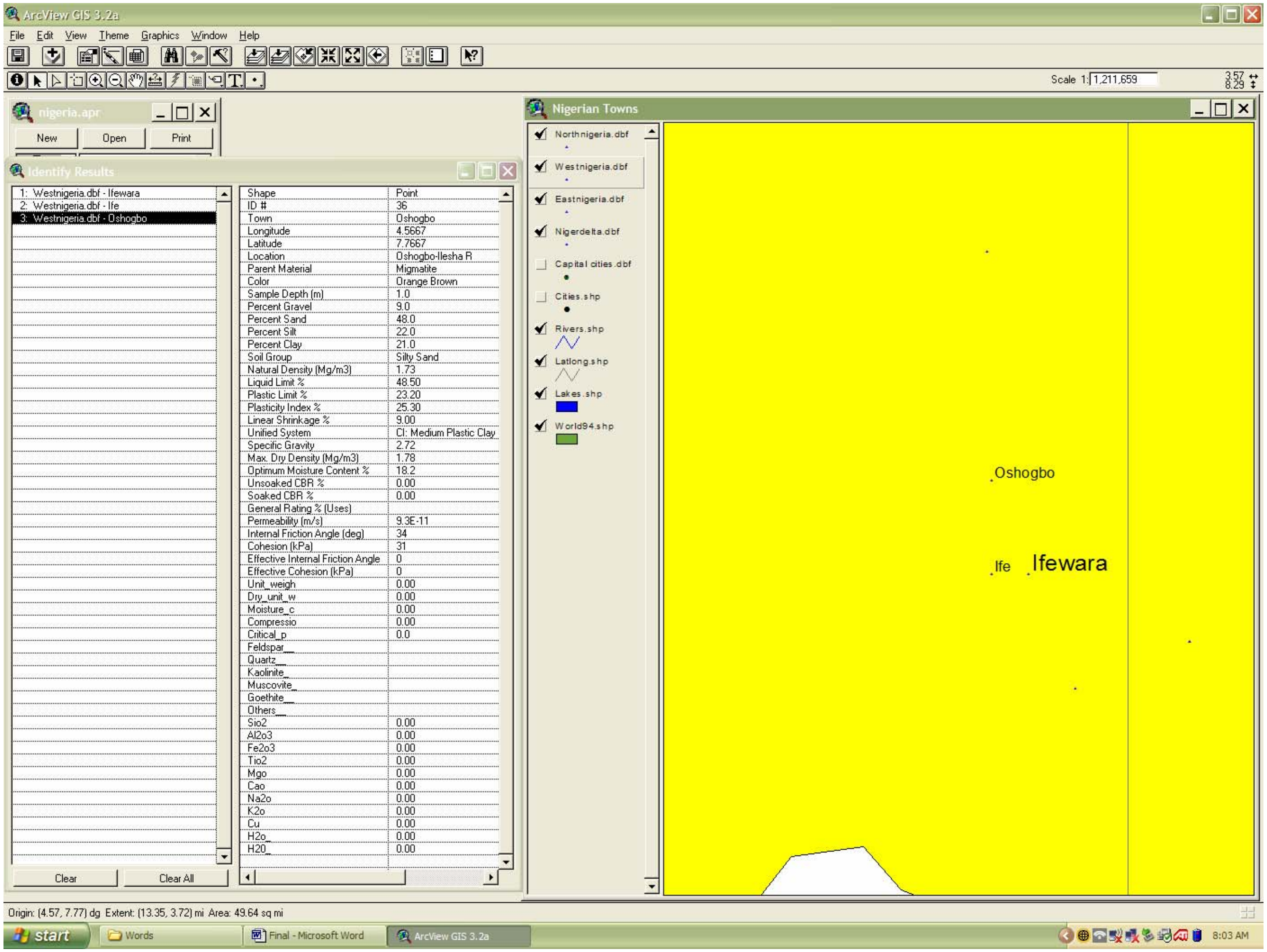


Figure 44: Soil properties of Oshogbo

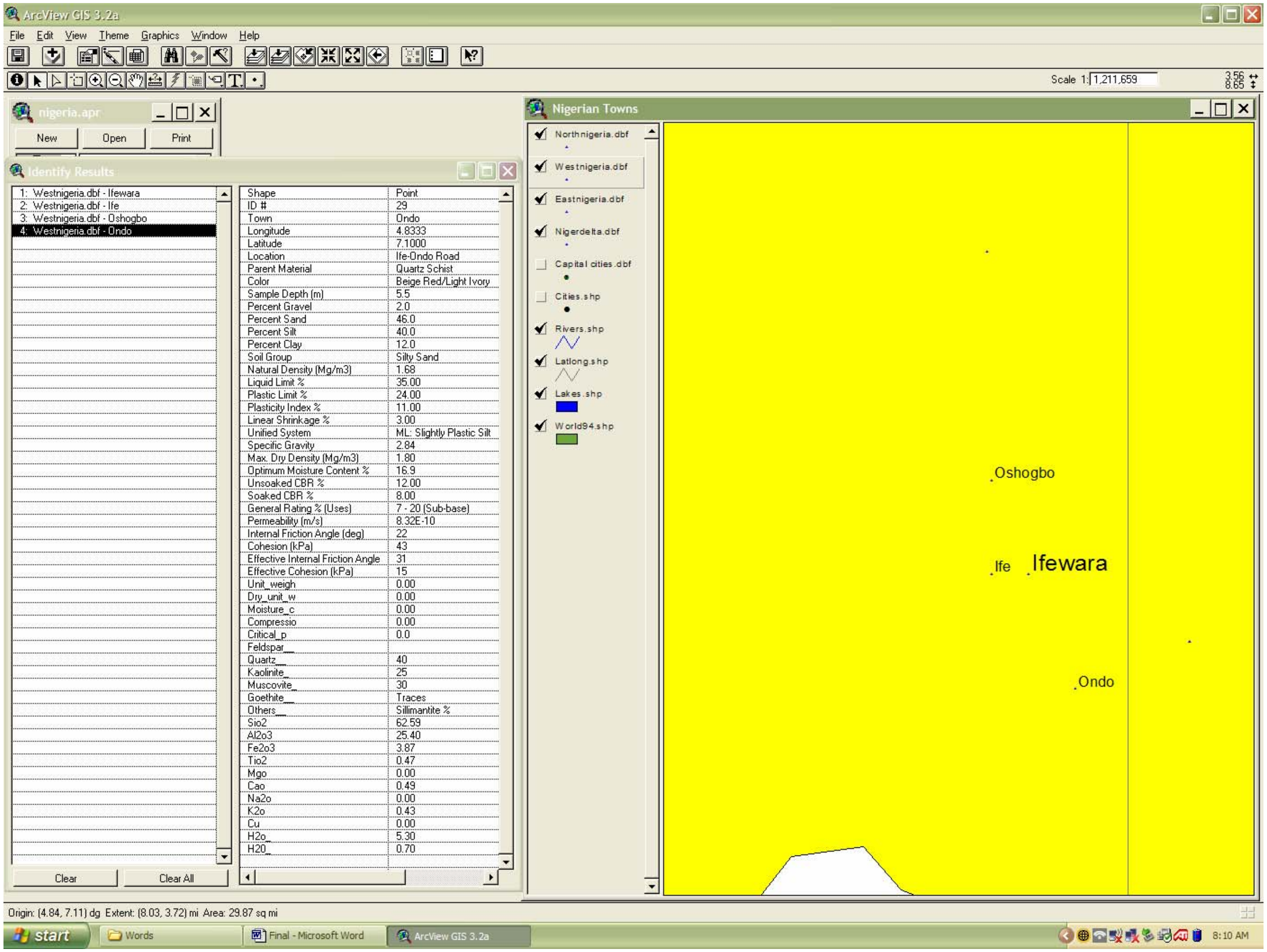


Figure 45: Soil properties of Ondo

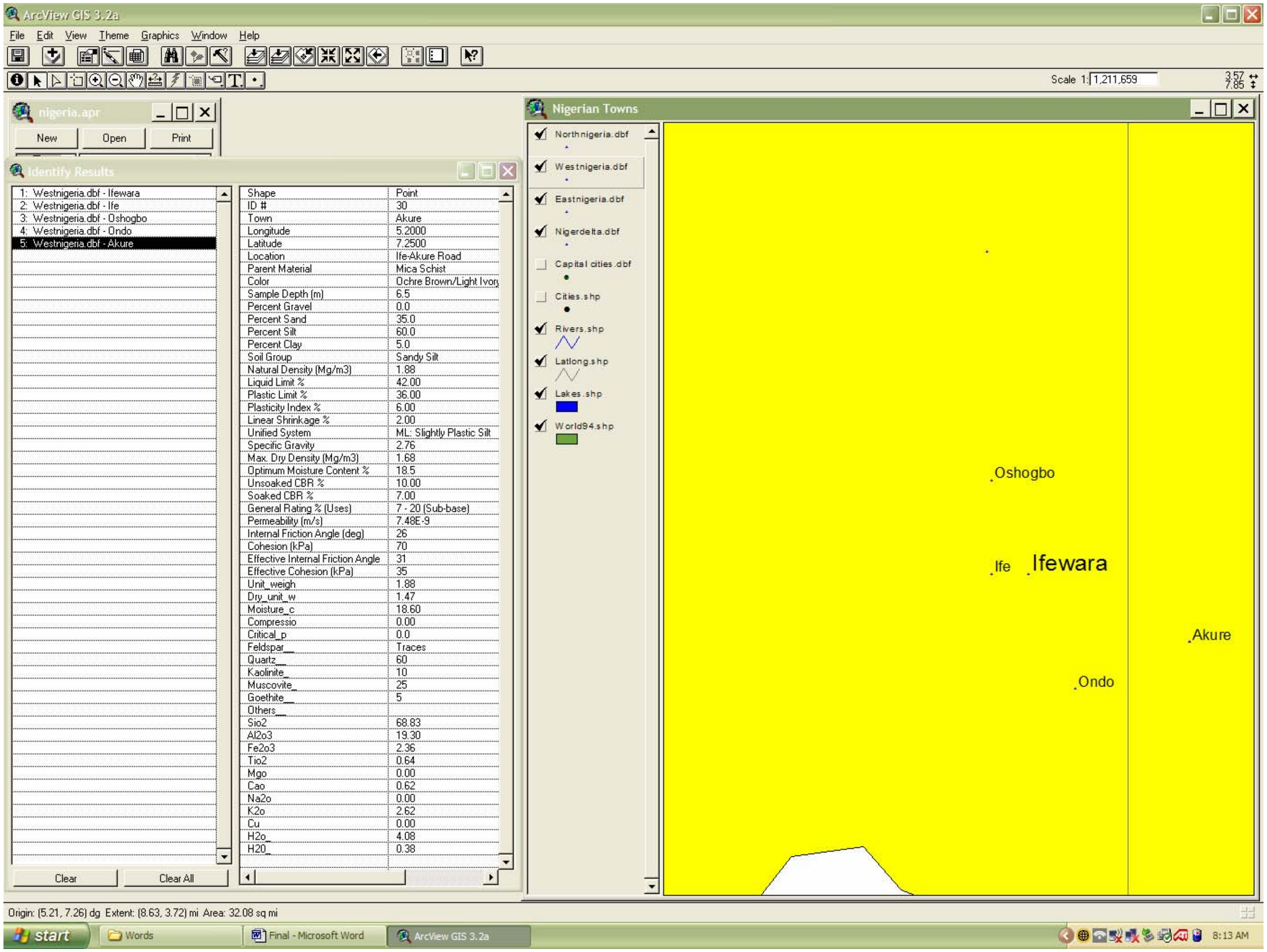


Figure 46: Soil properties of Akure

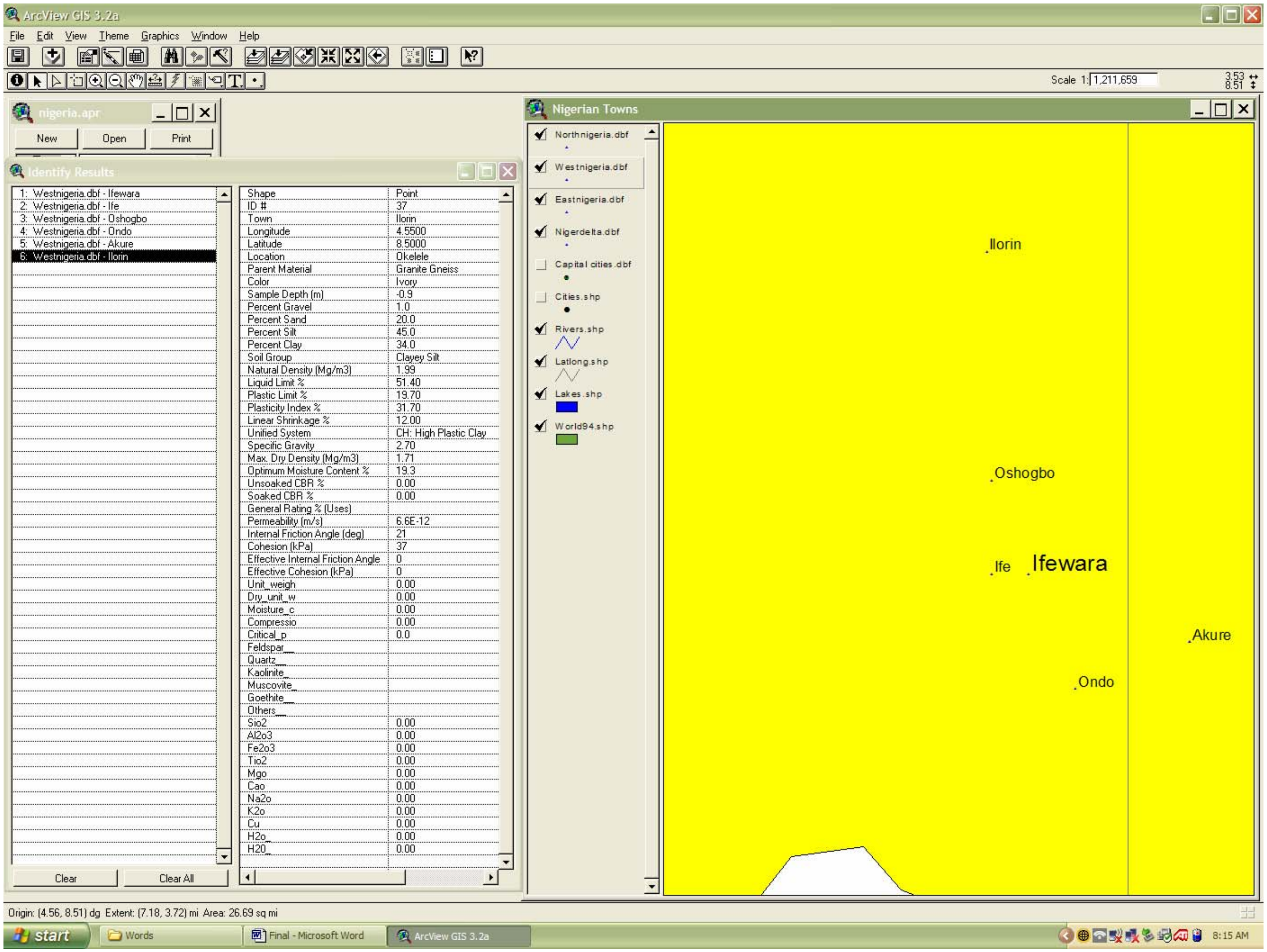


Figure 47: Soil properties of Ilorin

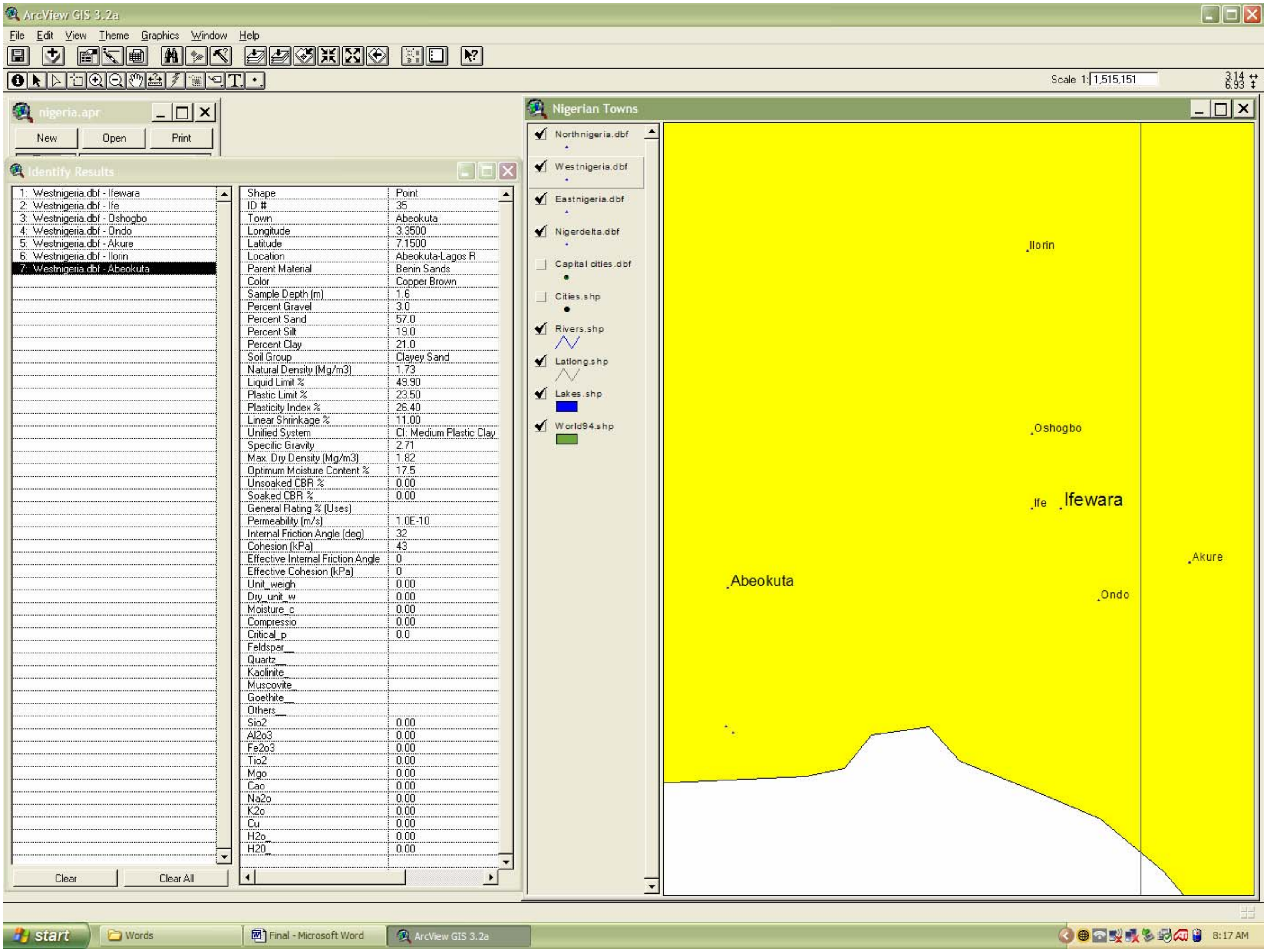


Figure 48: Soil properties of Abeokuta

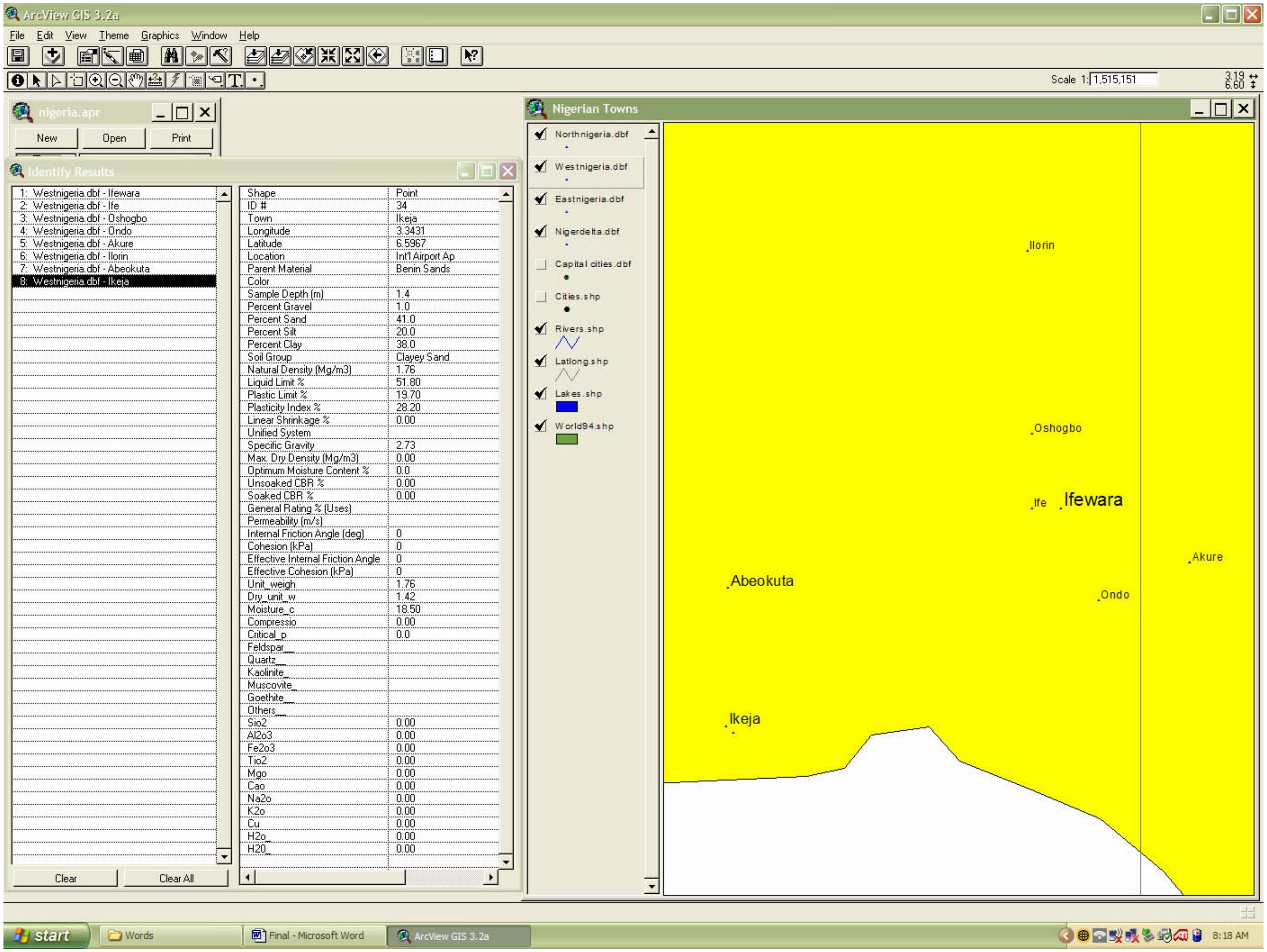


Figure 49: Soil properties of Ikeja

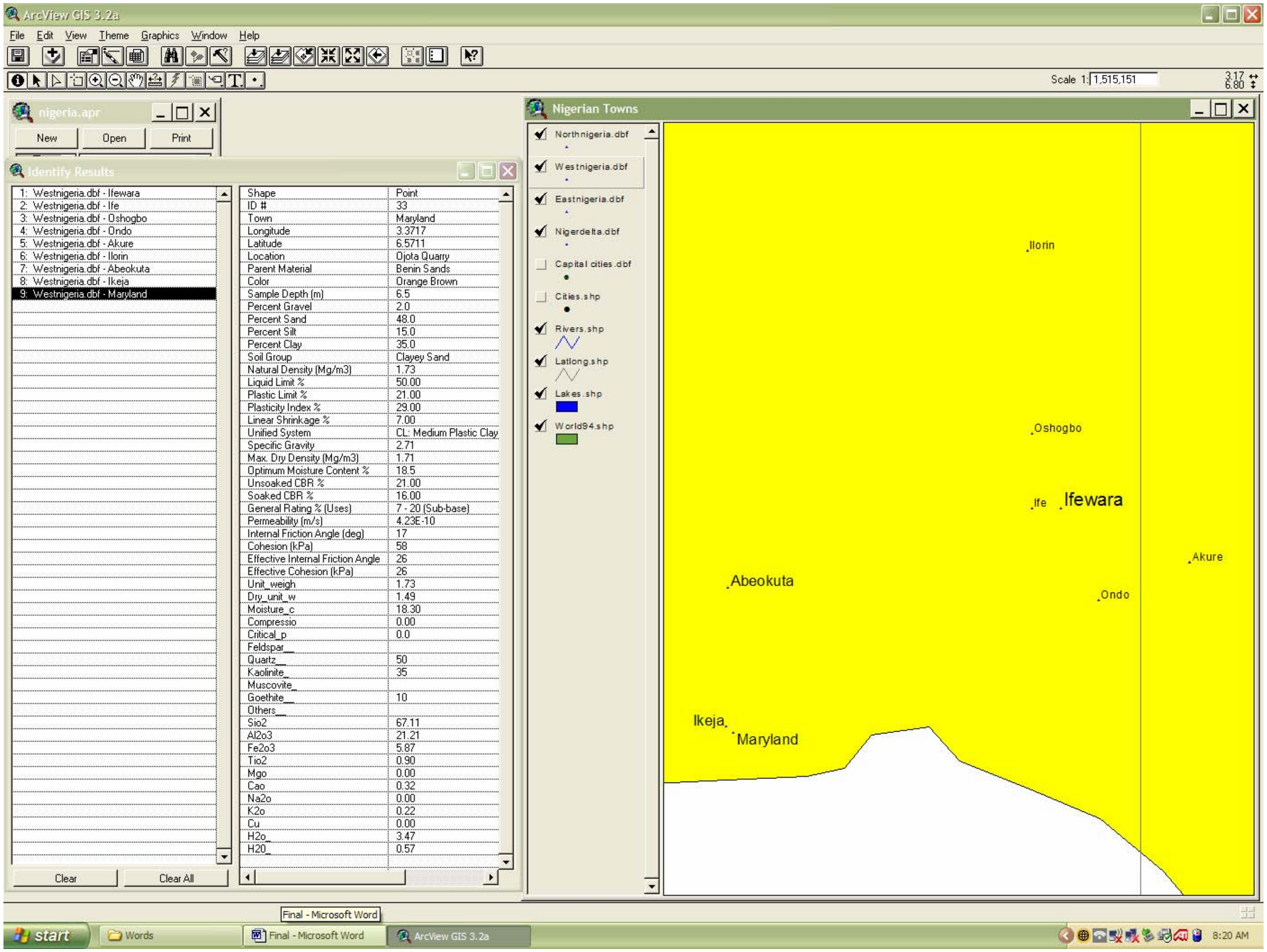


Figure 50: Soil properties of Maryland

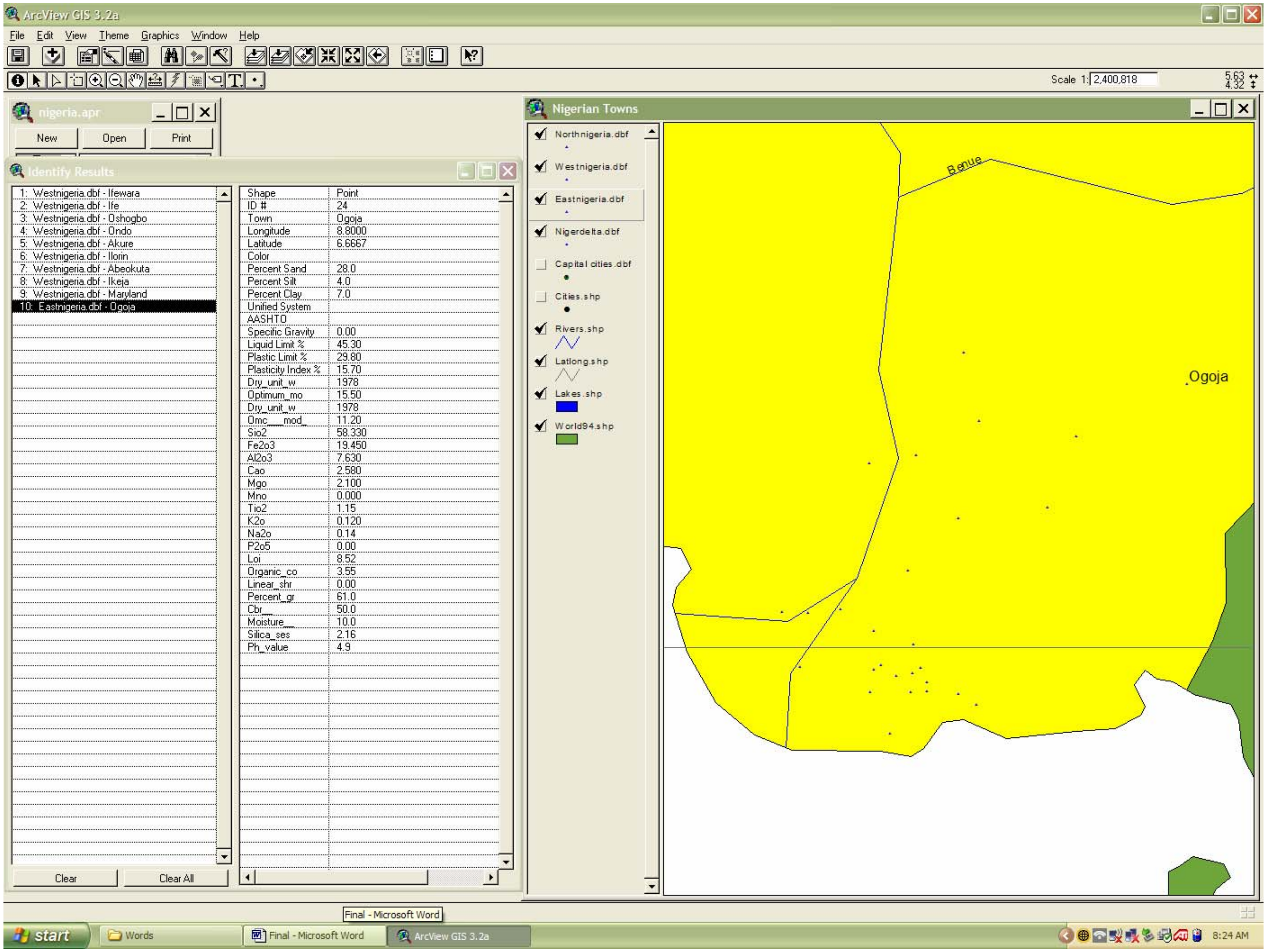


Figure 51: Soil properties of Ogoja

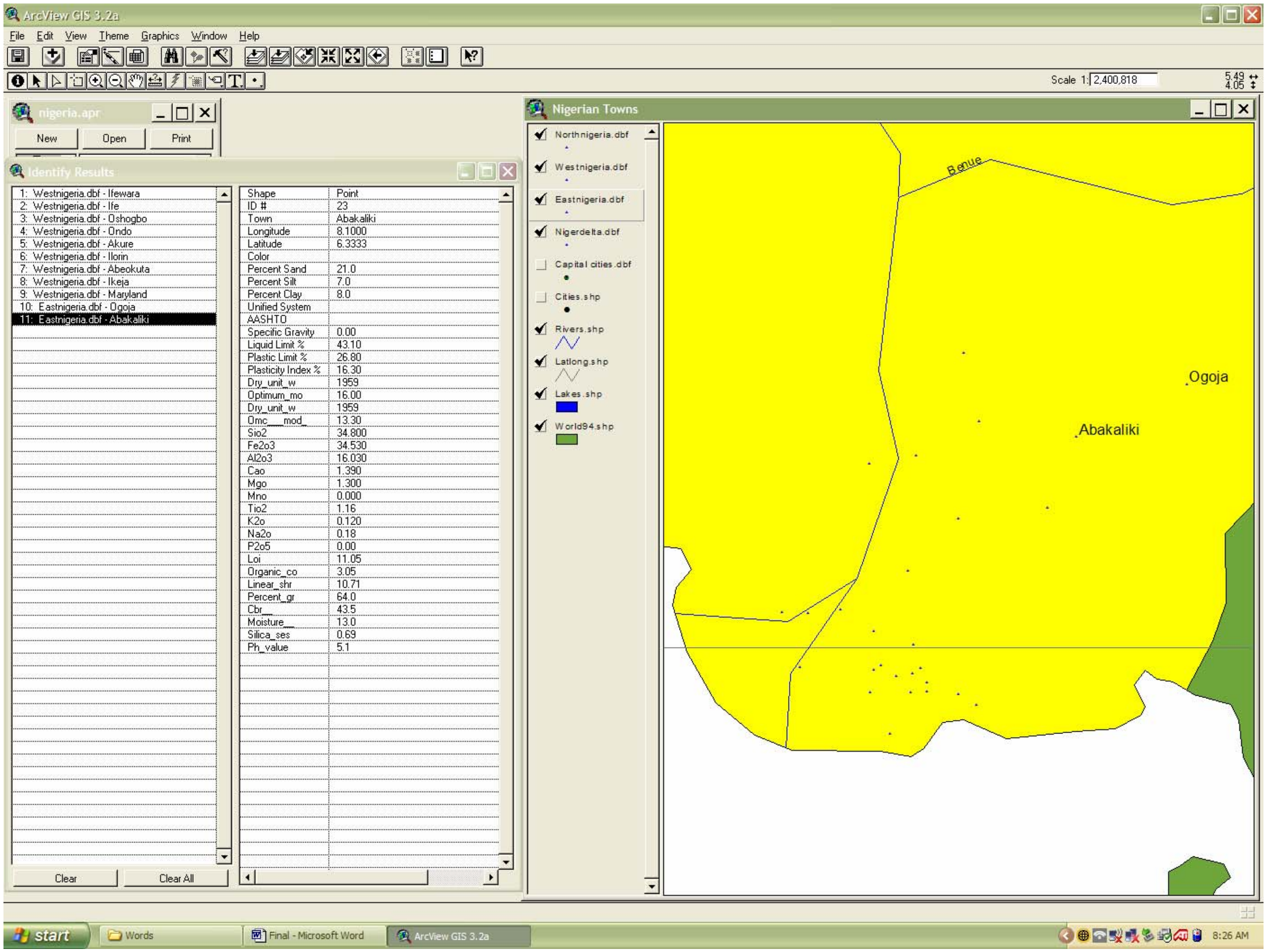


Figure 52: Soil properties of Abakiliki

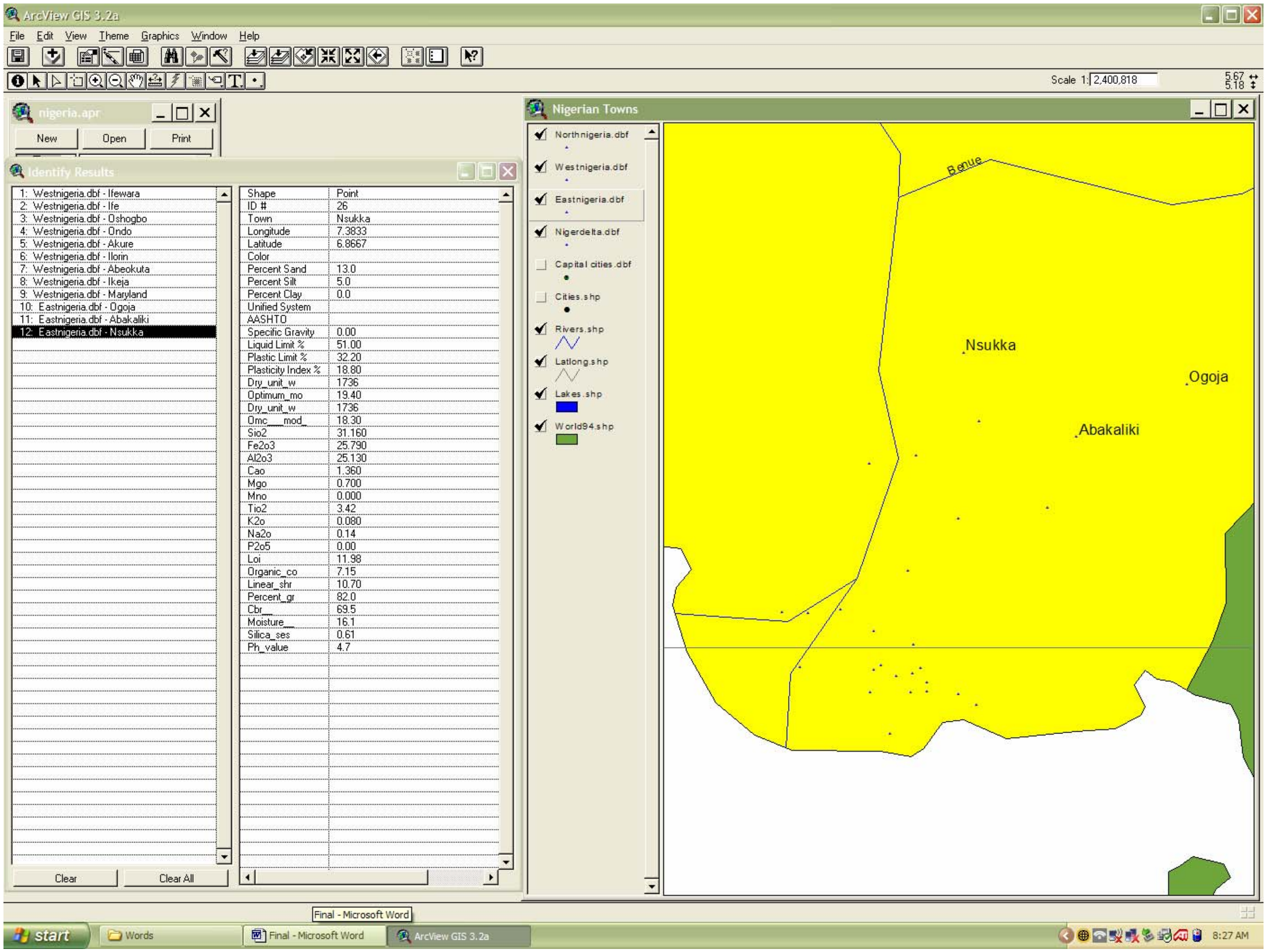


Figure 53: Soil properties of Nsukka

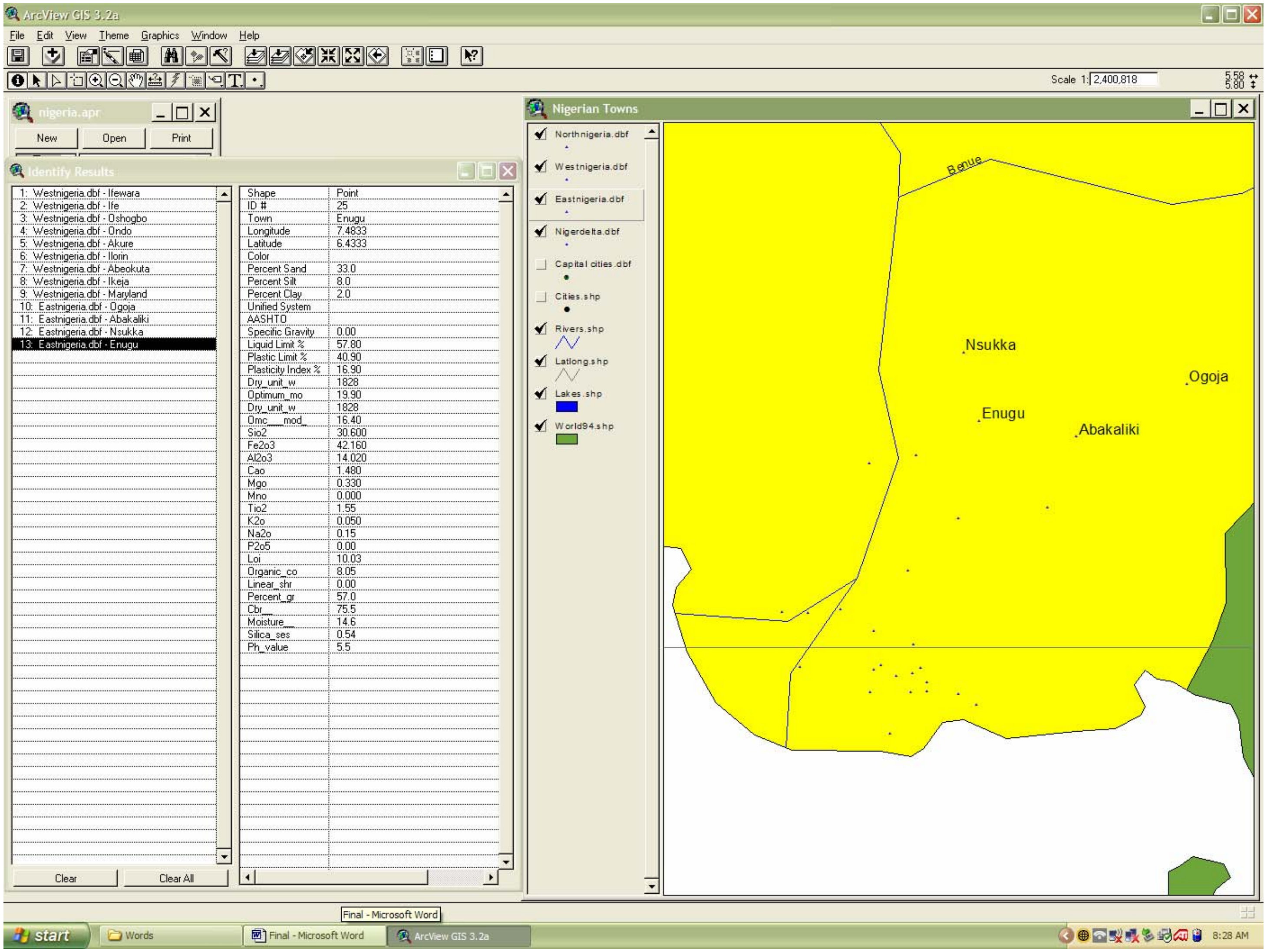


Figure 54: Soil properties of Enugu

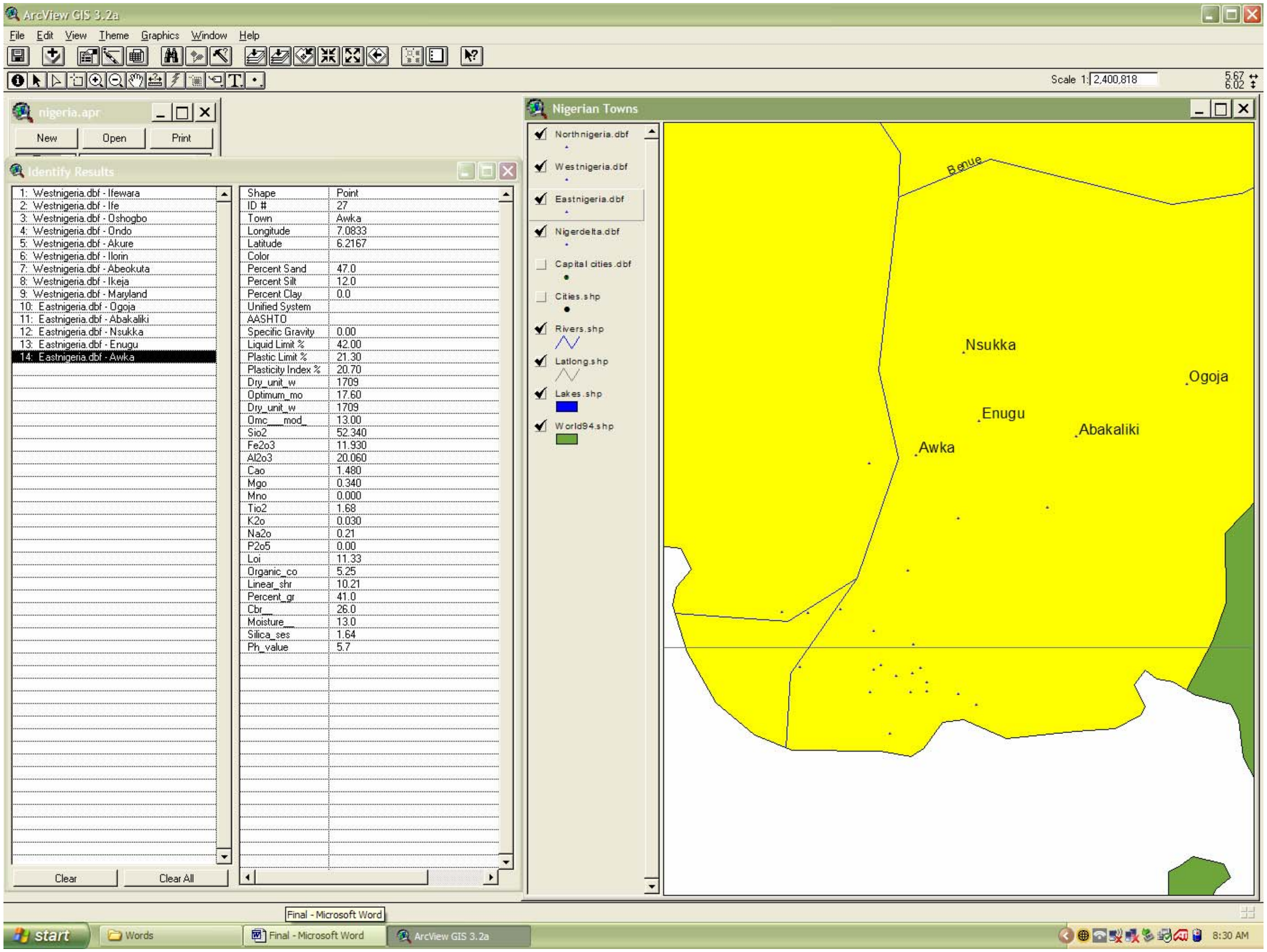


Figure 55: Soil properties of Awka

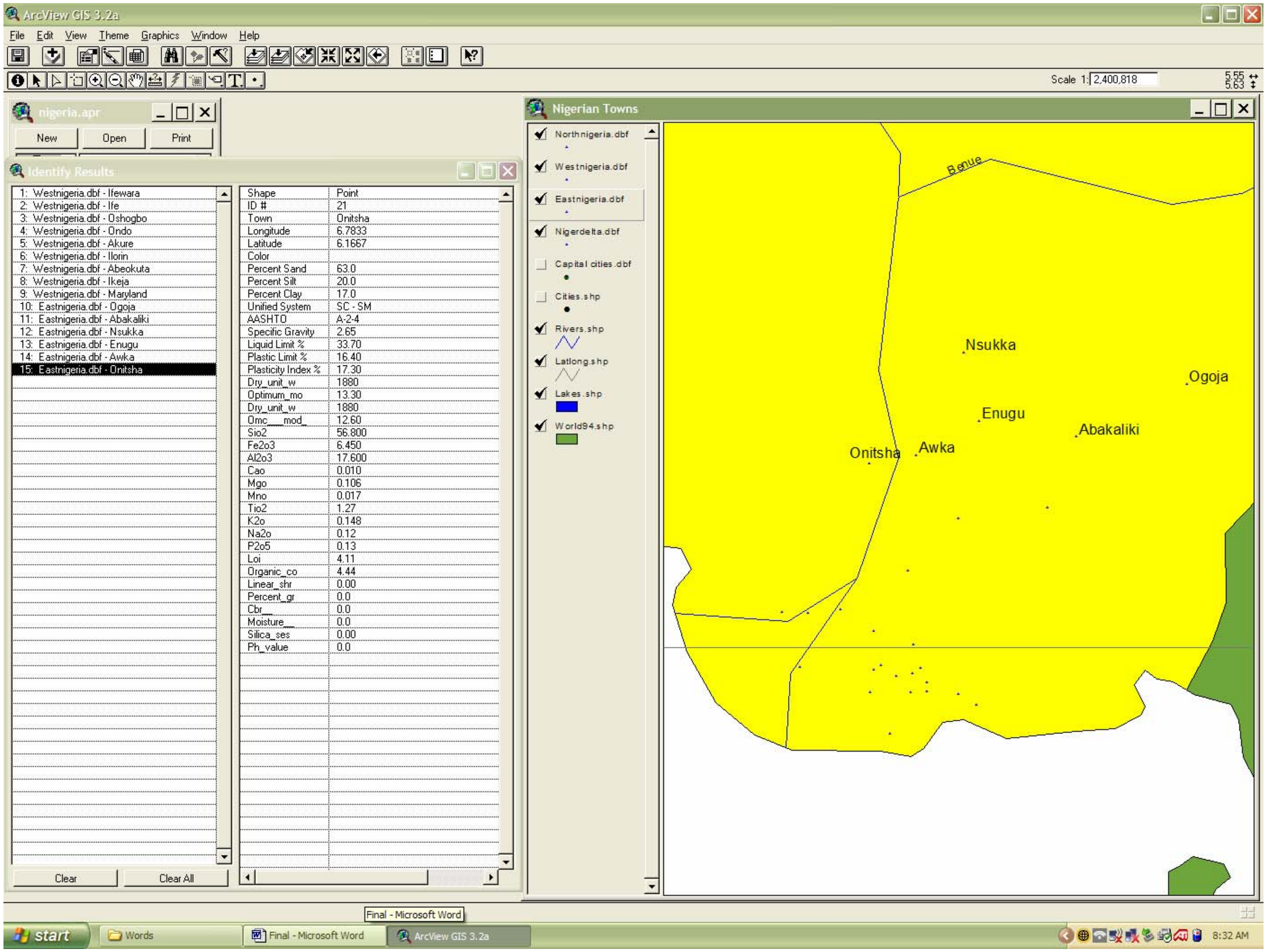


Figure 56: Soil properties of Onitsha

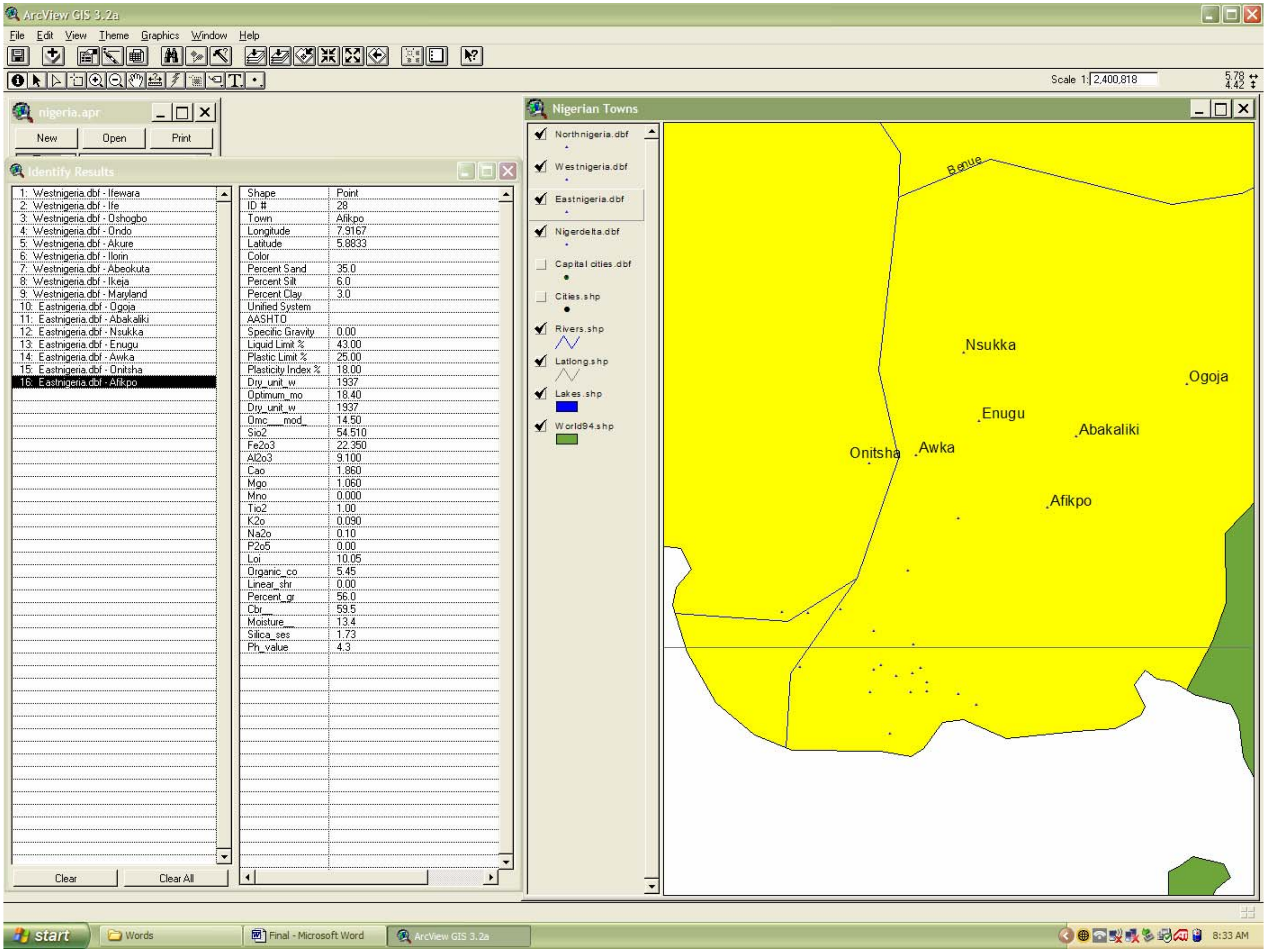


