WAD AND FERROAN SOIL DEVELOPED IN THE DOLOMITIC AREA SOUTH OF PRETORIA

by

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Abstract

The geotechnical investigation of most sites located on dolomite invariably includes the assessment of the nature and properties of the residual weathering product of the dolomite, termed "wad". Ironically, much confusion previals concerning the geotechnical properties of this material leading to its potential behaviour often being grossly misinterpreted. This study attempts to improve the understanding of this complex material, its origin, structure and geotechnical properties.

Two principal types of weathering product of dolomite rock have been identified namely wad and ferroan soils. These respective groups of materials may be subdivided into laminated or massive wad and laminated or massive ferroan soil on the basis of the macrofabric they display. Secondary features, such as bedding planes and joints superimposed on the original parent rock may be retained as residual features.

The disturbance, displacement, slumping and reworking of the residual

massive and laminated wad and ferroan soils, with the possible addition of external impurities, give rise to a material which may be classed as a totally reworked wad or ferroan soil.

The geotechnical properties of the different wad and ferroan soils have been ascertained through laboratory and field testing. Relationships between the nature, form and spatial arrangement of macrofabric features and laboratory measurements have been examined. The influence of secondary features or discontinuities imposed on these soils, are considered.

Wad and ferroan soils are noted to possess both poor and very positive behavioural characteristics. The assessment of these materials, requires that particular attention is paid to fabric description and degree of reworking. Several additions to the MCCSSO system of soil profile description are proposed to embrace discriptors essential for the engineering geological appreciation of a site underlain by wad and/or ferroan soil.

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Samevatting

Die geotegniese ondersoeke van meeste terreine wat op dolomiet geleë is, sluit meesal die bepaling van die eienskappe van die residuele verweringsproduk van dolomiet, naamlik "wad" in. Ten spyte hiervan bestaan daar heelwat verwarring met betrekking tot die geotegniese eienskappe van hierdie materiaal, wat dikwels lei tot wanvertolking van die potensiële gedrag daarvan. Hierdie studie beoog om die kennis van dié komplekse materiaal se oorsprong, struktuur en geotegniese eienskappe te verbeter.

Twee hooftipes verweringsprodukte van dolomietrots word geïdentifiseer, naamlik wad en ysterryke grond. Hierdie groepe mag op grond van makro maakseleienskappe verder verdeel word in respektiewelik gelamineerde of massiewe wad en gelamineerde of massiewe ysterryke grond. Sekondêre kenmerke soos laagvlakke en nate in die oorspronklike rots het in die wad as residuele eienskappe behoue gebly.

Die versteuring, verplasing, versakking en herwerking van die residuele massiewe en die gelamineerde wad en ysterryke gronde, met die moontlike toevoeging van eksterne onsuiwerhede, gee aanleiding tot ŉ materiaal wat as totale herwerkte wad of ysterryke grond geklassifiseer word.

Die geotegniese eienskappe van die verskillende wad en ysterryke gronde is deur laboratorium en veldtoetse bevestig. Die verhoudings tussen die aard, vorm en verspreiding van die makro maakseleienskappe en laboratoriumtoetse is ondersoek. Die invloed van sekondêre kenmerke of diskontinuiteite is oorweeg.

Wad en ysterryke grond het geblyk swak asook sterk positiewe gedragseienskappe te vertoon. Die evaluasie van die wad en ysterryke gronde vereis dat aandag aan die maakselbeskrywing en die graad van herwerking gegee moet word. Verskeie byvoegings tot beskrywende terme van die VKKSGO-sisteem van grondprofielbeskrywing wat vir die ingenieursgeologiese terreinevaluasie benodig word, word voorgestel.

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Chapter 1 - Introduction

1.1 Purpose of the study

The geotechnical investigation of most sites located on dolomite invariably includes the assessment of the nature and properties of wad and/or ferroan soils generally collectively referred to as wad which are weathering products of dolomite. Ironically, despite years of related geotechnical work, much confusion prevails concerning these materials. Misconceptions have, on occasion, lead to the potential behaviour of the wad being grossly misinterpreted.

The identification of the wad type on the basis of fabric is essential to the assessment of the potential behaviour of the residual, weathered dolomite profile on a site. Knowledge of the potential behavioural characteristics of the wad will provide the engineering geologist or geotechnical engineer with an initial perspective of the stability of the site. Wad, located in the critical parts of a soil profile, near the rock interface and as filling material in grikes, may play a major role in sinkhole and doline formation.

During the execution of a stability investigation attention is focussed on the overall geology and the groundwater position in the subsurface profile. When examining the geology, particular attention is paid to the position of wad in the profile. Wad has always been viewed with a negative bias and the tendency has been to assume that the material possesses only poor behavioural characteristics. Investigations have tended to concentrate on the following aspects : the presence and thickness of wad and the nature of the materials overlying and underlying the wad. This tendency is clearly mirrored in the classification systems developed to assist in the process of zoning a dolomitic terrain. These classification systems by Weaver (1979), Venter (1981) and Van Rooy

(1984) have been based on the thickness and geological context in which the wad occurs. The nature and properties of the wad are usually ignored. As a consequence of overconservative reaction and assessment, much valuable ground may have been designated as unsuitable for development.

The intention of this study is to identify the types of wad that may be distinguished on the basis of fabric. The geotechnical properties of the different wad types have been ascertained through extensive laboratory and field testing. Relationships between the nature, forms and spatial arrangement of macrofabric features and laboratory measurements have been built up. The influence of secondary features or discontinuities imposed on these soils has been considered.

1.2 Study area

The area selected for the purposes of this study encompasses the outcrop of dolomite of the Chuniespoort Group, Transvaal Sequence, occurring on the 1:50 000, Geological Sheet, 2528 CC Lyttelton (Figure 1.2.1).

The boundaries of this study area enclose some 330 square kilometres underlain by dolomite. The area has been intensely developed with the entire municipal areas of Verwoerdburg, Clayville, Olifantsfontein, Erasmia, Laudium, some suburbs of Pretoria and almost the entire military complex being underlain by dolomite.

The area included on the Lyttelton Sheet must represent one of the most intensely geotechnically investigated dolomitic areas in South Africa. Numerous stability investigations have been conducted in the military area, and intensive geotechnical investigations have been conducted for all proposed new townships and subdivisions proclaimed since 1973. These investigations have been conducted in compliance with Provincial Ordinance 25 of 1965 pertaining to township planning and Ordinance 19 of 1973 relating to the subdivision of property.

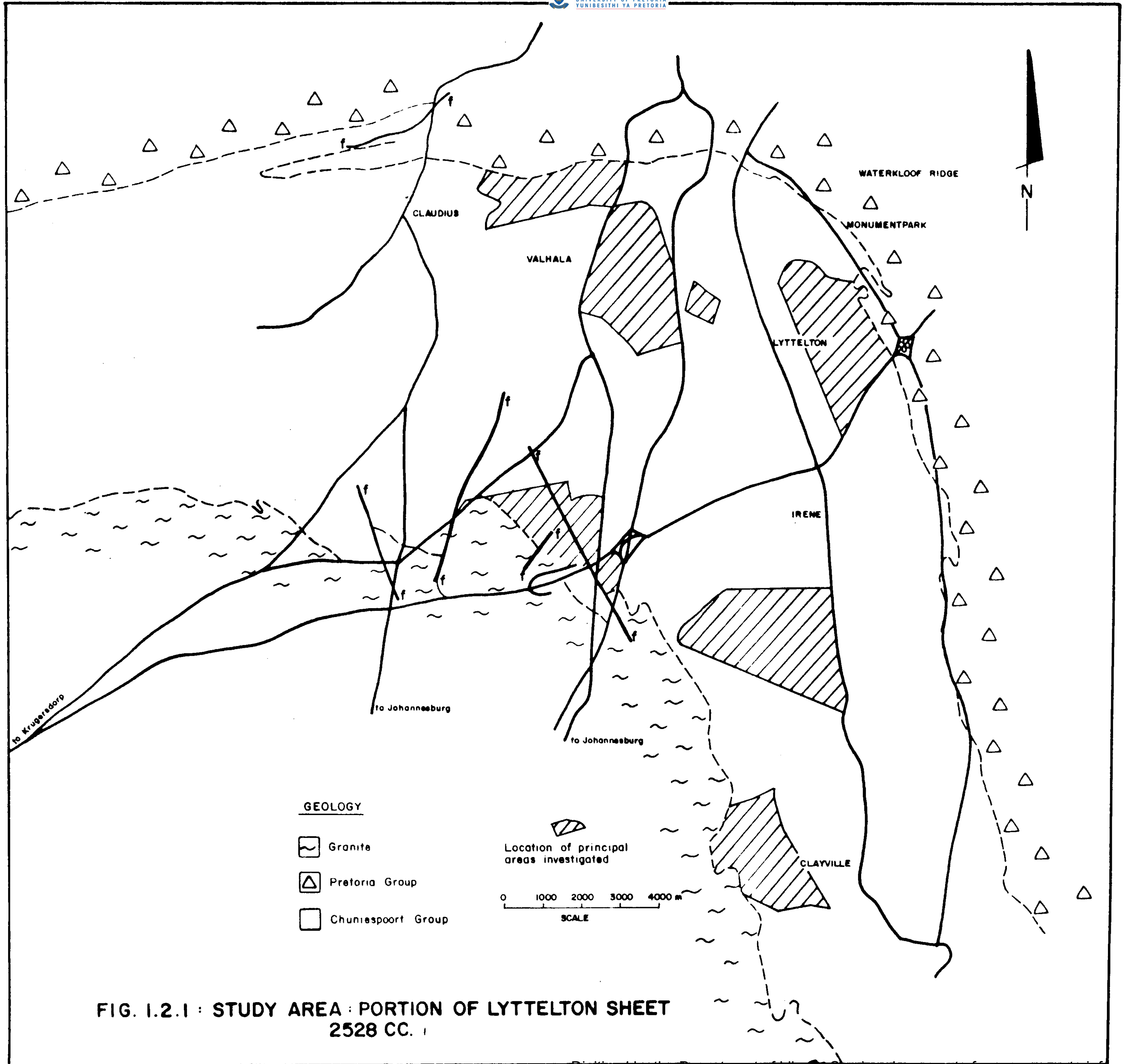


FIG. 1.2.1 : STUDY AREA : PORTION OF LYTTELTON SHEET 2528 CC.

The Geological Survey has over the years received much of the information and geotechnical reports pertaining to these townships for comment and record purposes. This organisation thus possesses a wealth of geotechnical information concerning the area which could be utilised for this study.

The area thus lends itself to the complex task of researching the weathering products of dolomite which include wad and ferroan soils.

The research of this material is an ongoing process and once an understanding of the material has been achieved in this area, the findings of the study may be extrapolated to other dolomite areas. An attempt is made to establish whether the classification, origin, structure and geotechnical properties of the wad and ferroan soils may be applied nationally or merely to this particular area.

1.3 Scope and Method of Study

Approximately 340 geotechnical reports pertaining to township development and subdivisions, and 180 reports related to stability investigations in the military area south of Pretoria have been studied to obtain (all) relevant information pertaining to wad.

The following information was extricated from the reports :

i) General descriptions, applied by various workers to the material designated as wad.

ii) Pneumatic percussion borehole, small diameter augerhole, large diameter augerhole, and test pit profiles which had been compiled for various geotechnical investigations, were studied to locate those sites underlain by substantial thicknesses of wad. Those profiles indicating substantial thicknesses of wad, to which access could be gained by large diameter augering or trenching, were considered for further study. Suitable sites were studied in detail and in some instances small diameter augerholes were drilled to retrieve representative, disturbed samples for examination and confirmation. This initial study was followed up by either a large diameter augering programme using a double LDH machine, Hotline rig or the excavation of test pits utilizing an excavator of the capacity of a Liebherr 941.

Accurate soil profiles were compiled according to the MCCSSO system (Jennings et al. 1973). Particular attention was paid to the examination of structure (fabric). Only samples in which the original fabric of the parent rock is still discernable have been used in this study. Descriptions and test results thus pertain mainly to partially reworked material. Partially reworked material refers to a soil in which the fabric inherited from the parent rock is clearly discernable. Disturbance of the fabric by various agencies such as bioturbation is minimal.

Undisturbed and disturbed samples were extricated for the following purposes :

i) Detailed examination of the physical state of the material utilizing visual inspection and a scanning electron microscope.

ii) Comprehensive mineralogical and chemical analyses based on
   a) XRD Studies
   b) XRF Studies
   c) EDAX Studies

iii) An assessment of the geotechnical properties of the material utilizing the following tests :

Grading Analyses

Atterberg Limits and Linear Shrinkage

Consolidation Tests

Collapse Potential Tests

Triaxial Shear Tests

Permeability Tests

Dispersiveness Tests

Erodibility Tests

The following field tests were conducted :

Plate Load Tests

Permeability Tests

Shear Vane Tests

The geotechnical properties, so obtained, have been categorised with reference to fabric type. The residual material has therefore been classified on the basis of the inherited fabric and geotechnical properties assigned to characterise the 'material type' behaviour.

Chapter 2 : Existing Definitions and Proposed Definitions of Wad and Ferroan Soils

Prior to expounding on the definitions of wad and ferroan soil derived from, and for the purposes of this study, a brief review of existing definitions, of the term 'wad' so loosely used in the description of residual dolomite, must be made.

2.1 Review of existing definitions of wad

A number of sources have been consulted concerning the definition of the term wad. The application of this mineralogical term to a residual dolomitic soil is assumed to be based on the presence of the amorphous mineral wad in the soil in varying concentrations. A number of these definitions and their sources are noted below :

Whitten and Brooks (1972) :

"Wad is a soft black earthy mass of hydrated manganese oxides, usually containing iron oxides and occasionally barium and cobalt as well. Probably a kind of residual deposit."

American Geological Institute (1976) :

"Wad or bog manganese. Wad is an impure mixture of manganese and other oxides, contains ten to twenty percent water and is generally soft, soiling the hands."

Hurbult (1971) :

"Wad is the name given to manganese ore composed of an impure mixture of hydrous manganese oxides."

Ford (1949) :

"Wad : In amorphous and reinformed masses, either earthy or compact, also encrusting or as stains. Usually very soft, soiling the fingers, often loosely aggregated and feeling very light to the hand. Dull black, bluish or brownish black in colour."

"Wad is a mineral substance, a mixture of various oxides, chiefly of manganese (MnO_2 also MnO), cobalt with iron and ten to twenty percent water. This material is the result of the decomposition of magnesiun carbonate and can hardly be regarded as representing distinct mineral species."

Pelache et al. (1944) :

"The term wad is applied as a field or genetic term to substances whose chief constituent is a hydrous manganese oxide and whose true identity is unknown. Wad thus stands in much the same relation to the well-defined manganese oxides that limonite has to iron oxides and bauxite to the aluminum oxides. The substances included under the name are largely mixtures, probably chiefly of pyrolusite."

The following types of wad are listed by Pelache et al. (1944) :

Ordinary Wad : Bog manganese consisting chiefly of manganese oxide.

Colbaltian Wad : Wad containing CoO.

Cuprian Wad : Wad containing CuO consisting up to 25 percent of the sample and

often Fe_2O_3.

Ferrian Wad : Small amounts of Fe_2O_3 are usually present in the sample and with increasing admixture the material grades into goethite or limonite.

Aluminian Wad : Wad containing relatively large amounts of Al_2O_3 presumably due to the admixture of gibbsite and other hydrous oxides.

Wad occurs typically as a bog or lake deposit in clays, in shallow marine sediments, in oxidised portions of ore deposits' and as a residual weathering product in areas of manganiferous rocks.

Wad is a common substance and includes many of the occurrences formerly ascribed to pyrolusite and psilomelane (Pelache et al. 1944).

De Villiers (1965) :

"This soft, black mineral is present in earthy masses and readily soils the fingers. It can be described as amorphous, owing to the impossibility of obtaining an X-ray diffraction pattern. Dispersed through the amorphous material are minute hematite granules."

Geological Survey of South Africa : Standard Definition Provided in an Information Sheet Accompanying Reports.

An earthy, dark brown or black exceptionally fine-grained material composed essentially of a submicroscopic silica network (lattice structure) upon which iron and manganese oxides are deposited.

2.2 Proposed definitions for wad and ferroan soils

The literature review reveals that the term wad is often incorrectly applied to many soils which would more acurately be described as ferroan soils. XRF-analyses of samples retrieved at various localities within the study area indicate that in the majority of the samples tested, the iron content exceeds the manganese content. In many instances the iron content is in fact more than double the manganese content (Table 1). The predominant constituent in these soils is silica. The silica content is usually in excess of forty percent of the sample. Other major elements present in these soils are, aluminum (Al_2O_3) usually constituting less than ten percent of the sample, magnesium (MgO) usually constituting less than five percent of the sample and sodium (Na_2O), calcium (CaO), pottasium (K_2O), phosphor (P_2O) and chromium (Cr_2O_3) all individually constituting less than one percent of the sample. In less "mature" samples the concentrations of calcium and magnesium are much greater. The "fixed" or crystal water content varies from 2 to 20 percent (Figure 2.2.1).

The X-ray differaction analyses conducted on samples retrieved in the study area indicate that the so called wad material consists of minerals such as quartz (SiO_2) goethite ($HFeO_2$), pyrolusite (MnO_2), ilmenite ($FeTio_3$), hematite (Fe_2O_3), phlogopite ($KMg_3(Al_3Si_5O_6)$ $6H_2O$), illite, $Al_4Si_4O_{10}$ $(OH)_4$ kaolinite ($Al_2(SiO_{10})(OH)_8$), sphalerite (ZnS), epidote $Ca_2(Al, Fe)$ Al_2O (SiO_4), montmorillonite ($(Al, Mg)_8(Si_4O_{10})_3$), chlorite ($Mg_3(Si_4O_{10})(OH)_2$ - Mg_3 $(OH)_6$), actinolite (Ca_2 $(MgFe)_5(Si_8O_{22})(OH)_2$) and tremolite ($Ca_2Mg_5(Si_8O_{22})(OH)_2$). Minerals such as tremolite and actinolite indicate low grade metamorphism of the original dolomite. Groupings of several of the above listed minerals in varying concentrations usually constitute the wad and ferroan soils.

MAJOR ELEMENTS ANALYSES

Sample No.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
SiO_2	51,62	16,52	22,16	46,57	46,95	14,36	17,96	14,56	33,02	14,77	11,67	12,63	20,41	2,79	12,41
TiO_2	0,74	0,54	0,26	0,57	0,68	0,16	0,64	0,10	0,60	0,05	-0,01	- 0,01	-0,01	0,61	0,30
Al_2O_3	9,81	9,67	4,11	10,14	9,71	2,34	12,46	0,36	10,84	0,55	0,82	0,41	0,82	2,38	4,91
Fe_2O_3	16,99	32,64	21,91	19,82	21,06	40,10	27,33	30,12	20,69	36,61	16,92	14,70	15,02	40,98	39,12
FeO	-	-	-	-	-	-	-	-	-	-	- 0,2	- 0,2	1,48	-0,01	-0,01
MnO	6,85	10,33	21,51	8,51	8,87	14,44	13,83	30,04	9,85	24,60	6,78	9,21	6,94	52,18	37,38
MgO	0,98	3,69	0,72	1,00	1,11	4,69	4,54	2,51	10,90	4,62	20,49	21,18	20,44	0,81	4,80
CaO	0,07	0,58	0,05	0,08	0,10	1,70	0,29	1,98	0,21	1,20	41,16	41,46	33,62	0,06	0,14
Na_2O	0,09	0,07	0,08	0,09	0,06	0,06	0,06	0,10	0,09	0,05	0,11	0,08	0,10	< 0,1	- 0,1
K_2O	0,60	0,01	0,17	0,28	0,68	0,08	0,08	0,08	0,09	0,08	-0,01	-0,01	-0,01	< 0,1	- 0,1
P_2O_5	0,34	0,31	0,30	0,42	0,35	0,32	0,40	0,42	0,36	0,35	-0,01	-0,01	- 0,01	0,02	0,14
Cr_2O_3	0,01	0,04	0,06	0,07	0,04	0,04	0,01	0,02	0,05	0,02	-	-	- 0,01	0,10	0,18
NiO															
BaO															
S											-0,001	- 0,001	- 0,001	0,003	0,002
Cl															
F															
H_2O^+	5,96	9,21	8,43	6,65	6,88	11,39	11,25	11,39	9,68	10,96	1,52	1,55	1,60		
H_2O^-	5,72	16,23	20,17	5,59	3,30	10,16	11,00	7,96	3,42	6,02	1,14	1,47	0,90		
CO_2	0,22	0,16	0,07	0,21	0,21	0,16	0,15	0,36	0,20	0,12	30,81	32,93	24,45	0,23	0,24

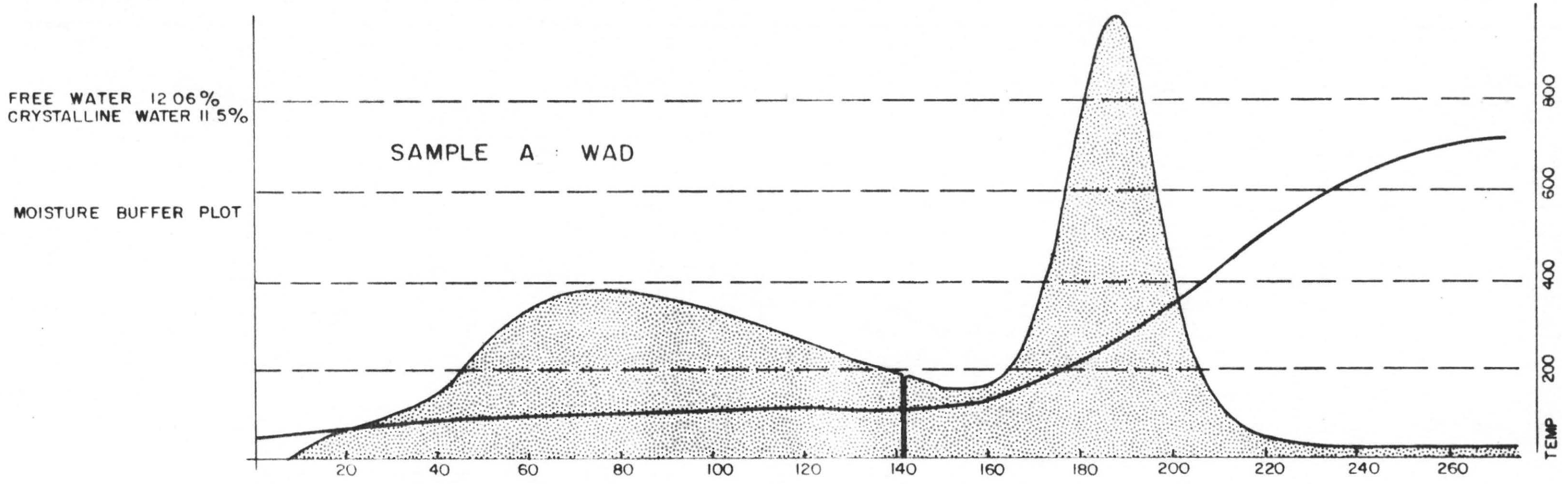
TABLE: I. XRF TEST RESULTS.

All major elements on dry basis at 1000°C.

MAJOR ELEMENTS ANALYSES

Sample No.	16	17	18	19	20	21	22	23	24	25	26	27			
SiO_2	25,53	33,37	24,65	37,72	42,56	43,93	38,74	49,70	42,12	51,10	38,08	54,72			
TiO_2	0,15	0,39	0,19	0,27	0,85	0,14	0,13	0,12	0,13	0,09	0,09	0,17			
Al_2O_3	1,80	5,80	2,64	4,58	11,09	2,17	1,54	1,52	1,53	0,76	1,07	2,22			
Fe_2O_3	23,41	19,90	23,09	17,37	11,09	11,75	11,74	15,63	20,10	14,32	10,97	17,75			
FeO	-	-	-	-	-	-	-	-	-	-	-	-			
MnO	22,79	20,78	22,74	14,90	9,59	11,14	8,84	13,07	5,56	8,05	8,69	6,69			
MgO	9,14	5,13	9,81	11,22	1,34	0,45	1,23	2,08	1,15	4,46	1,75	1,72			
CaO	3,62	0,86	3,34	1,67	1,34	0,08	0,33	0,10	0,32	1,86	0,48	0,49			
Na_2O	0,07	0,10	0,09	0,07	0,09	0,08	0,10	0,07	0,08	0,09	0,07	0,08			
K_2O	0,09	0,04	0,09	0,09	0,25	0,16	0,01	0,02	0,09	-	-	0,21			
P_2O_5	0,29	0,36	0,32	0,32	0,30	-	0,02	0,02	0,01	-	0,01	0,02			
Cr_2O_3	0,05	0,04	0,04	0,03	0,02	0,02	-	-	0,24	-	0,04	-			
NiO															
BaO															
S															
Cl															
F															
H_2O^+	9,39	8,43	9,08	7,62	16,58	6,14	5,92	7,60	4,20	4,81	5,59	4,79			
H_2O^-	3,48	4,51	3,74	3,96	4,57	31,15	32,85	15,71	25,33	21,61	39,59	16,36			
CO_2	0,19	0,29	0,18	0,18	0,33	0,87	0,22	0,21	0,19	0,27	0,15	0,26			

TABLE: I. (Continued) XRF TEST RESULTS.



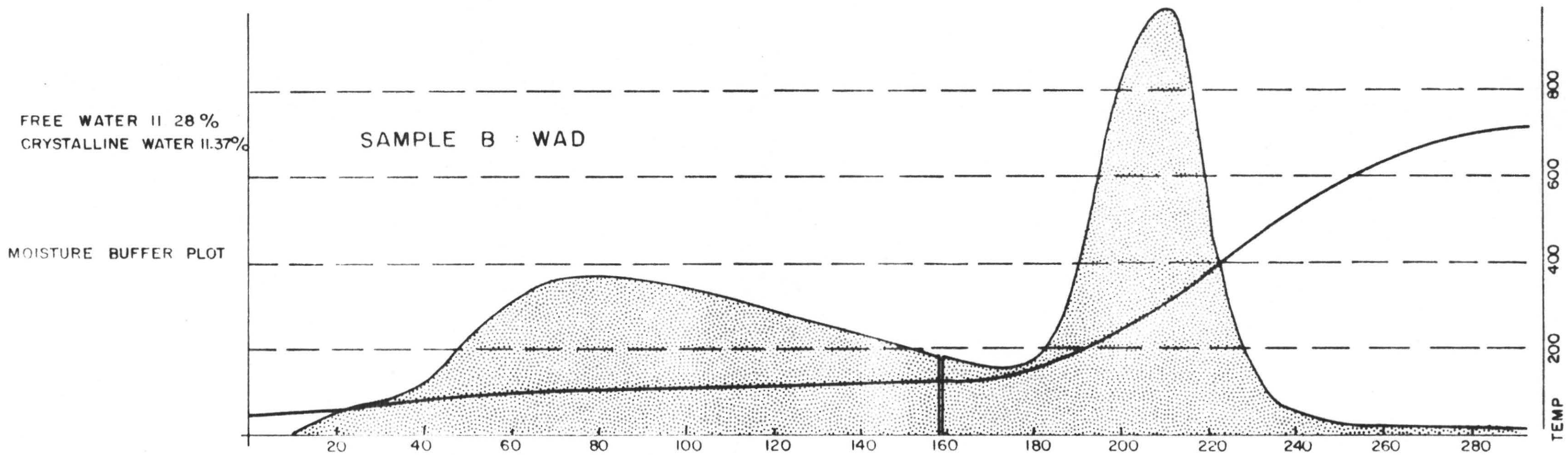


FIGURE. 2.2.1 INFRARED ABSORPTION TECHNIQUE UTILISED TO DETERMINE CRYSTALLINE WATER CONTENT OF WAD SAMPLES.

MINERAL	SAMPLE NUMBER																						
	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W
Actinolite									X														
Amorphous MnO		X														X	X	X					
Annite										X													
Antigorite									X														
Augite							X	X		X													
Calcite					X			X													X		
Chlorite		X	X	X	X		X	X							X								
Dolomite					X			X												X	X	X	X
Enstatite	X																						
Epidote			X																				
Goethite			X								X		X	X	X								
Greenalite	X																						
Hematite		X		X		X													X				
Heulandite	X																						
Hornblende								X		X													
Illite												X	X	X	X				X				
Ilmenite	X		X																		X		
Kaolonite				X	X						X		X	X	X					X	X	X	X
Limonite		X																					
Minnesotiate	X								X														
Montmorrillonite	X						X		X	X		X			X								
Palygorskite	X																						
Phlogophite	X		X																				
Pyrolusite		X	X	X		X	X																
Quartz		X		X	X	X					X	X	X	X	X					X	X	X	X
Sericite		X		X	X	X				X													
Sphalerite	X		X																				
Talc	X		X																				
Tremolite					X																		
Gypsum																				X	X	X	X

X = Mineral idenfified as being present in sample.

**TABLE 2 : XRD - RESULTS OF ANALYSES ON WAD SAMPLES.
ANALYSES CONDUCTED BY GEOLOGICAL SURVEY LABORATORY.**

Table 2 gives the results of X-ray diffraction analyses made of samples retrieved in the study area south of Pretoria. A typical "wad" sample would consist of the following minerals in order of importance: quartz, pyrolusite, goethite, talc, chlorite and phlogopite. The silica and pyrolusite predominate in the sample. A typical ferroan soil consists of the following: quartz, goethite limonite, and small amounts of hematite, pyrolusite, chlorite, sericite and kaolinite.

Although chemical differences exist between the wad and ferroan soils, no substantial variations in geotechnical properties are noted. The stress related fabric and secondary features such as the discontinuities inherited by both these soil types from the parent rock, are important distinguishing factors. Thus the compositionally different ferroan soil and wad may be grouped into one class of material reflecting certain common behavioural characteristics as a consequence of a particular fabric. These aspects will be discussed at length in chapter six of this text.

Based on all the above information the following definitions of wad and ferroan soils are offered.

Wad : This soil is a black or blue-grey, fine-grained, clayey silt or silty clay, rich in silica, manganese oxides and lesser components such as FeO, Al_2O_3, MgO, CaO, NaO, P_2O and Cr_2O_3. This soil is derived as a weathering product of a magnesium carbonate.

On the microscale the material is characterised by sheetlets or alternatively spheres of oxides which are sometimes cemented together by secondary deposits of calcite or silica.

The literature survey has revealed that the term wad is, in the strictest sense, applied incorrectly here, as silica usually constitutes the greatest part of the analysed materials, rather than manganese oxides.

Ferroan Soil : This soil is a reddish-brown or purplish-brown, clayey silt or silty clay, rich in silica, iron oxides and lessor impurities such as MnO, MgO, CaO, NaO and Al_2O_3. This soil is derived as a weathering product of a magnesium carbonate.

On the microscale the material is characterised by sheetlets or alternatively spheres of oxides which are sometimes cemented together by secondary deposits of calcite and silica.

The tendency in the past has been to use the term wad to denote these materials collectively. It is advisable to continue using this term, as convention dictates, being mindful that the adopted usage is not entirely correct. In this text, for reason of convenience, "wad" will be adopted to denote both iron manganiferous soils and manganiferous iron soils.

Chapter 3 - Previous Work - A brief Literature Study

The literature survey has revealed the remarkable amount of confusion that prevails concerning wad. Most workers have paid little attention to structure during geotechnical assessments with the exception of Day (1981) and Wagener (1982).

Day (1981) describes wad as the insoluble residue derived from the weathering of a manganese rich dolomite. He states that wad may be divided into two categories based on the structure of the material. The terms "structured" wad and "non-structured" wad are used in the paper. The term "structured" wad refers to material in which the structure of the material has been preserved and "non-structured" wad to material in which the structure has apparently been destroyed.

Day (1981) regards the "non-structured" wad as pure wad, free of transported impurities but having "practically no structure". The wad may be powdery or blocky having been dessicated. The intact, structured wad, Day (1981) believes, is still very much in its original state, as witnessed by the frequently occurring chert bands and shale lenses.

In a later publication, Wagener (1982) defines wad as a dark brown or purplish residue, consisting of manganese or iron, which develops when dolomite weathers.

Wagener (et al.) (1981, 1982) investigated wad from three sites located on the Oaktree Formation and the Black Reef Quartzite Formation. Scanning electron microscope work indicates that the material resembles "rice crispies" with large voids between material. The grains appear to be interlocked, with no cementing material present.

Wagener (1982) reiterates Day's (1981) subdivision of the material into "intact" (structured) and "powdery" (non-structured) wad. The former reflects the structure of the rock as well as joints and bedding planes. "The powdery wad is envisaged as structural and as having a loose consistency (Wagener 1982)".

The nomenclature adopted to characterise the physical state of the wad has been contentious. Brink (1981) contends that Day (1981) has incorrectly labelled the wad. Day's (1981) "intact wad" is in fact reworked having been compressed or consolidated. The reworked material is, Brink (1981) believes, intact wad. Brink (1981) reiterates that wad is composed of the insoluble components left after the carbonates of a manganese rich dolomite have been completely dissolved. This insoluble residue would usually be characterised by a very low density state. If the material were to be compressed or consolidated, in the geological environment, it would be described as "reworked".