Figure 57: Soil properties of Afikpo

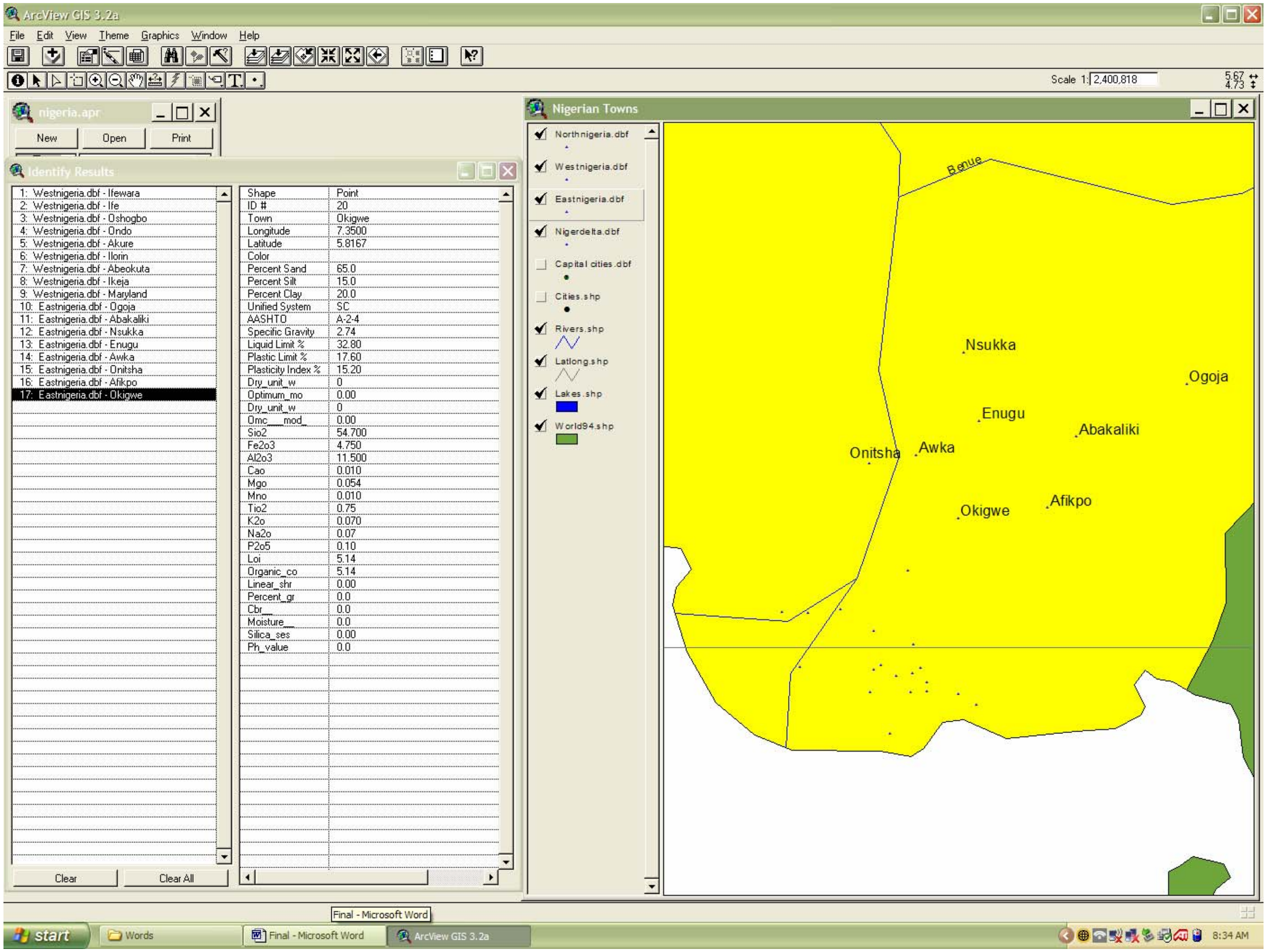


Figure 58: Soil properties of Okigwe

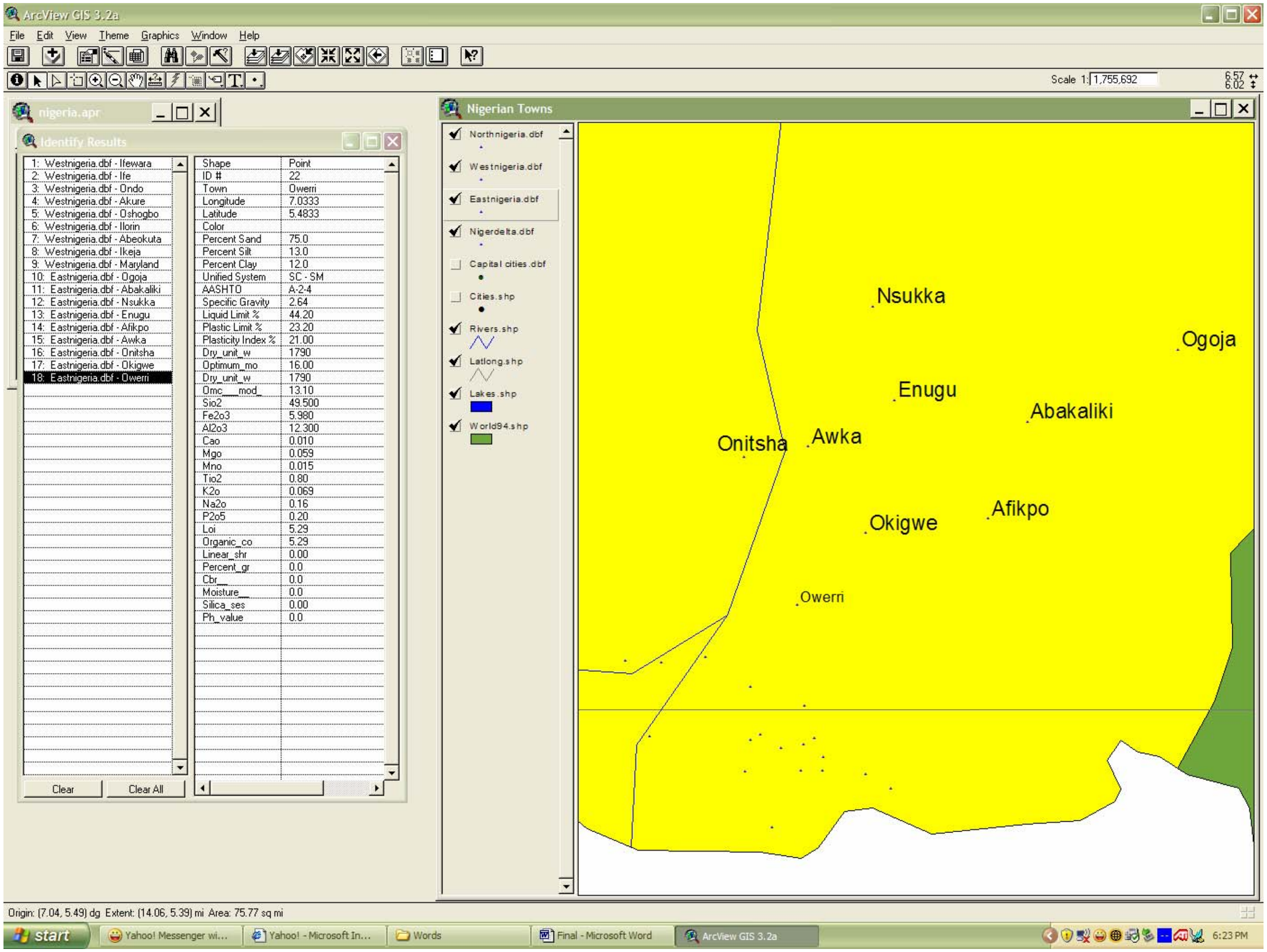


Figure 59: Soil properties of Owerri

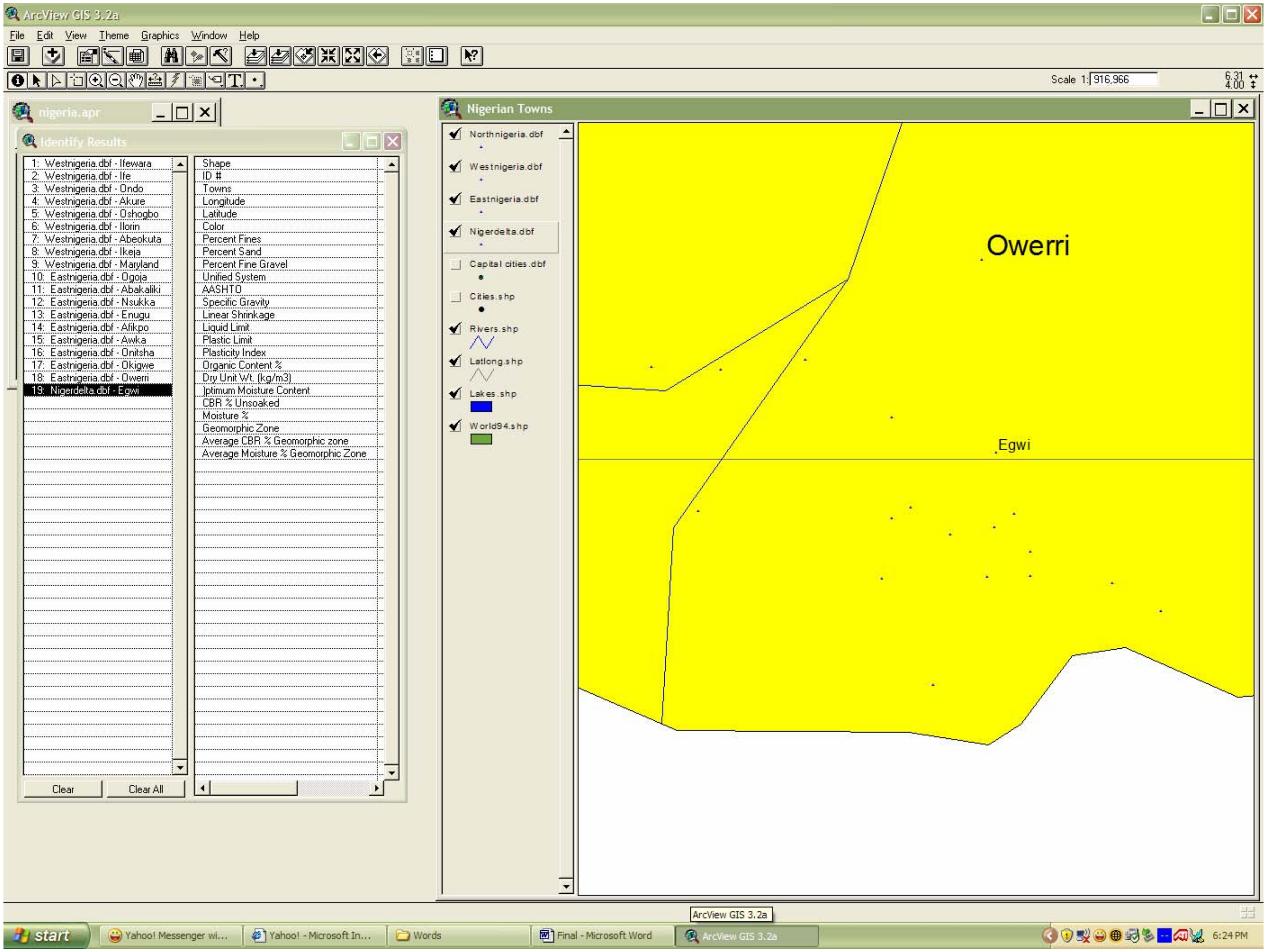


Figure 60: Soil properties of Egwi

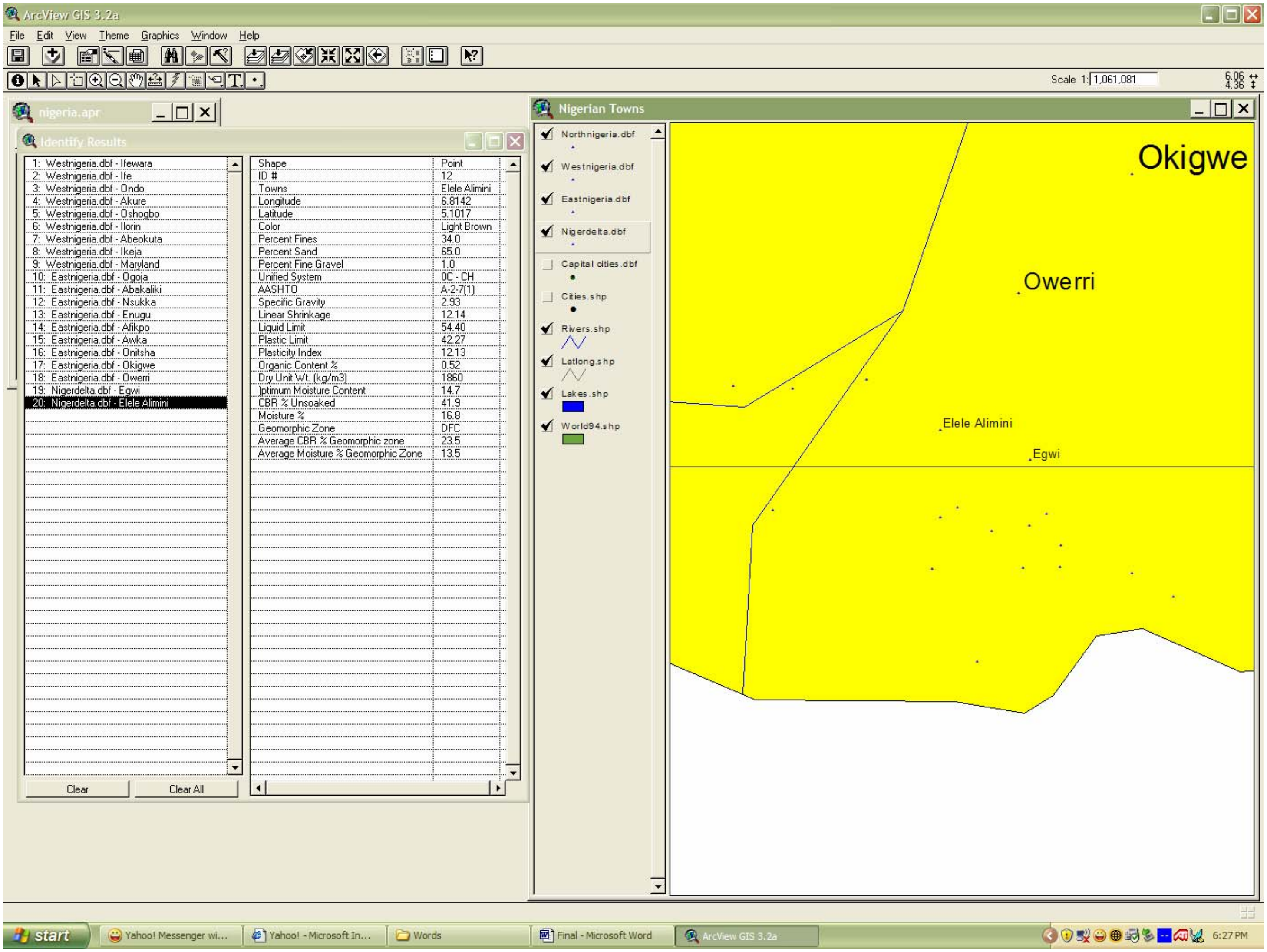


Figure 61: Soil properties of Elele Alimini

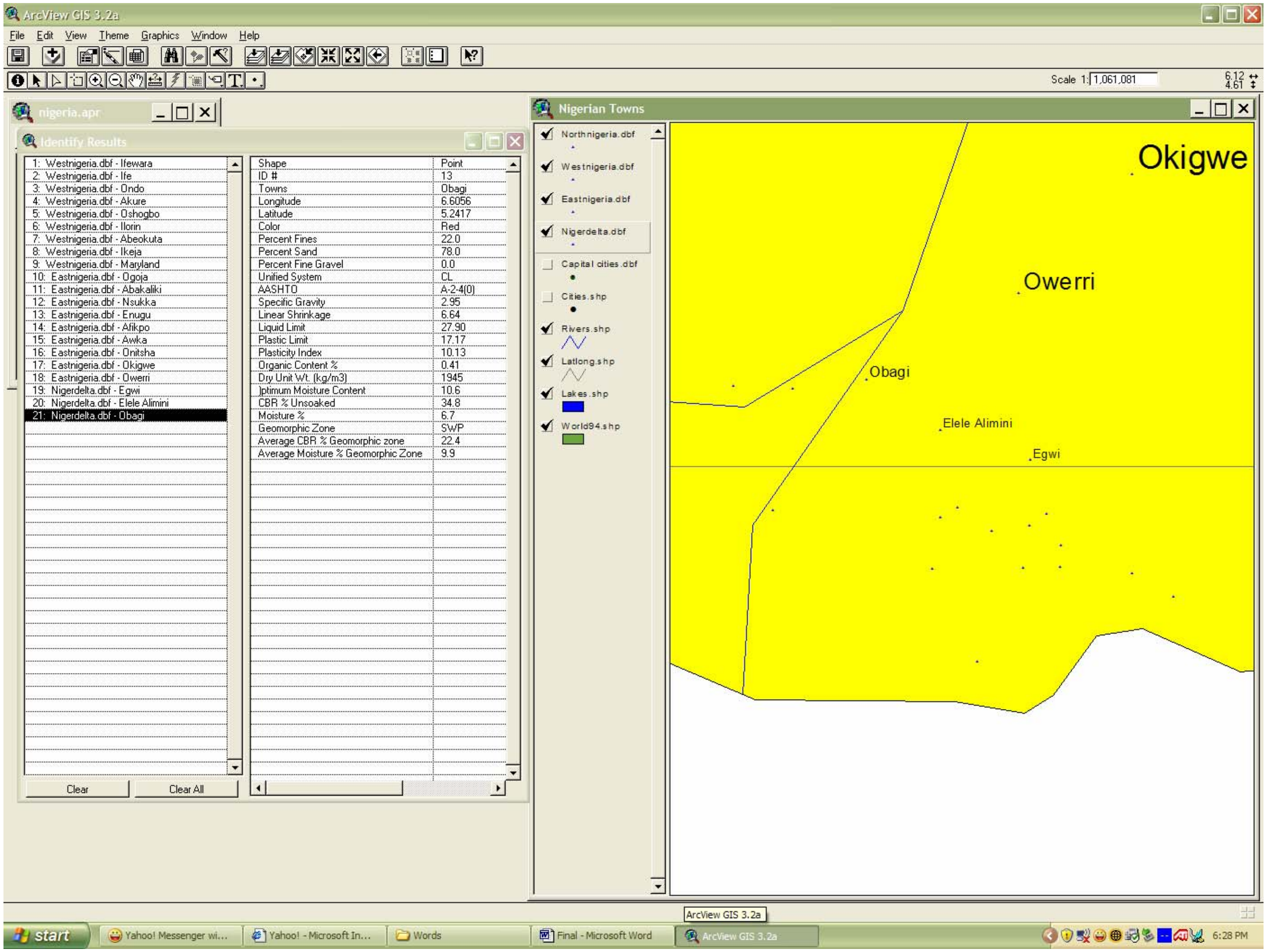


Figure 62: Soil properties of Obagi

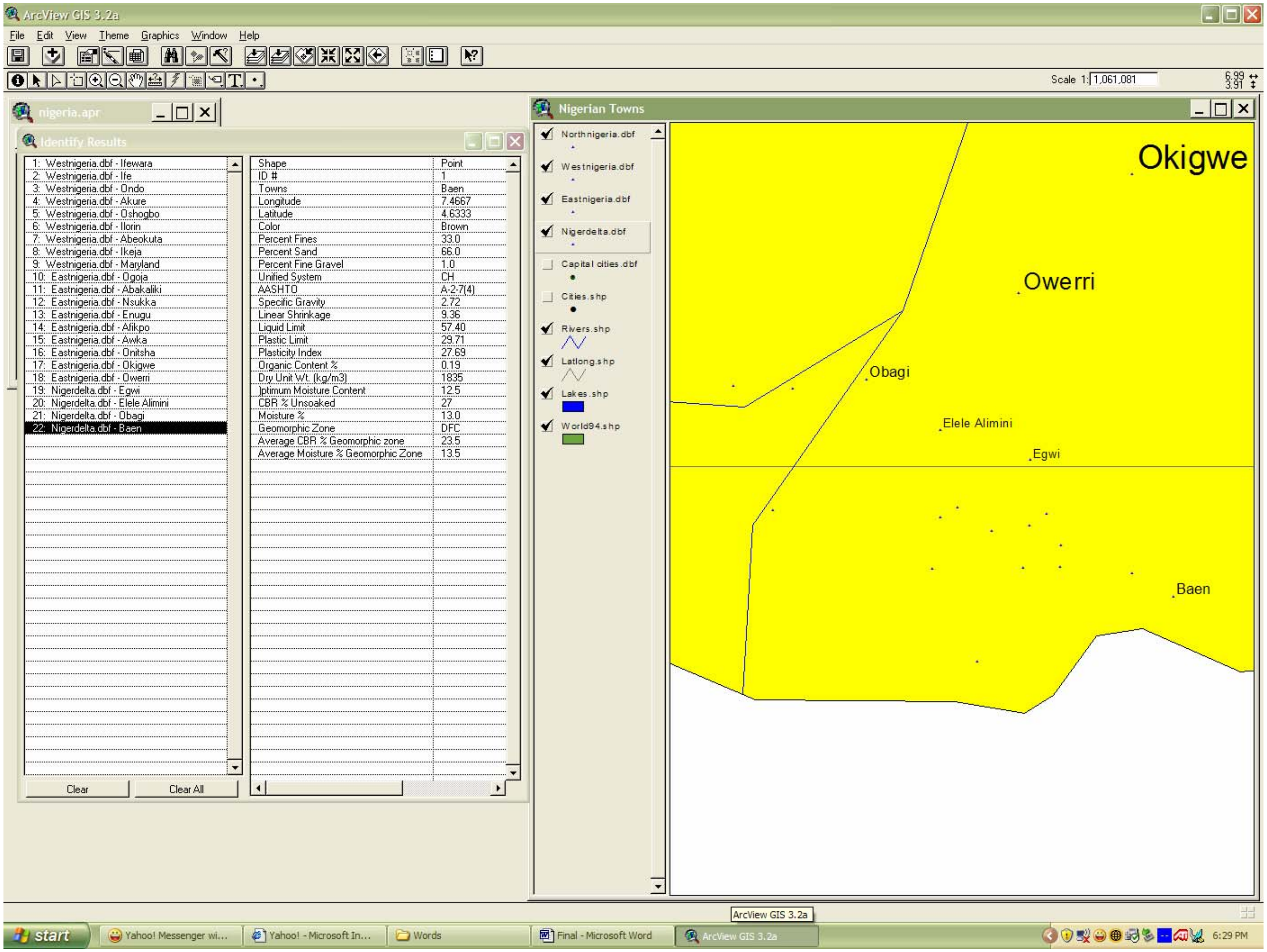


Figure 63: Soil properties of Baen

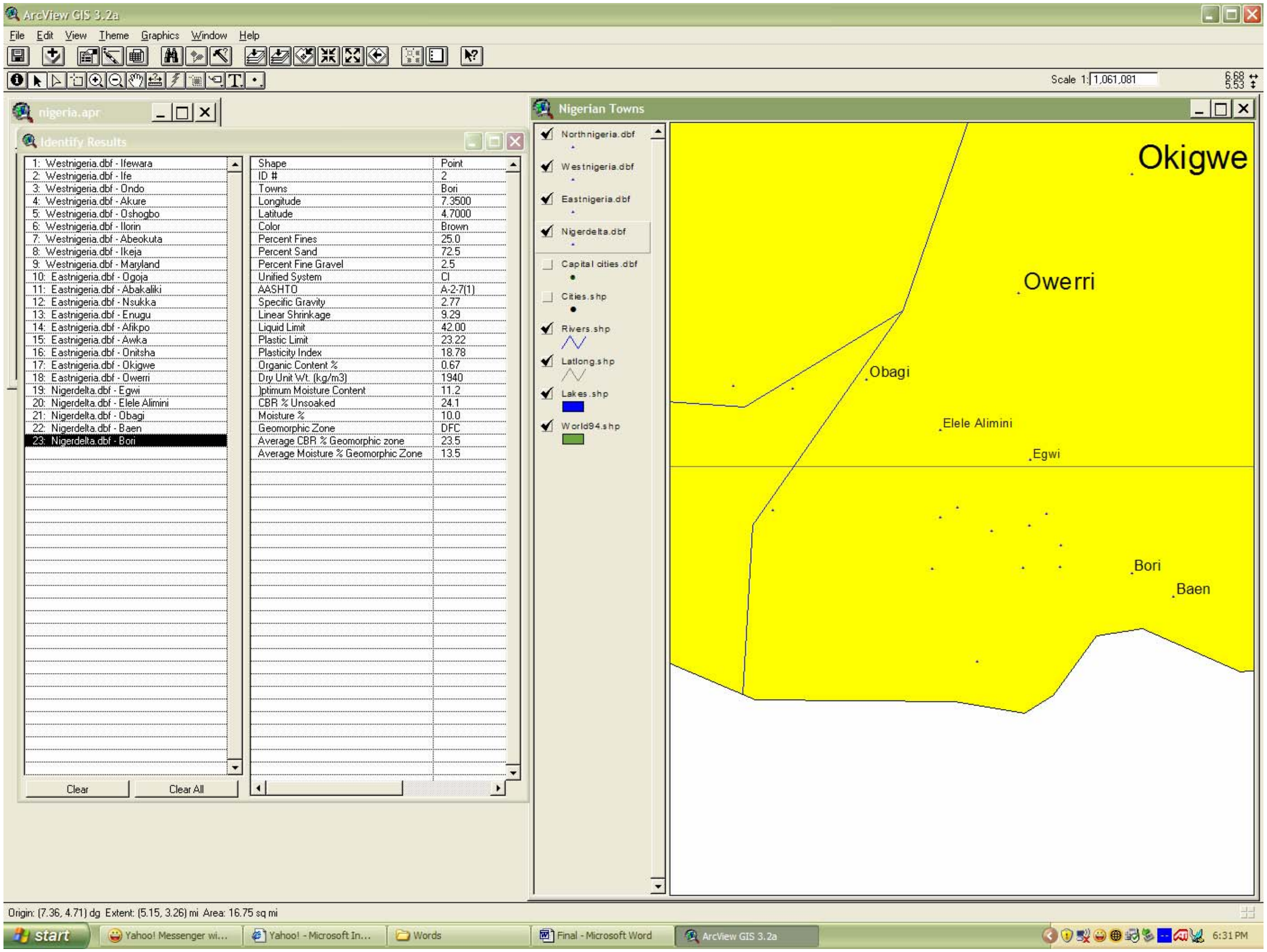


Figure 64: Soil properties of Bori

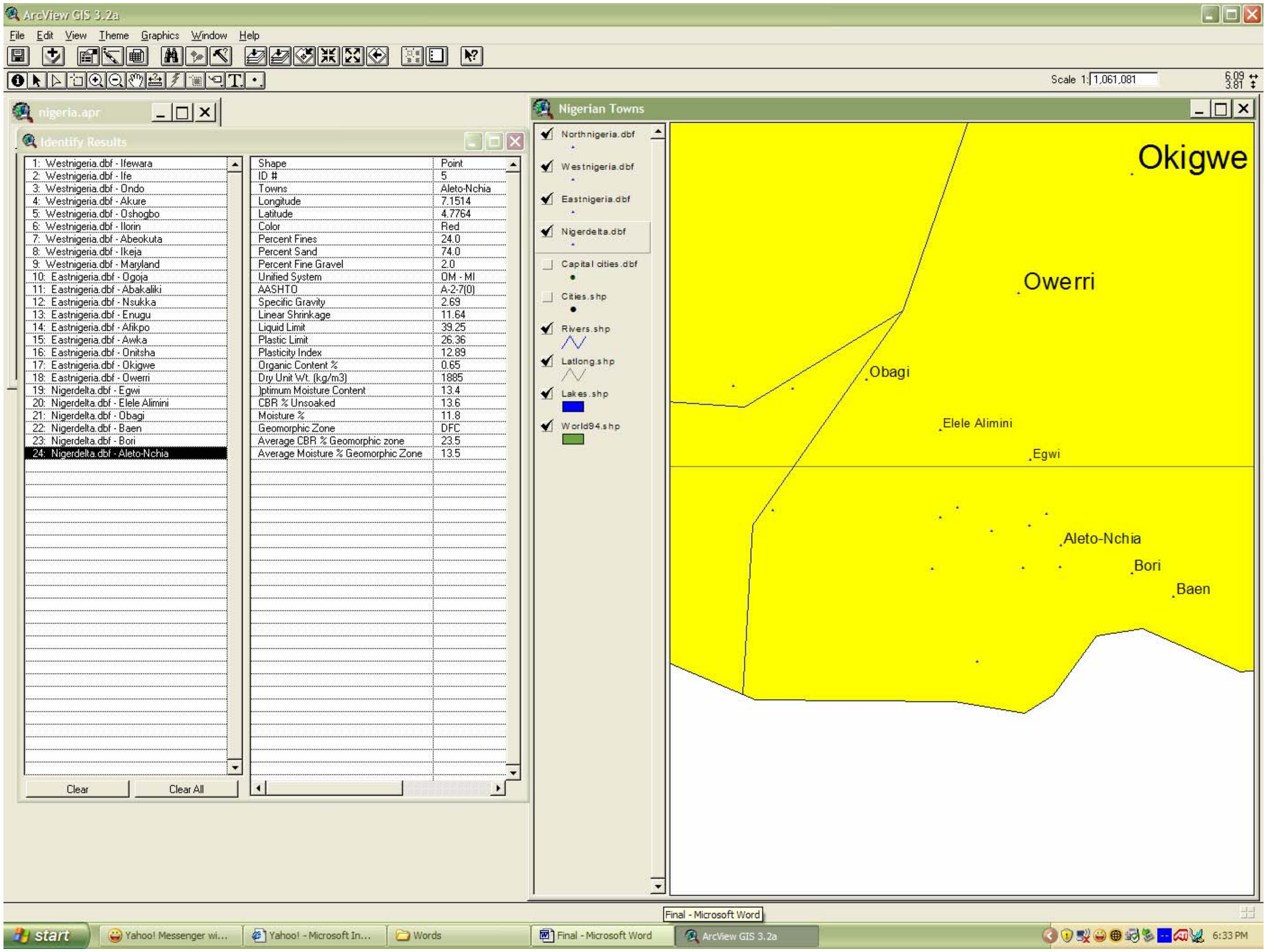


Figure 65: Soil properties of Aleto-Nchia

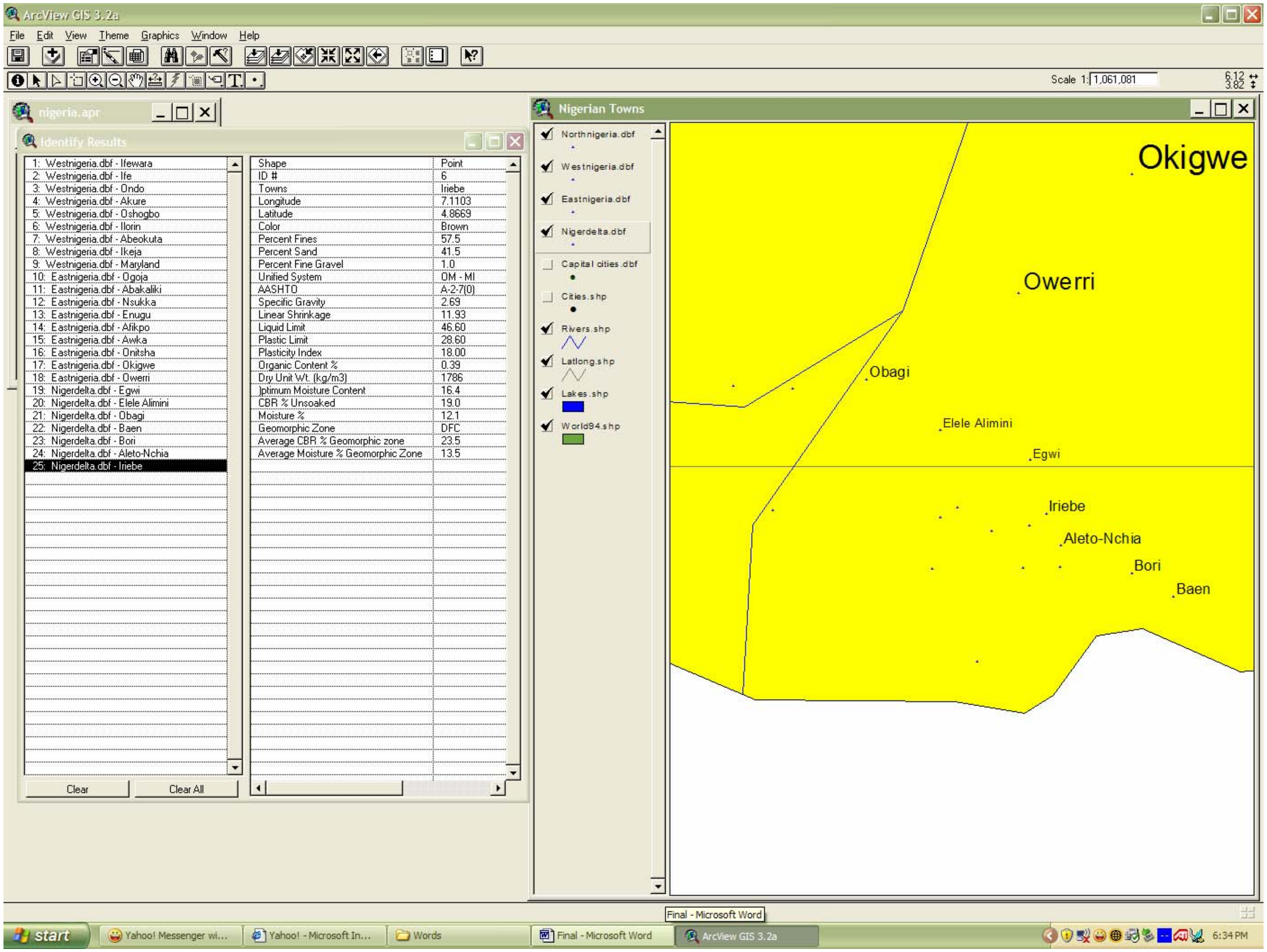


Figure 66: Soil properties of Iriebe

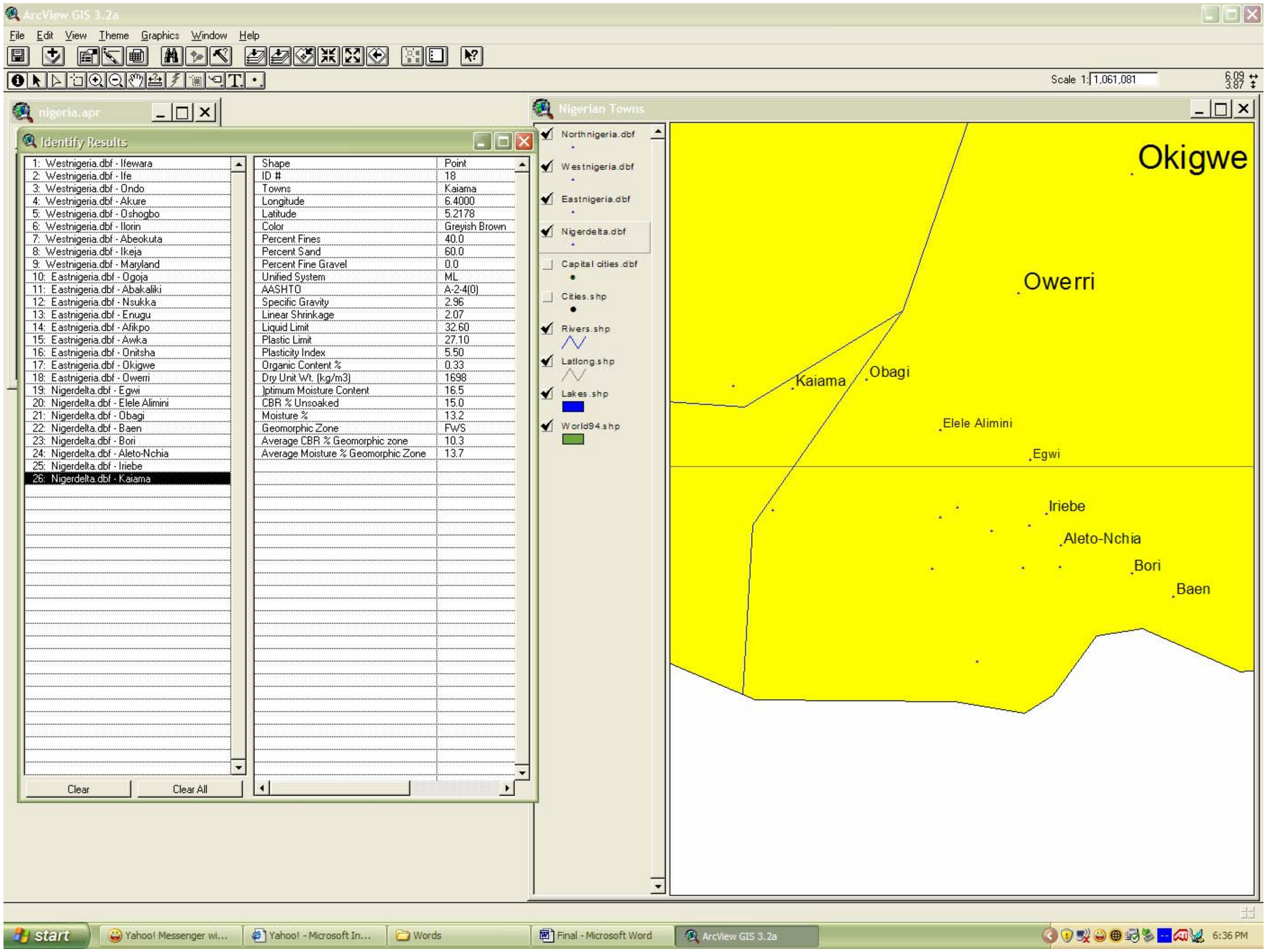


Figure 67: Soil properties of Kaiama

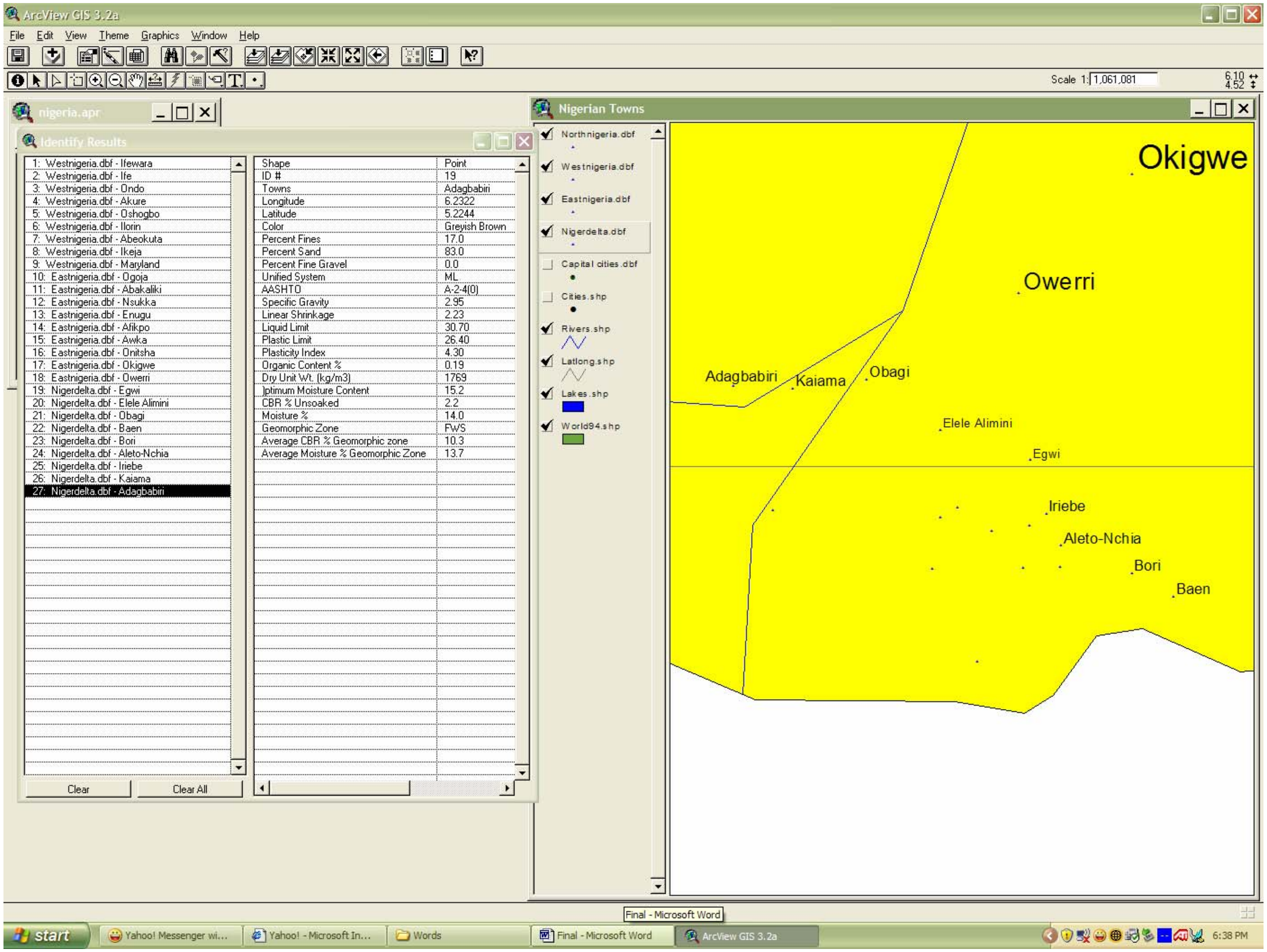


Figure 68: Soil properties of Adagbabiri

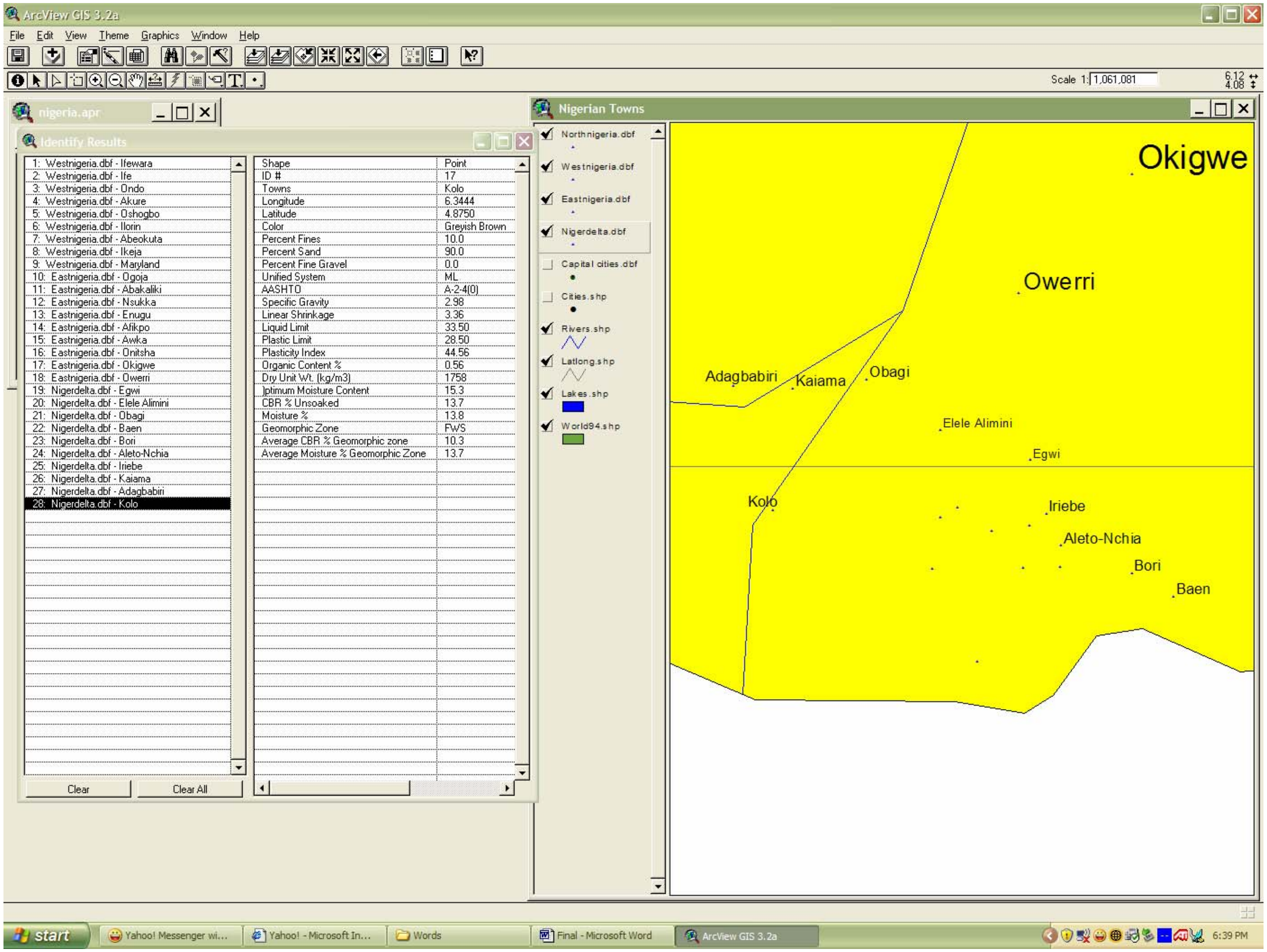


Figure 69: Soil properties of Kolo

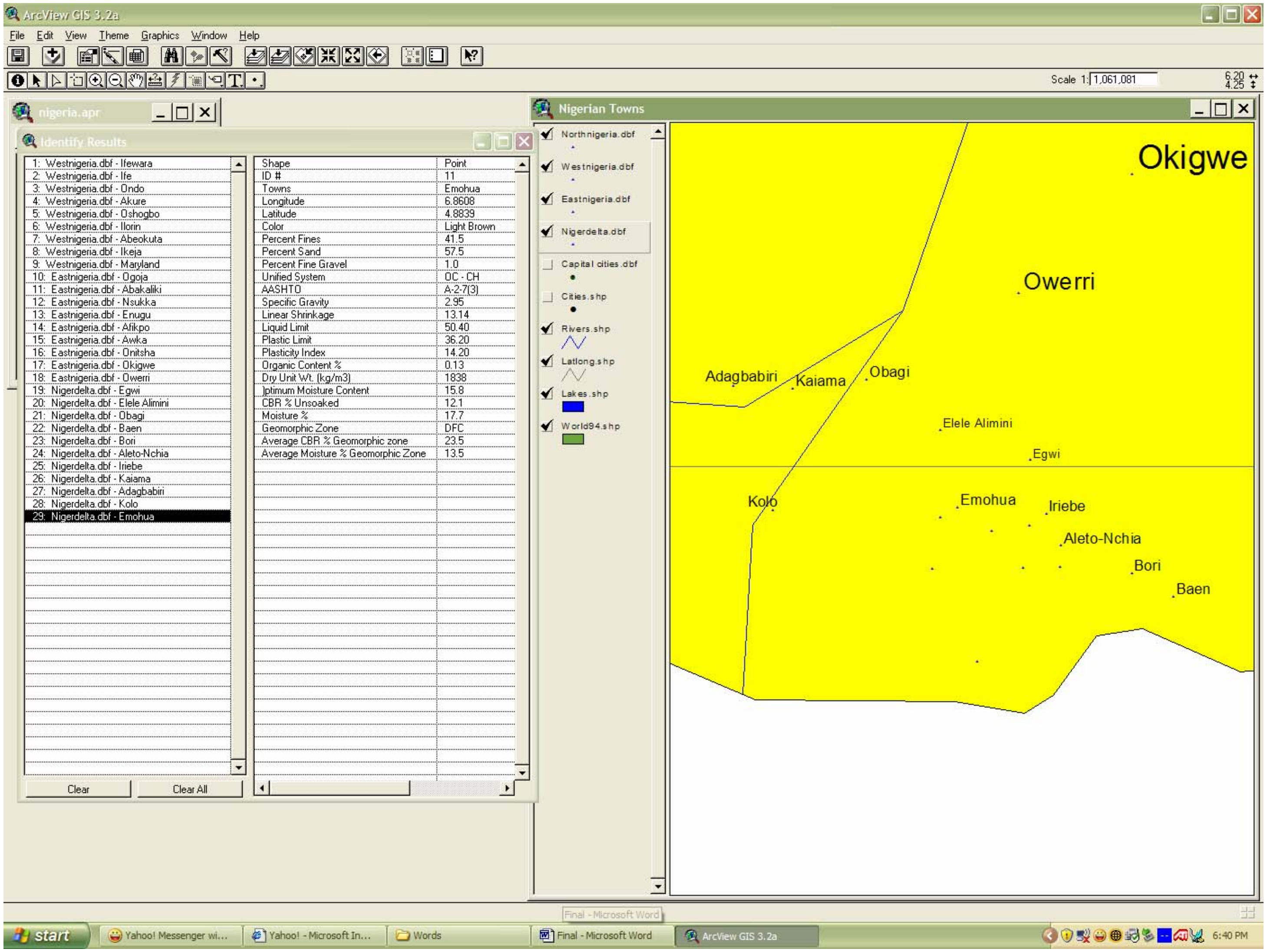