Results of a number of tests conducted by Wagener et al. (1981, 1982) during site investigations, indicate that the wad grades as a clayey silt, has a dry density of 225 to 1481 kg/m^3, a void ratio of 0,9 to 11,2 per cent and is usually overconsolidated. The moisture contents often exceed the liquid limit. Wagener (1982) determined that there is no correlation between dry density of the wad and the E modulus (Figure 3.1). His research indicates that the low density materials often display the higher elastic moduli. Elastic moduli calculated for the pressure range po to (po + 50) kPa vary between 7 and 54 MPa (Wagener 1982). (po refers to the present overburden pressure).

Shearbox test results indicate an average angle of friction of 29° and an average cohesion value of 26 kPa. The shear strength of the wad is found not to be dependent on the dry density (Wagener 1982). The material has been assessed as of a high permeability. Wagener (1982) indicates that the samples of wad tested are not dispersive.

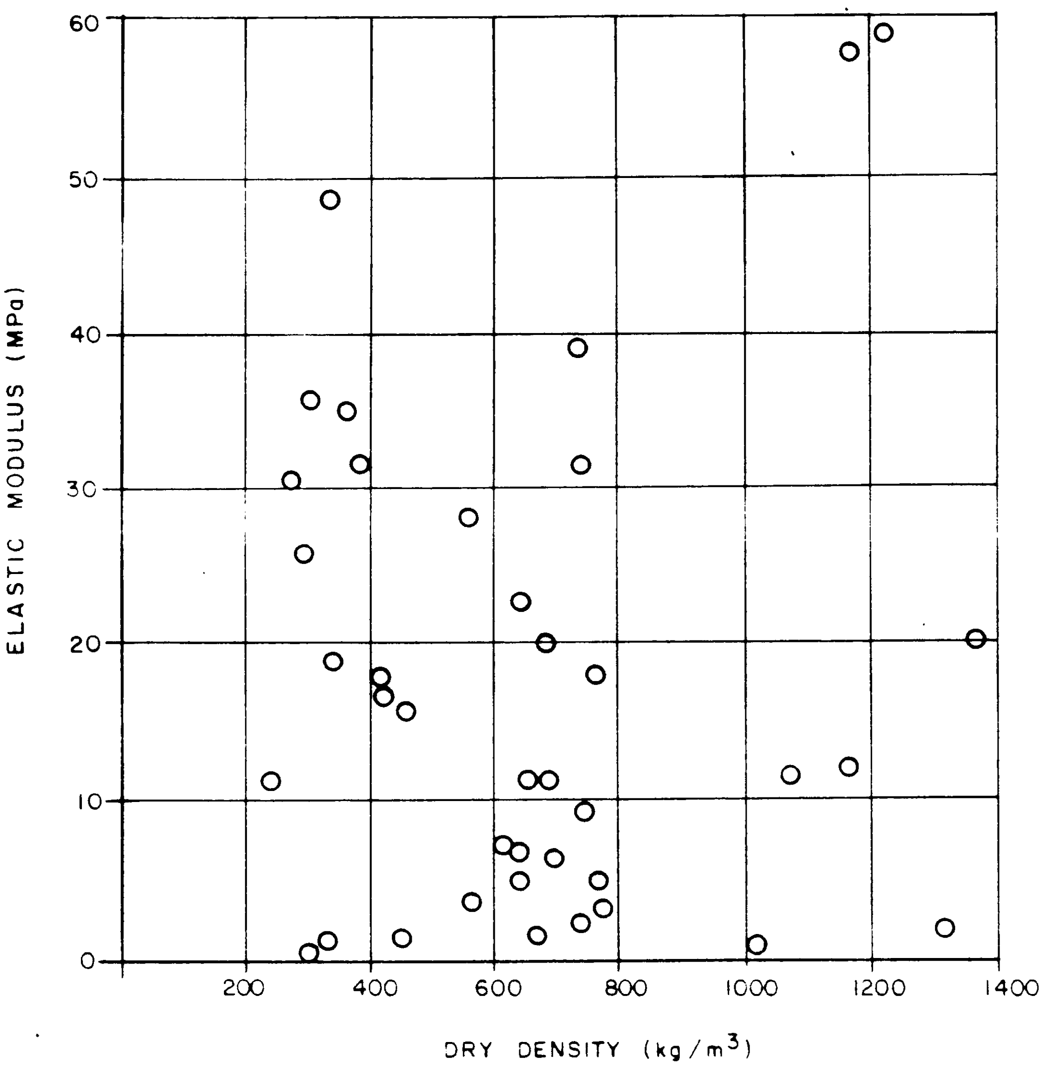


FIG.3.1. ELASTIC MODULUS vs DRY DENSITY FOR WAD SAMPLES. (After Wagner 1982)

Wagener and Day (1981, 1982) conducted a number of modified oedometer tests. The material was loaded at natural moisture content in increments to 50 kPa or 125 kPa and saturated. The amount of heave or collapse was observed before proceeding with the test. The interesting observation made is that the wad did not collapse on saturation but continued to undergo gradual settlement. At higher loads, in the region of 400 kPa, collapse was noted.

Day (1981) reports that the plasticity index values of wad samples are not high, averaging 20 percent. The average recorded linear shrinkage value is about 9 percent. The amount of silt and sand in wad is high, on average, at 50 per cent, and 20 per cent respectively. Elastic moduli (oedometer) values quoted by Day (1981) for "intact wad" is in the region of 21 MPa and the elastic moduli (plateload) approximately 24 MPa. A close correlation thus exists between these test results.

Day (1981) came to the conclusion that the compressibility of the wad depends on the structure of the material more than on any other factor (Figure 3.2).

Wagener (1982) and Day (1981) note that the wad liquifies under impact which is ascribed to a breaking down of the structure under conditions of high pore water pressure and shock loading.

Hawkins _et al._ (1986) have conducted several analyses and tests on samples of wad recovered in the Tokozo area on the East Rand. This investigation identified two distinctly different forms of wad, namely a laminated form and what is described as a "typical dolomitic residuum".

The former material is described as occurring in laminated beds and as being slightly cemented. Samples of this laminated material were subject to mineral analyses and petrographic investigation. The results of this study indicate that the sample is manganese and iron rich (Table 3).

RESULTS ON MOISTURE - FREE BASIS

(Expressed in Percent Unless Stated Otherwise)

Loss on Ignition (1000°C) :	11,0
Silicon, as SiO_2	28,1
Aluminium, as Al_2O_3	2,7
Total Iron, as Fe_2O_3	36,1
Titanium, as TiO_2	0,23
Phosphurus, as P_2O_5	0,09
Manganese, as MnO	19,2
Calcium, as CaO	0,18
Magnesium, as MgO	0,4
Sodium, as Na_2O	< 0,1
Potassium, as K_2O	0,53
Carbon, as C	0,31

< Sign = Less than

(From Hawkins et al 1986)

TABLE 3 : XRF ANALYSES OF A WAD SAMPLE FROM THE TOKOZA AREA.

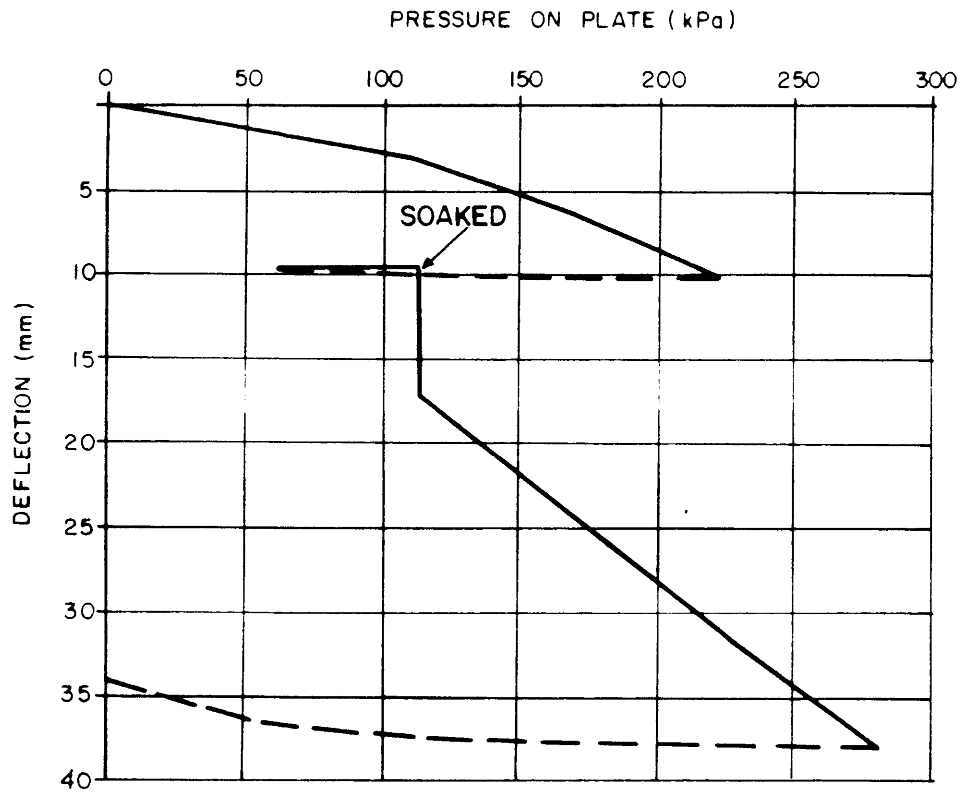


FIG.3.2. VERTICAL PLATE LOAD TEST ON WAD AT ROOIHUISKRAAL. (After Day 1981)

Hawkins et al. (1986) reports after extensive investigation, that the inorganic analysis of these samples reveals the following features:

1. Almost pure manganese oxide minerals are present

2. Barium is absent (this is apparently unusual in a typical wad)

3. Fe- and Mn- oxides and Fe, Si oxides are present

4. Cross sections of some of the minerals indicate secondary deposition around central quartz grains suggesting accretion.

The laminated material has a dry density of 500-600 kg/m^3, a moisture content of 95 per cent, plasticity index of 18, liquid limit of 71 per cent and a linear shrinkage value of 8.9 per cent.

De Beer (1985) notes that wad is traditionally regarded as an extremely compressible and low-strength material.

De Beer (1985) presents the results of indicator tests conducted on eight wad samples (Table 4). The dry density of the wad varies from 273 to 1558 kg/m^3 but it is noted that no correlation exists between the dry density and field consistency description. Similarly no correlation was noted between the dry density of the wad and the overconsolidation ratio. The in situ moisture content varied from 25 percent to 314 percent with the degree of saturation varying from 61 to 97 percent.

This study revealed that one of the most important properties is its fairly high degree of overconsolidation in the region of 16. Correlation between the overconsolidation ratio and wad sample depth below ground surface is noted as being good (Figure 3.3). De Beer (1985) notes that

TABLE 4 - SUMMARY OF WAD PROPERTIES

HOLE NO.	DEPTH (m)	CLAY FRACTION % <0,002	L.L.	P.I.	C (kPa)	Ø°	D.D. (kg/m^3)	w %	e_o	C_c	C_r	S_r %	O.C.R.	AVERAGE 1/m_v (MPa)	SOIL DESCRIPTION
TH1	3,0	10,8	126	3	22	33	273	314	8,901	3,256	0,107	95	13	8,0	Firm to stiff clayey silt (wad)
TH1	4,8	25,0	69	5	40	31	438	117	5,114	1,413	0,070	61	16	18,0	Soft clayey silt (wad)
TH2	3,3	26,8	66	20	25	32	772	64	2,652	0,807	0,043	68	7	7,6	Firm to stiff clayey silt (wad)
TH3	3,5	40,8	53	20	67	24	1514	25	0,770	0,265	0,024	88	10	29,0	Firm clayey silt (wad)
TH6	2,3	39,0	52	25	18	24	1147	30	1,389	0,383	0,049	59	1,3		Firm clayey fine sand (Residual dolomite)
TH18	7,3	18,0	49	27	60	25	1558	26	0,803	0,408	0,056	90	5	12,0	Soft to firm clayey silt (wad)
TH19	9,0	59,6	74	40	54	18	1165	42	0,267	0,530	0,050	88	2,2	7,5	Soft clayey silt (wad)
TH19	11,0	21,3	75	21	33	22	4012	206	5,714	3,415	0,147	97	1,7	3,0	Soft clayey silt (wad)

Where:

- L.L. = Liquid Limit
- P.I. = Plasticity Index
- C = Cohesion Intercept
- Ø = Friction angle
- O.C.R. = Apparent Over Consolidation Ratio
- S_r = Saturation Ratio
- D.D. = Dry Density
- w = Initial Moisture Content
- e_o = In-situ void ratio
- C_c = Compression Index
- C_r = Swell Index (Rebound)
- $1/m_v$ = Modulus of Elasticity

(After de Beer 1985)

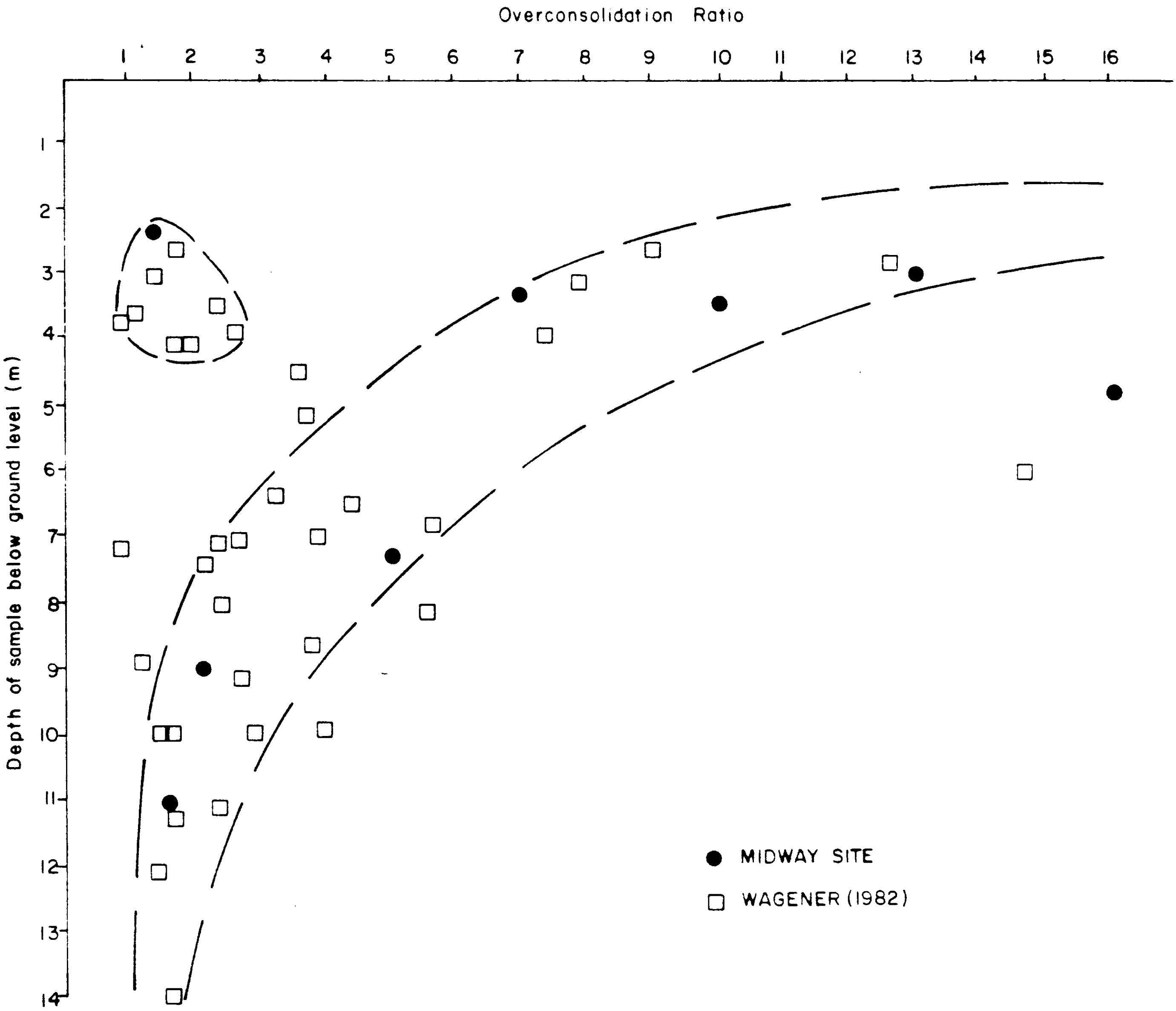


FIGURE. 3.3 RELATIONSHIP BETWEEN OVERCONSOLIDATION RATIO AND DEPTH BELOW GROUND SURFACE. (After de Beer 1985)

the material generally exhibits a heavy degree of overconsolidation near the ground surface and tends towards a normally consolidated state as the watertable is approached. It must, of course, be borne in mind that materials situated at shallow depth and above the watertable are usually prone to the effects of dessication, hence indicating high pre-consolidation pressure which have in fact never existed in the soil. The nature of the relationship between overconsolidation ratio and depth is stated as indicating that overconsolidation ratio of the wad is not attributable to the loads imposed by Karoo sediments, which have been eroded away, but rather due to the dessication effect.

Results obtained by Wagener (1982) and plotted in a similar manner indicate the same results as noted by De Beer (1985). These results also suggest the same process of overconsolidation caused by dessication (Figure 3.3).

Brink (1979) indicates that the wad is the most highly compressibly residual soil known to occur on the Highveld. Consolidation coefficient values ranging from 294 to 320 mm^2/minute, compressive indices (at po) of 0,03 to 0,07, dry densities of 285 to 700 kg/m^3 initial void ratio's of 2,7 to 9,6 and overconsolidation ratio's of 2,3 to 15 are cited.

Brink (1979) reports on a mechanism of doline formation, emphasising the effect that dewatering may have on the behaviour of wad. As the water table is lowered through the wad, the water in the voids drain out under surcharge loading. Excessive settlements and extraordinary rapid rates of settlement have been observed as a consequence of dewatering of thick layers of wad.

The amount of settlement is determined by the compression index (C_c) and the rate of settlement by the coefficient of consolidation (C_v) of the wad. Brink (1979) has cited figures of greater than one for the compression index and values of greater than 300 mm^2/minute for the consolidation coefficient. These values accord with the observation of dolines in the Carletonville area during the early nineteen sixties. In excess of 3 metres of surface subsidence occurred in a period of just three years (Brink 1979).

Brink (1979) presents the engineering properties of eight samples of wad retrieved in varying localities, including four samples from a cave. The initial void ratio values are shown to vary from a minimum value of 2,76 to a maximum of 9,6. Bulk density and dry density values fall in the range of 858 kg/m^3 to 1462 kg/m^3 and 285 kg/m^3 to 722 kg/m^3 respectively.

Brink (1979) cites natural moisture content values for these samples, in the range 57 per cent to 202 per cent. Several of these natural moisture content values appear to be far in excess of the liquid limit values of the samples. As an example, a sample with a natural moisture content of 202 per cent, possesses a liquid limit of 96 per cent.

The highest compression index (C_c) value noted in this particular study is 1,8, while the average specific gravity value is noted to be in the region of 3,2.

The literature study emphasises three important points, namely :

i) The need to identify and classify different wad types. No attempts to classify this material on the basis of its structure, origin and associated properties has thus far been successful. Day (1981) has attempted to subdivide the material into reworked and non reworked wad on the basis of macroscale appearance but has permitted dessication effects to influence his classification.

ii) Detailed information and research of this material's geochemistry, origin, physical state (structure) and geotechnical properties is lacking.

iii) Those studies making the geotechnical properites of this material available, offer no explanation or speculation concerning the sometimes unique behavioural characteristics.

Chapter 4 : General Overview of the Geology of the Study Area

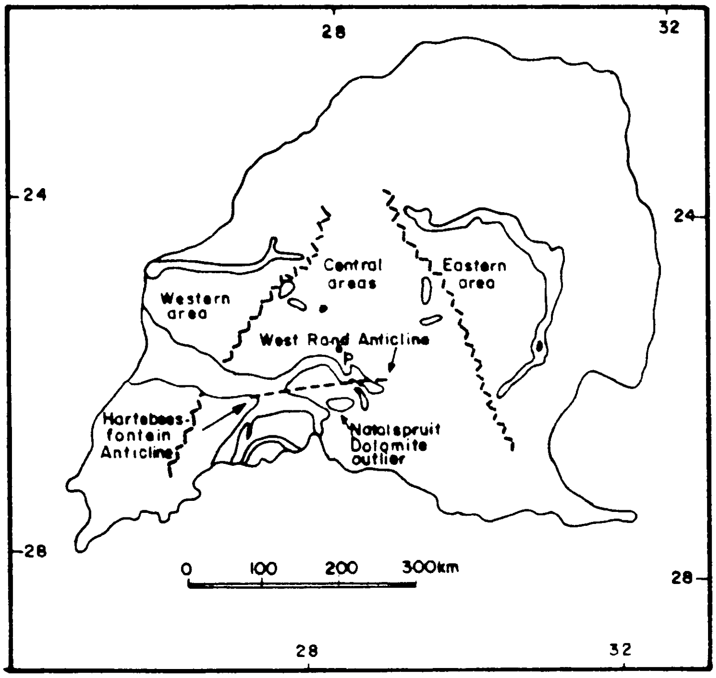
The study area is underlain by approximately 330 km^2 of dolomite of the Chuniespoort Group. This study area thus constitutes a very small portion of the 15 500 km^2 area in the Transvaal that is underlain by the strata of the Chuniespoort Group.

4.1 Dolomite

Dolomite is a rock composed mainly of the mineral of the same name which is a calcium magnesium carbonate ($CaMg\ (CO_3)_2$). The composition is usually in the $CaMg(CO_3)_2$ -Ca(Mg, Mn)$(CO_3)_2$ - Ca(Mg, Fe)$(CO_3)_2$ triangle.

The mineral dolomite consists of CO^{2-}_3-2 groups alternating with layers of cations. The cation layers are alternatively calcium and magnesium. This ordered structure results from the large difference in ionic radii (33 pecent) of calcium and magnesium (Hurbult 1971). Bradley et al. (1953) thus proposed that the structure of the dolomite may be represented as layers of calcite ($CaCO_3$) and magnesite ($MgCO_3$). In ordinary dolomite, the proportion of $CaCO_3$ to $MgCO_3$ is 1:1. Calcium may, however, be substituted for magnesium up to a Ca:Mg ratio of 1:5.

Dolomite is therefore, theoretically, a simple carbonate of magnesium and calcium as defined above. A considerable content of iron and manganese may be present. Iron, manganese and magnesium are diadochic in the structure of dolomite. These elements therefore have the ability to occupy the same lattice position in the crystal system. Iron and manganese may be substituted for magnesium in the dolomite lattice. Eriksson et al. (1974) has suggested that iron and/or manganese may have been present in the initial $CaCO_3$ precipitate.



• P PRETORIA

FIGURE 4.2.1 CENTRAL AREA LOCATION, CHUNIESPOORT GROUP

CENTRAL TRANSVAAL

GROUP	FORMATION	LITHOLOGY and Mb	Thickness (m)
PRETORIA	RAYTON	Beynestpoort Quartzite Mb Silty shale, andesitic lava Feldspathic quartzite Shale Quartzite Subgraywacke and shale Baviaanspoort Quartzite Mb Shale and quartzite	1 200
	MAGALIESBERG QUARTZITE	Orthoquartzite	300
	SILVERTON SHALE	Silty and graphitic shale with thin interbedded limestone	600
	DASPOORT QUARTZITE	Orthoquartzite	80-95
	STRUBENKOP SHALE	Iron-rich shale Iron-rich quartzite	105-120
	HEKPOORT ANDESITE	Andesitic lava, agglomerate and tuff Conglomerate, tuffaceous quartzite and shale	340-550
	TIMEBALL HILL	Shale Diamictite Klapperkop Quartzite Mb wacke and ferruginous quartzite Graphitic and silty shale	270-660
	ROOIHOOGTE	Quartzite Shale Bevets Conglomerate Member Breccia	10-150
CHUNIESPOORT	ECCLES	Chert-rich dolomite with large and small stromatolites	380
	LYTTELTON	Dark chert-free dolomite with large elongated stromatolitic mounds	150
	MONTE CHRISTO	Light coloured recrystallised dolomite with abundant chert; stromatolitic; basal part oolitic	700
	OAKTREE	Dolomite, becoming darker upwards; chocolate-coloured weathering	200
	BLACK REEF QUARTZITE	Shale Quartzite Arkosic grit	25-30

(SACS 1980)

FIGURE 4.2.2 CHUNIESPOORT AND PRETORIA GROUPS IN THE CENTRAL AREA.

Dolomite possesses a problem of origin since the mineral is not excreted by organisms as shell material. Direct precipitation from solution is not considered adequate to explain the great thicknessess of dolomite rock that are developed in the geologic record. The most widely held explanation of the formation of dolomite is by the process of dolomitization, be it penecontemporaneous or post depositional dolomitization. Limestone is considered to have been the original precipitate and dolomite and chert represent secondary replacement.

4.2 Stratigraphy of the study area

4.2.1 Chuniespoort Group

The dolomite rocks of the Chuniespoort Group are about 2200 to 2300 Ma years old and occupy an area of approximately 15 000 square kilometres in the Transvaal. Van Schalkwyk (1981) estimates that these outcropping rocks constitute about twenty percent of the surface area of the Pretoria/Witwatersrand/Vereeniging Complex.

The Chuniespoort Group consists of four formations in the central area, namely the Oaktree, Monte Christo, Lyttelton and Eccles Formations (Fig. 4.2.1). The Frisco Formation is absent in the study area with the Pretoria Group sediments resting unconformably on the dolomite of the Eccles Formation. The absence of the Frisco Formation in this central area precludes the use of the Malmani Subgroup as a sack term (SACS 1980).

The four formations collectively are approximately 1430 metres thick and are identified on the basis of the relative abundance of interbedded chert. The Oaktree and the Lyttelton Formations are chert poor while the Eccles and Monte Christo Formations are rich in chert (Figure 4.2.2).

Oaktree Formation

The Oaktree Formation is approximately two hundred metres thick, consisting of dark coloured, chert-poor dolomite with some carbonaceous shale towards the base (SACS 1980). This formation constitutes the basal unit of the Chuniespoort Group.

Monte Christo Formation

The Monte Christo Formation, which is in excess of 700 metres thick, is the most thickly developed formation in the area south of Pretoria. The formation is chert rich and displays stromatolites in recrystallised dolomite. The basal zone is oolitic. This strata rests concordantly on the rocks of the Oaktree Formation.

Lyttelton Formation

The Lyttelton Formation, which is 150 metres thick, consists of dark chert free dolomite with large elongated stromatolitic mounds (SACS, 1980). The width of the structures may range from less than five to over 30 metres (Eriksson and Truswell, 1974). The dolomite tends to weather into sharp pinnacles.

Eccles Formation

The dolomite of the Eccles Formation is rich in chert with the chert content increasing upward, in the succession. This formation is approximately 400 metres thick.

Frisco, Penge and Duitschland Formations

The dolomite of the Frisco, Penge and Duitschland Formations is not present in the central area of the country. These formations are therefore not represented in the study area.

4.2.2 Black Reef Quartzite Formation

The Black Reef Quartzite Formation which underlies the Chuniespoort Group rocks, is approximately 30 metres thick and consists of shale, quartzite, dolomite and conglomerate.

4.2.3 Syenite/Diabase dykes and sills

A number of syenite/diabase sills and dykes have intruded the dolomite of the study area.

4.3 The environment of deposition

The early Proterozoic Transvaal and Griqualand Sequence accumulated in a 500 000 km^2 intracratonic epeiric basin on the Kaapvaal crustal fragment. This enormous basin was developed during a major period of erosion in post Ventersdorp times. The north east-south westerly orientated basin contains a substantial thickness of Chuniespoort chemical sediments. The Black Reef quartzite covers a regional unconformity overstepping the basement granites and the Ventersdorp volcanics.

Both fluvial and shallow marine facies are discernable in the Black Reef strata (Button 1973). The Black Reef quartzite fines upwards into interbedded shale before grading into the overlying Chuniespoort Group.

Recrystallised dolomite with chert; dark, iron-poor dolomite; clastic textural dolomite; and ankeritic dolomite, with limestone, constitute the Chuniespoort Group (Tankard 1982).

Waters flowing into the basin were rich in bi-carbonates and silica, leached from the decomposed rocks of the Basement Complex and Ventersdorp Lavas.

Work done by Eriksson (1972), and Eriksson and Truswell (1974) indicates that the four formations, representing the Chuniespoort Group in the study area, south of Pretoria, may be seen to record three depositional environments in accordance with Irwin's (1972) model. The environments represented in the epeiric sea are the subtidal, supratidal and intertidal zones.

4.3.1 Subtidal Zone : Oaktree and Lyttelton Formations

The characteristic features of the dolomite deposited in the subtidal zone are: i) The development of large domical stromatotites
ii) The notable absence of chert
iii) The presence of a high percentage of manganese and iron.

The deep sea, subtidal zone was not influenced by meteoric waters and was essentially alkaline, precluding the precipitation of silica. These waters were supersaturated with respect to iron and manganese. Mason (1966) argues that iron is soluble in acidic waters, hence weakly acidic iron bearing waters flowing into the sea from neighbouring land areas must precipitate most of their iron in the weakly alkaline environment. This postulation is borne out by actual recorded figures in modern environments which show that the average content of iron in river waters is about one part per million whereas in sea water the amount is exceedingly small, about 0,008 parts per million (Mason, 1966).

Iron could have been derived by sub-aerial weathering and transportation under oxygen deficient conditions. Tankard et al. (1982) believes that a substantial reservoir of Fe^{2+} could have been established in the epeiric sea. Furthermore all the metals that would have been released by the deep chemical weathering of a Ventersdorp type parent rock, occur in the Chuniespoort Basin, including calcium, magnesium, sodium, iron and manganese.

4.3.2 Intertidal Zone : Monte Christo Formation

The intertidal zone lies between the tidal flats and the subtidal zone. The dolomite of the Monte Christo Formation deposited in this zone is recrystallised, reflecting a meteoric influence. The cherts developed may also be related to a lower pH environment. According to Illing (1964), the intertidal zone is the ideal environment for the development of chert. At low tide, tidal channels develop. As the tide fluctuates, blue green algae acts as a trap for sediment. The inflow of slightly acidic meteoric water and the effect of sub-aerial exposure results in an acidic environment. Carbonates, already deposited, are unstable under the prevailing acidic conditions resulting in dissolution and subsequent reprecipitation of coarser grained mosaics. Silica precipitates as chert.

4.3.3 Supratidal Zone or Sabkha : Eccles Formation

The supratidal zone constitutes that area which is only flooded during exceptionally high tides and storms. Deposits are in the form of evaporites and carbonates such as anhydrite, gypsum and halite (Brink 1981). The influence of slightly acidic meteoric waters results in an acidic environment with a chert rich dolomite being deposited.

4.4 Origin of the chert

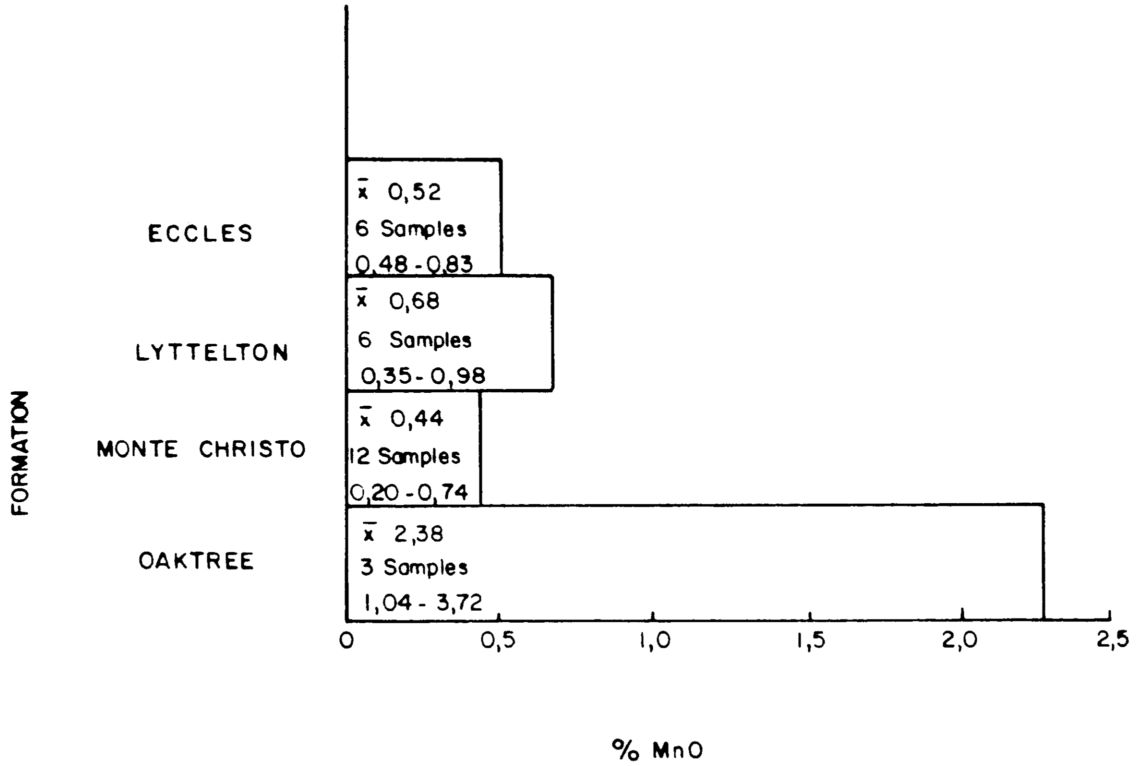
Eriksson (1975) indicates a cyclic distribution of the chert in the Chuniespoort Group. The chert commonly occurs in association with domical stromatolites and oolites. Chert in the group is of secondary origin, the cyclic distribution of which was controlled by the pH of the solutions and the availability of silica in solution. In the proximal supratidal or shallow water high temperature environment alkaline conditions may have prevailed, favouring the solubility of silica.