Figure 70: Soil properties of Emohua

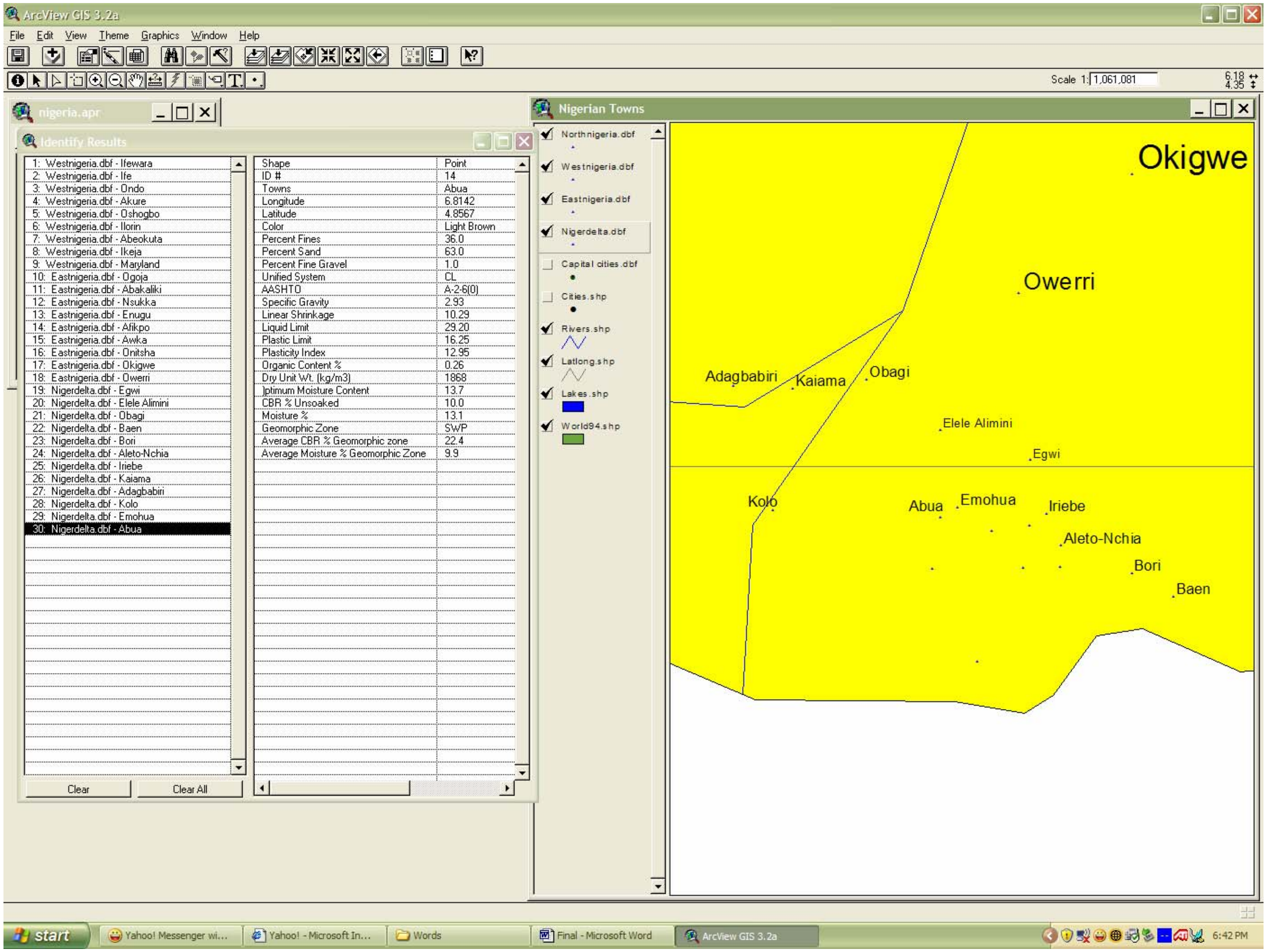


Figure 71: Soil properties of Abua

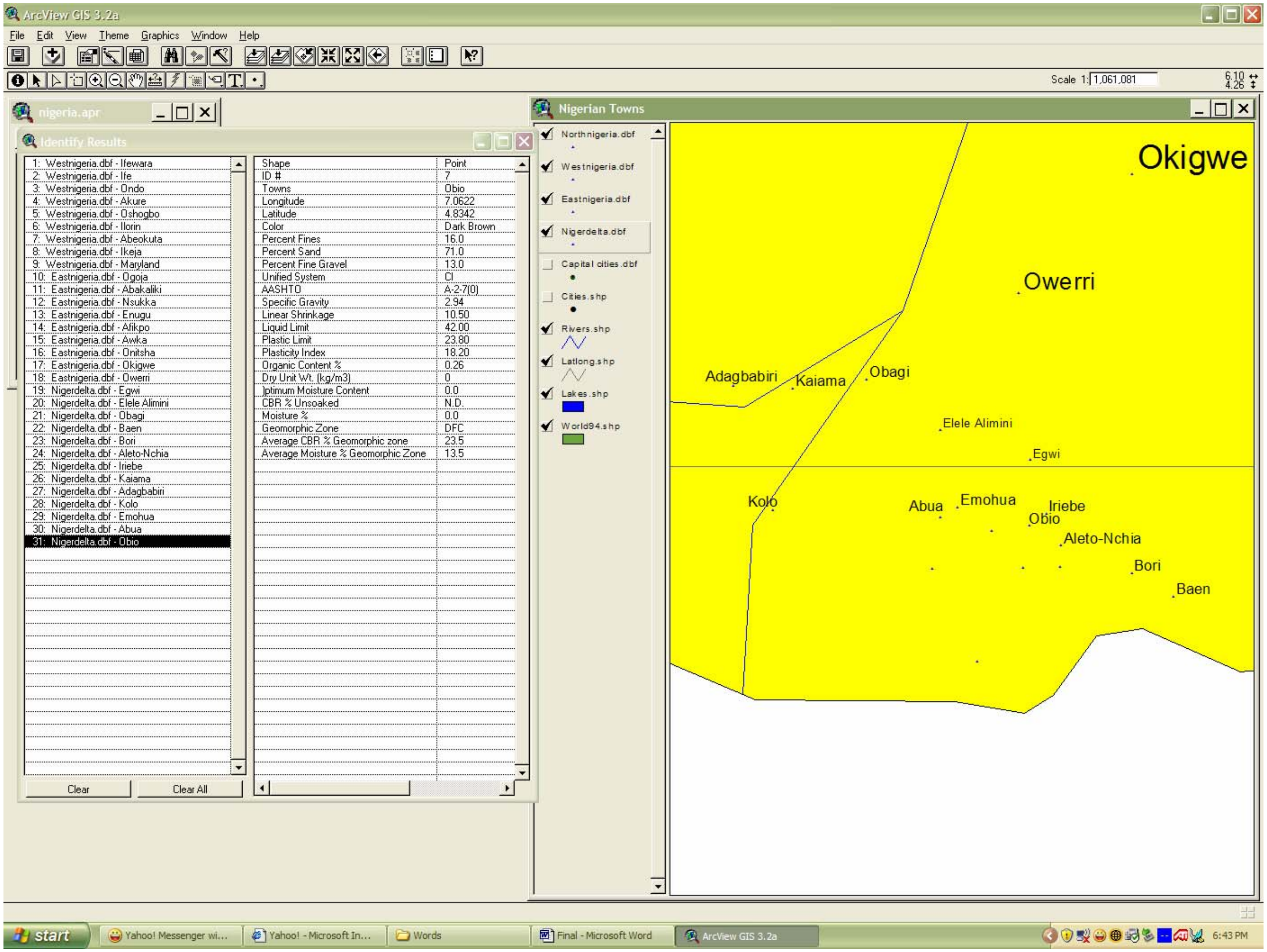


Figure 72: Soil properties of Obio

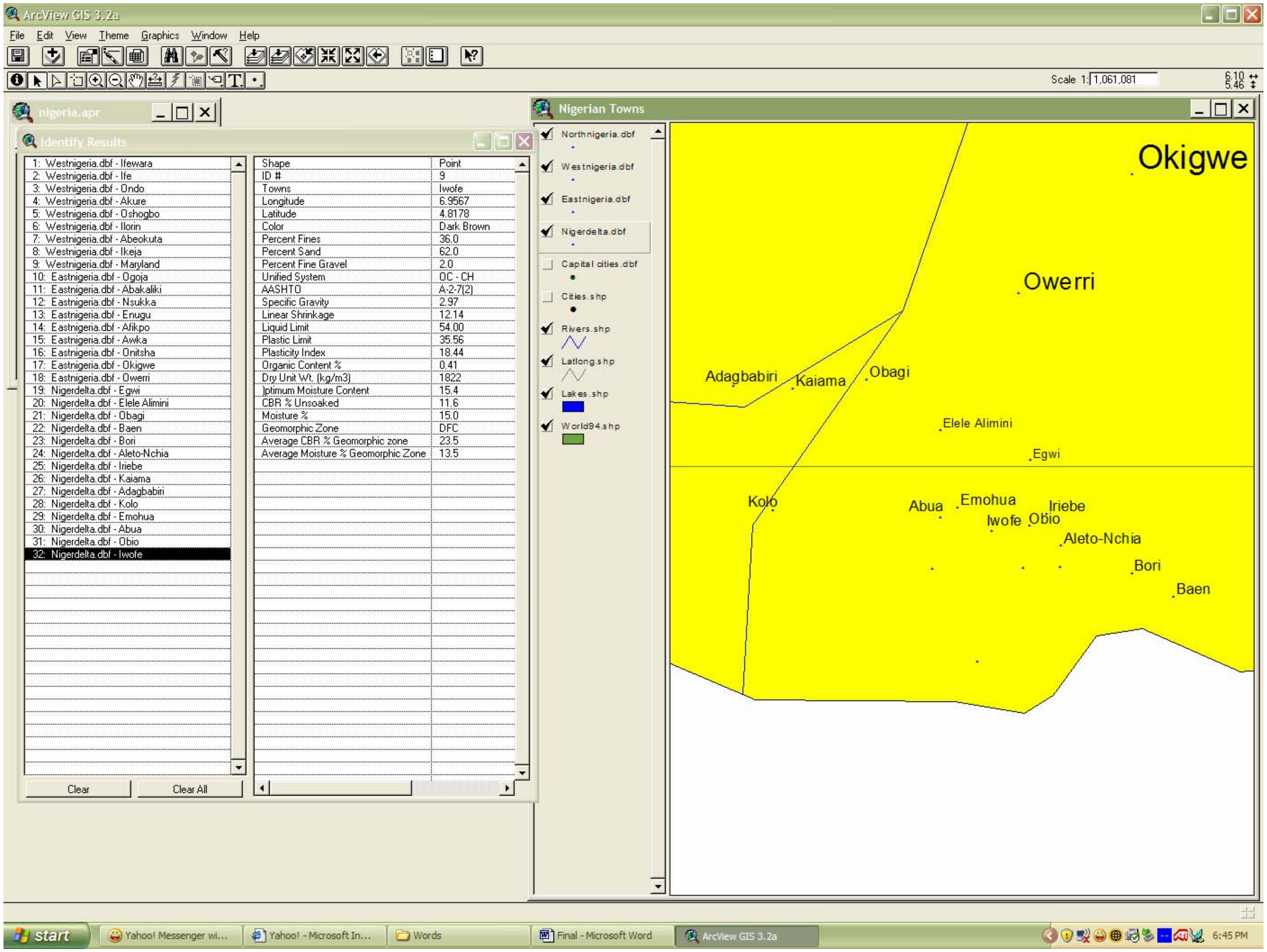


Figure 73: Soil properties of Iwofe

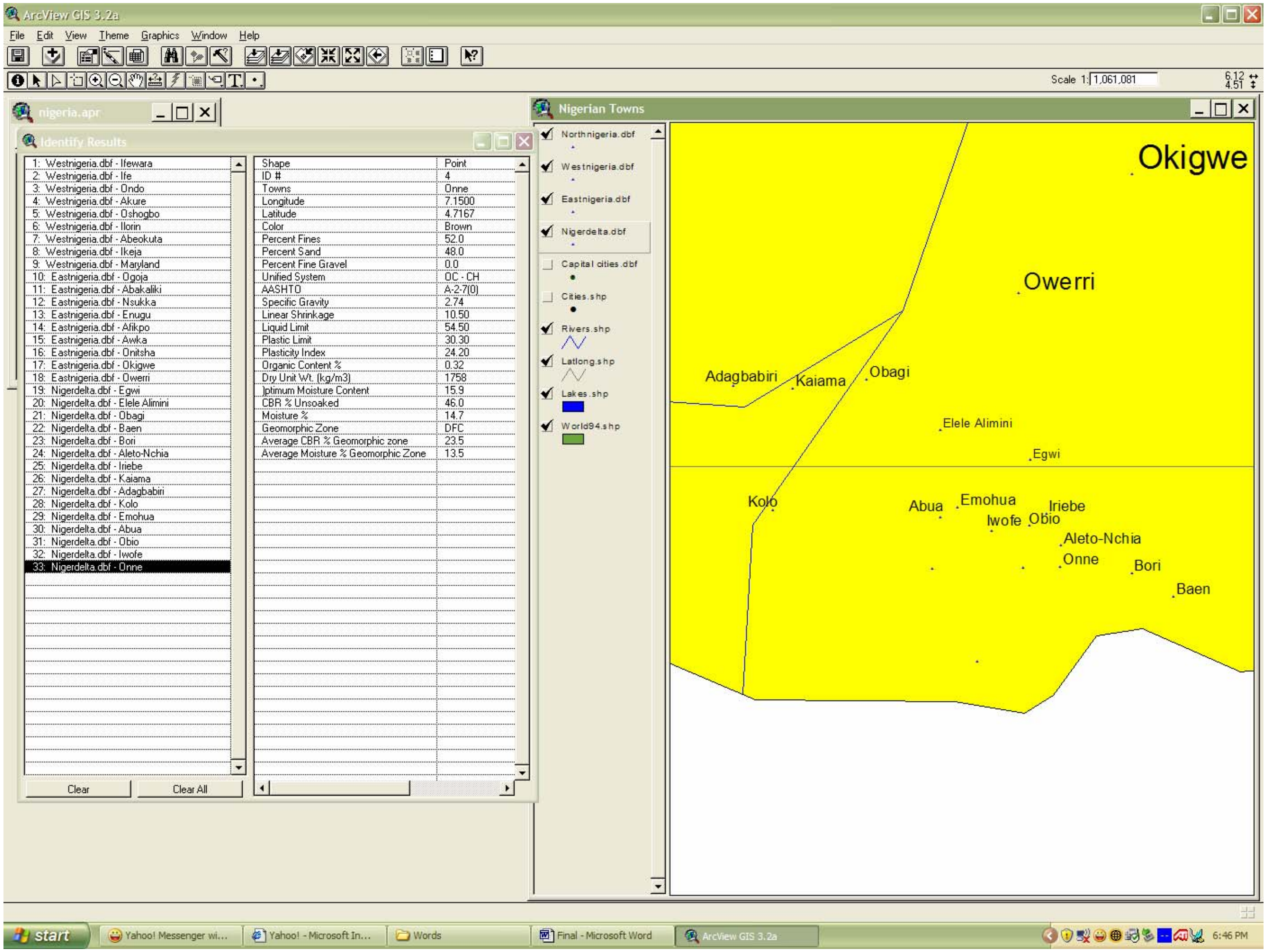


Figure 74: Soil properties of Onne

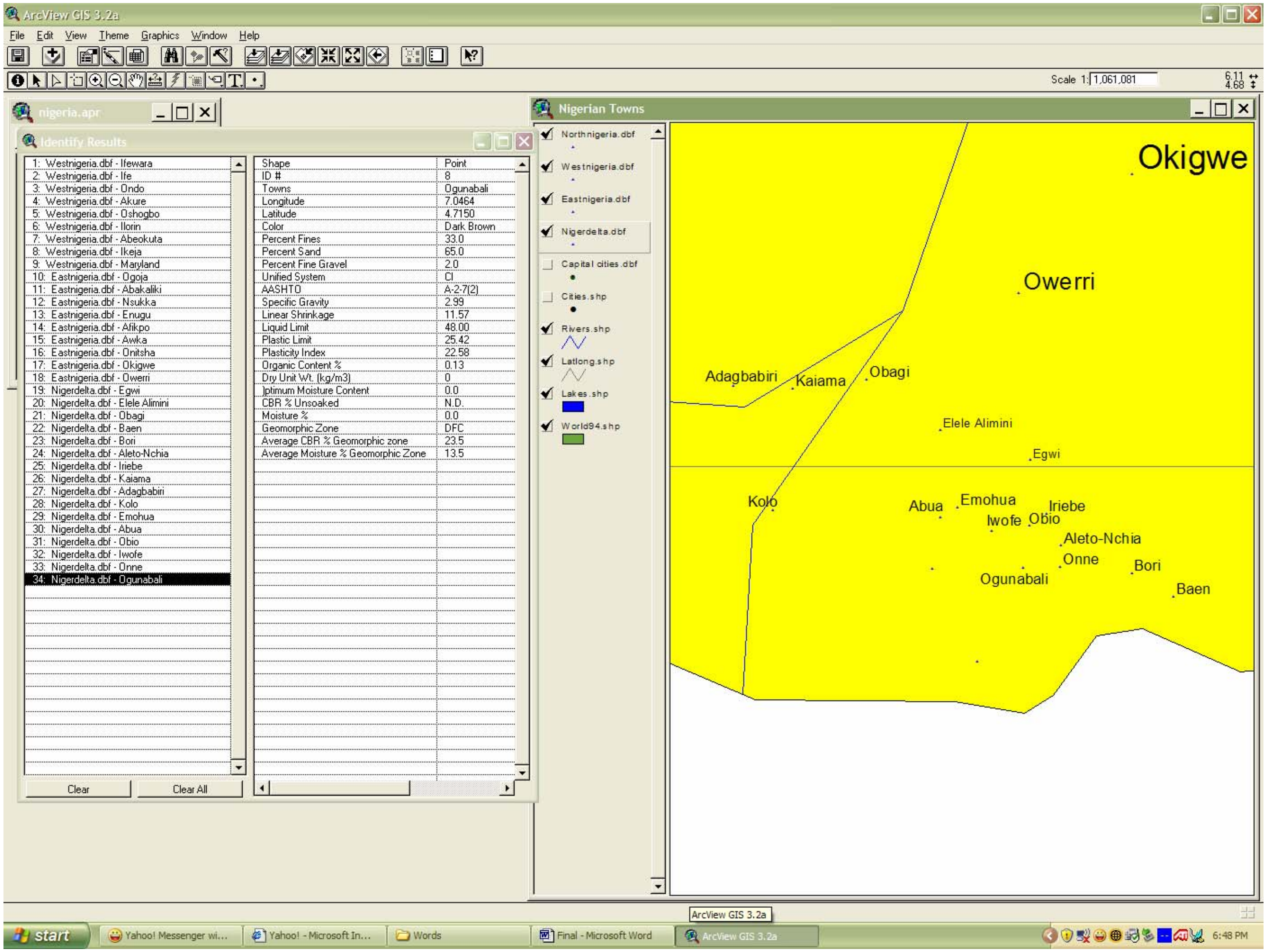


Figure 75: Soil properties of Ogunabali

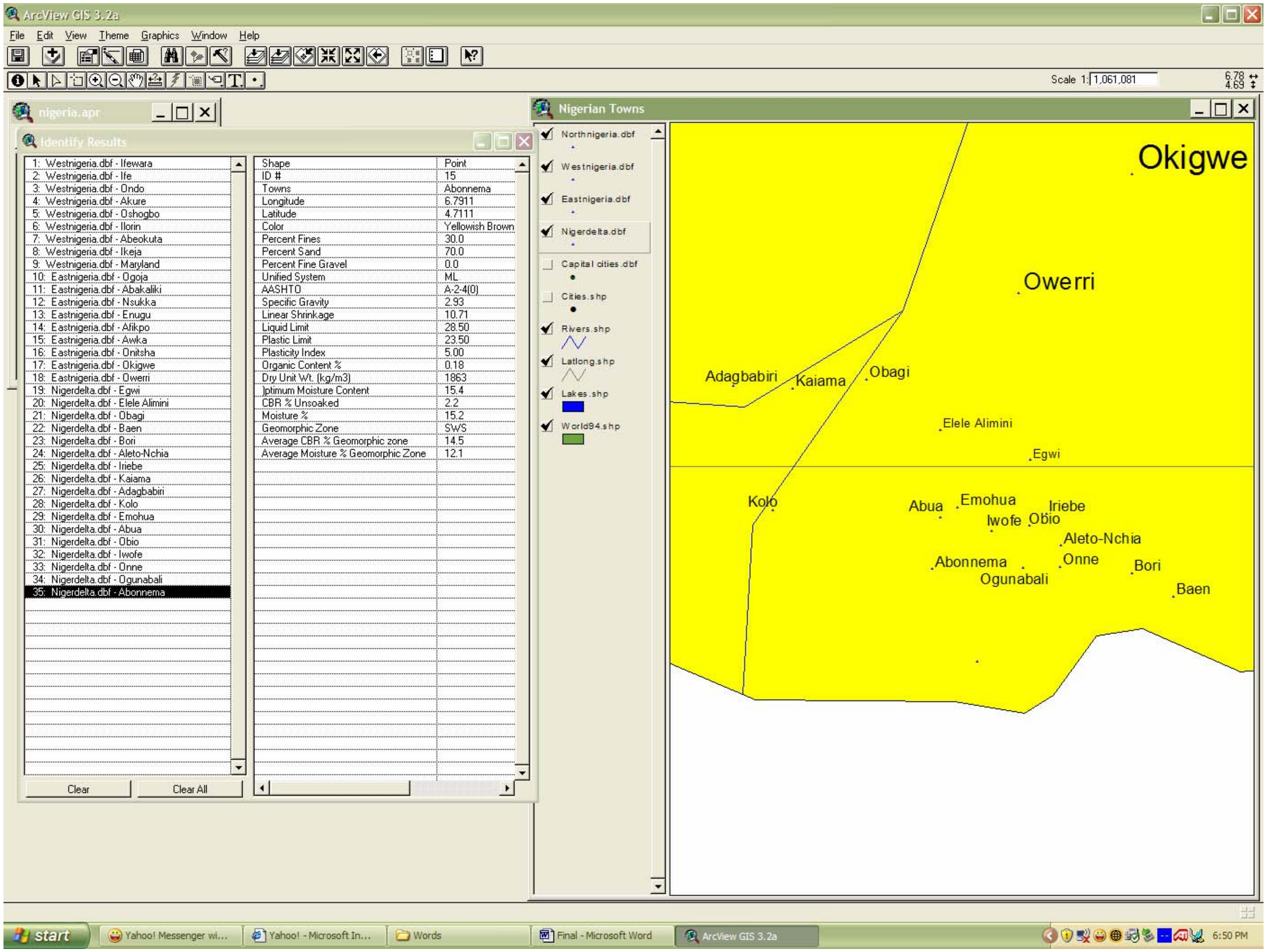


Figure 76: Soil properties of Abonnema

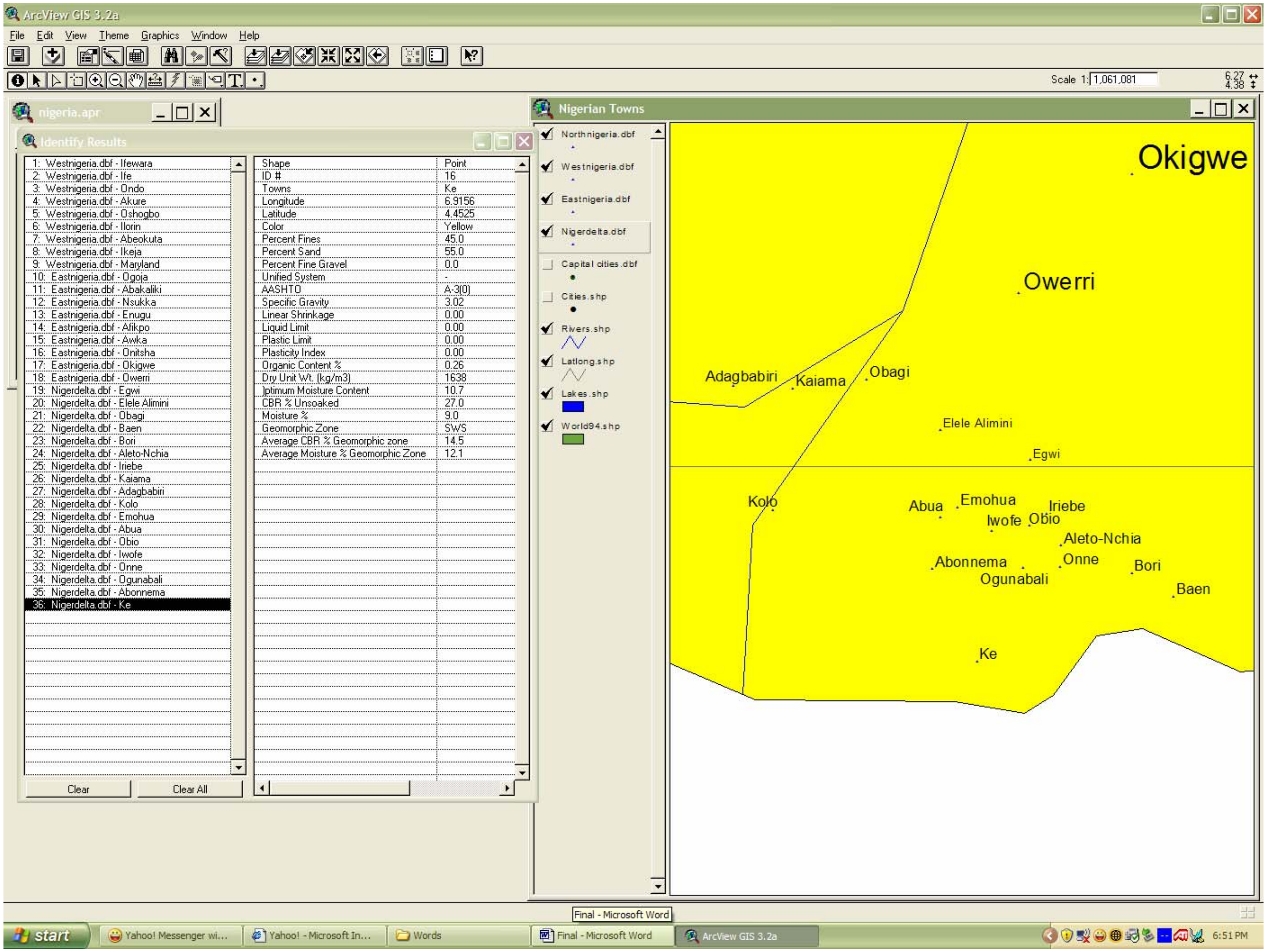


Figure 77: Soil properties of Ke

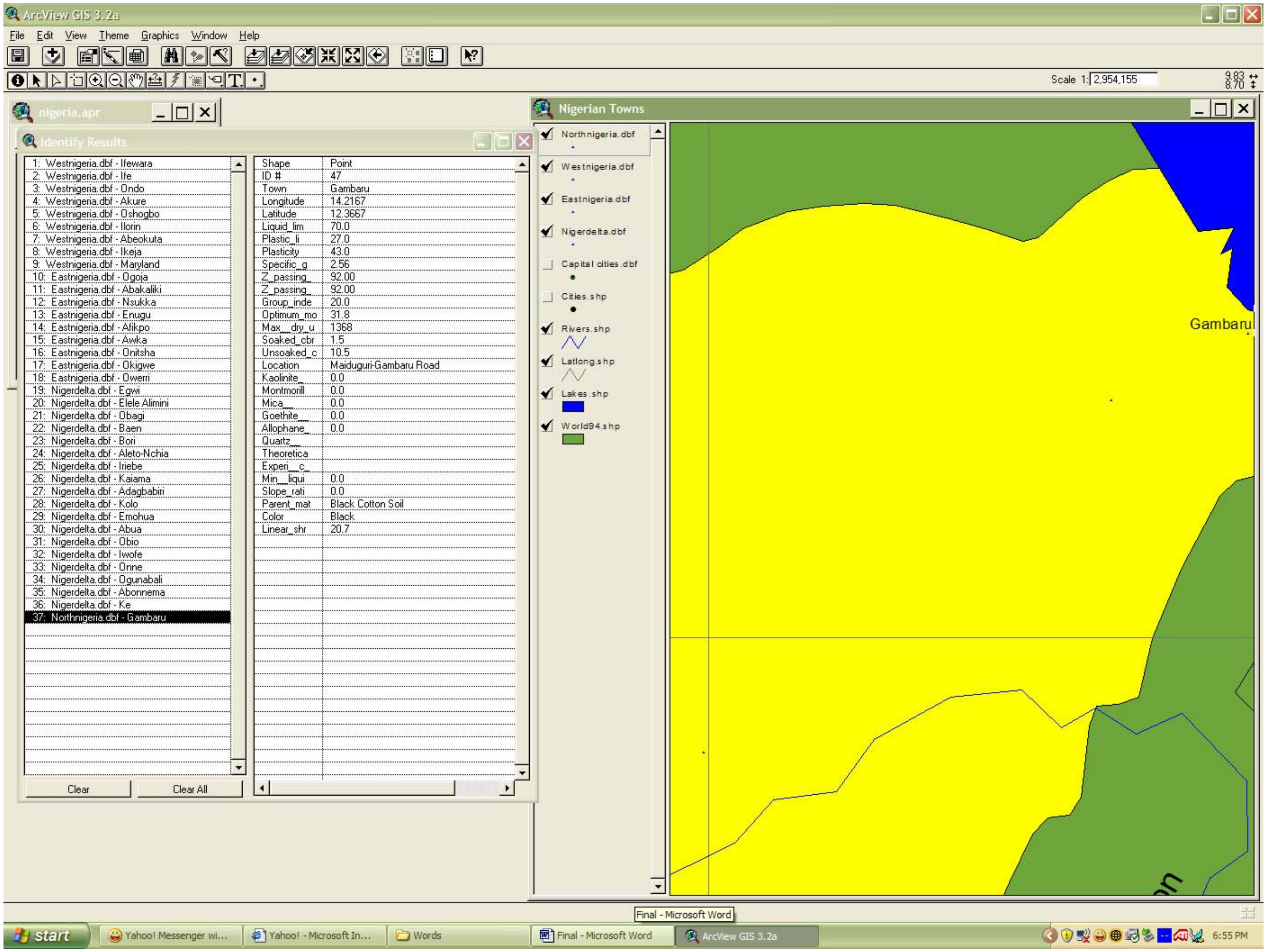


Figure 78: Soil properties of Gambaru

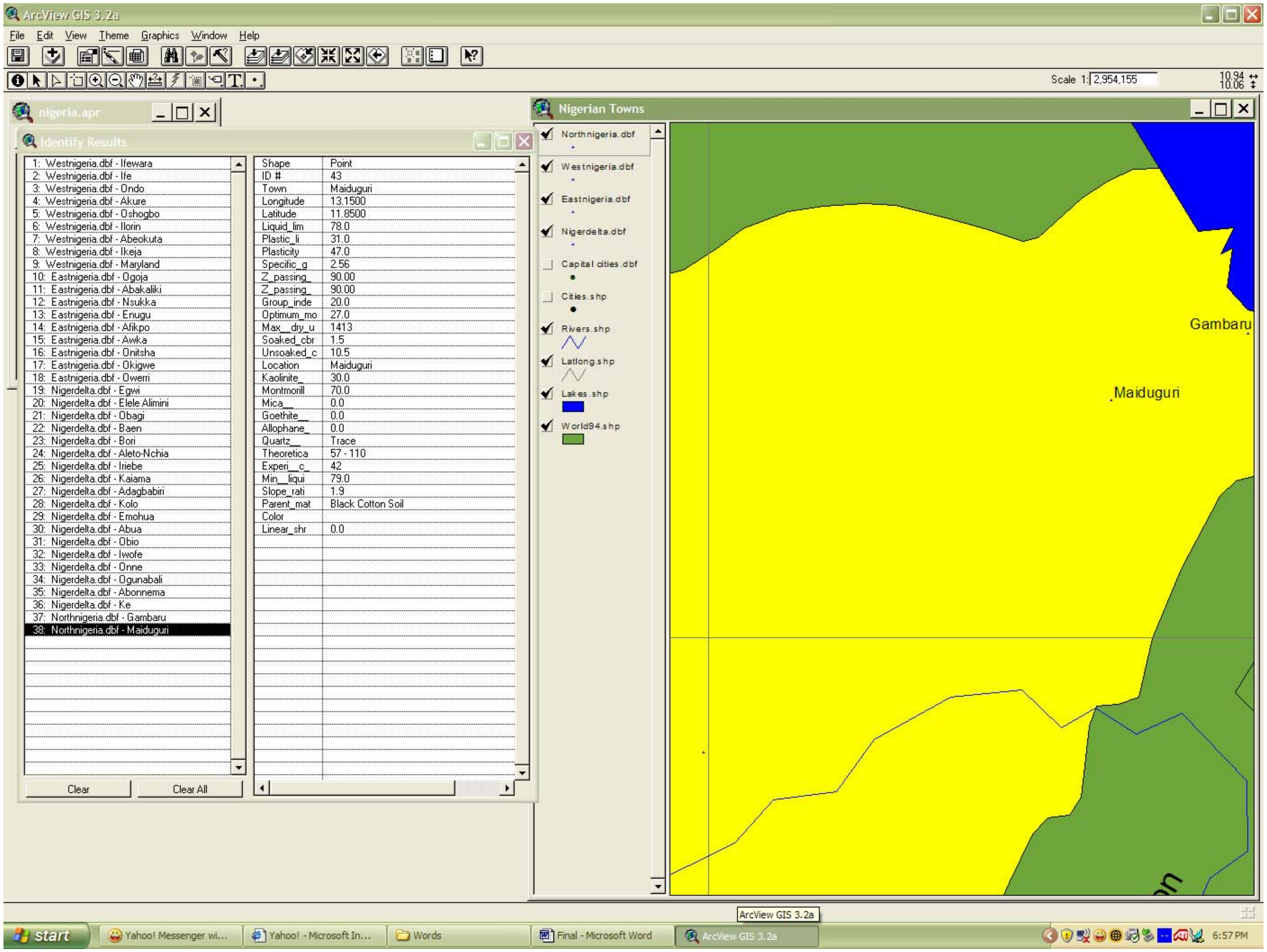


Figure 79: Soil properties of Maiduguri

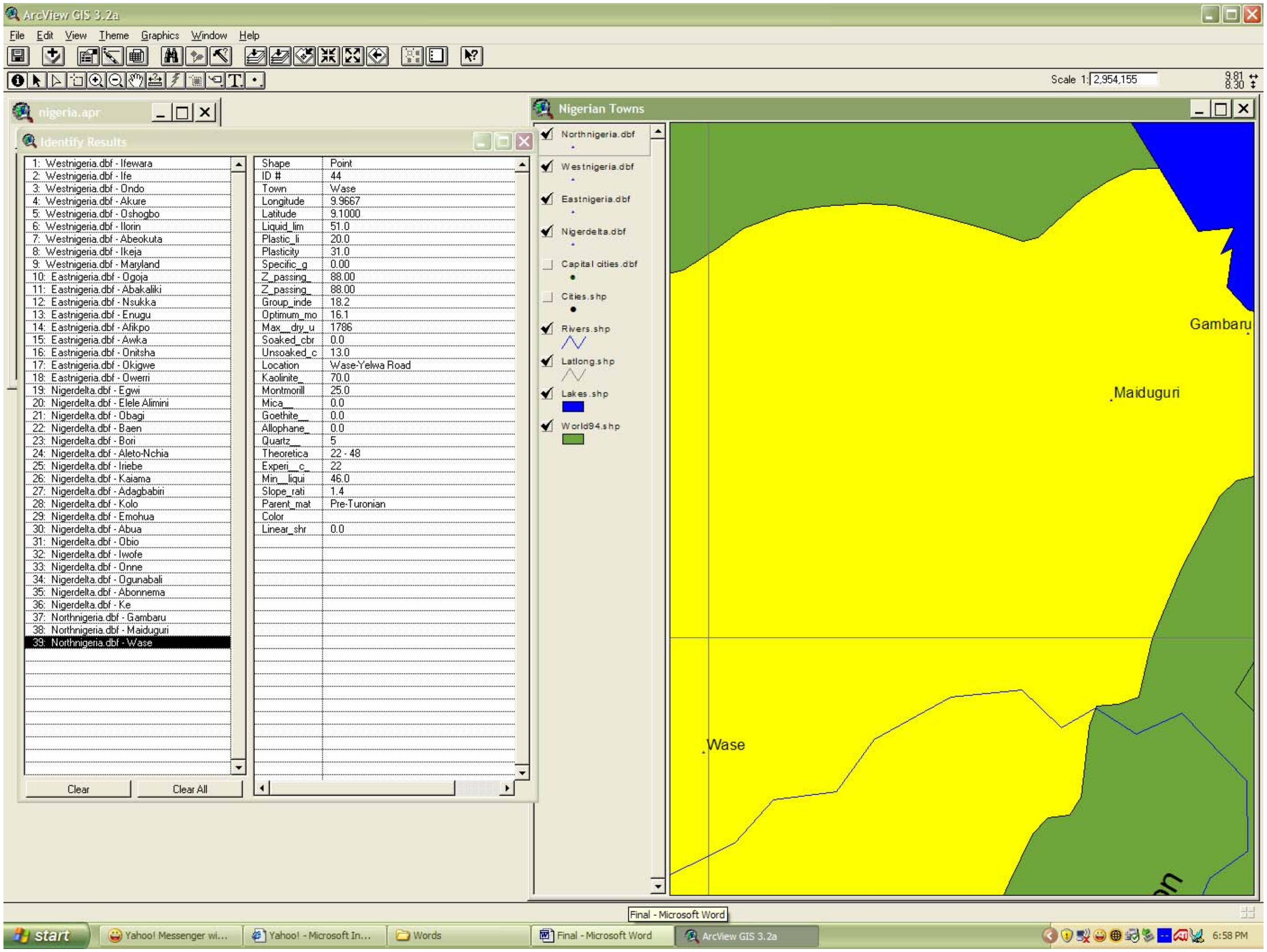


Figure 80: Soil properties of Wase

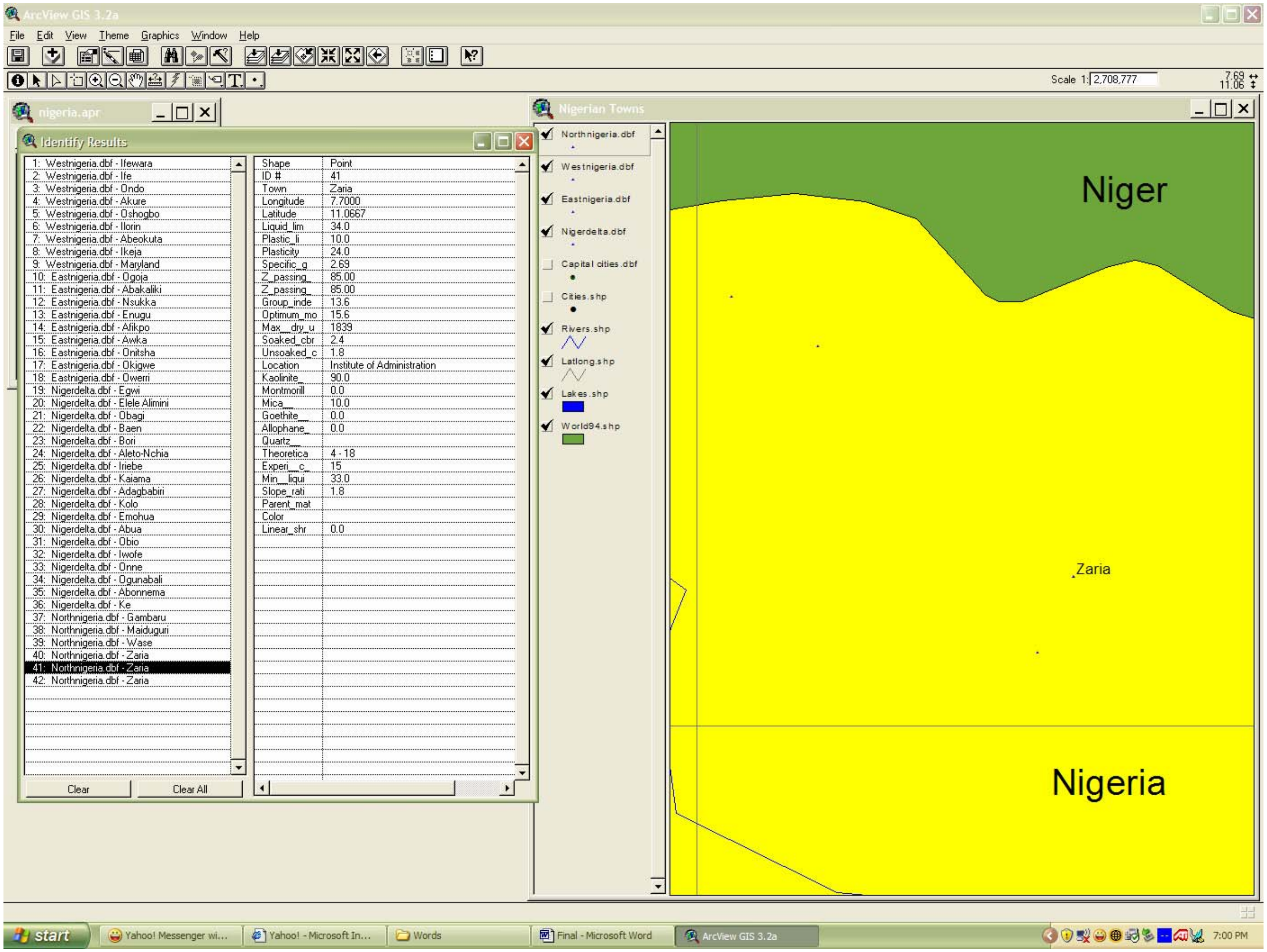


Figure 81: Soil properties of Zaria

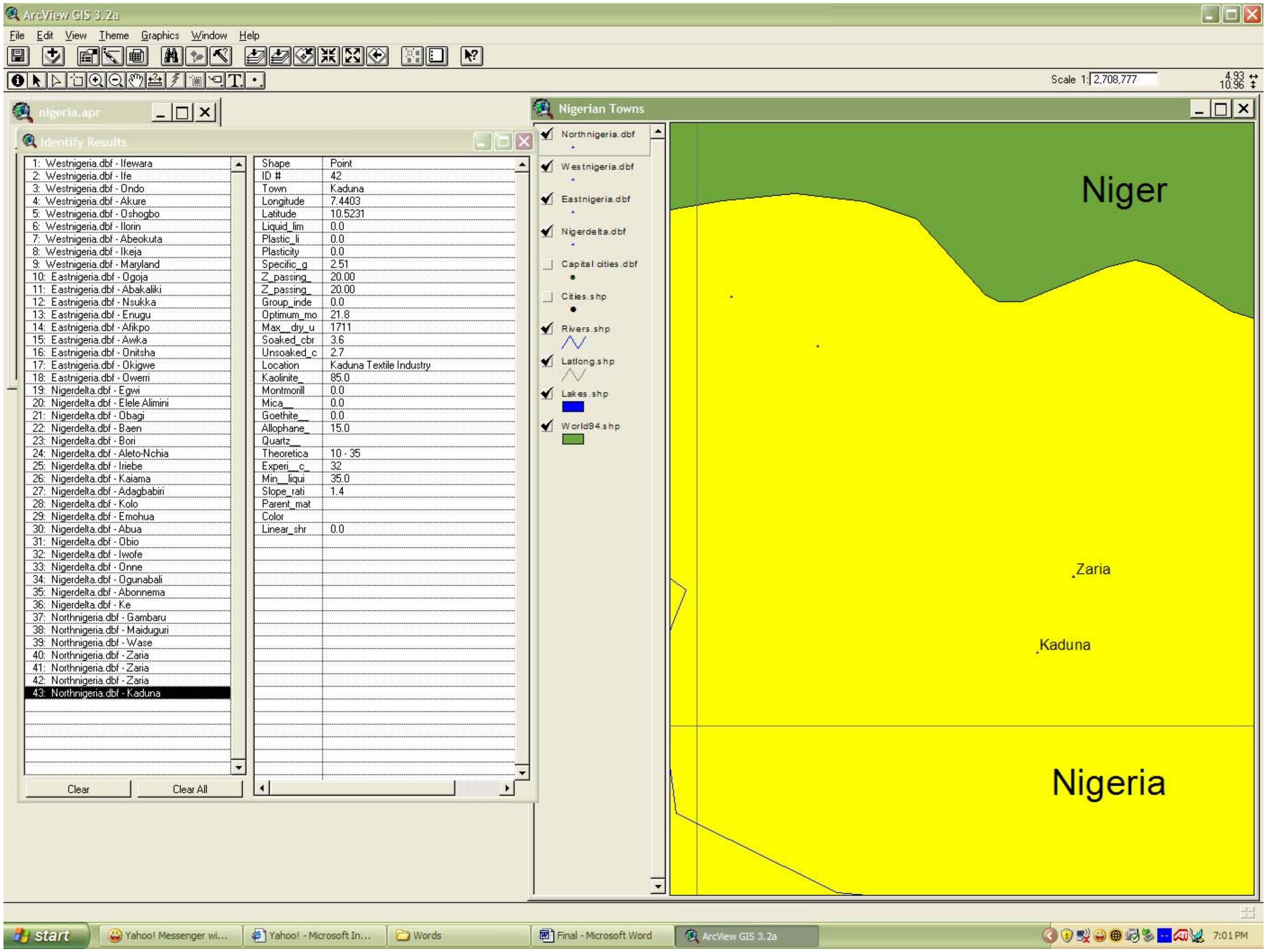


Figure 82: Soil properties of Kaduna

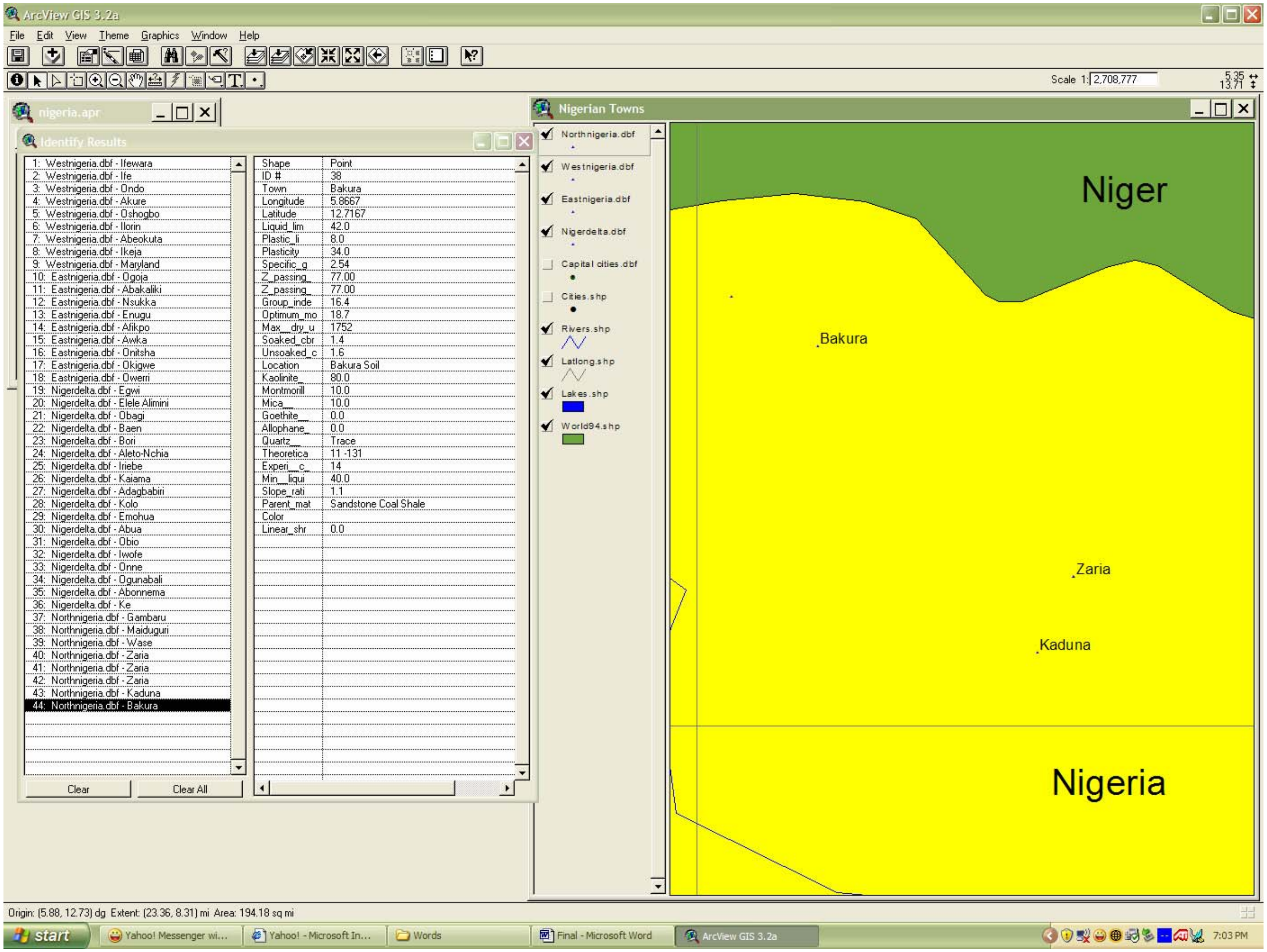


Figure 83: Soil properties of Bakura