The time at which chertification occurred is problematical, related essentially to a post consolidational or penecontemporaneous diagenetic replacement of the carbonate by chert. Eriksson (1975) believes that a penecontemporaneous diagenetic origin more adequately explains the observed chert relationships than a late stage siliceous solution percolating through a thick carbonate succession such as the Chuniespoort Group.

4.5 Manganese and iron oxide contents of the dolomite

Roux (1981) conducted analyses on dolomite samples from 44 localities in the dolomitic area south of Pretoria (Figure 4.5.1). This research shows that the iron oxide and manganese oxide contents in the dolomite vary respectively between 0,09 and 6,11 and 0,22 and 3,88. A good correlation was found between the iron oxide and manganese oxide values in the dolomite.

There is a large variation in composition of the dolomite, with respect to the iron oxide and manganese oxide contents, along the strike of any of the stratigraphic horizons. In the vicinity of Rooihuiskraal there is 6,11 percent iron oxide and 3,6 percent manganese oxide respectively in



ADAPTED FROM RESEARCH BY ROUX (1981)

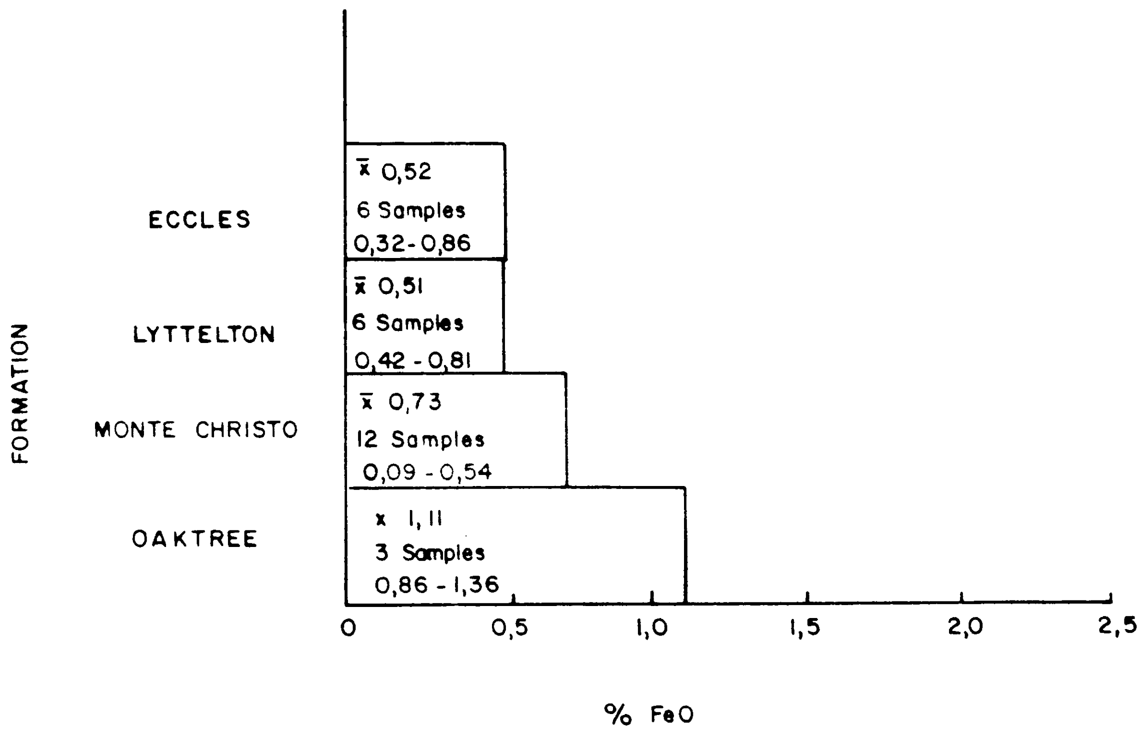


FIGURE 4.5.1 : DISTRIBUTION OF THE IRON AND MANGANESE CONTENT OF DOLOMITE ROCKS SOUTH OF PRETORIA

the dolomite of the Oaktree formation. Further westward, in the direction of Johannesburg-Pelindaba road, values of 0,25 percent and 0,22 percent respectively were obtained, for the iron oxide and manganese oxide contents (Roux, 1981). This variation, laterally, would be attributable to changing pH and Eh conditions in the environment of deposition.

Eriksson (1971) plotted the vertical variations in the manganese content of the dolomite in Chuniespoort Group. Although this study pertains to dolomite outside the study area it is probably representative of the general trends in the central portion of the basin (Figure 4.2.1 and 4.5.2).

4.6 Weathering of the dolomite

The introduction of carbon dioxide in groundwater greatly increases its solvent ability. Rainwater, on reaching the soil surface contains a small amount of carbon dioxide in solution. As this water percolates through the profile, enrichment with respect to carbon dioxide occurs. Brink (1979) indicates that the concentration of this gas may be up to ninety times greater in the air in the soil voids, than in the atmosphere. The water and the carbon dioxide combine to form weak carbonic acid.

$$H_2O + CO_2 = H_2CO_3$$

The dolomite rock material is particularly impervious with a porosity of less than 0,3 per cent (Brink 1979). The dolomite rock mass is, however, highly fractured, jointed and faulted, permitting access and percolation of water. This intensity of fracturing, particularly, characterises the dolomite rock mass within the study area, which encompasses a zone of intense deformation of the strata.

Above the watertable in the vadose zone solution results in the widening of joints and fractures. Dolomite, calcite and magnesite dissolve in the

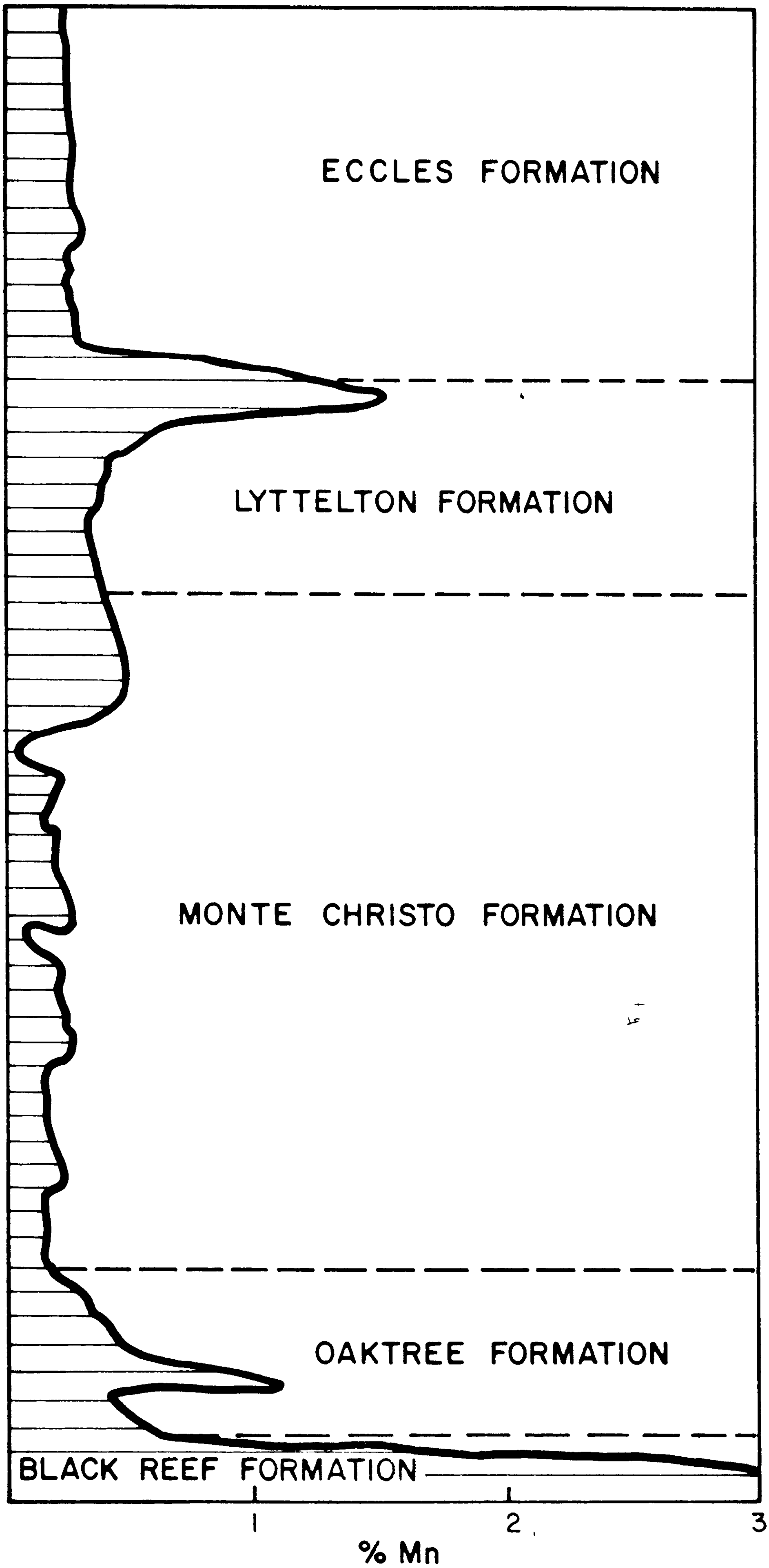


FIG. 4.5.2 : VERTICAL DISTRIBUTION OF THE MANGANESE CONTENT IN THE DOLOMITE ROCK OF THE FAR WEST RAND. (after Eriksson, 1974).

weakly acidic groundwater to form bicarbonates. The solution of the dolomite by water enriched with carbon dioxide may be represented as follows :

$$CaMg\ (CO_3)_2 + 2H_2CO_3 \longrightarrow Ca(HCO_3)_2 + Mg(HCO_3)_2$$

This process of dissolution progresses slowly in the slightly acidic groundwater. The resultant bicarbonate water emerges as springs and is carried away. Joints and fractures are gradually exploited, opening into slots. The pinnacles thus develop as remnant pillars of rock subrounded by solution. Chert present in the dolomite is almost insoluble and remains intact in the residuum between the pinnacles. Prolonged exposure results in some cherts weathering to a friable white grit. The cherts tend to break up principally by mechanical action, mainly slumping.

Immediately below the watertable, the water is more acidic and has the highest rate of movement, resulting in the development of caverns at a very slow rate by corrosion seepage of carbon dioxide charged water through the jointed rock. The magnesite, which is about a hundred times more soluble than calcite, is preferentially dissolved in the rock (Jennings, 1966).

Iron and manganese, which are diadochic in the structure of dolomite differ from the alkali earth metals in that they are oxidised to Fe^{3+} and Mn^{4+} during the weathering process. The solution and oxidation of iron and manganese carbonates may be represented by the following reactions :

$$2\ MnCO_3 + H_2O \longrightarrow 2\ Mn(HCO_3) \qquad (1)$$

$$2\ Mn(HCO_3)_2 + 2H_2O + O_2 \longrightarrow 2\ MnO_2 + 4H_2CO_3 \qquad (2)$$

$$(1) + (2) :\ 2\ MnCO_3 + 2H_2O + O_2 \longrightarrow 2\ MnO_2 + 2H_2CO_3$$

and

$$4\ FeCO_3 + 4H_2CO_3 \longrightarrow 4\ Fe(HCO_3)_2 \qquad (3)$$

$$4\ Fe\ (HCO_3)_2 + 4H_2O + O_2 \longrightarrow 2Fe_2O_3 + 8H_2CO_3 \qquad (4)$$

$$(3) + (4) :\ 4\ FeCO_3 + 4H_2O + O_2 \longrightarrow 2\ Fe_2O_3 + 4H_2CO_3$$

Snyman (1981) reports that under more intensely oxidating conditions the solubility of iron and manganese are greatly reduced (Figures 4.6.1 and 4.6.2). The solubility is reduced such that hydrated iron and manganese oxides are deposited with the other soluble constituents of the original dolomite, to form wad.

Similtaneous widening of vertical slots and horizontal planes of weakness, mentioned earlier, results in isolated blocks or floaters of dolomite set in this residual wad soil. Completely isolated sub-rounded floaters have been observed in profile in the Oaktree Formation at Irene. This profile was intensely sampled as it presented an ideal residual soil in contact with its parent rock. Samples were taken laterally and vertically at 0,5 m intervals moving away from the rock. The weathered, as well as the partially leached rock was also sampled. This programme has permitted examination of the compositional changes that take place when the dolomite is weathered to produce wad in various stages of maturity.

The composition of fresh dolomite, leached dolomite and various wad samples determined by means of XRF analyses, were plotted on addition subtraction diagrams after the method of Bowen (1928). All analyses were normalised to one hundred percent on the anhydrous basis.

The formation of wad from fresh dolomite appears to require the addition of up to ninety percent of the material with a typical wad composition to the fresh dolomite composition (Nel, Personal Communications 1985) (Figure 4.6.3). Such an addition process is unlikely since wad is a weathering product. The formation of wad is, therefore, envisaged as a complex leaching process.

The initial leaching of wad, as deduced from analyses of wad samples in

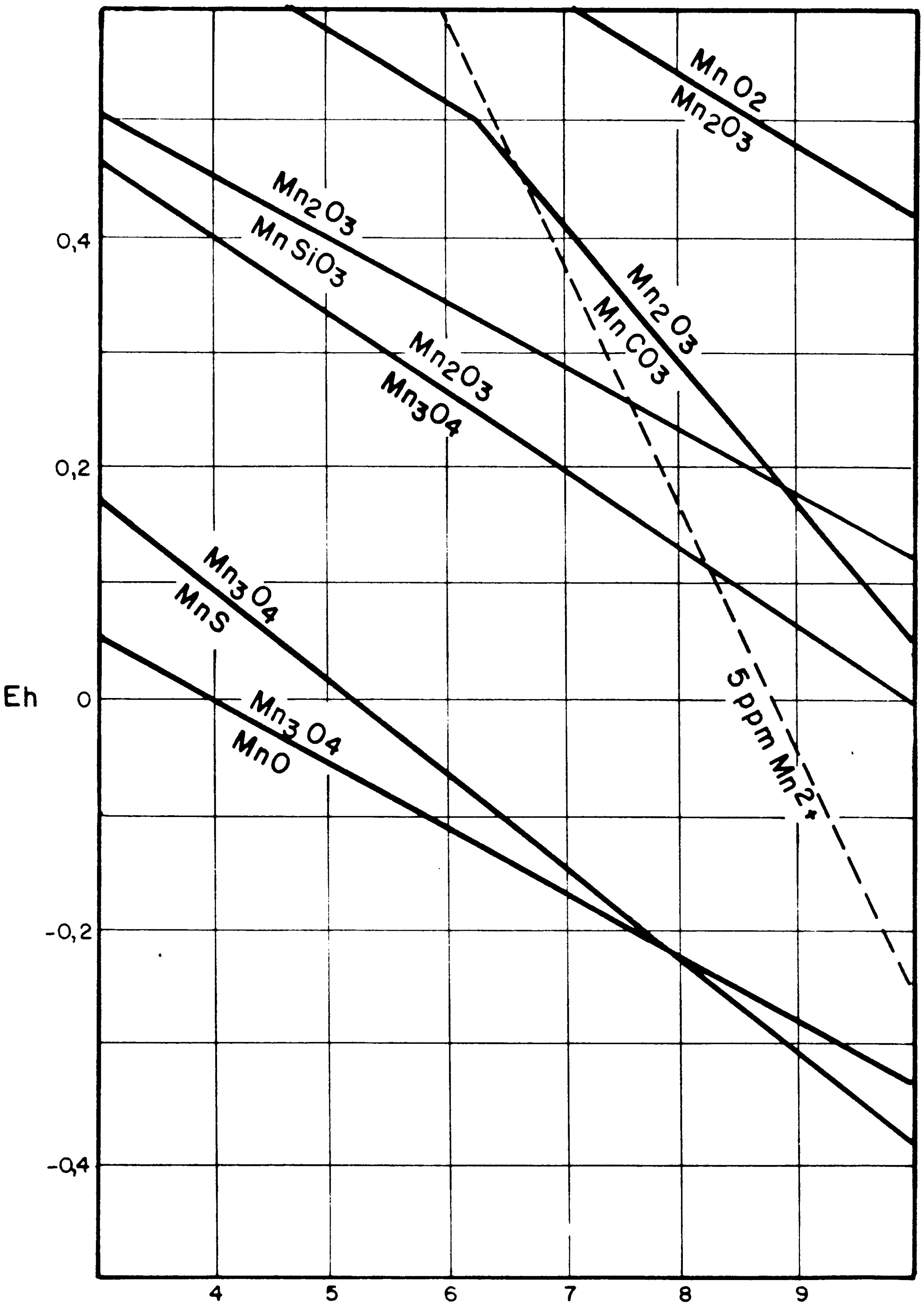


FIGURE 4.6.1 Eh/pH DIAGRAM.

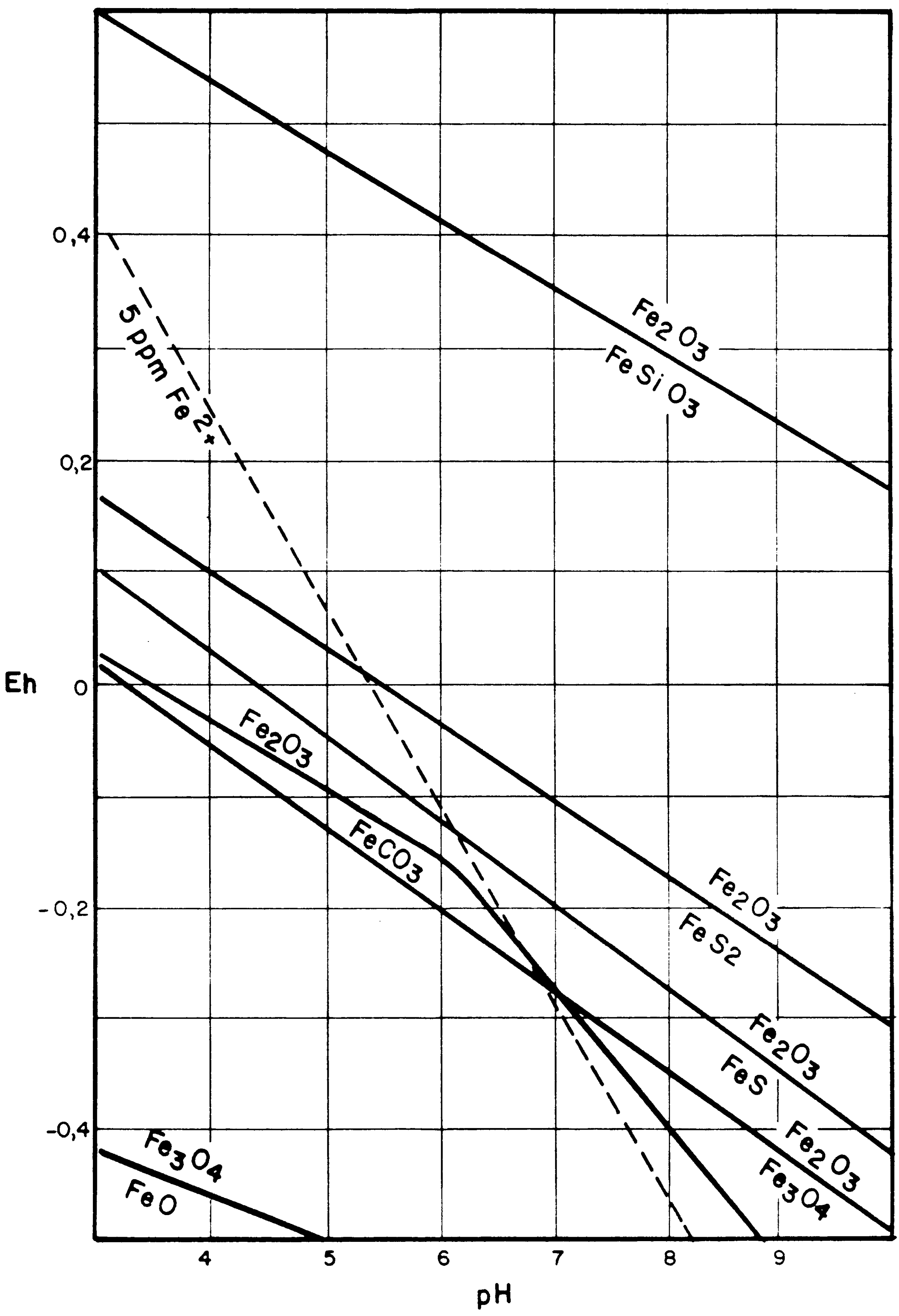


FIGURE 4.6.2 Eh /pH DIAGRAM.

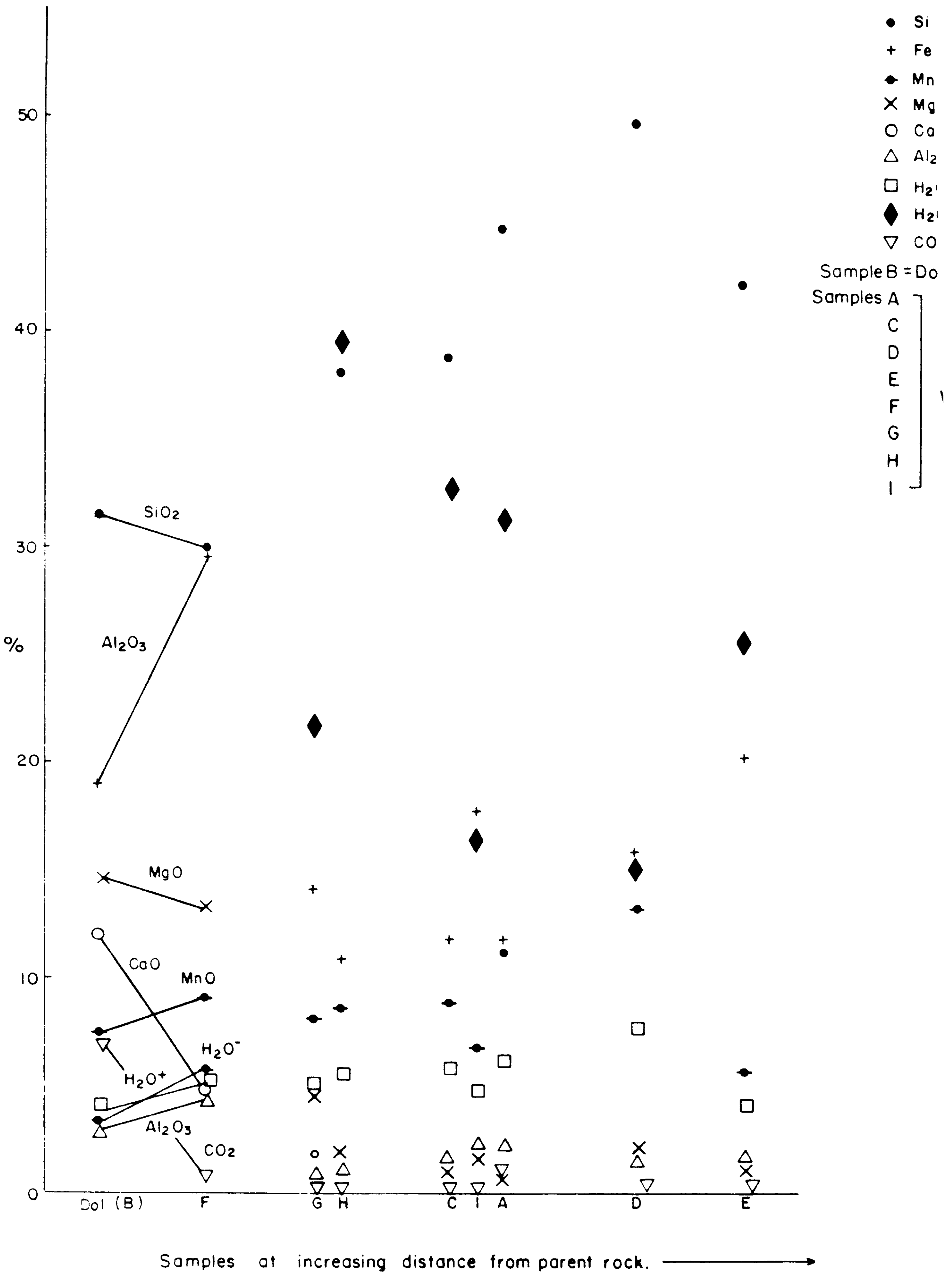


FIG. 4.6.3 WEATHERING OF THE DOLOMITE.

close proximity to the dolomite, involves the depletion of SiO_2, MgO and CaO (Figure 4.6.3). The removal of these elements results in a relative enrichment of the Al_2O_3, Fe_2O_3 and MnO which are comparatively less mobile. Depletion of MgO and CaO is expected in view of the mobility of Ca^{2+} and Mg^{2+} during the weathering process. Silica depletion, although not surprising, as the presence of silica, in natural waters has been proven by Krauskopf (1955) appears to be initiated at a fairly early stage. The enrichment of iron relative to manganese is attributable to the lower oxidation potential required to convert ferrous (Fe^{2+}) iron, from the form it occurs in dolomite, to the ferric state (Fe^{3+}) as compared to that required to convert manganese Mn^{2+} (fresh dolomite) to manganese dioxide. Iron readily precipitates as hydrated ferric oxide whereas the manganese remains in solution for a longer period before it is deposited under more oxidising conditions as manganese dioxide (Mason, 1966).

The more "mature" wad is represented by wad samples taken higher up in the residual soil profile and furtherest away from the dolomite. This wad is characterised by an increase in the SiO_2 and MnO concentrations and a depletion in the Al_2O_3, Fe_2O_3, CaO and MgO concentrations relative to the composition of leached dolomite. These compositional changes may be brought about by the precipitation of Si^{4+} and Mn^{4+} and the continued removal of Mg^{2+} and Ca^{2+} from the leached dolomite. The depletion of the Al_2O_3 and Fe_2O_3 concentrations results in an increase in relative concentrations of silica and manganese present in the soil (Nel, 1984 Personal Communication).

Calcite and SiO_2 in circulating groundwaters, leached from wad located higher in the profile may be deposited as secondary layers on sheetlet and sphere contacts. This secondary cementing may dramatically affect the geotechnical properties of the material.

Scanning electron microscope studies conducted on wad samples in contact with parent rock reveal an extremely sharp contact or transition zone between the rock and the soil. The amount of biotite and tremolite increases towards the weathered zone (Plates 1 and 2). The leaching process rapidly produces extensive voids. These voids are represented by the black zones in plate 2.

Chapter 5 : The Physical States of Wad

The physical state of a soil refers to the structure which is inherent in it as a consequence of a particular stress history and chemical interactions. The physical state or structure thus refers to the orientation and distribution of particles (fabric) in the soil mass and the forces between adjacent soil particles. Account must therefore be taken of both the fabric and intraparticle stability in the soil when assessing the engineering geological properties.

Wad is composed of discrete soil particles and particle groups but must be treated as a continuum for purposes of analysis. This assumption of a continuum is not surprising, as adequate theory of particulate mechanics is not available to directly characterise geotechnical properties of soils, such as strength, permeability, compressibility and deformation modulus. Classical soil mechanics is based on the assumption of homogeneity in the material undergoing assessment. Nonetheless, the values of properties that are chosen for use in continuum theories of soil mechanics are controlled directly by the particle characteristics, their arrangements, and the forces between them. Thus an understanding of the geotechnical properties characterising the wad requires consideration of these factors. Consequently the structure of the wad has been examined and classified.

This study has permitted examination of both the macrofabric and microfabric detail. Microfabric refers to the level of fabric requiring at least an optical microscope for study. Those features discernable to the naked eye are referred to as the macrofabric.

Wad has been classified into two primary groups on the basis of the microfabric and macrofabric observed. Two soils may, however, have the same fabric, but still exhibit different properties. The forces between particles and particle groups are not the same in each material. There thus exist similar fabrics but different fabric stabilities. Secondary cementing would also effect differences in stability. Moisture content variations in a soil of the same fabric will cause differing behavioural characteristics.

This discussion will be divided into consideration of primary and secondary features. The former concern the rock and soil fabric and the latter the discontinuities.

5.1 The Primary features of wad

Two types of wad may be distinguished on the basis of the fabric they possess (Figure 5.1.1).

5.1.1 Laminated wad

Laminated wad is characterised by a distinct layering on the microscale and on the macroscale (Figure 5.1.1). The layering is constituted on the microscale by stacked, fine sheets. These sheetlets display what appears to be varying degrees of leaching manifest in cavities, embayments and platelet or remnant structures (Plate 5). The wad consists of iron/-manganese oxides and hydroxides. Amphiboles may be present in the material. Macroscopically the layering is clearly developed and can be distinguished with the naked eye (Plates 3 and 6).

The parent rock from which this laminated wad is derived has been sampled and thin sections made for examination.

The fabric developed in the wad is determined by the nature of the fabric inherent in the parent dolomite. The sheeted material displays a remnant

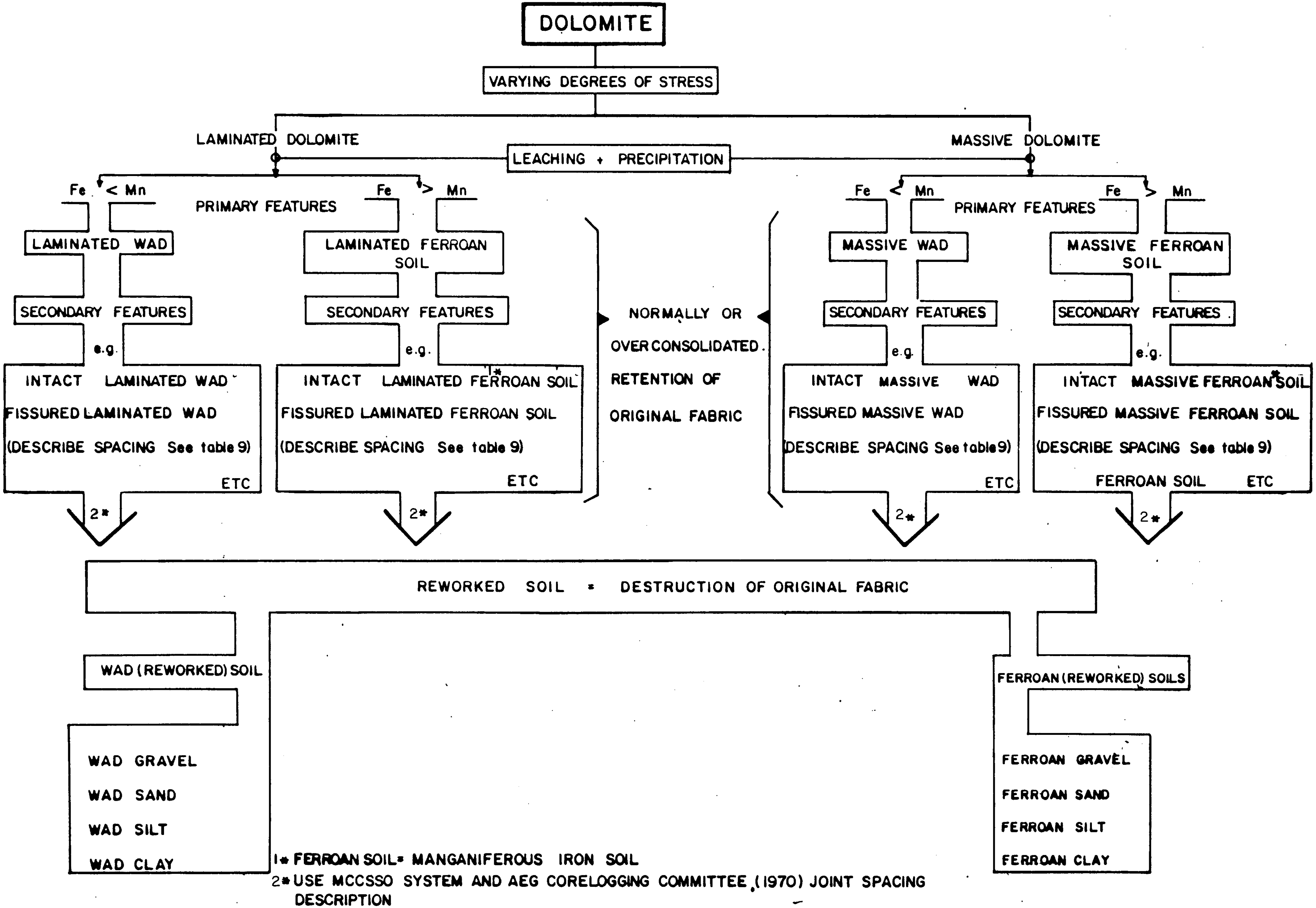


FIGURE 5.11: PHYSICAL STATES OF WAD

PLATE 3 : LAMINATED WAD. SECONDARY FEATURES FILLED WITH RED SOIL.