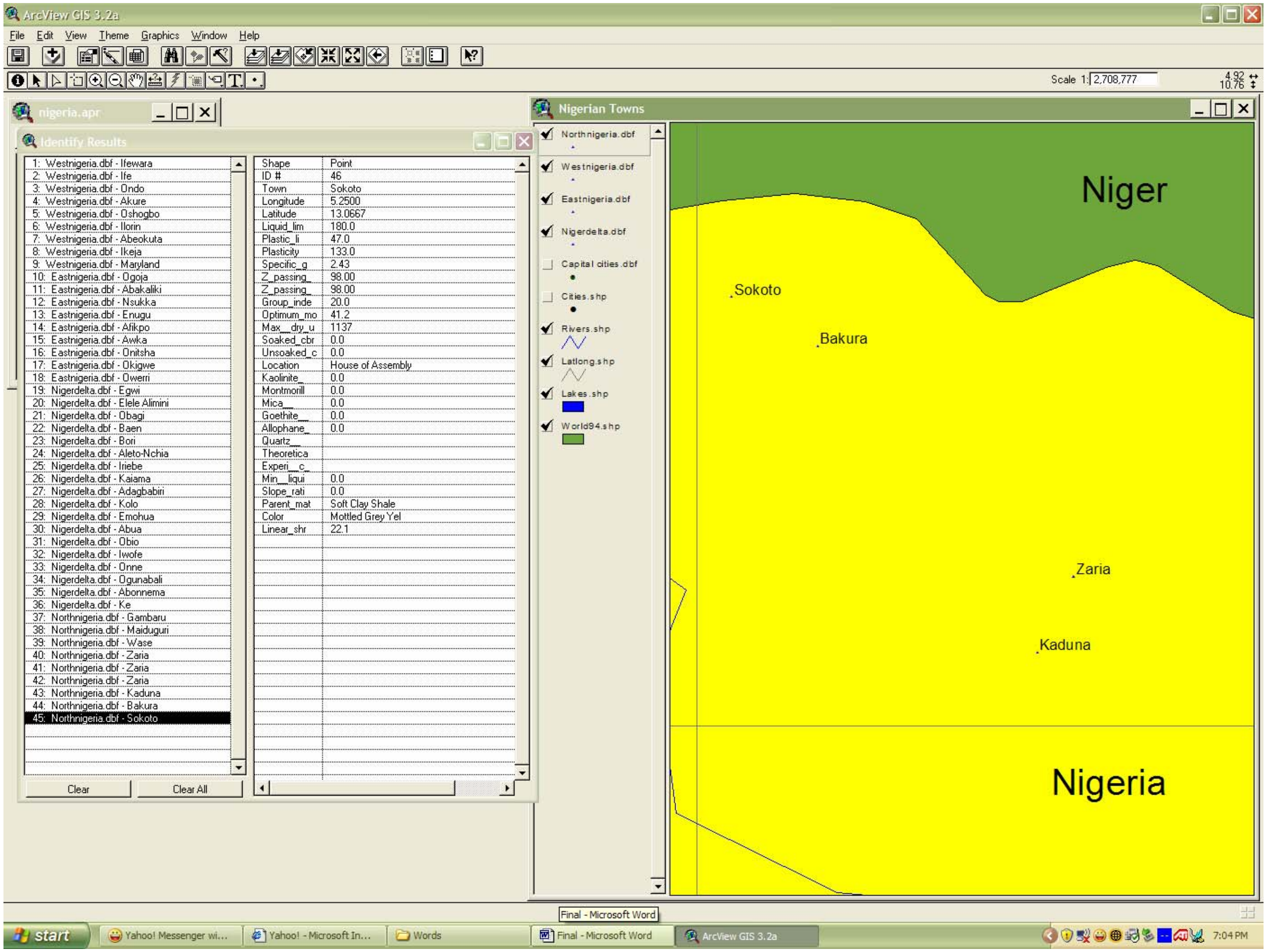


Figure 84: Soil properties of Sokoto

APPENDIX B: PROBABILITY DENSITY FUNCTIONS FOR SLOPE OF 1:1

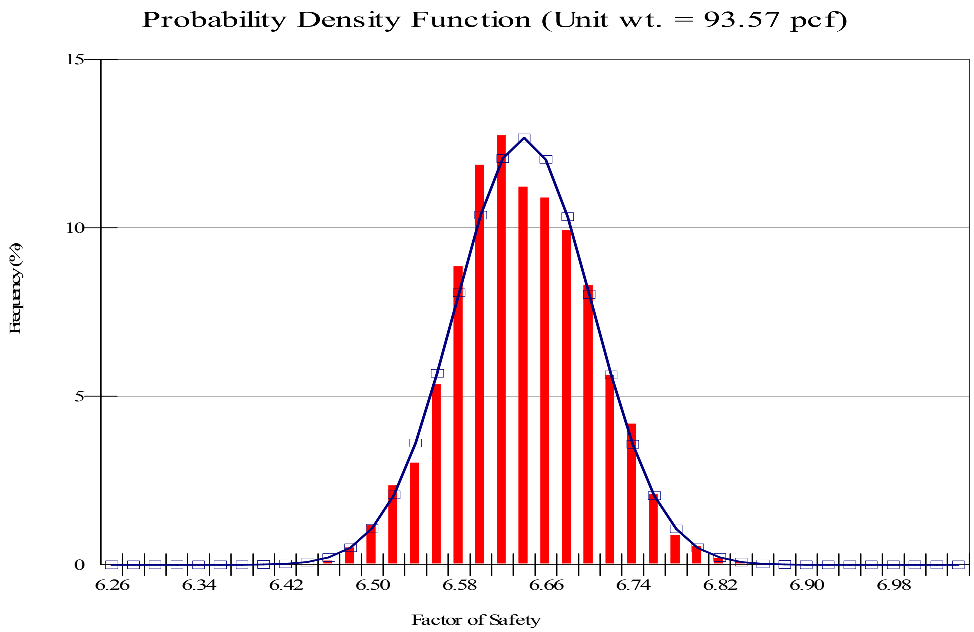


Figure 85: Probability density function ($\phi = 0$, c = 2088.54 psf) Unsaturated

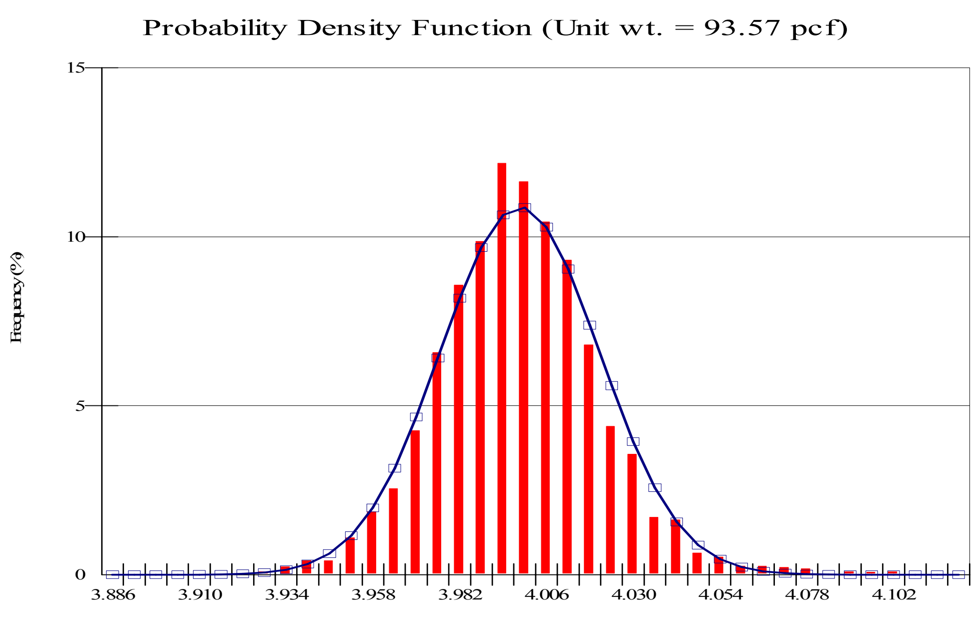


Figure 86: Probability density function ($\phi = 0$, c = 1253.12 psf) Saturated

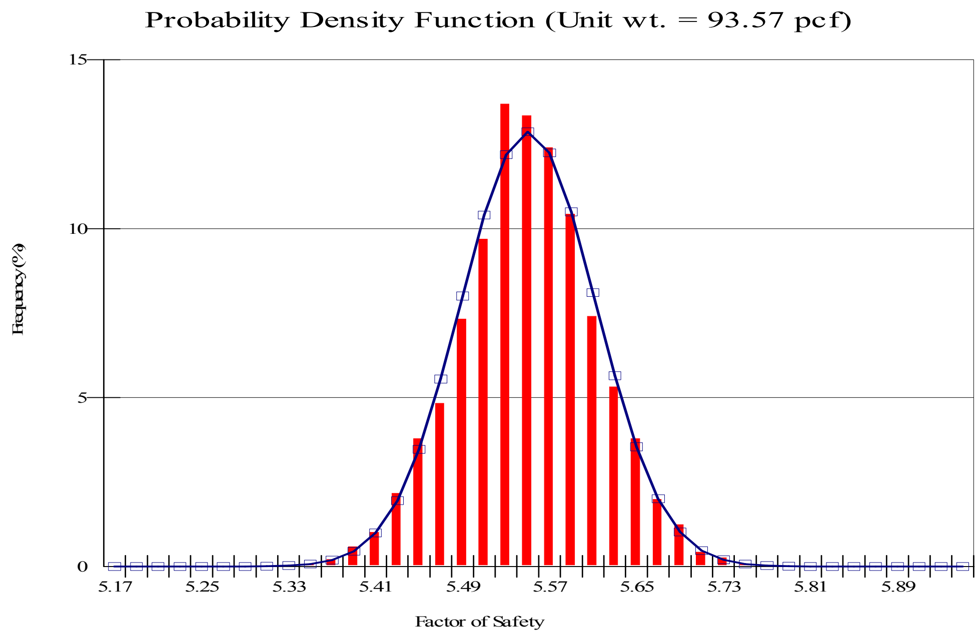


Figure 87: Probability density function ($\phi = 10$, c = 1584.02 psf) Unsaturated

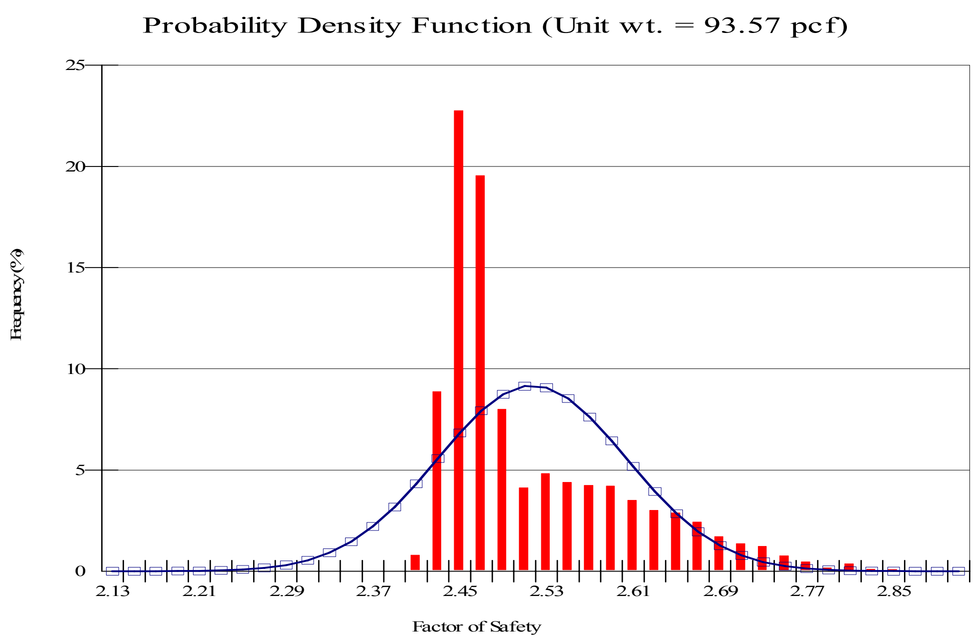


Figure 88: Probability density function ($\phi = 10$, c = 748 psf) Saturated

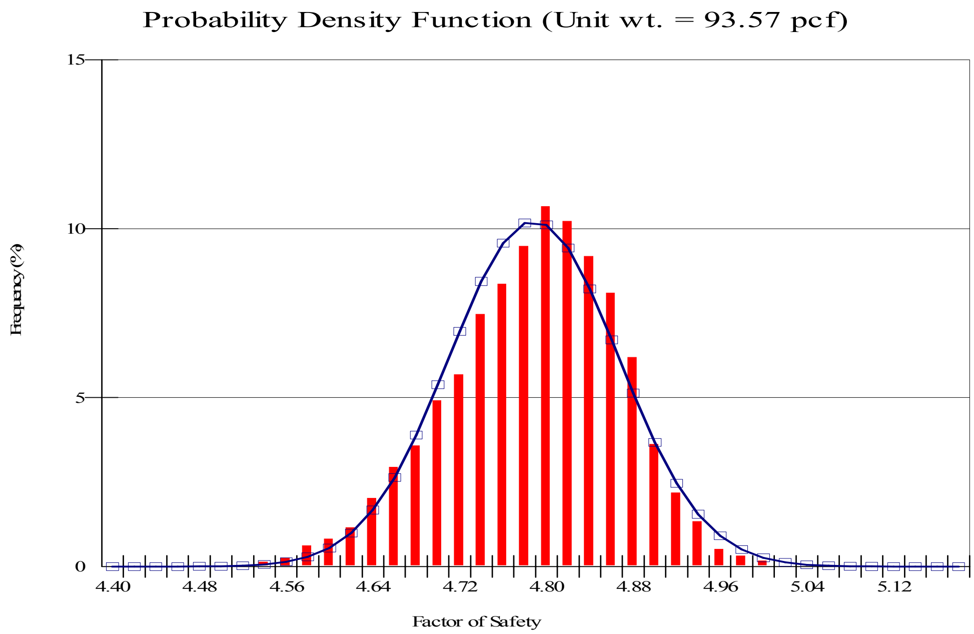


Figure 89: Probability density function (ϕ = 15, c = 1321.86 psf) Unsaturated

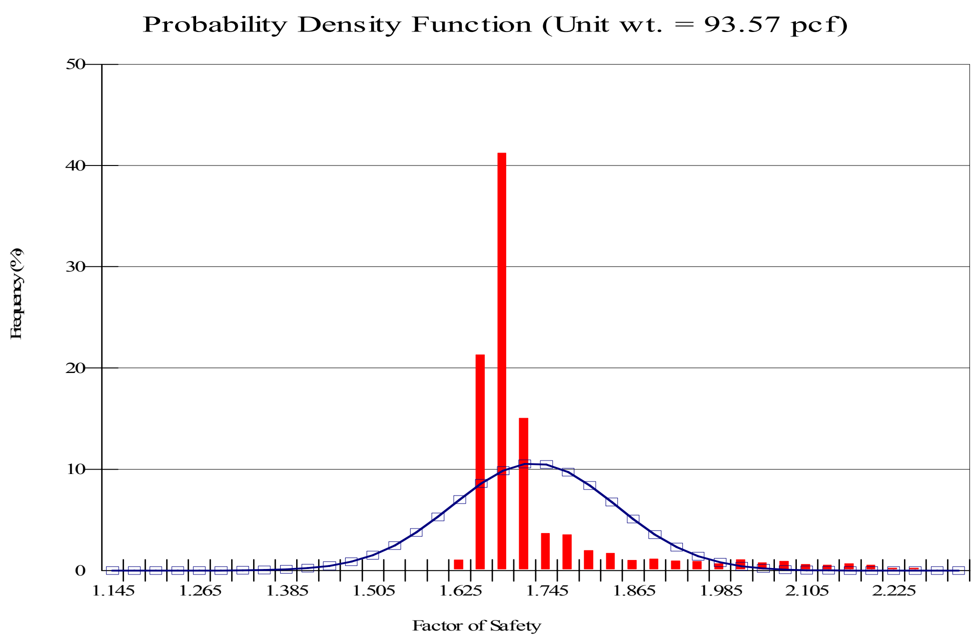


Figure 90: Probability density function (ϕ = 15, c = 486.44 psf) Saturated

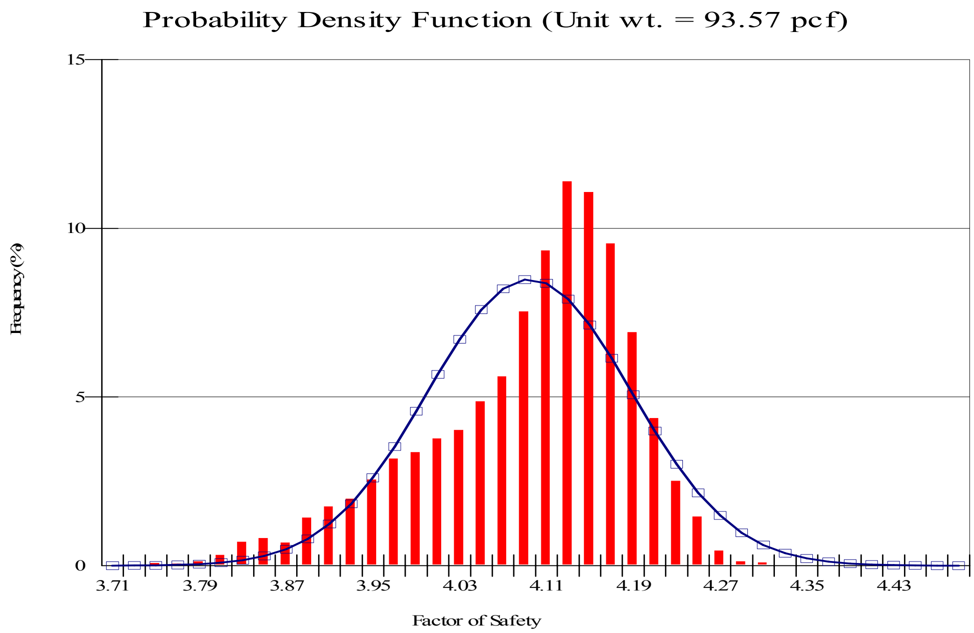


Figure 91: Probability density function ($\phi = 20$, c = 1047.11 psf) Unsaturated

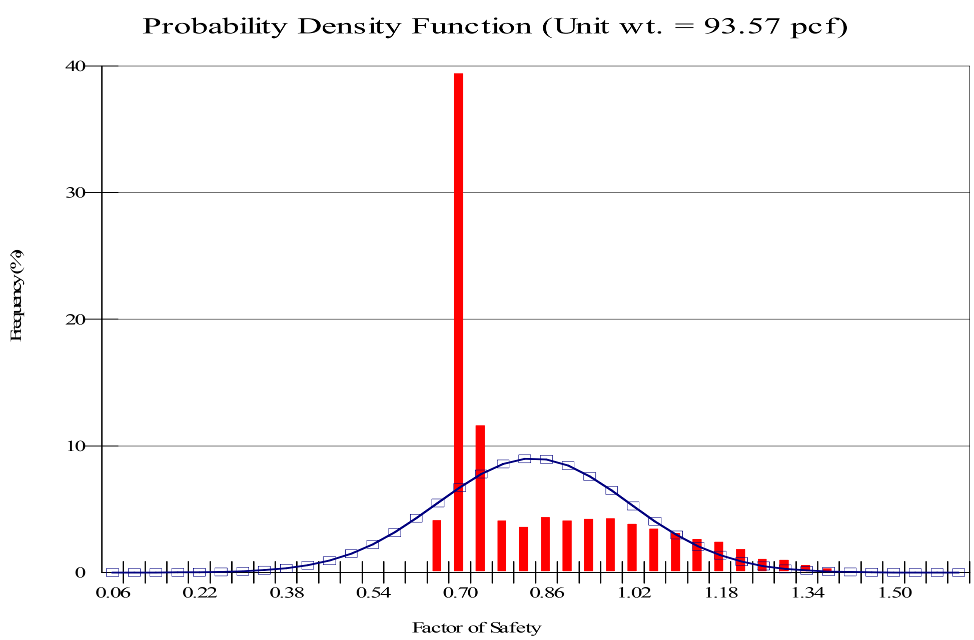