PLATE 4: BLOCKS OF LAMINATED WAD REMOVED FROM SOIL PROFILE. BLOCKS DEFINED BY FISSURES.

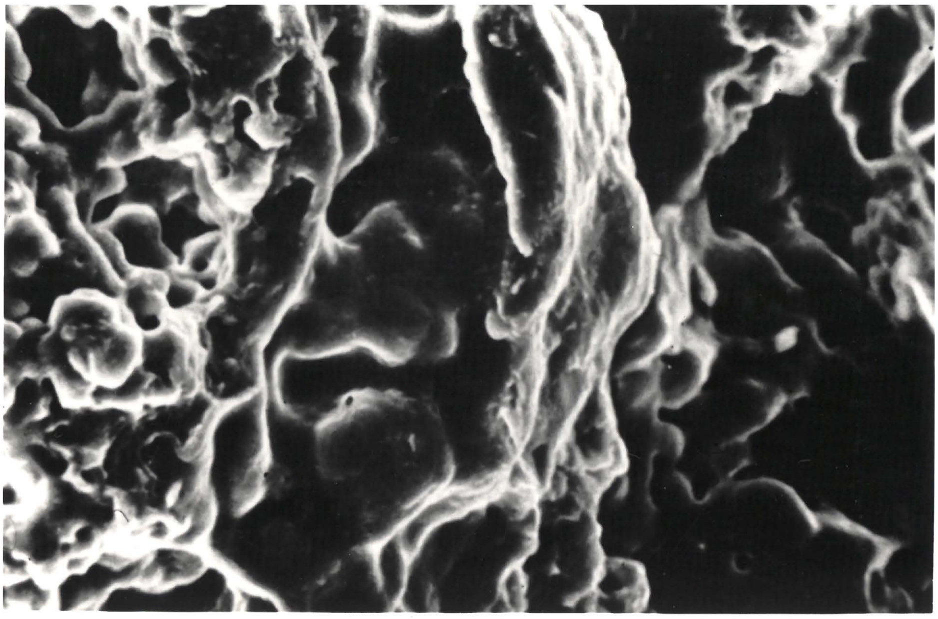


PLATE 5 : SCANNING ELECTRON MICROSCOPE PHOTOGRAPH OF LAMINATED WAD.

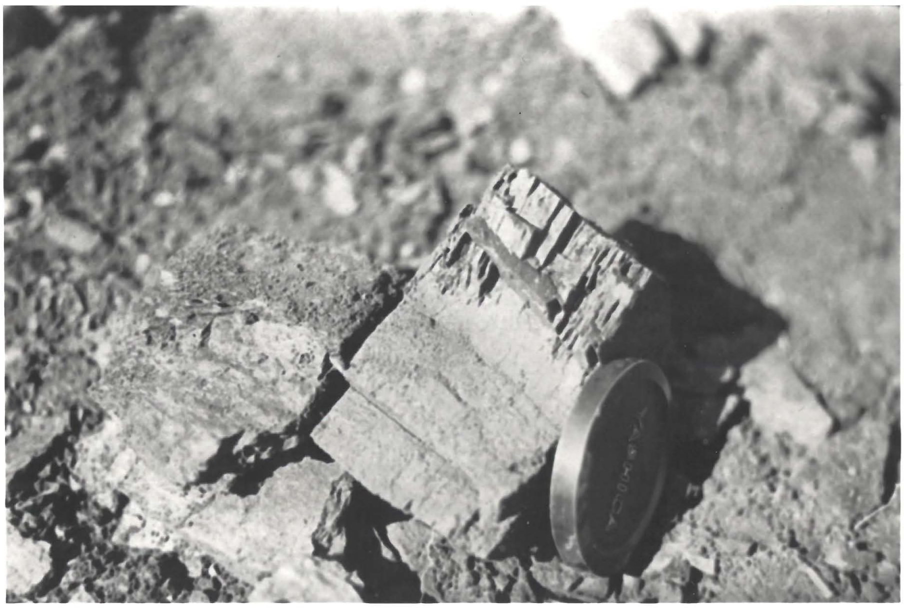


PLATE 6 : FISSURED LAMINATED WAD.

structure derived from laminations present in the dolomite. The layered fabric in this dolomite is defined by elongated grains that are developed co-planar with the original sedimentary layering in the rock. Manifestations of this layering are discernable on the weathered surface of the dolomite on the macroscale (Plate 7).

The dolomite contains short sub-idioblastic amphibole grains, namely tremolite, that are often associated with calcite. The tremolite and calcite assemblage is probably the result of reaction between dolomite and silicon at low metamorphic grades. The heat source is believed to have been the syenite sills and dykes that occur in close proximity to the dolomite sampling localities.

In this laminated dolomite the elongated dolomite grains are often warped around the amphiboles and calcite intergrowths to produce an augen texture. This texture suggests the development of the fabric subsequent to the metamorphic event.

The development of this layered fabric in the dolomite is probably attributable to the rock being subjected to stress. This stress may be associated with the intrusion of the sills or subsequent tectonic activity.

The postulated stress origin of laminated dolomite due to tectonic activity is favoured for the following reasons :

1) The presence of laminated wad in the Eccles Formation where no intrusions are discernable in close proximity to the sample localities.
2) The development of massive and laminated wad in close proximity to the sills and dykes in the Oaktree Formation.
3) The development of lineaments on fine carbonate and chert layers and on slip planes parallel to the fabric in samples of laminated dolomite.

4) The warping of dolomite crystals around amphiboles and calcite intergrowths suggesting a post-metamorphic origin for the fabric.

"Stressed" dolomite is randomly distributed, suggesting local variations in stress buildup in the Chuniespoort Group. The stressing of the dolomite may be a manifestation of the tectonic activity such as folding and faulting under low temperatures after the intrusion of the syenite.

The structure of the wad is thus composed of fabric and interparticle force systems that reflect, to some degree, all the facets of the soil composition and history. The structure determining factors are summarised in figure 5.1.1.1 The laminated wad fabric is anisotropic which will give rise to anisotropic properties.

5.1.2. Non laminated or massive wad

The non laminated or massive wad is characterised by loosely packed spheres of iron and manganese oxides (Plate 7). Amphiboles were found in samples collected near igneous intrusions. On the macroscale no structuring of the material is discernable and it appears massive (Plate 8). Massive is used in the context as defined in the Oxford Dictionary, as indicating a material with no form or distinguishing features.

Macroscopically, the parent dolomite, from which the massive wad is derived, has no discernable features.

Microscopic examination of the dolomite fails to reveal a preferential mineral orientation as is the case with the laminated dolomite. The chemical composition is, however, similar to that of the laminated dolomite (Nel Personal Communication 1985).

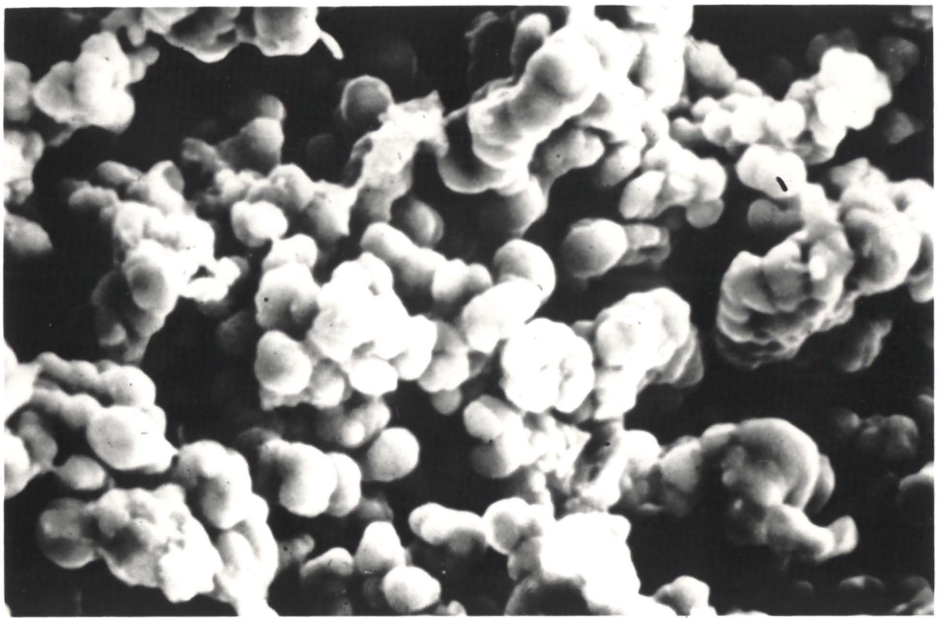


PLATE 7: SCANNING ELECTRON MICROSCOPE PHOTOGRAPH OF MASSIVE WAD.

PLATE 8: MASSIVE WAD.

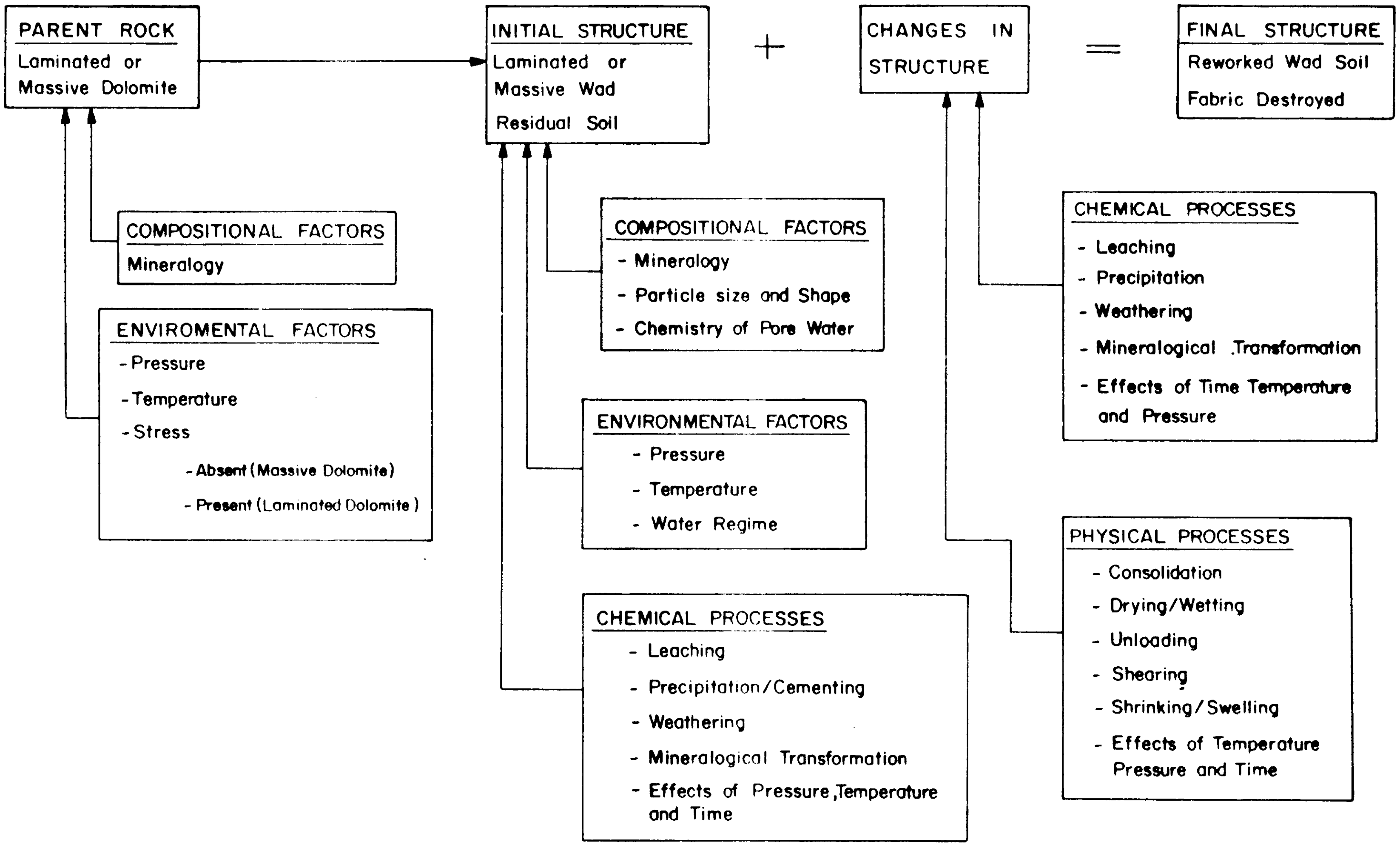


FIGURE 5.1.1.1 : STRUCTURE DETERMINING FACTORS AND PROCESSES FOR LAMINATED WAD, MASSIVE WAD AND REWORKED WAD SOIL.

5.2 The Secondary features of wad

Secondary features refer to bedding planes, joints or any discontinuity super-imposed on the original dolomite and retained as remnant features is the residual wad (Plate 6 and 8). These secondary features may influence the geotechnical properties of the soil mass as a whole.

Residual non-reworked or partially reworked wad may, on a scale of centimeters be visually classified as follows :

i) Intact laminated residual wad. (No Fissures).

ii) Fissured laminated residual wad (Spacing of fissures must be described e.g. widely fissured. Refer Chapter 8).

The massive dolomite may have been subjected to jointing of various intensities and orientations resulting in :

i) Intact massive residual wad. (No fissures).

ii) Fissured Massive Residual Wad. (Spacing described).

5.3 Reworked Wad

The disturbance, displacement, slumping, reworking or remoulding of the residual massive and laminated soils with the possible addition of external impurities gives rise to material which may be classified as totally reworked wad soil (Plate 10 and 11 and Figure 5.1.1.1). Terms of description could include "reworked wad clay" or "wad gravel". The wad clay could for instance, consist primarily of montmorrillonite with very little amorphous wad present (Buttrick 1985).

PLATE 9: LAMINATED WAD MACROSCALE APPEARANCE

PLATE 10: RESIDUAL WAD ON A PINNACLE AND ADJACENT REWORKED WAD SOIL

PLATE II : REWORKED WAD SOIL.

Chapter 6 : Test Methods and Definitions of Soil Parameters

The purpose of this chapter is to give a brief definition and description of the test methods and parameters discussed in this study. These parameters and test methods are not expounded on in any great detail as this is done elsewhere, in other publications, particulary in British Standards 1377 (1975).

This chapter is thus presented to assist the reader who is not entirely familiar with the field of geotechnics, in understanding the parameters and test methods used to characterise the material behaviour.

6.1 Oedometer test

The oedometer consolidation test is utilized to determine the potential compressibility of a soil and the rate of compression. The compressibility of the soil is expressed in terms of the coefficient of volume compressibility which is essentially a measure of the magnitude by which the soil may be compressed under the influence of an imposed load. The rate of compression is obviously a time-related parameter which indicates the time period over which consolidation settlement will occur.

Some of the typical expressions used in association with consolidation tests are listed and defined below :

Consolidation :

The process by which solid particles are packed more closely together over a period of time under the influence of an applied load. The consolidation process is accompanied by the drainage of water from the pore spaces between solid particles (Figure 6.1.1).

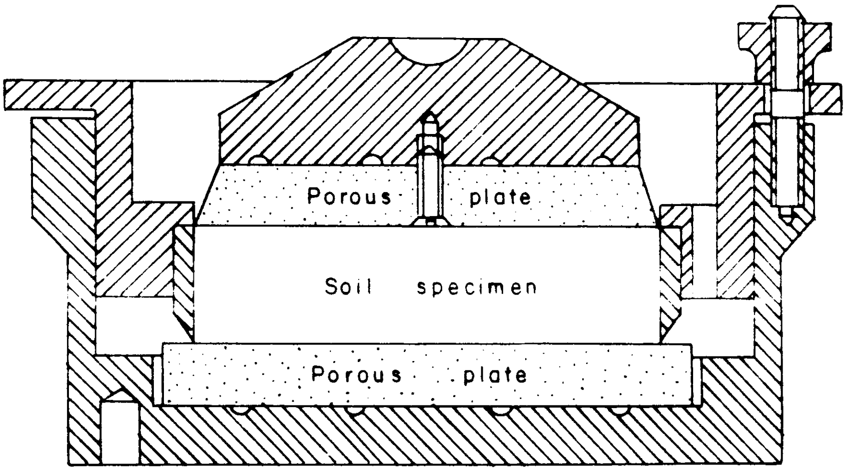


FIG. 6.1.1 DIAGRAMMATIC ILLUSTRATION OF A TYPICAL CONSOLIDATION CELL.