Figure 92: Probability density function ($\phi = 20$, c = 211.69 psf) Saturated

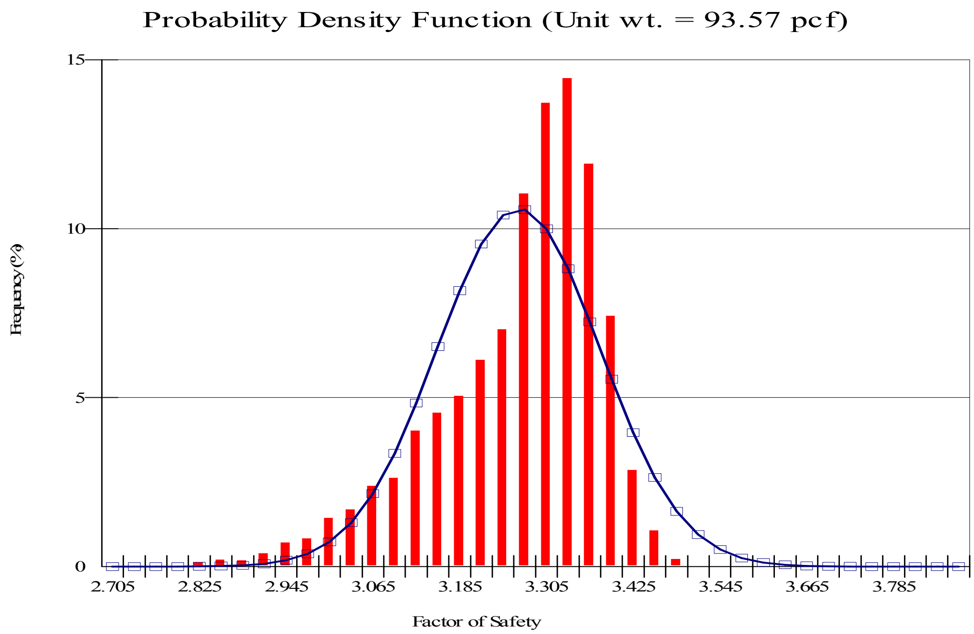


Figure 93: Probability density function ($\phi = 25$, $c = 754.29$ psf) Unsaturated

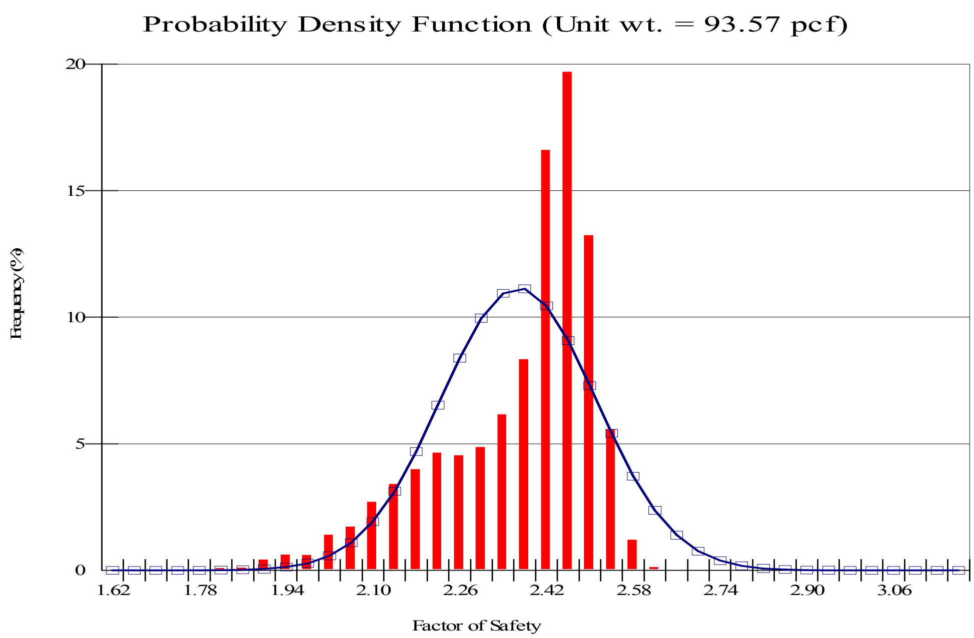


Figure 94: Probability density function ($\phi = 30$, $c = 436.57$ psf) Unsaturated

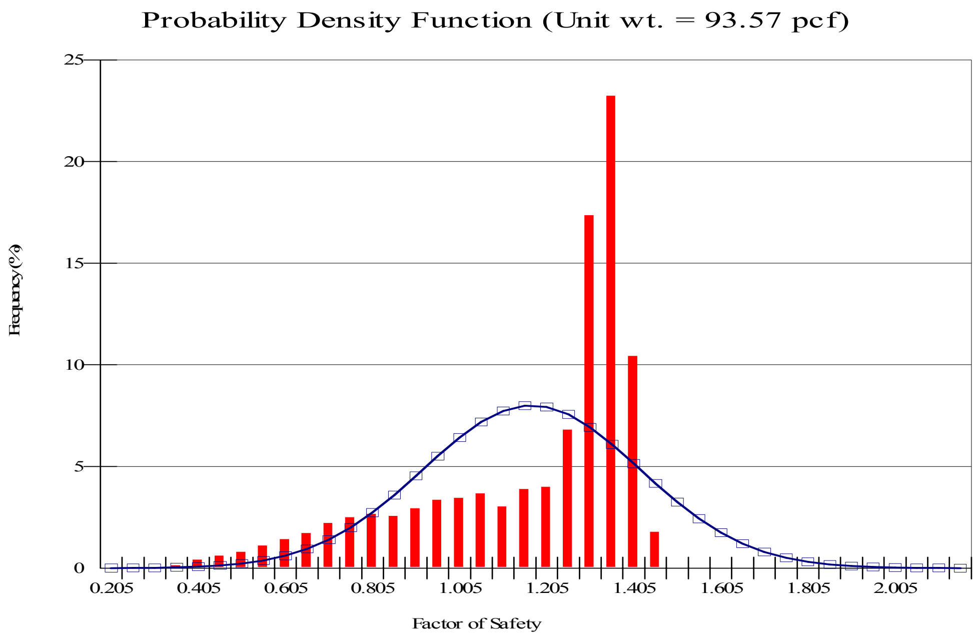


Figure 95: Probability density function ($\phi = 35$, $c = 85.04$ psf) Unsaturated

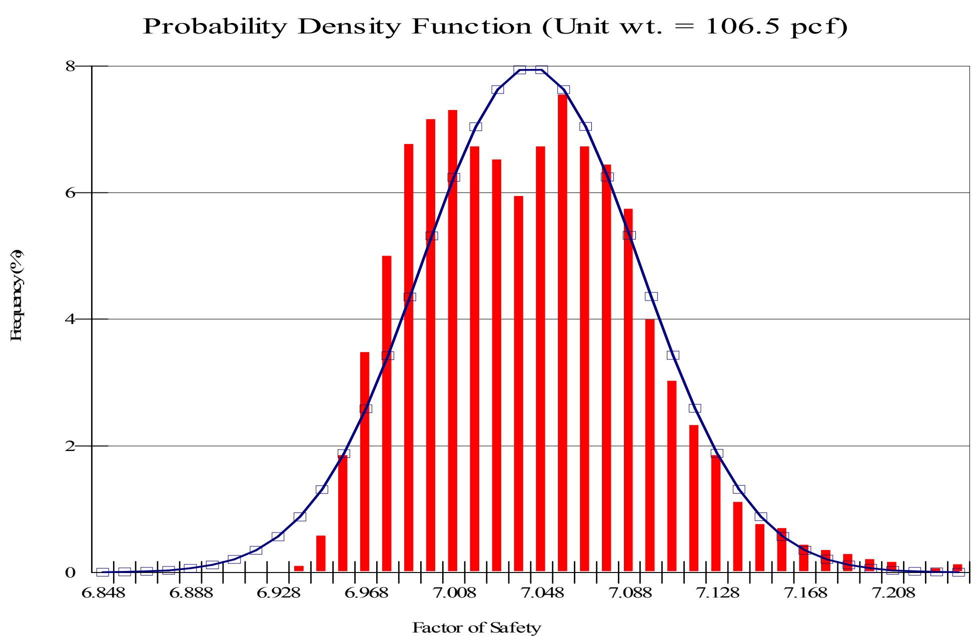


Figure 96: Probability density function ($\phi = 0$, $c = 2506.25$ psf) Unsaturated

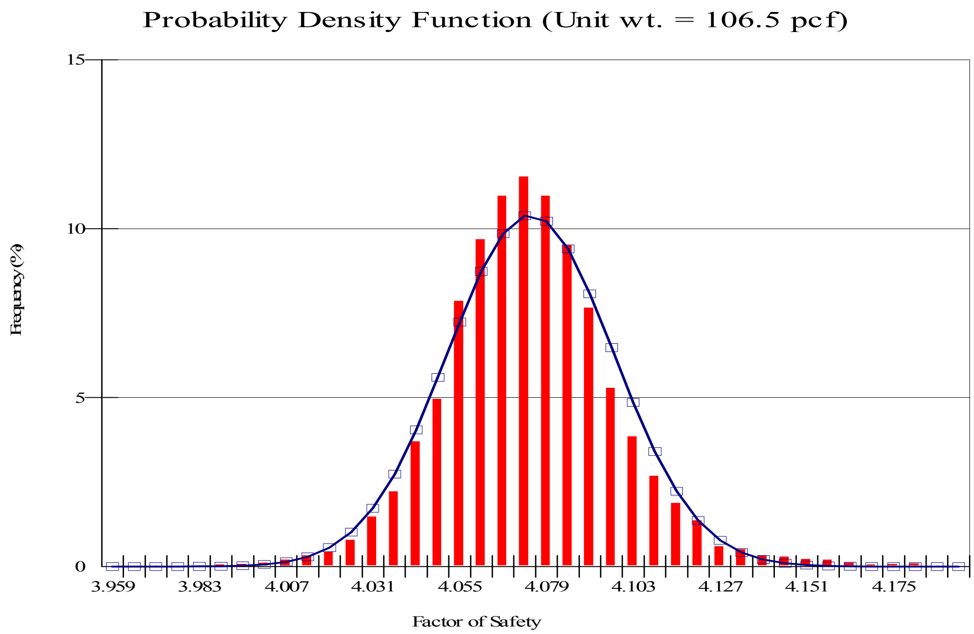


Figure 97: Probability density function ($\phi = 0$, $c = 1453.12$ psf) Saturated

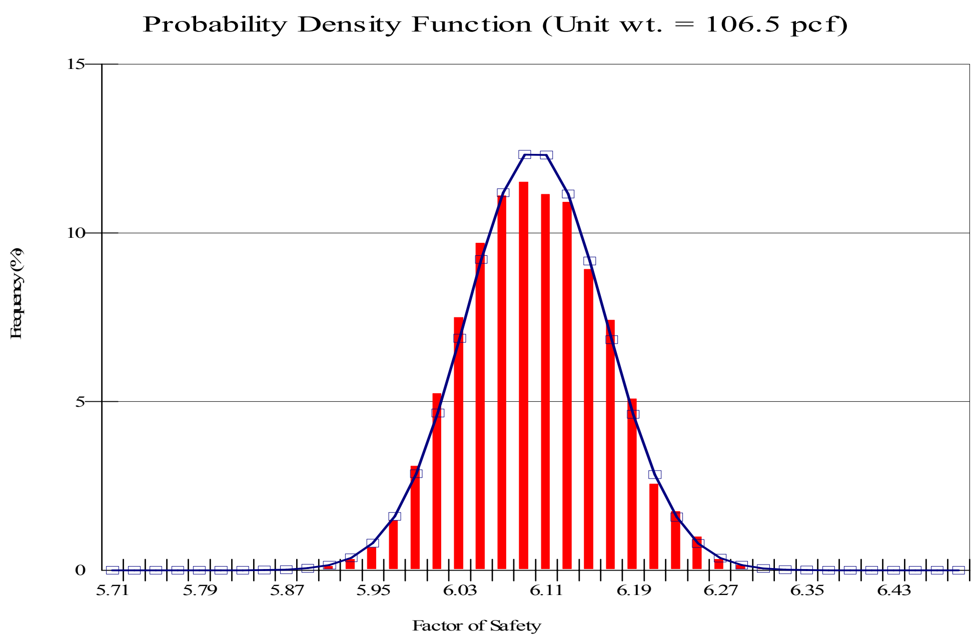


Figure 98: Probability density function ($\phi = 10$, $c = 2001.73$ psf) Unsaturated

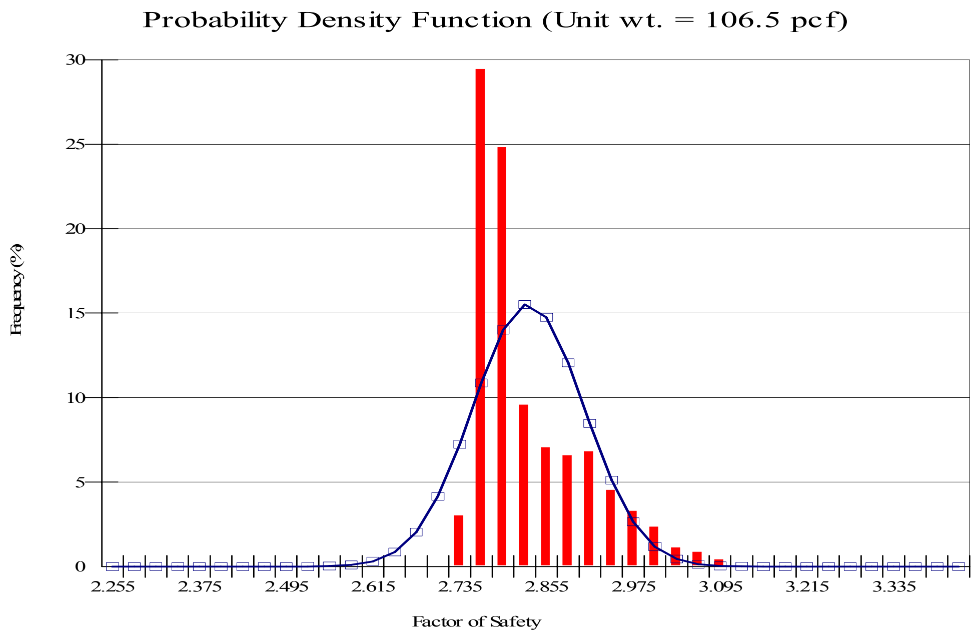


Figure 99: Probability density function ($\phi = 10$, $c = 948.6$ psf) Saturated

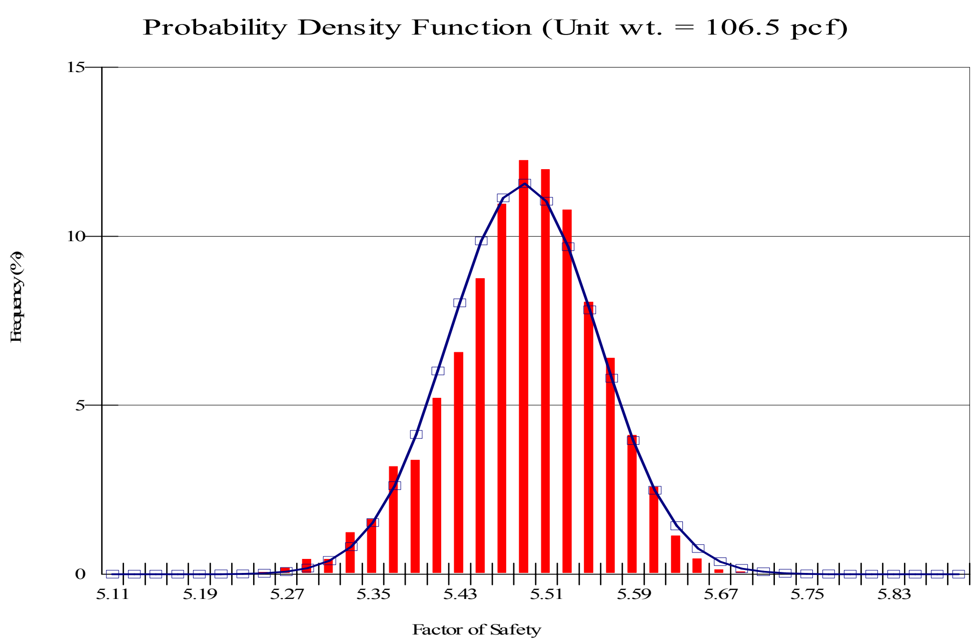


Figure 100: Probability density function ($\phi = 15$, $c = 1739.57$ psf) Unsaturated

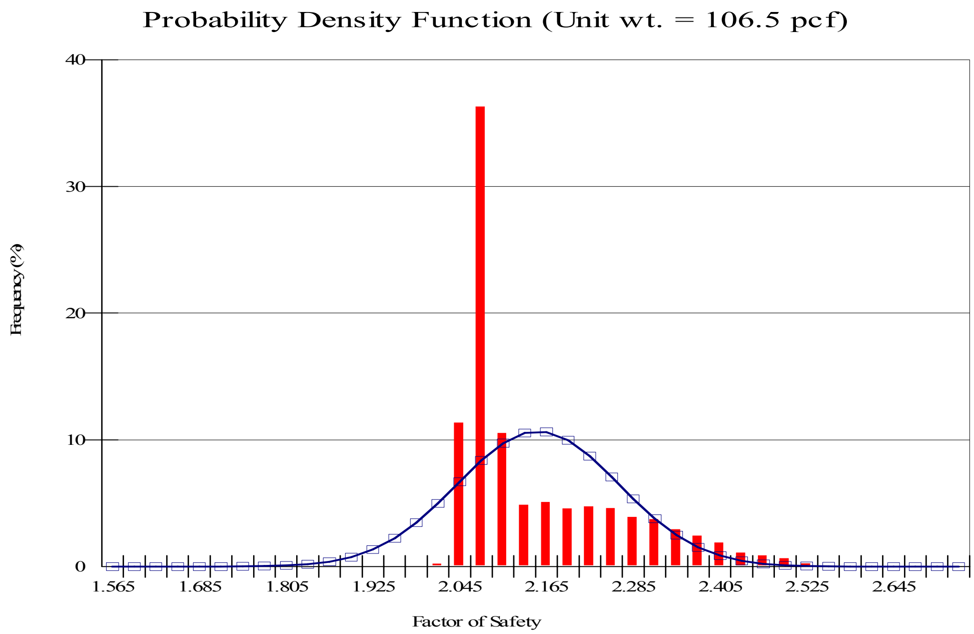


Figure 101: Probability density function ($\phi = 15$, $c = 686.44$ psf) Saturated

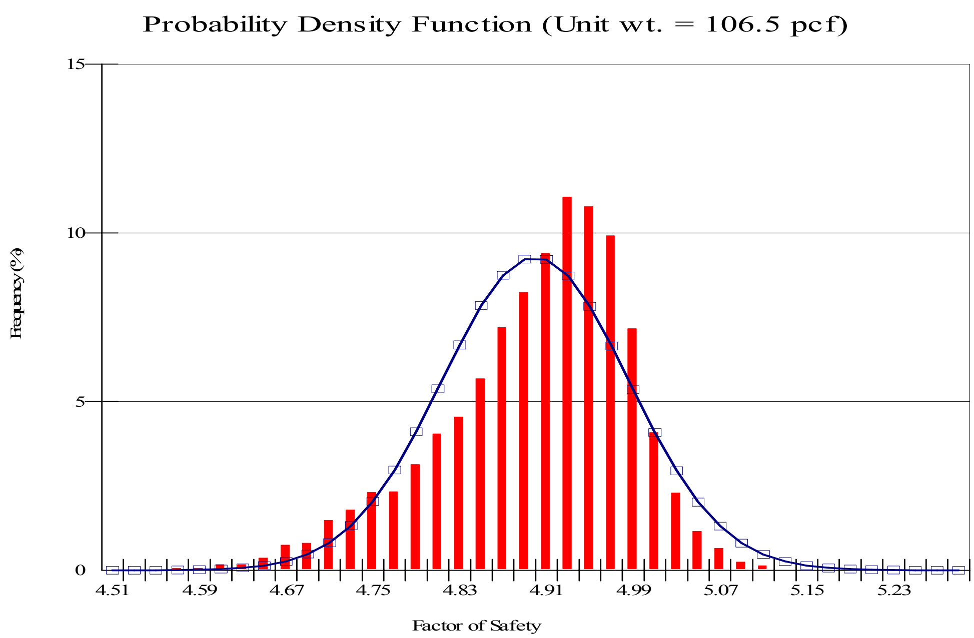


Figure 102: Probability density function ($\phi = 20$, $c = 1464.82$ psf) Unsaturated

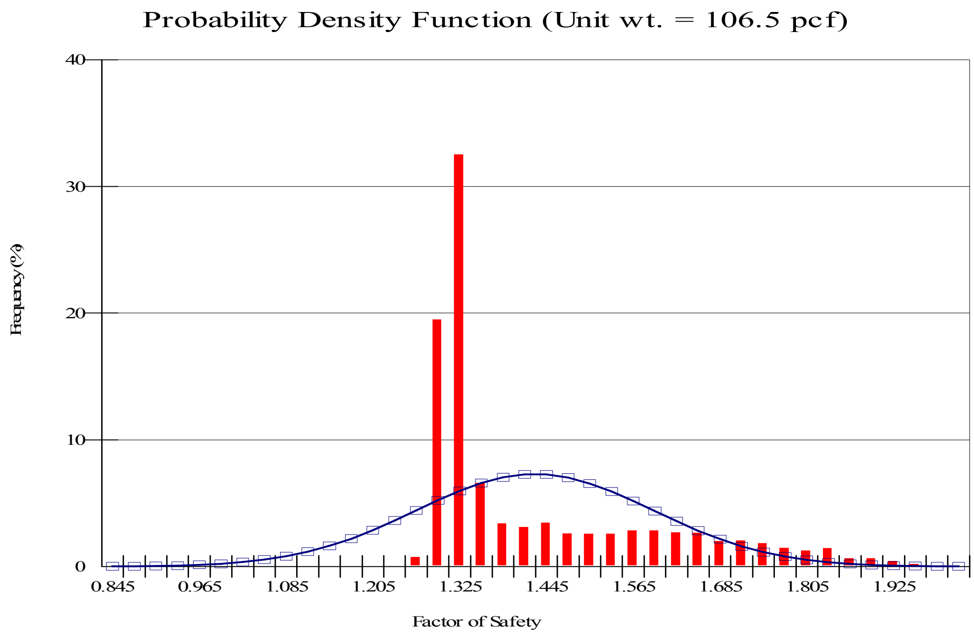


Figure 103: Probability density function ($\phi = 20$, $c = 411.69$ psf) Saturated

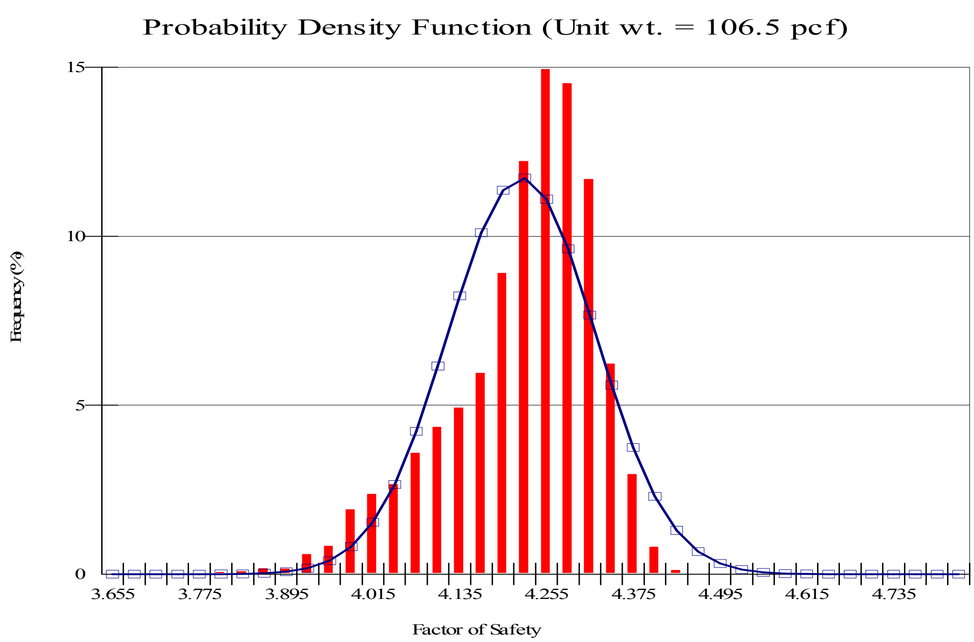


Figure 104: Probability density function ($\phi = 25$, $c = 1172.0$ psf) Unsaturated

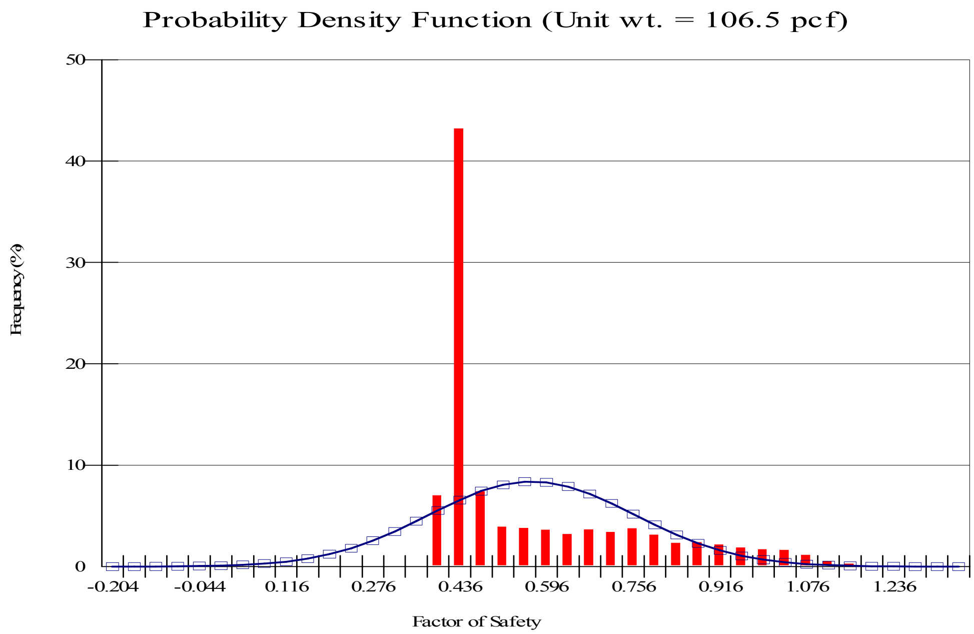


Figure 105: Probability density function ($\phi = 25$, c = 118.87.0 psf) Saturated

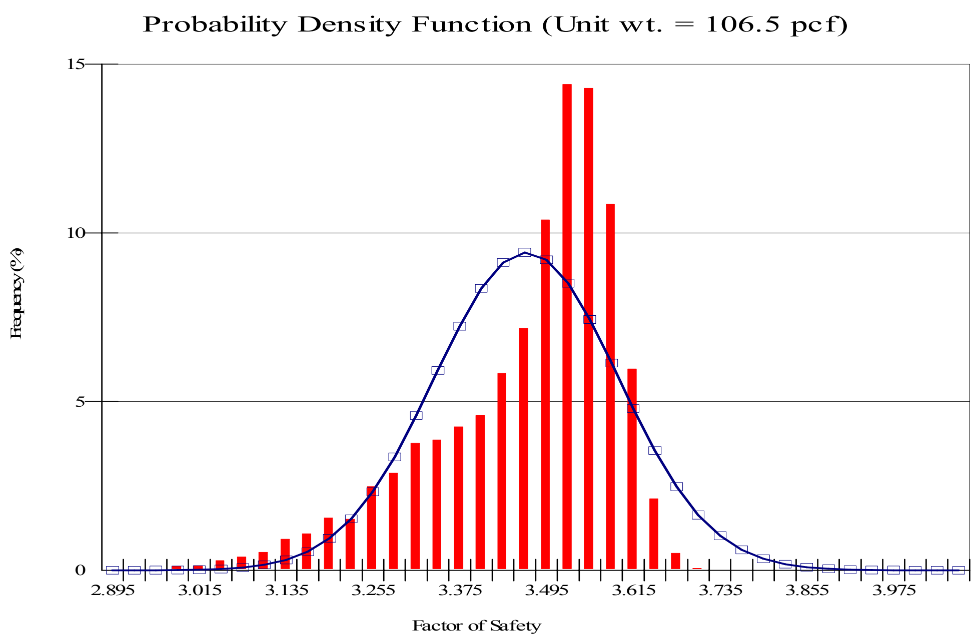


Figure 106: Probability density function ($\phi = 30$, c = 854.28 psf) Unsaturated

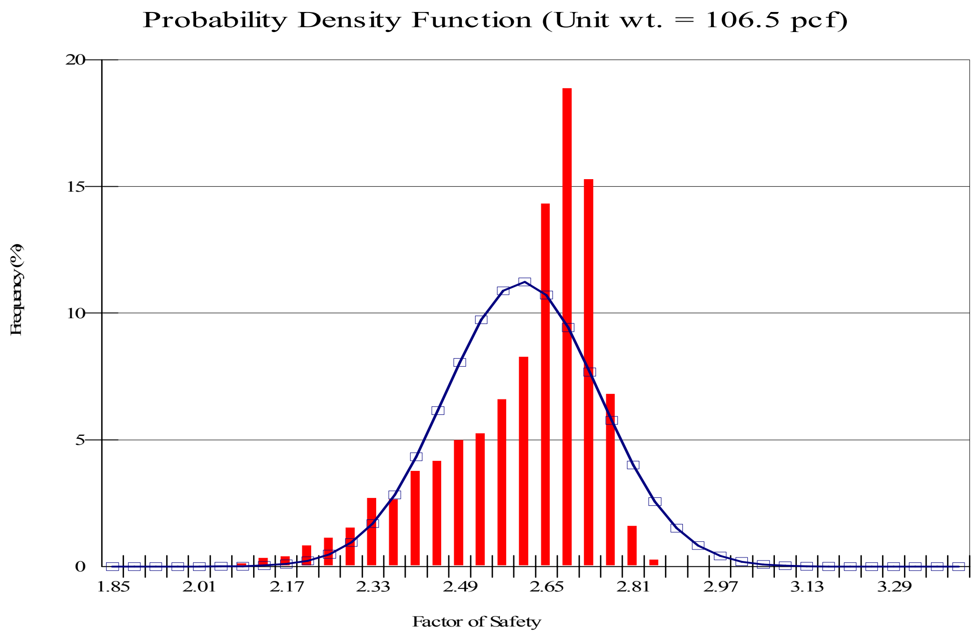


Figure 107: Probability density function ($\phi = 35$, $c = 502.75$ psf) Unsaturated

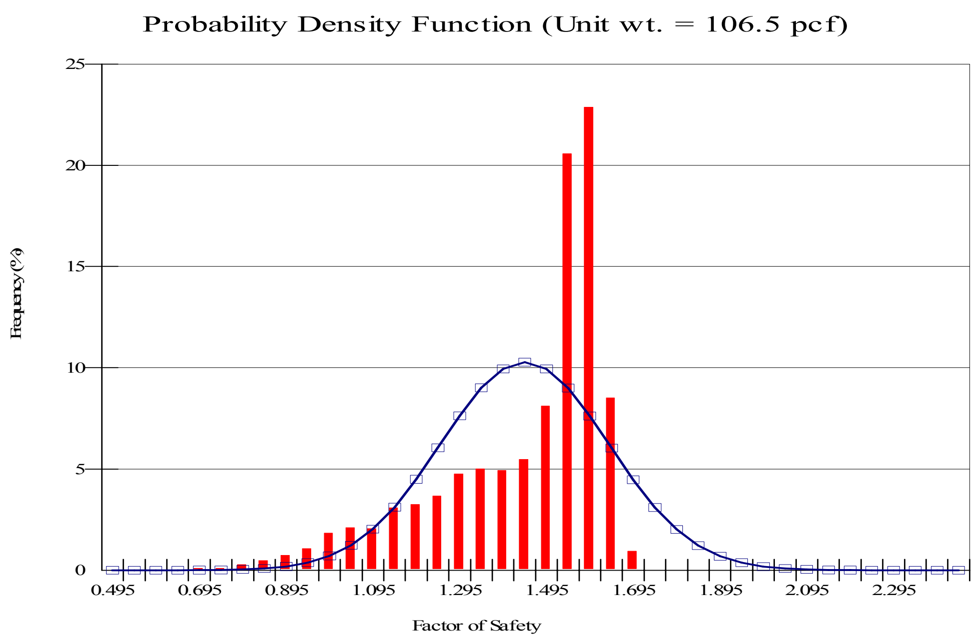


Figure 108: Probability density function ($\phi = 40$, $c = 105.33$ psf) Unsaturated

APPENDIX C: PROBABILITY DENSITY FUNCTIONS FOR SLOPE OF 2:1

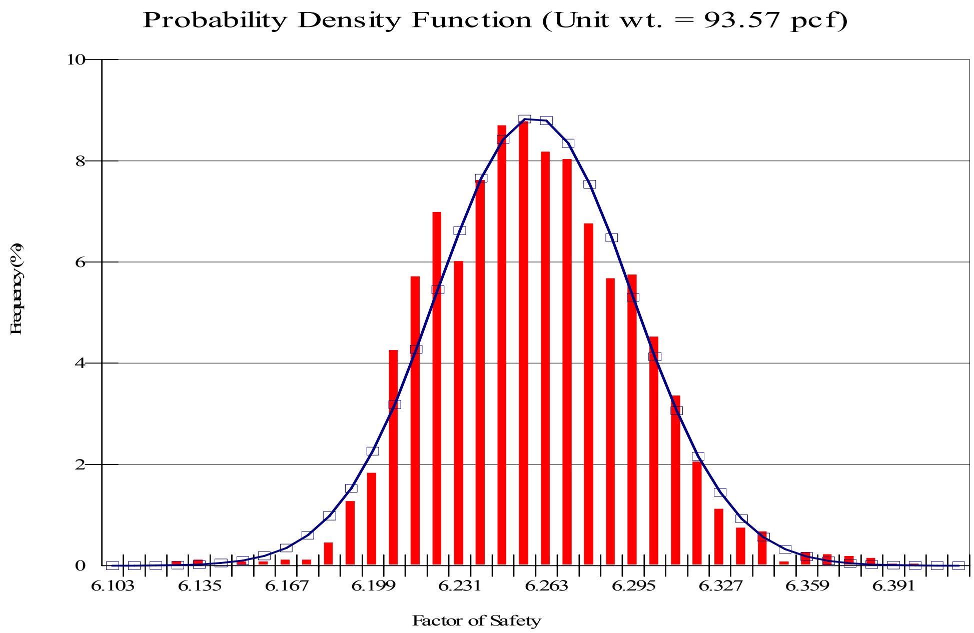


Figure 109: Probability density function ($\phi = 0$, c = 2088.54 psf) Unsaturated

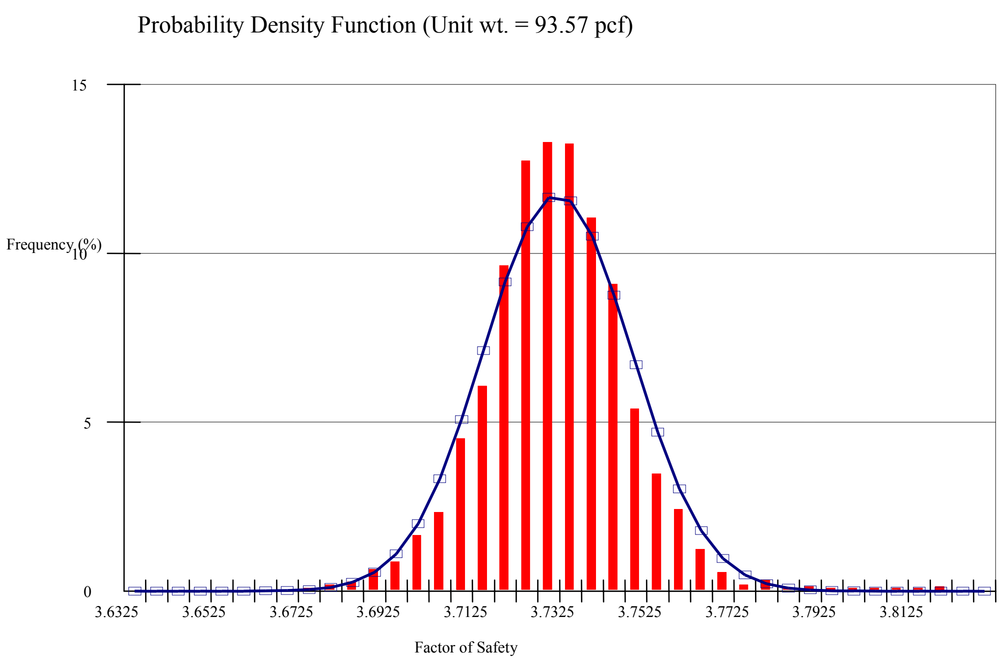


Figure 110: Probability density function ($\phi = 0$, c = 1253.12 psf) Saturated

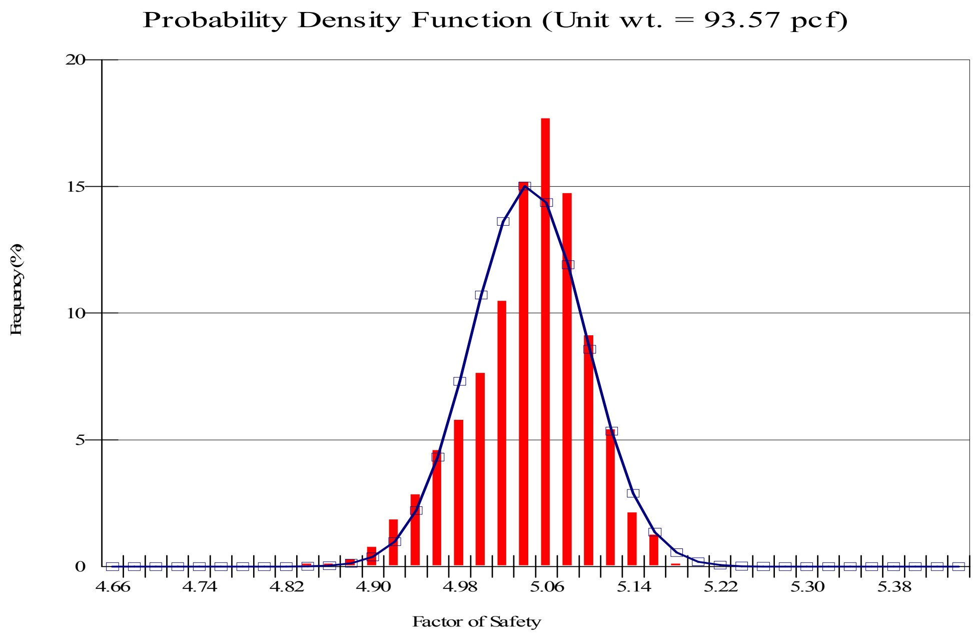


Figure 111: Probability density function ($\phi = 10$, $c = 1584.02$ psf) Unsaturated

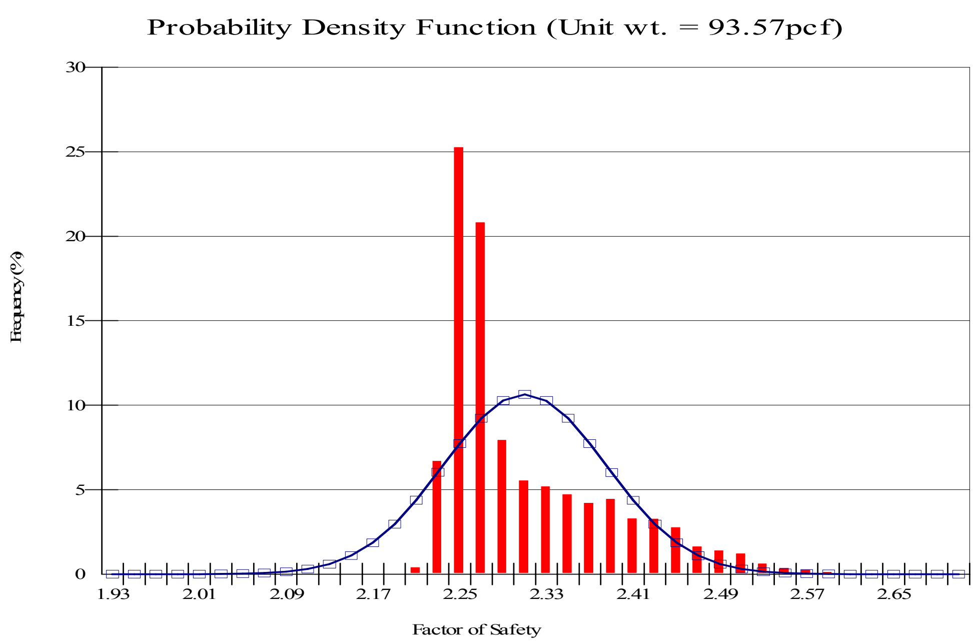


Figure 112: Probability density function ($\phi = 10$, $c = 748.0$ psf) Saturated

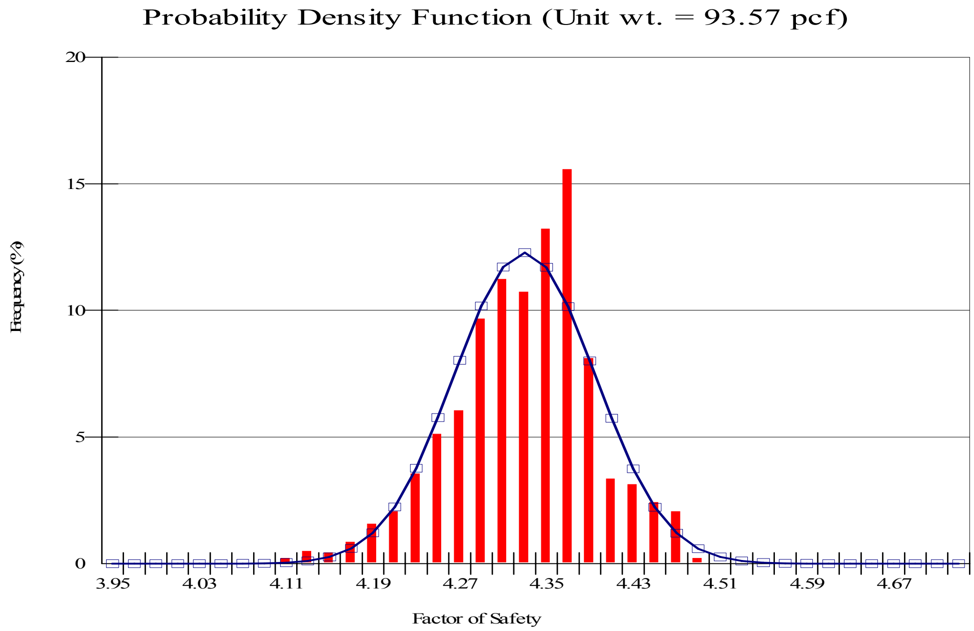


Figure 113: Probability density function (ϕ = 15, c = 1321.86 psf) Unsaturated

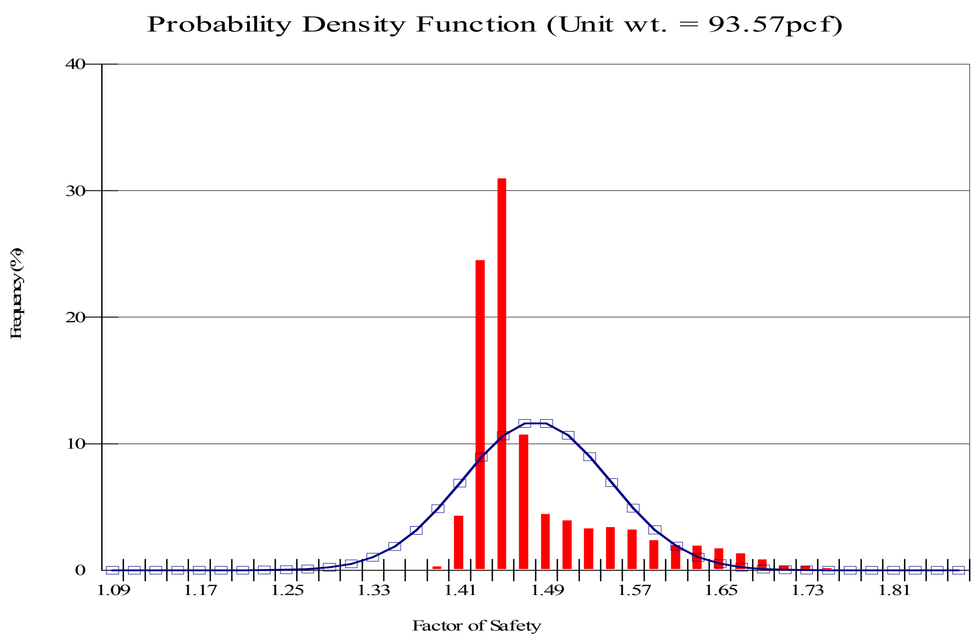


Figure 114: Probability density function (ϕ = 15, c = 486.44 psf) Saturated

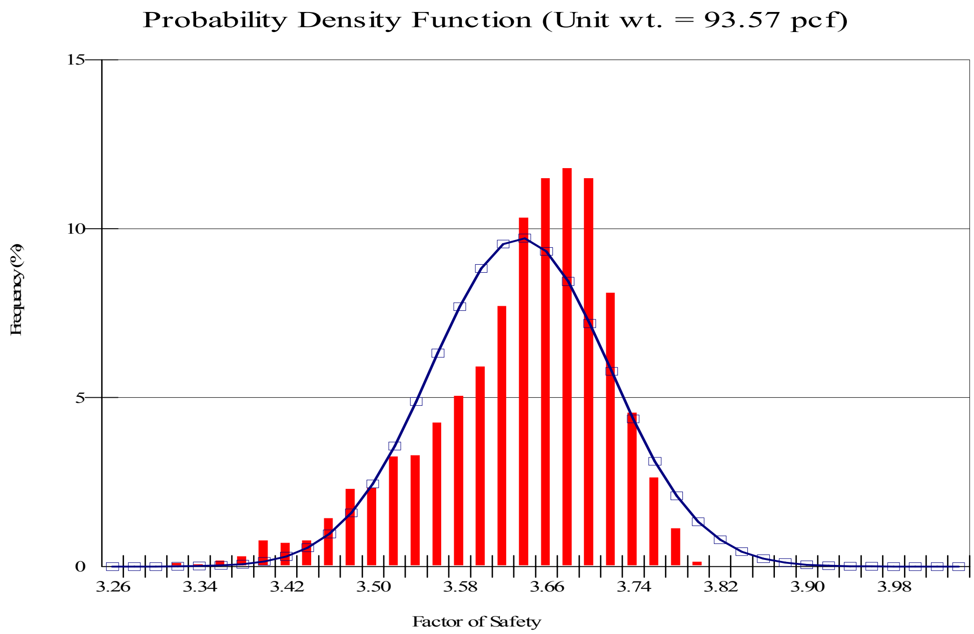


Figure 115: Probability density function ($\phi = 20$, $c = 1047.11$ psf) Unsaturated

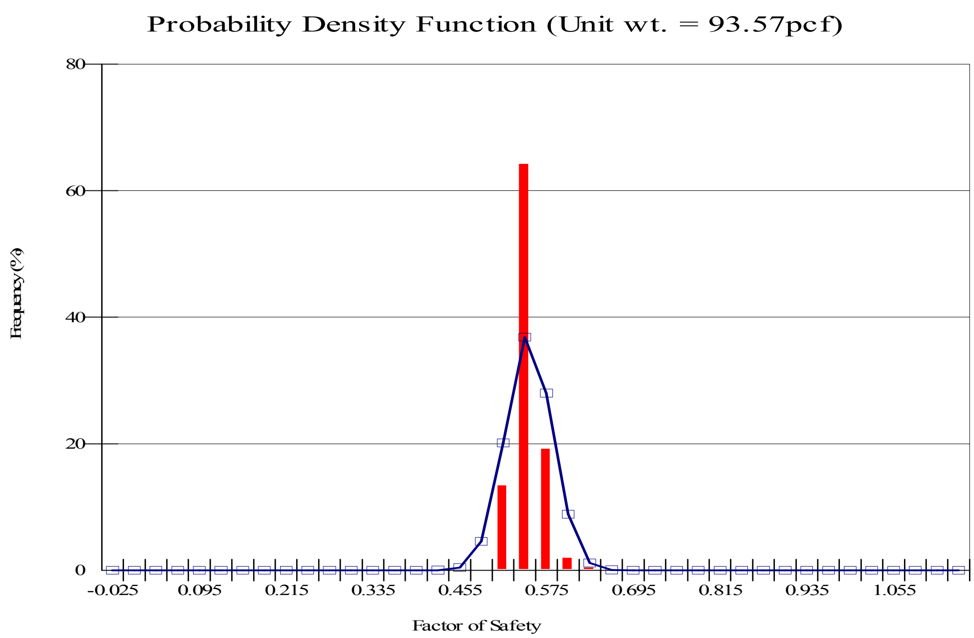


Figure 116: Probability density function ($\phi = 20$, $c = 211.69$ psf) Saturated

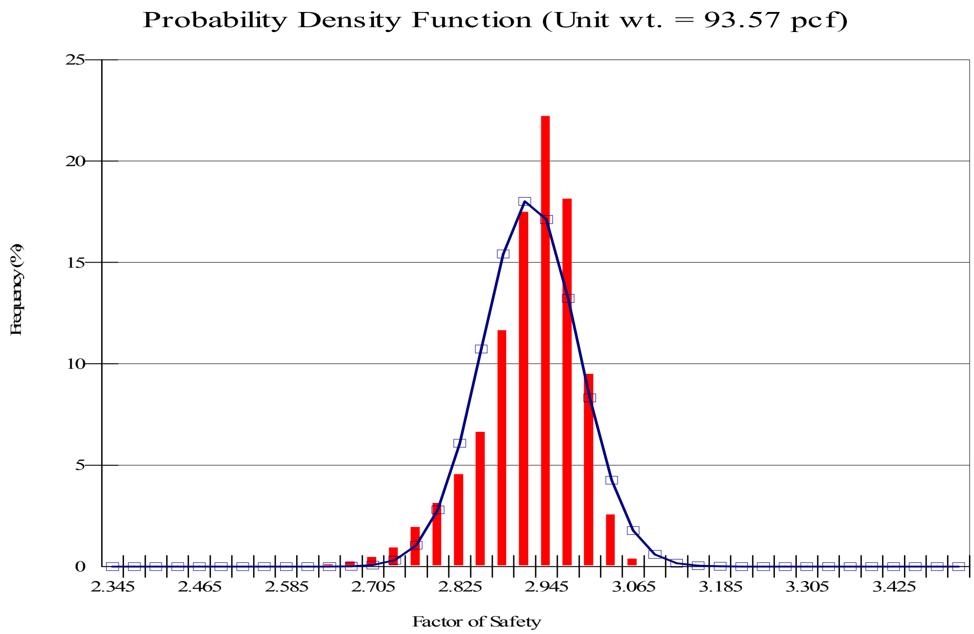


Figure 117: Probability density function (ϕ = 25, c = 754.29 psf) Unsaturated

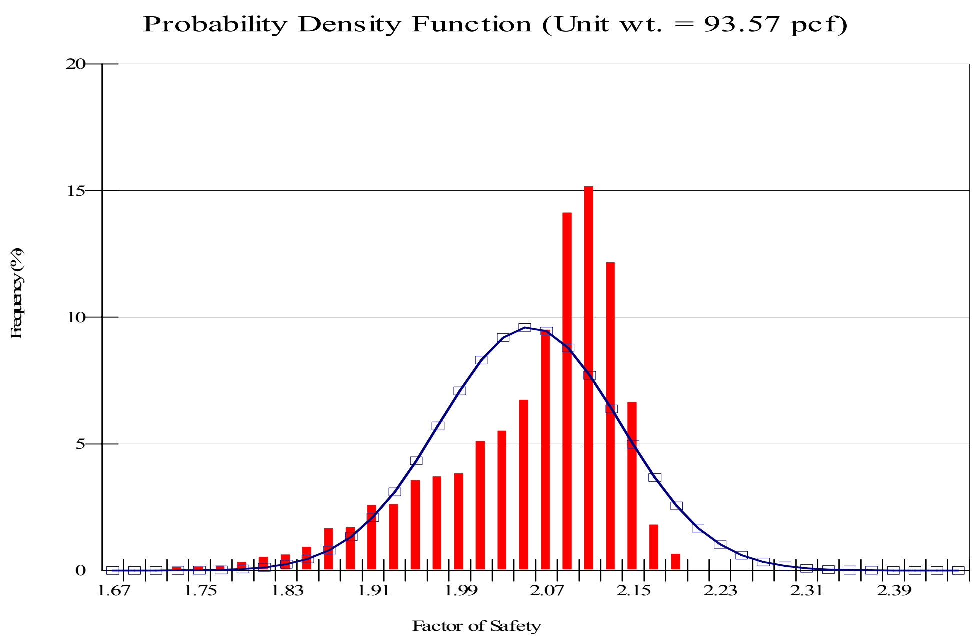


Figure 118: Probability density function (ϕ = 30, c = 436.57 psf) Unsaturated

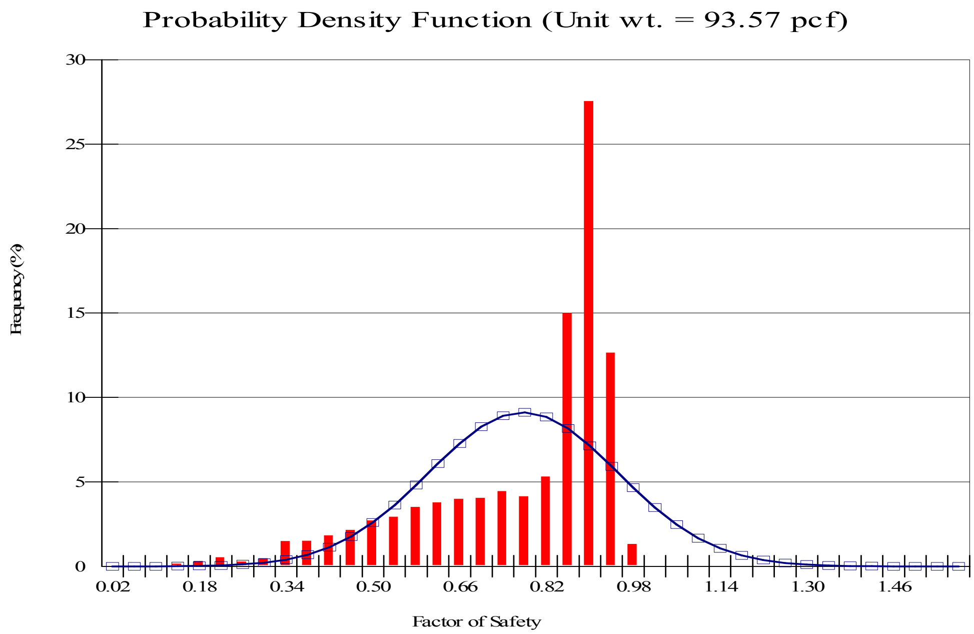


Figure 119: Probability density function ($\phi = 35$, $c = 85.04$ psf) Unsaturated

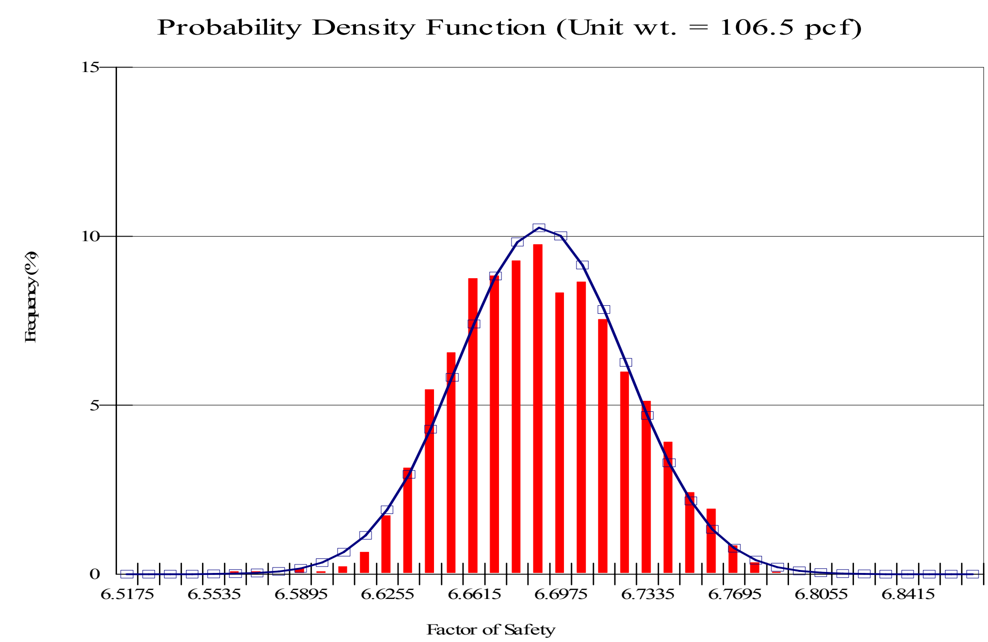


Figure 120: Probability density function ($\phi = 0$, $c = 2506.25$ psf) Unsaturated

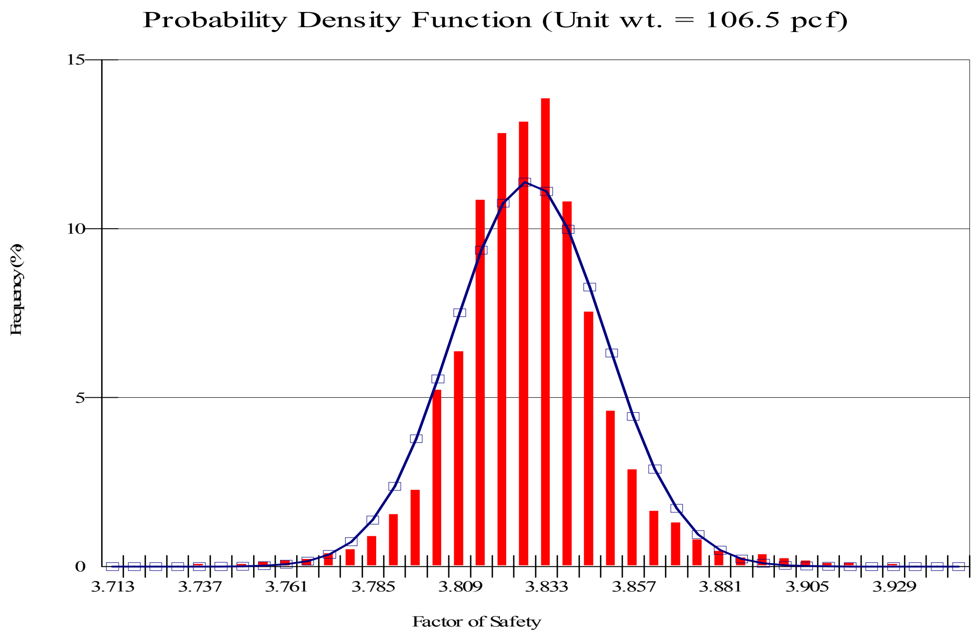


Figure 121: Probability density function ($\phi = 0$, c = 1453.12 psf) Saturated

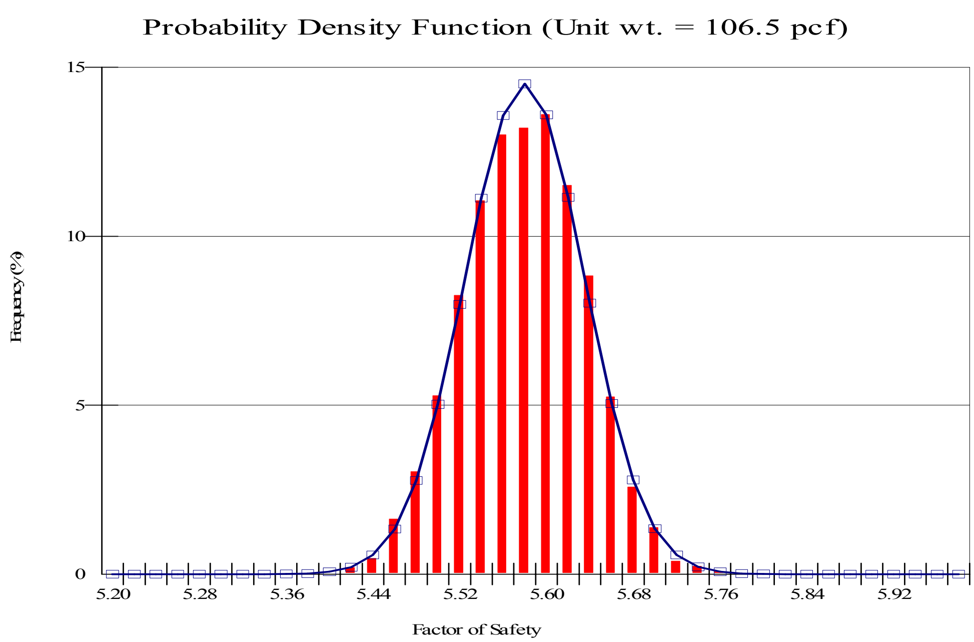


Figure 122: Probability density function ($\phi = 10$, c = 2001.73 psf) Unsaturated

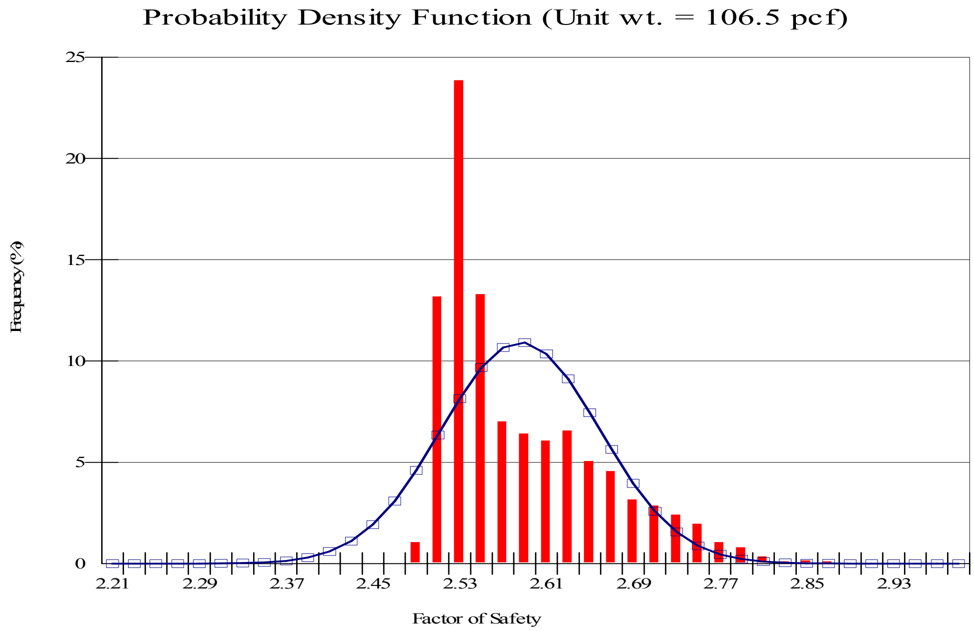


Figure 123: Probability density function (ϕ = 10, c = 948.6 psf) Saturated

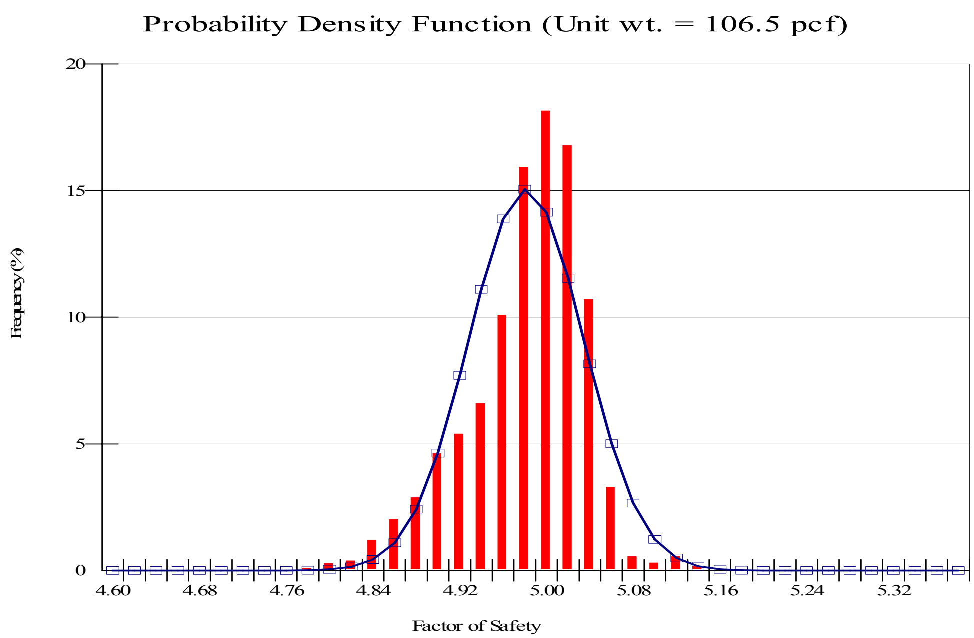


Figure 124: Probability density function (ϕ = 15, c = 1739.57 psf) Unsaturated

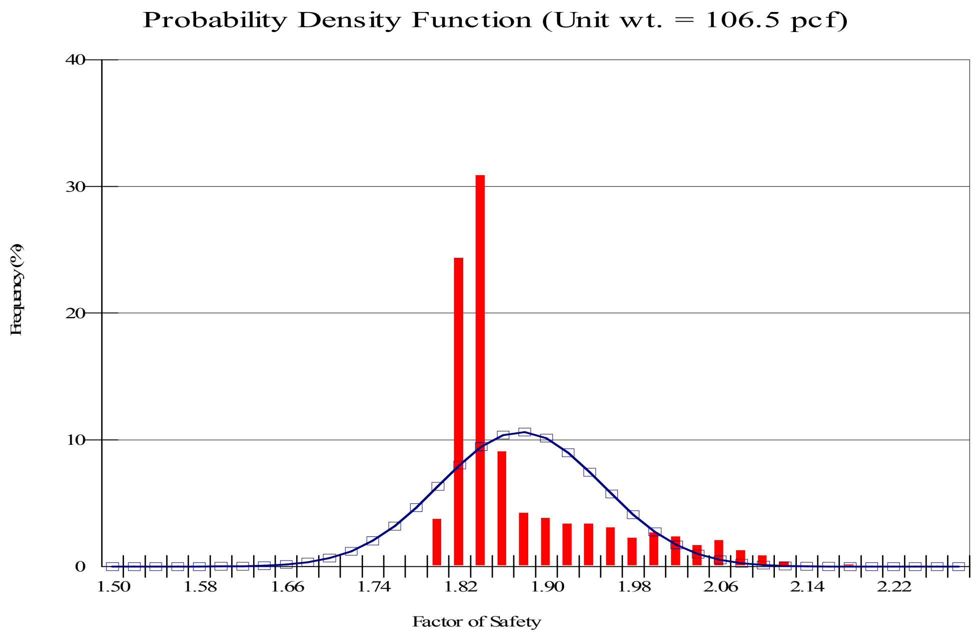


Figure 125: Probability density function ($\phi = 15$, c = 686.44 psf) Saturated

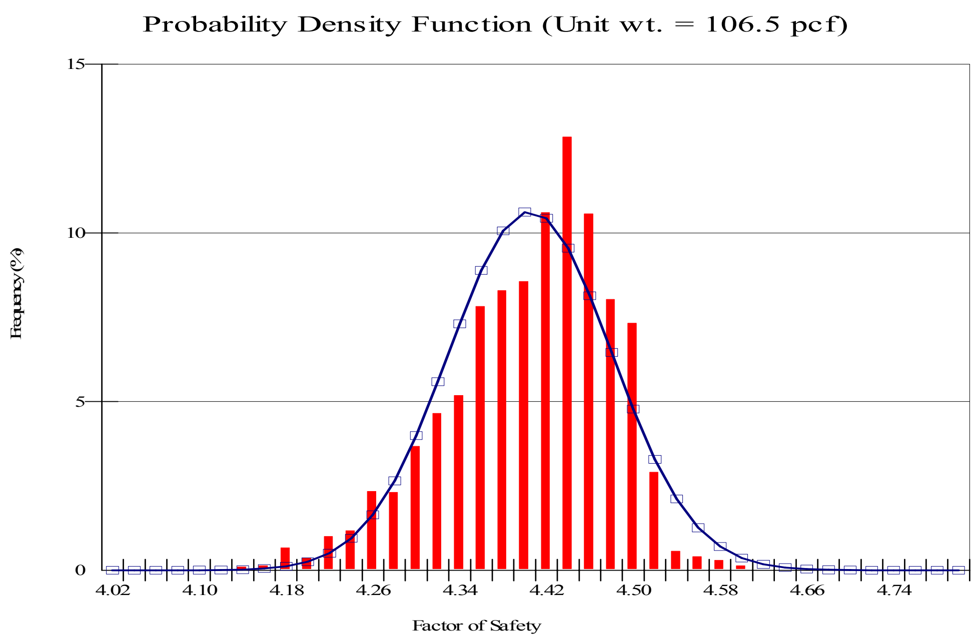


Figure 126: Probability density function ($\phi = 20$, c = 1464.82 psf) Unsaturated

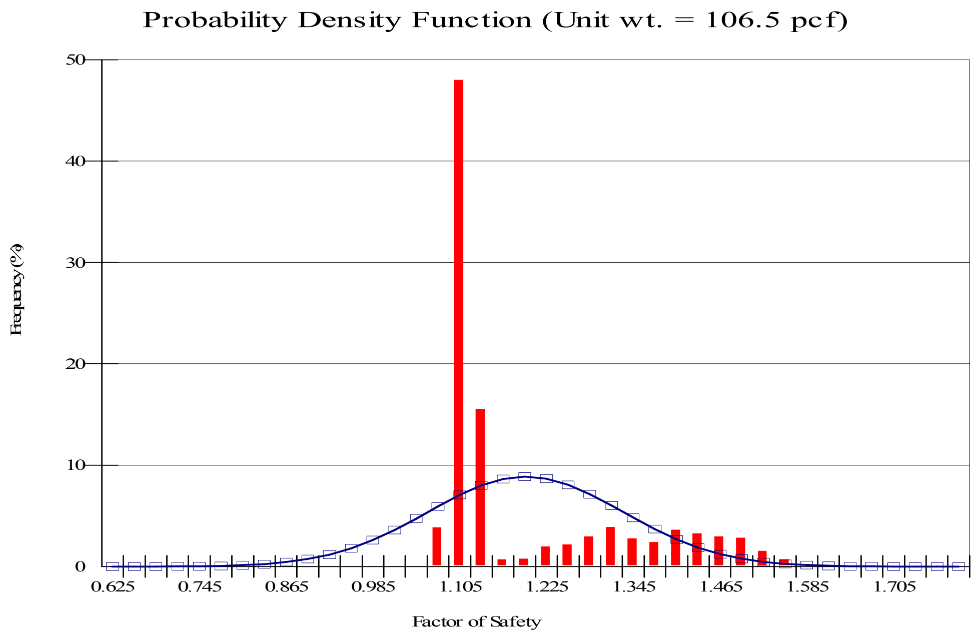


Figure 127: Probability density function ($\phi = 20$, $c = 211.69$ psf) Saturated

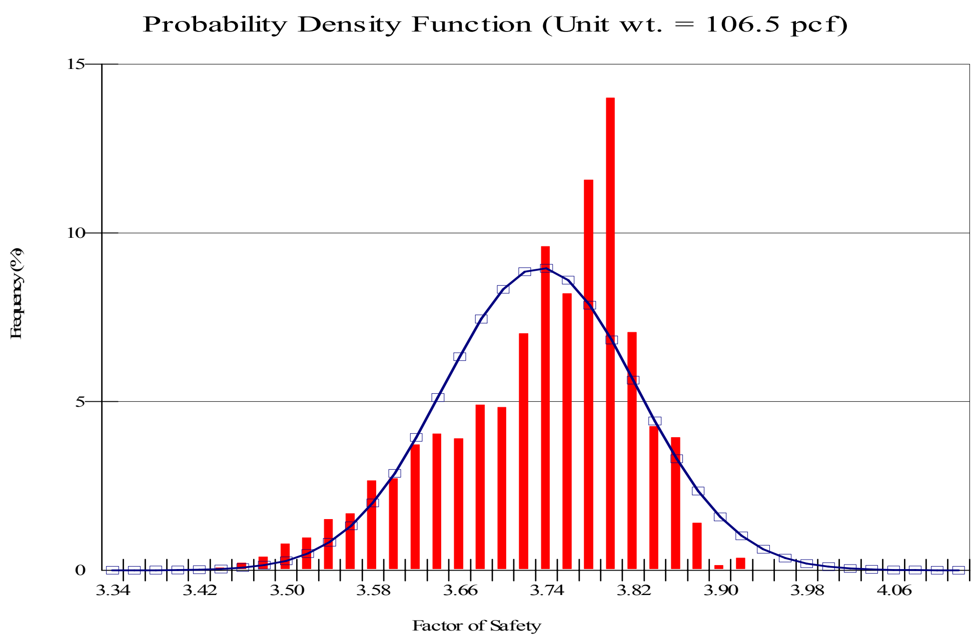


Figure 128: Probability density function ($\phi = 25$, $c = 1172.0$ psf) Unsaturated

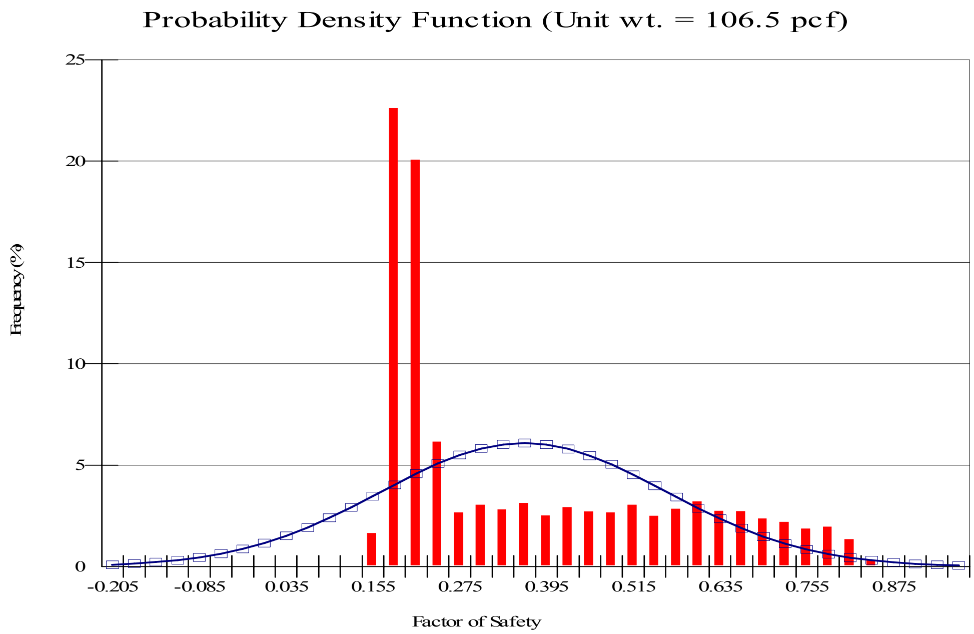


Figure 129: Probability density function ($\phi = 25$, c = 118.87 psf) Saturated

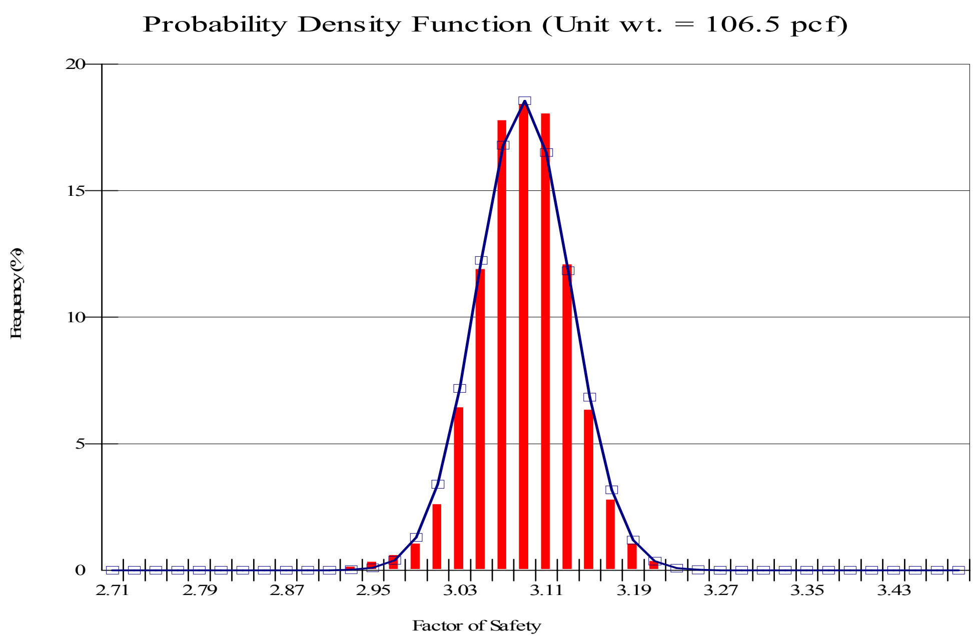


Figure 130: Probability density function ($\phi = 30$, c = 854.28 psf) Unsaturated

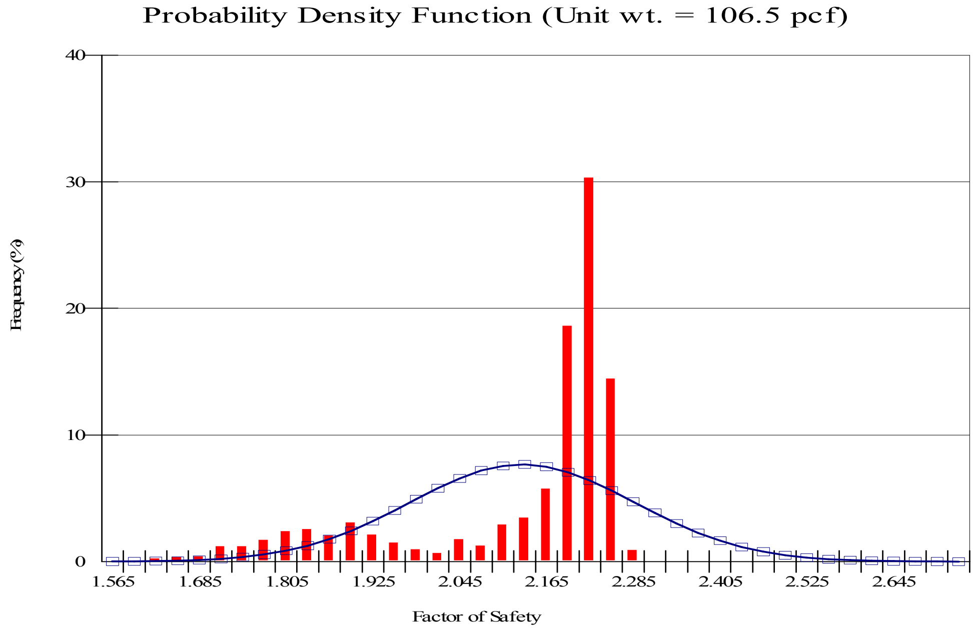


Figure 131: Probability density function ($\phi = 35$, $c = 502.75$ psf) Unsaturated

APPENDIX D: PROBABILITY DENSITY FUNCTIONS FOR SLOPE OF 3:1

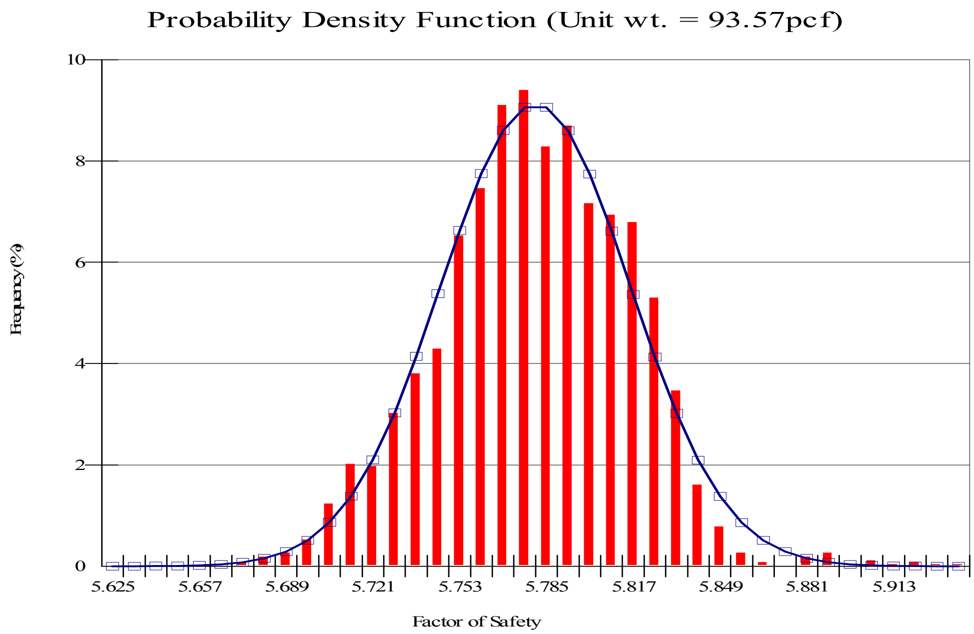


Figure 132: Probability density function ($\phi = 0$, c = 2088.54 psf) Unsaturated

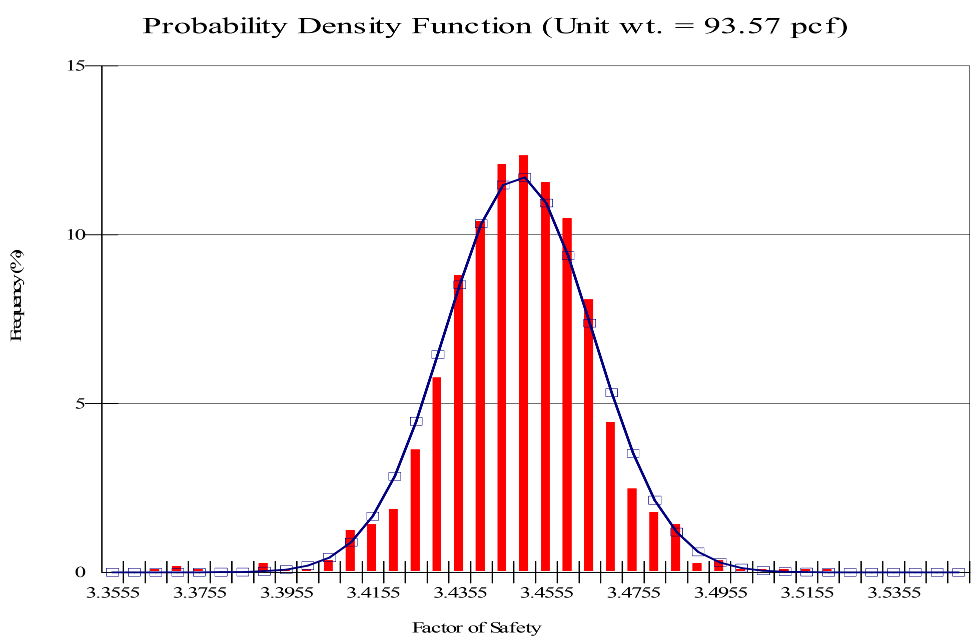


Figure 133: Probability density function ($\phi = 0$, c = 1253.12 psf) Saturated

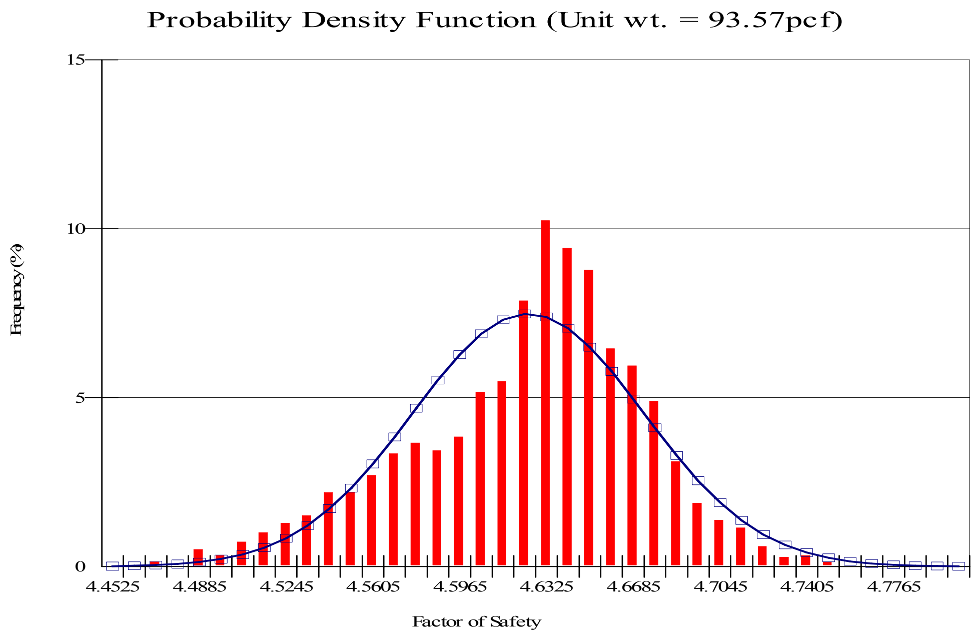


Figure 134: Probability density function ($\phi = 10$, c = 1584.02 psf) Unsaturated

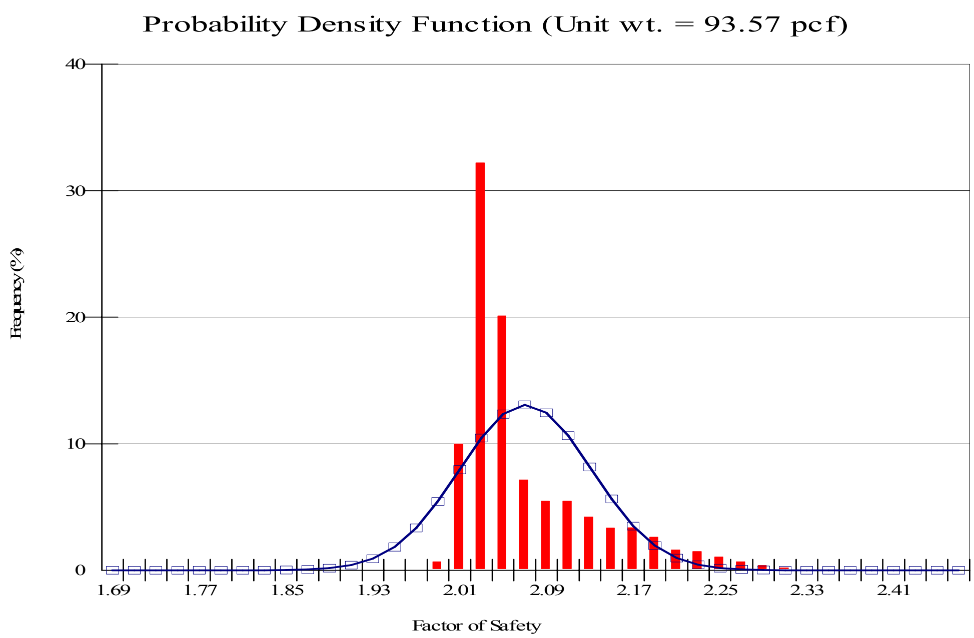


Figure 135: Probability density function ($\phi = 10$, c = 748 psf) Saturated

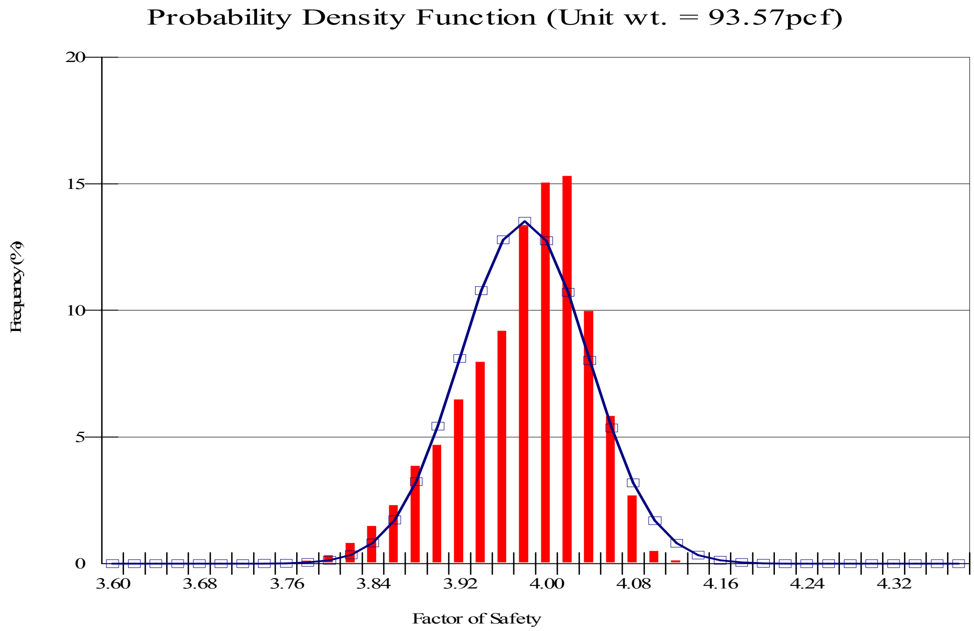


Figure 136: Probability density function ($\phi = 15$, $c = 1321.86$ psf) Unsaturated

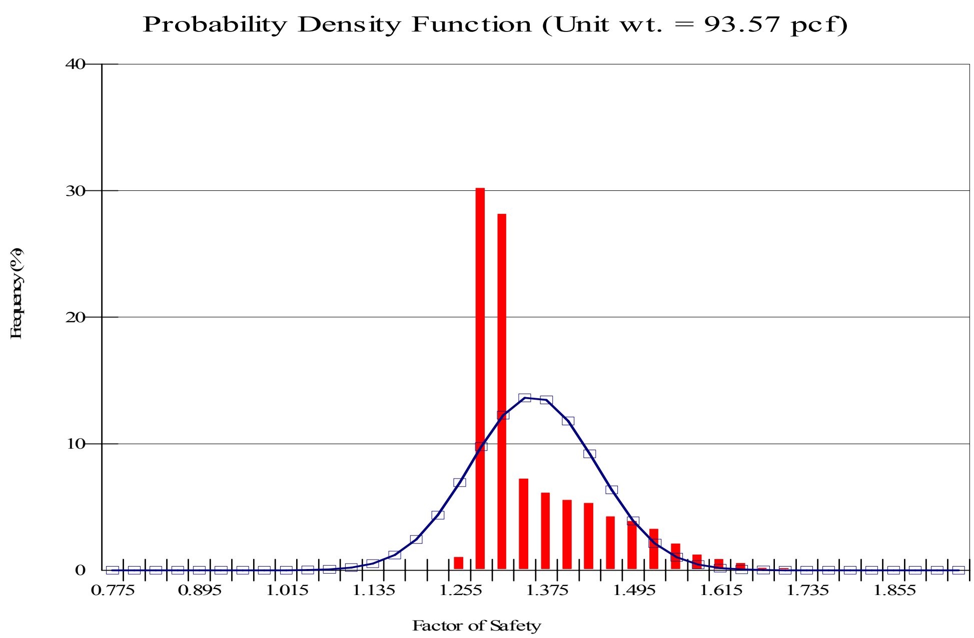


Figure 137: Probability density function ($\phi = 15$, $c = 486.44$ psf) Saturated

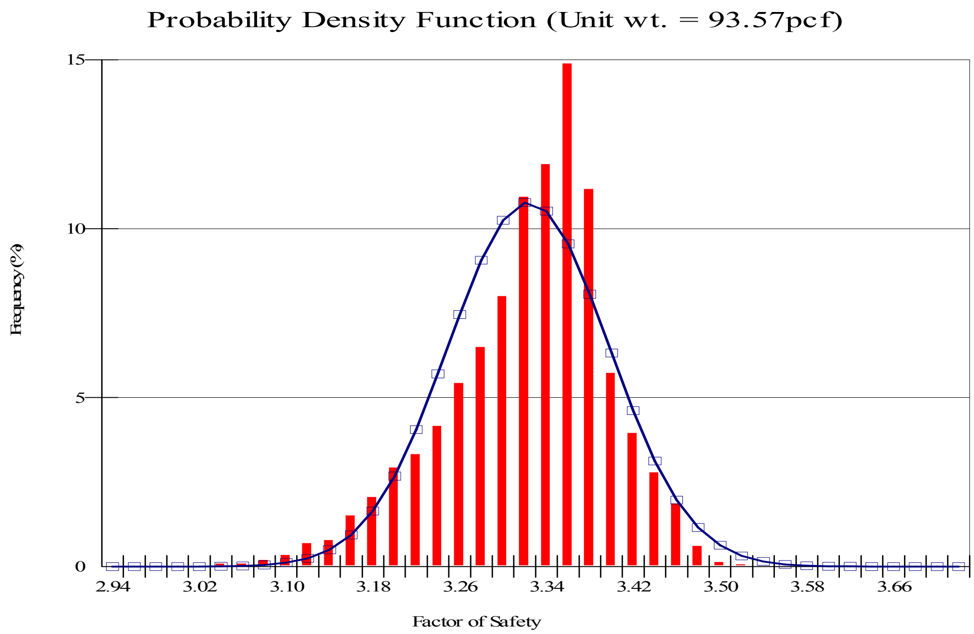


Figure 138: Probability density function ($\phi = 20$, $c = 1047.11$ psf) Unsaturated

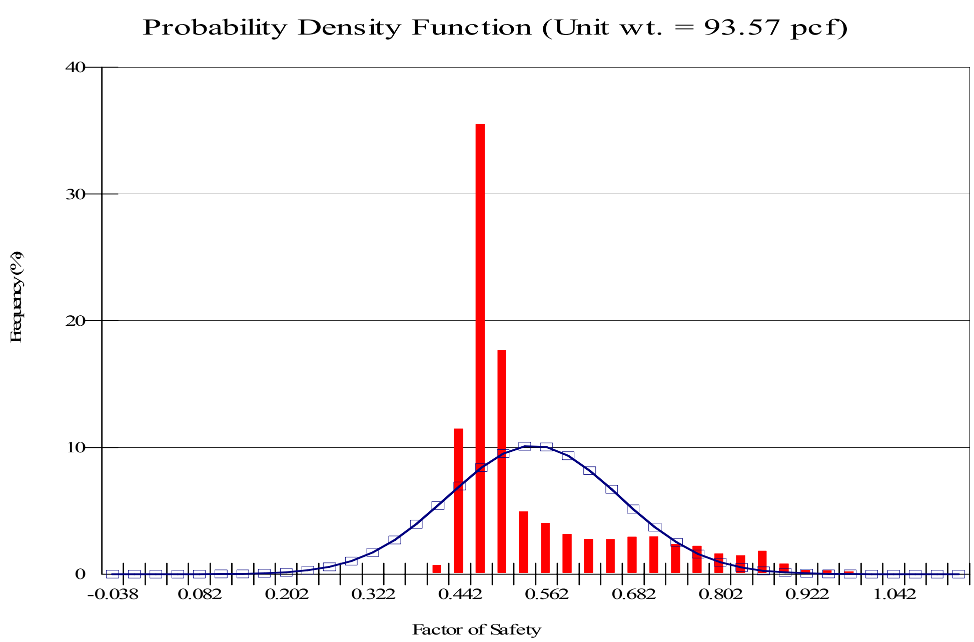


Figure 139: Probability density function ($\phi = 20$, $c = 211.69$ psf) Saturated

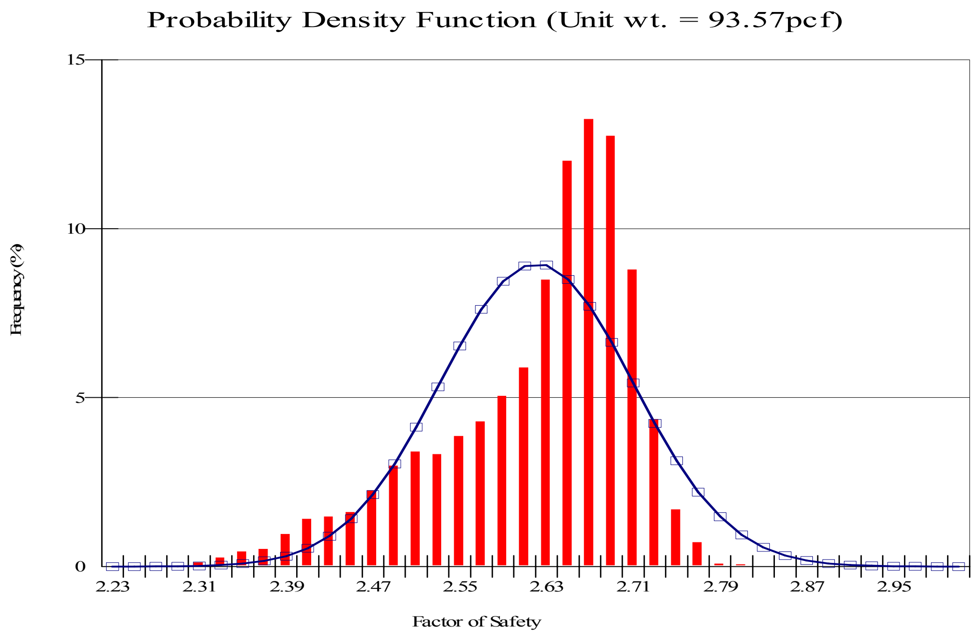


Figure 140: Probability density function ($\phi = 25$, c = 754.29 psf) Unsaturated

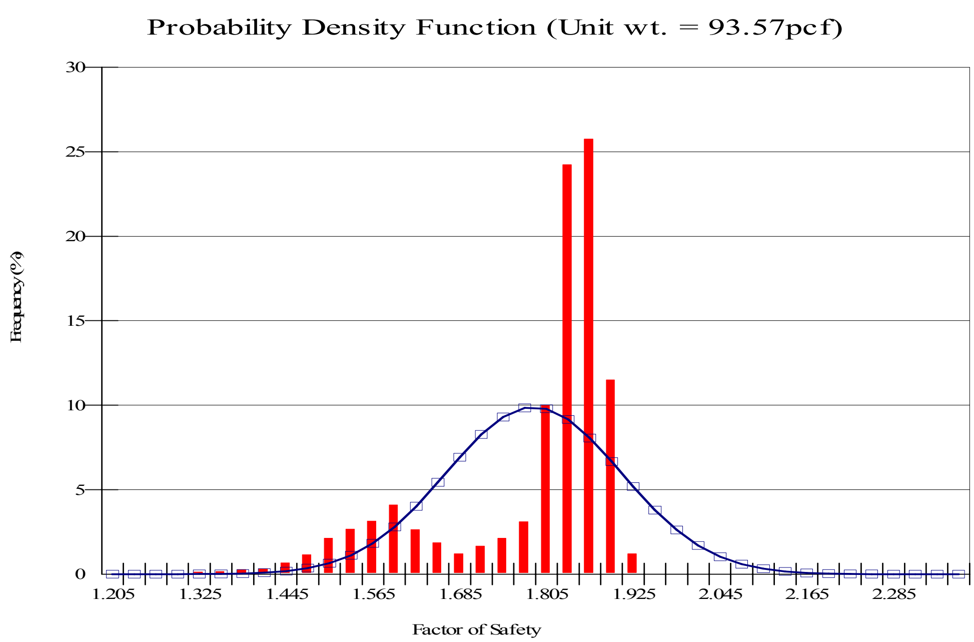


Figure 141: Probability density function ($\phi = 30$, c = 436.57 psf) Unsaturated

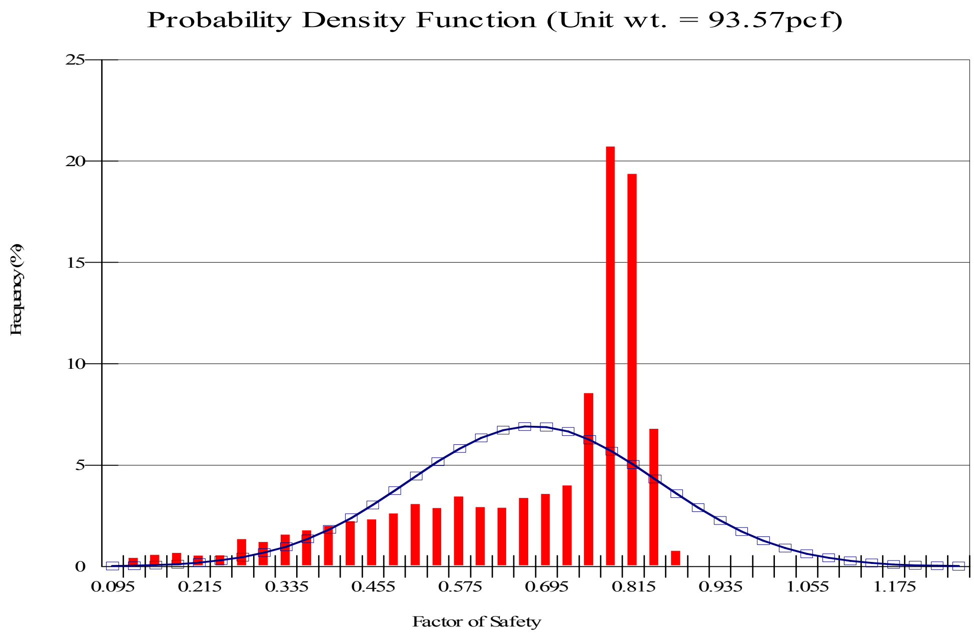


Figure 142: Probability density function ($\phi = 35$, $c = 85.04$ psf) Unsaturated

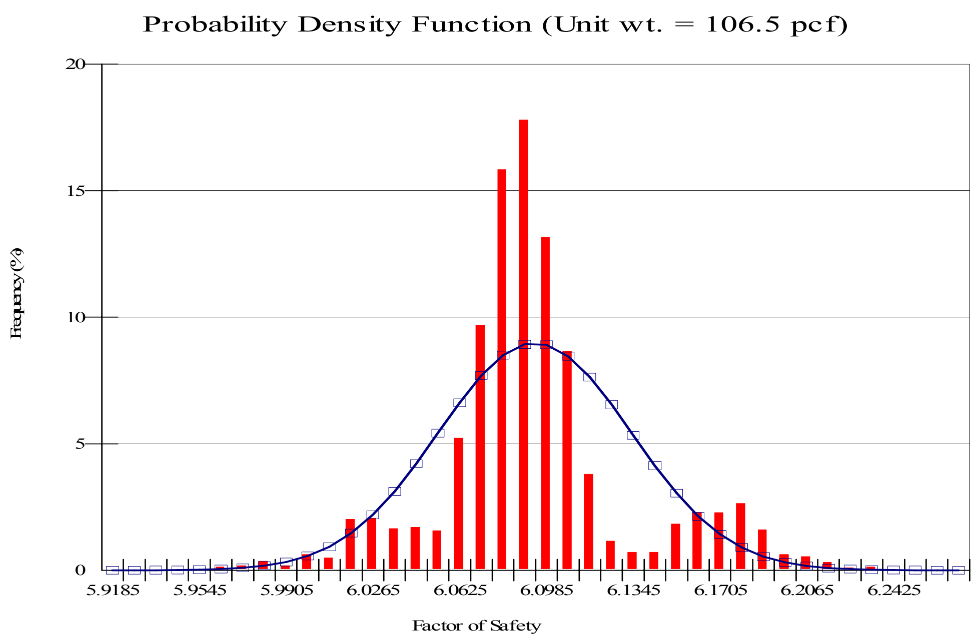


Figure 143: Probability density function ($\phi = 0$, $c = 2506.25$ psf) Unsaturated

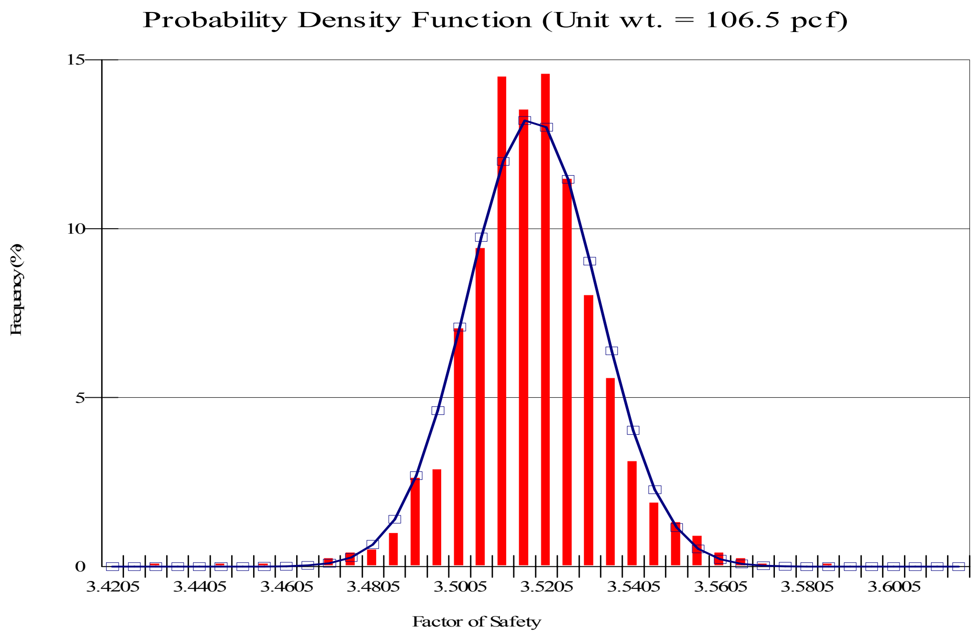


Figure 144: Probability density function ($\phi = 0$, $c = 1453.12$ psf) Saturated

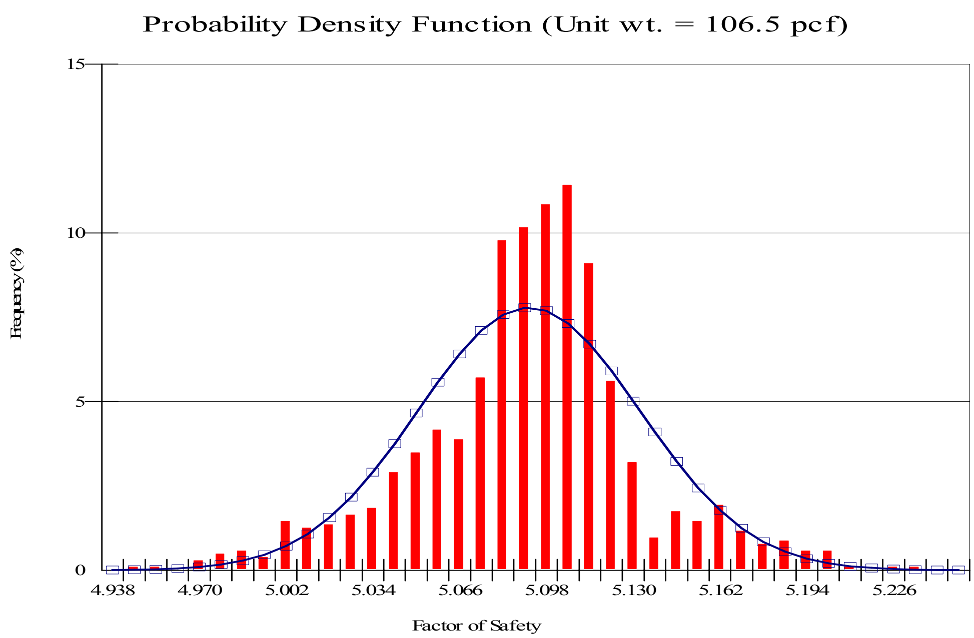


Figure 145: Probability density function ($\phi = 10$, $c = 2001.73$ psf) Unsaturated

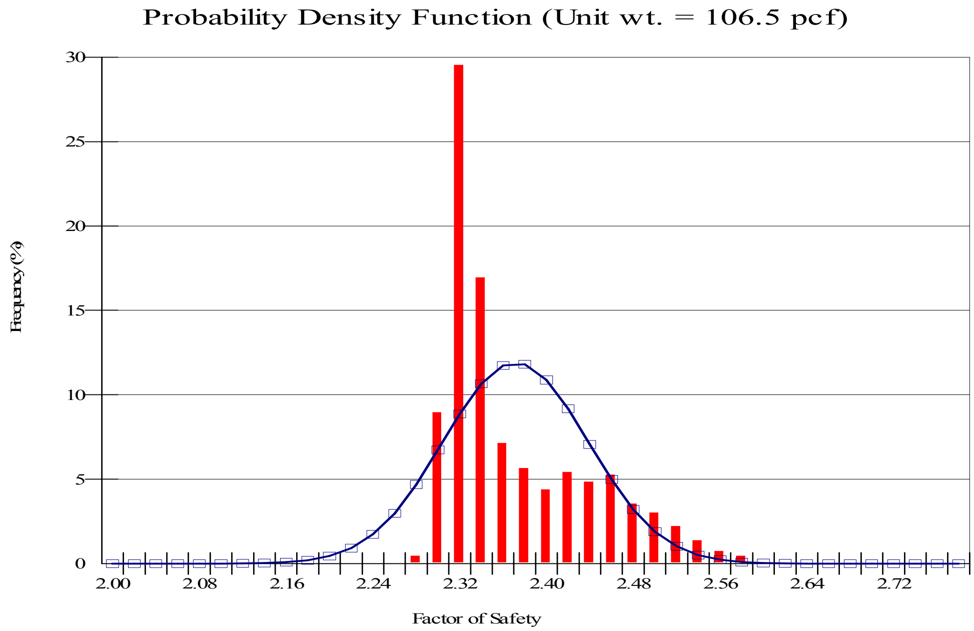


Figure 146: Probability density function ($\phi = 10$, $c = 948.6$ psf) Saturated

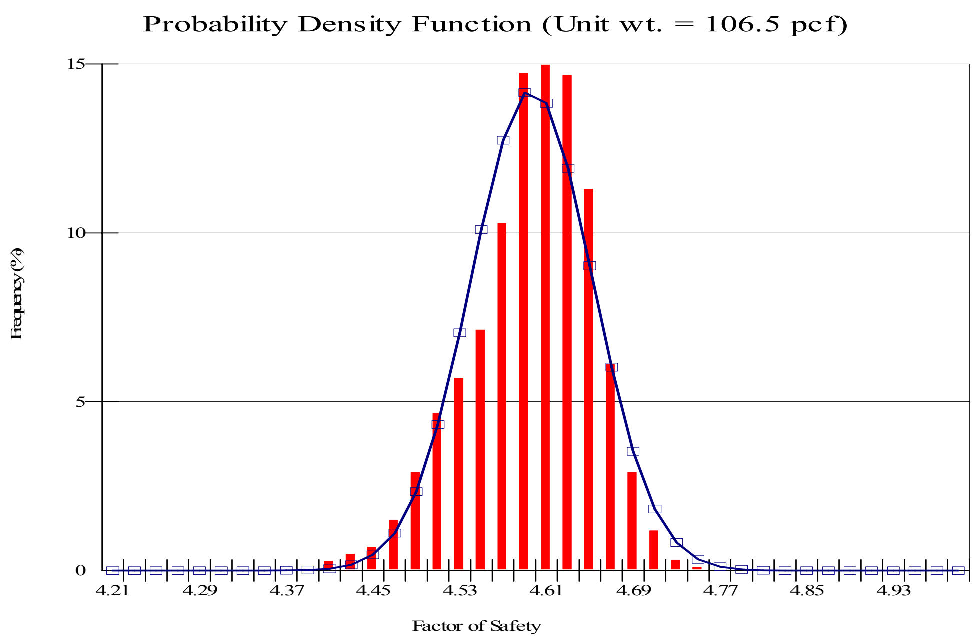


Figure 147: Probability density function ($\phi = 15$, $c = 1739.57$ psf) Unsaturated

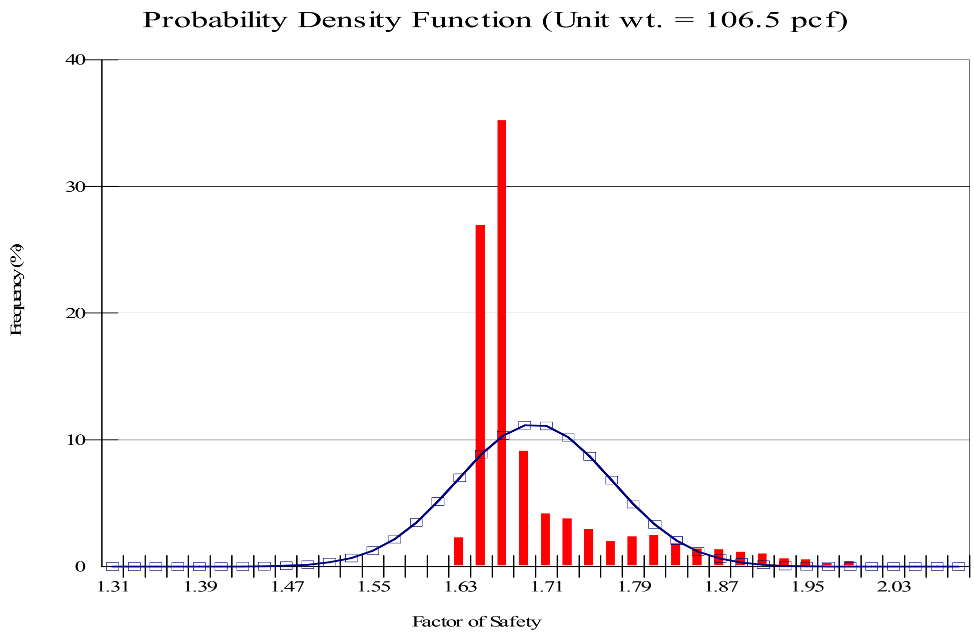


Figure 148: Probability density function ($\phi = 15$, $c = 686.44$ psf) Saturated

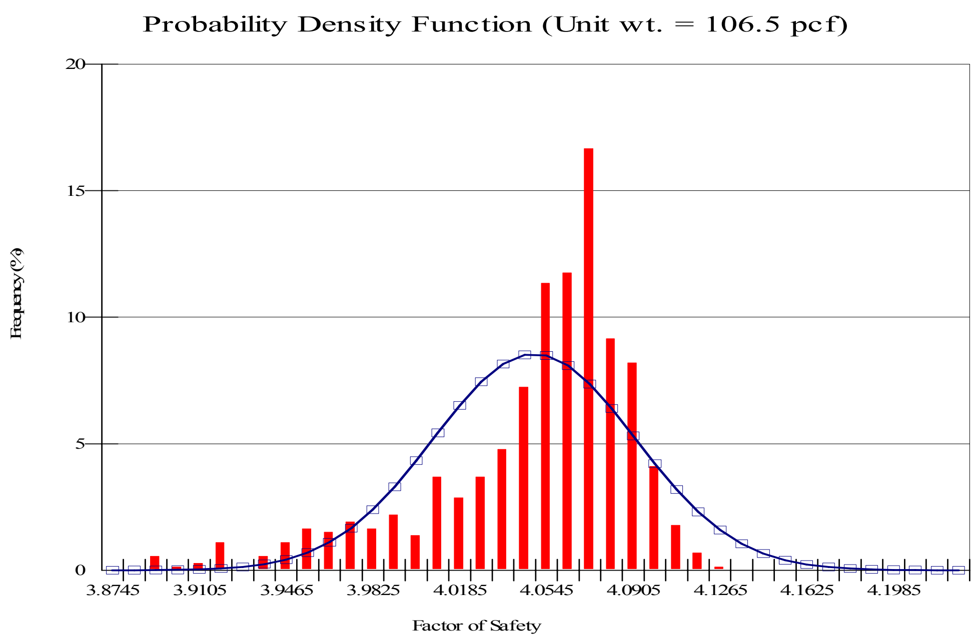


Figure 149: Probability density function ($\phi = 20$, $c = 1464.82$ psf) Unsaturated

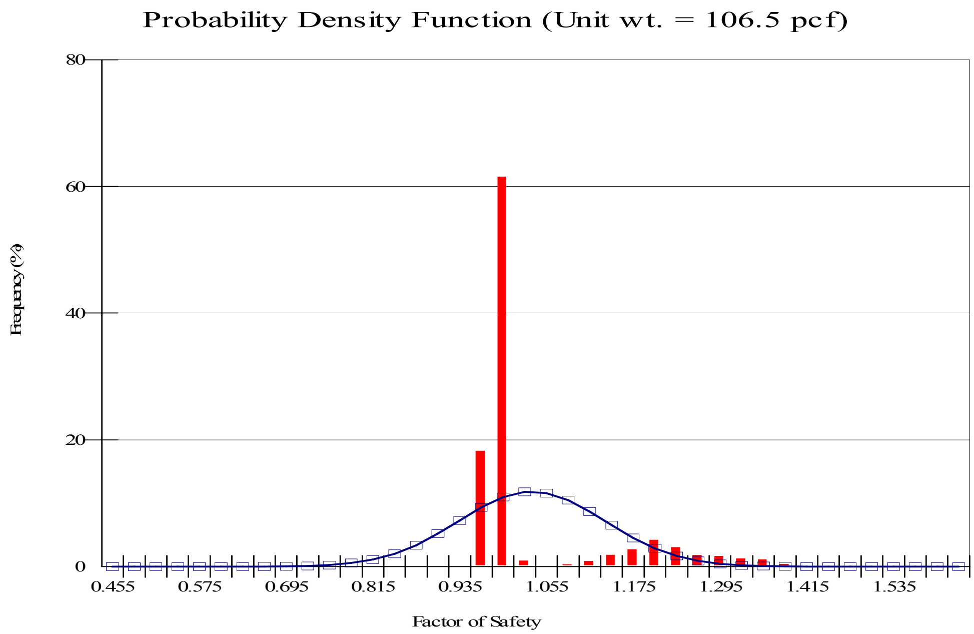


Figure 150: Probability density function ($\phi = 20$, $c = 411.69$ psf) Saturated

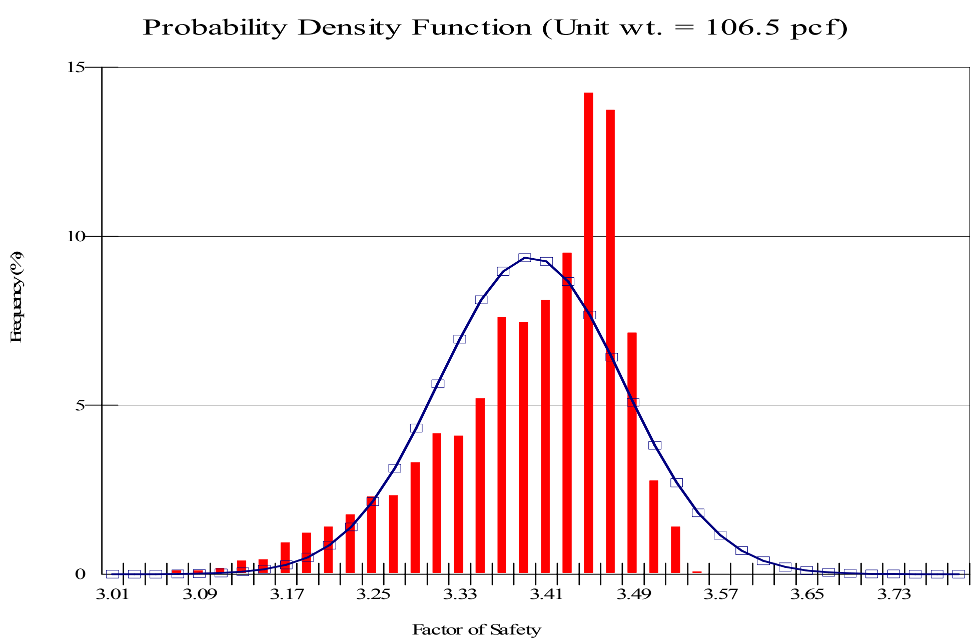


Figure 151: Probability density function ($\phi = 25$, $c = 1172.0$ psf) Unsaturated

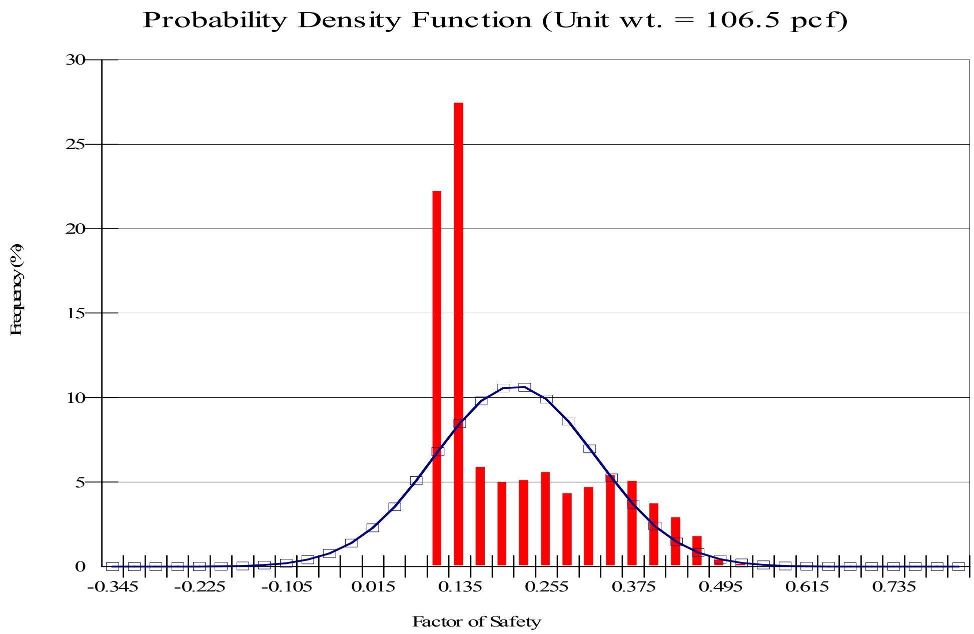


Figure 152: Probability density function (ϕ = 25, c = 118.87 psf) Saturated

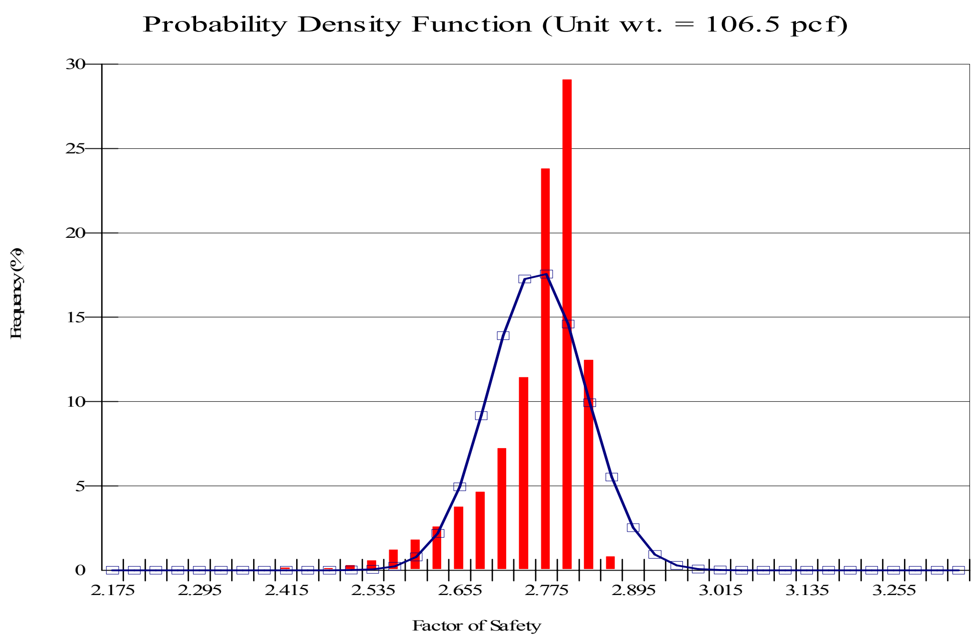


Figure 153: Probability density function (ϕ = 30, c = 854.28 psf) Unsaturated

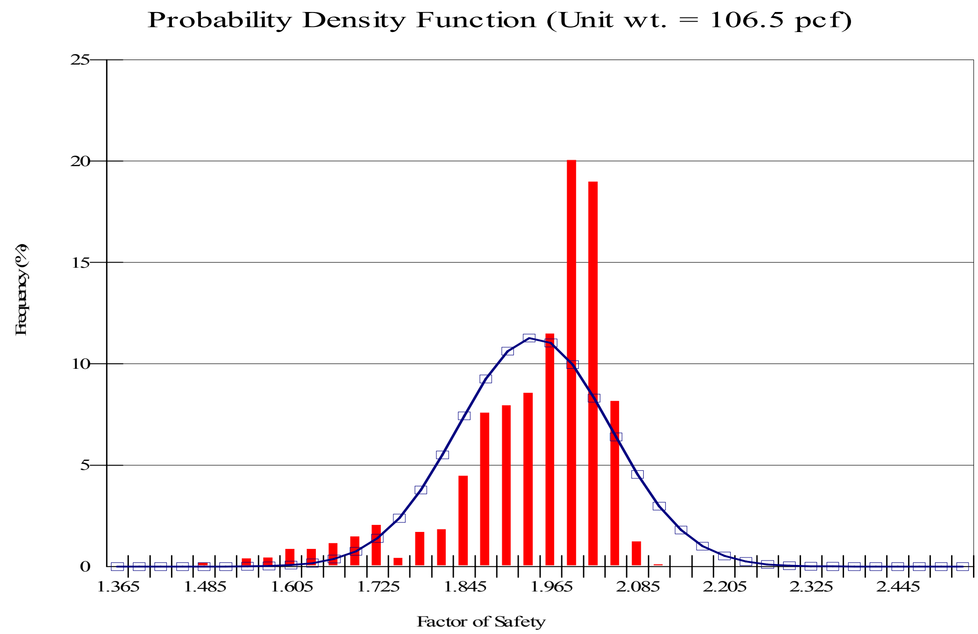


Figure 154: Probability density function ($\phi = 35$, $c = 502.75$ psf) Unsaturated

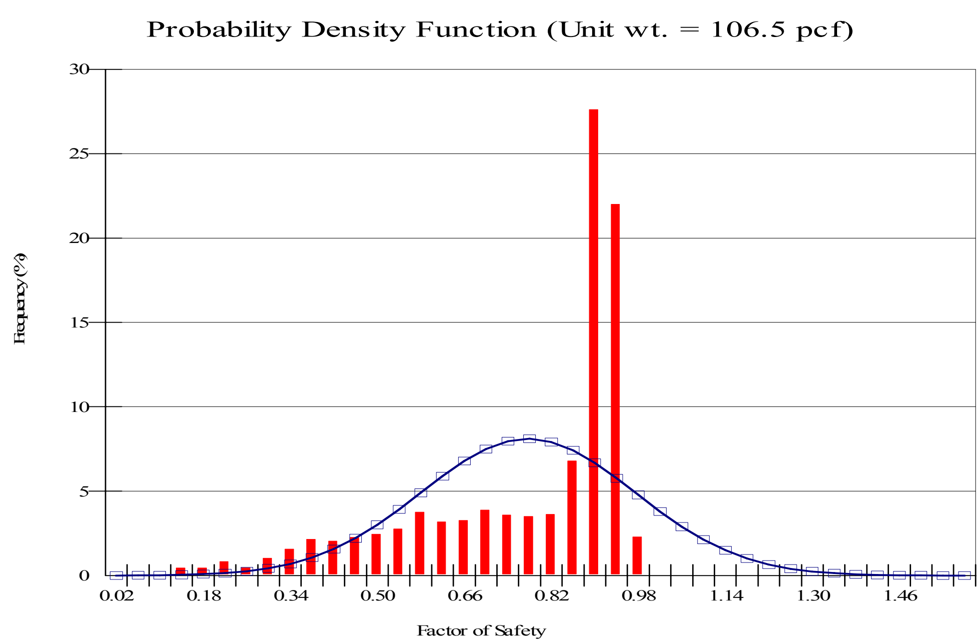


Figure 155: Probability density function ($\phi = 40$, $c = 105.33$ psf) Unsaturated

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