Void ratio (e)

The void ratio is the ratio of the volume of voids to the volume of solid particles in a mass of soil.

Degree of saturation (S)

The volume of water contained in the void spaces between solid particles, expressed as a percentage of the total voids.

Pore water pressure (μ)

The hydrostatic pressure of the water in the voids or pores between solid particles.

Total stress (σ)

The stress in the soil mass due to the application of an applied external pressure.

Effective stress (σ')

The effective stress is the difference between the total stress and the pore water pressure.

$$\sigma' = \sigma - \mu$$

The effective stress approximates to the stress carried by the solid soil structure.

Initial compression

Initial compression refers to the amount of compression which takes place between the instant of application of the load and the beginning of the primary consolidation phase.

Primary consolidation

The phase of total compression under load during which drainage and pore pressure dissipation occur is referred to as the primary consolidation phase.

Secondary consolidation

Secondary consolidation continues after primary consolidation has finished. Creep sometimes characterises the behaviour in this phase.

Coefficient of Compressibility (a_v)

The coefficient of compressibility is defined as the change in void ratio per unit pressure change, as a result of consolidation due to that pressure change

$$a_v = \frac{e_2 - e_1}{p}$$

The change in void ratio denoted by e and change in pressure denoted by p, refer to incremented changes. Void ratio's e_1 and e_2 are the voids ratio at the beginning and end of consolidation under the load increment po and po + p respectively. The coefficient of compressibility is thus equal to the negative slope of the void ratio/pressure curve. Units : m^2/ N (See Figure 6.1.2)

Coefficient of volume compressibility (M_v)

The coefficient of volume compressibility refers to the change in volume per unit volume, per unit pressure change as a result of consolidation due to that pressure change.

$$M_v = \frac{a_v}{1+e_1} = \frac{-(1)}{(1+e_1)} \cdot \frac{\Delta e}{p}$$

e_1 is the void ratio at the start of the increment of load p. The units are the same as those for a_v but are usually multiplied by 1000 to express M_v as M^2/MN avoiding inconveniently small numerical values.

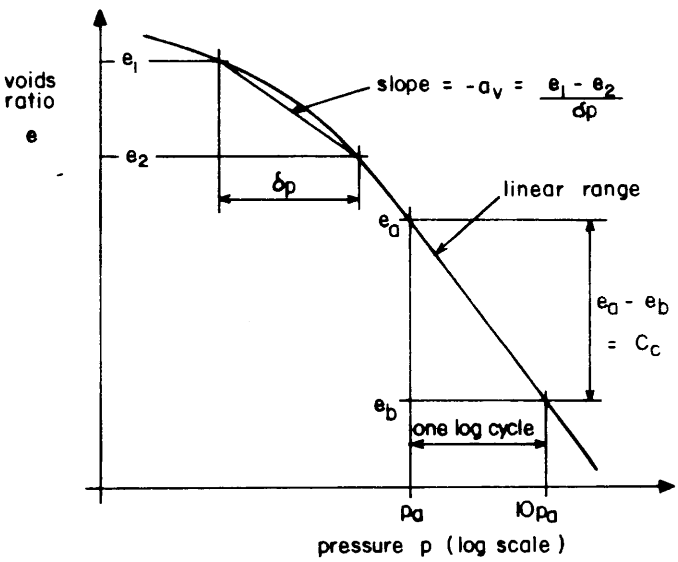


FIG. 6.1.2 LOG-PRESSURE/VOIDS RATIO CURVE (e/log p curve)

Coefficient of consolidation (C_v)

This parameter relates the pore pressure to time, to the amount of water draining out of the voids of a clay prism due to consolidation.

$$C_v = \frac{k}{M_v \rho_{w} g}$$

g = gravity ρ_w = density of water

k = permeability of material

Compression index C_c

The compression index is equal to the slope of the field consolidation curve in the linear range.

Normally consolidated clay

A normally consolidated clay is a clay which has never been subjected to a greater pressure than the present overburden pressure.

Overconsolidated clay

A clay deposit which in past geological times has been consolidated under a pressure greater than the present overburden pressure by overlying deposits which have since been eroded away.

Pre-consolidation pressure

The pre-consolidation pressure refers to the maximum pressure to which an overconsolidated clay has been subjected.

Over consolidation ratio (OCR)

The overconsolidation ratio is the ratio of the pre-consolidation pressure to the present effective overburden pressure.

$$OCR = \frac{pc}{po}$$

The consolidation test is carried out by applying a sequence of four to eight vertical loads to a laterally confined specimen having a height about one quarter its diameter. The vertical compression under the influence of each load increment is observed over a period of time, usually 24 hours. The test essentially determines one-dimensional consolidation parameters as no lateral deformation is permitted. The oedometer ring in which the sample is emplaced serves to confine or restrict the sample, permitting no lateral movement (Figure 6.1.1).

The test procedure used in this study is described in BS 1377 (1975),

Jennings and Knight (1975) proposed the use of the oedometer appartus to study the behaviour of soils with a collapsible fabric under the influence of an applied load and flooding.

A sample of soil is cut to fit neatly into an oedometer ring. Care is taken not to change the moisture content during transfer to the laboratory.

Consolidometer test is conducted at natural moisture content. Loads are increased incrementally to 200 kPa. The specimen is then flooded with water at 200 kPa, left for twenty four hours and the test is then carried on to its limit (Figure 6.1.3).

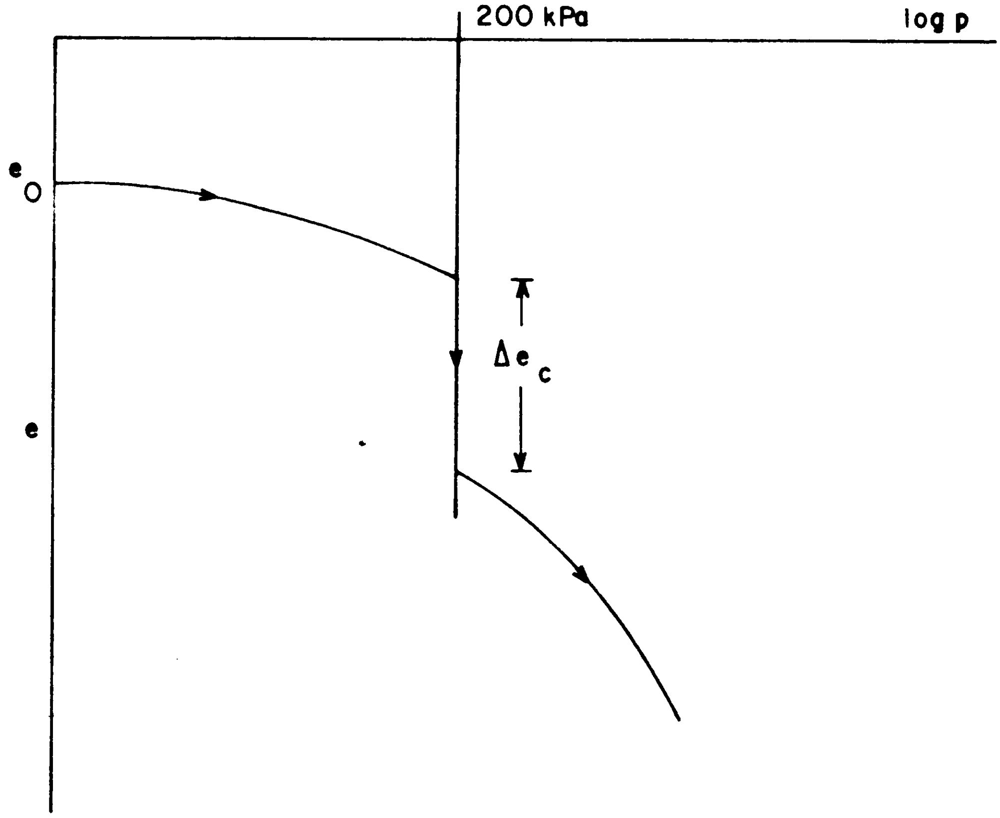


FIG: 6.1.3 TYPICAL COLLAPSE POTENTIAL TEST RESULT.

The collapse potential (CP) is defined as $\frac{\Delta e}{1+e_o} \times 100\%$ and is an index figure, providing a ball park guide to the potential collapse in a soil (Jennings et al. 1973).

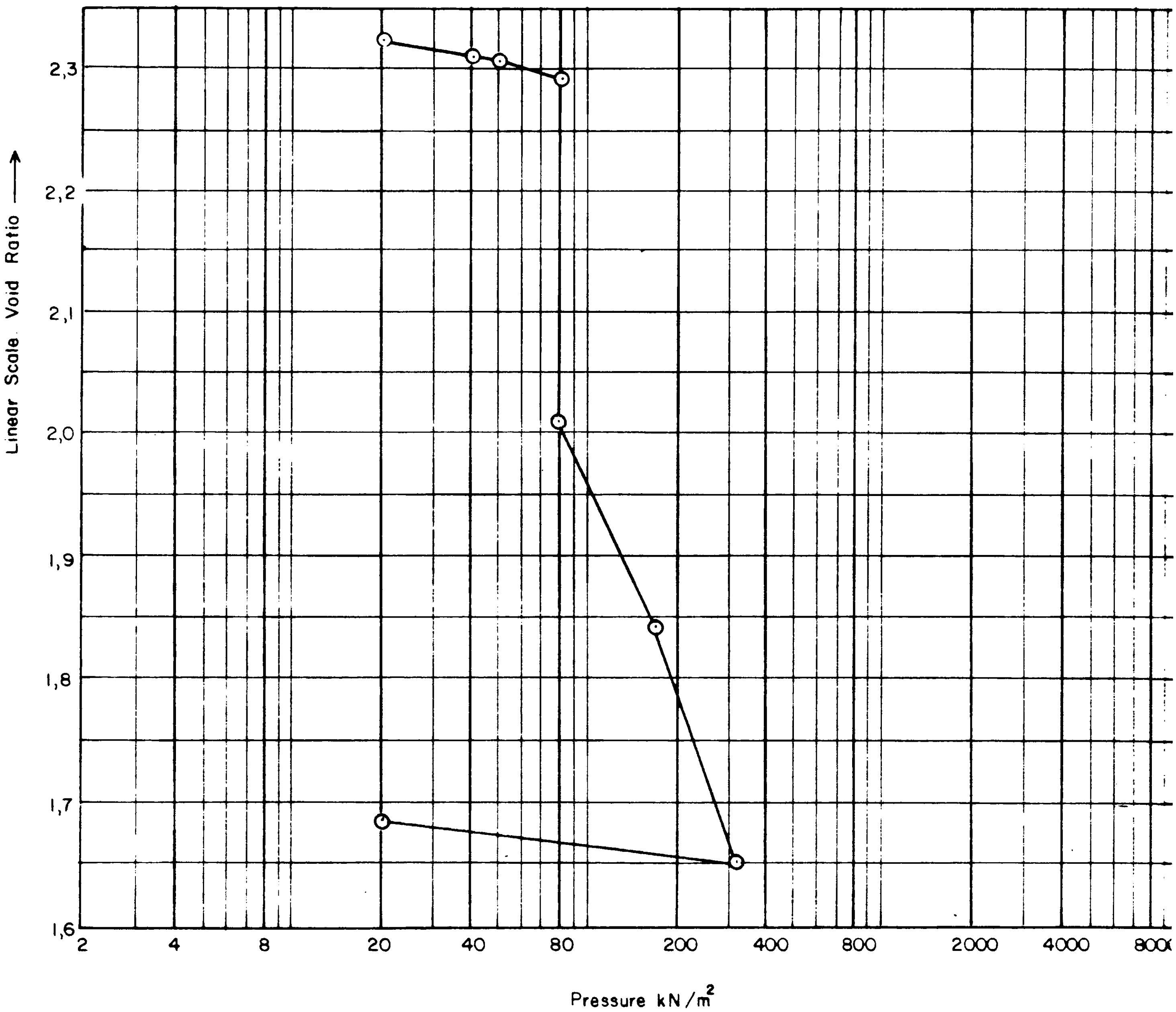
In this study inundation has been initiated at either 50 kPa or 80 kPa. (Figure 6.1.3). These values were chosen to permit comparisons to be drawn with the work already done by Wagener (1984) and Day (1981). These samples tested in this manner have been retrieved at shallow depth ensuring that the overburden pressure is exceeded during the test.

The collapse potential values has become synonomous with the Jennings method (1973). The author believes that the values obtained at loads other than 200 kPa should simply be referred to as potential volume change values (Figure 6.1.4).

6.2 Direct shear test

The shearbox test is the most straightforward procedure for measuring the 'immediate' or short term shear strength of soils. Parameters of soils determined during this test are the angle of friction and the cohesion of the soil.

In principle the shearbox test is an "angle of friction" test in which one portion of soil is made to slide along another by the action of an increasing horizontal shearing force. A constant load is applied normal to the plane of relative movement. The test is executed by placing the soil in a rigid box, square in plan and consisting of two halves. The lower half of the box can move relative to the upper half. This lower half of the shearbox is driven by a motorised unit. The normal pressure is provided by a yoke supporting a load hanger. The arrangement of the



BULK DENSITY 934 kg/m^3

INITIAL VOID RATIO 2,3416

SPECIFIC GRAVITY 2,67

NATURAL MOISTURE CONTENT 17 % dry wt

DRY DENSITY 797 kg/m^3

DEGREE OF SATURATION 94 %

FIG. 6.1.4. PERCENTAGE VOLUME CHANGE TEST RESULT.

shearbox is shown in figure 6.2.1 During the shearing process the relative displacement of the two portions of the sample and the applied shearing force are both measured so that a load/displacement curve can be plotted.

During the shearing process the vertical movement of the top of the specimen is monitored. The movement gives an indication of the volume changes and enables an evaluation to be made of the changes in the void ratio and density during shearing.

This test is not covered in the British Standard (1975) but the test is described by Head (1982). The apparatus is depicted in figure 6.2.1.

Some theoretical knowledge is necessary for a proper understanding of the test principles. Basic concepts are briefly defined below :

Normal force : A force which acts perpendicularly to a plane of section.

Shear force : A force which acts tangential to a plane of section.

Shear stress : Shear force per unit area.

Shear resistance of a Soil (kPa) : The resistance which a soil can offer to deformation when it is subjected to shear stress.

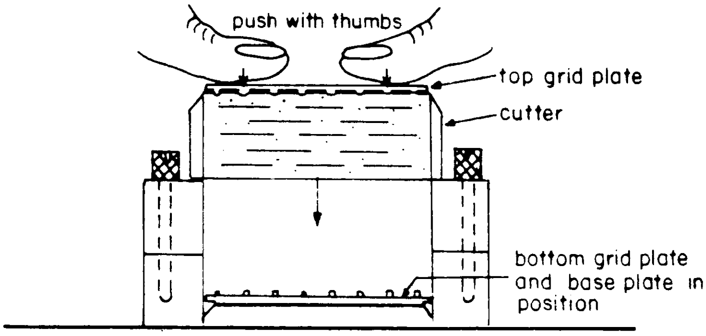
Shear strength : The maximum shear resistance that a soil can offer under defined conditions of effective pressure and drainage.

Angle of shear resistance : The component of shear strength of a soil which is due to friction between the particles.

Apparent cohesion (Cu) : The shear strength of a soil when subjected to zero normal stress or confining pressure.

Coulomb's law : The relationship between the shear stress τ (f) and the normal stress σ_n on a plane of failure, expressed by the empirical equation.

$$\tau_f = Cu + \sigma \tan \phi$$



PUSHING COHESIVE SPECIMEN OUT OF CUTTER INTO SHEARBOX.

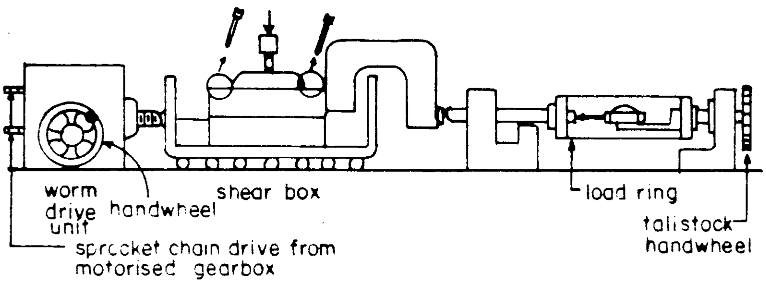


FIG. 6.2.1. SHEARBOX TEST APPARATUS.

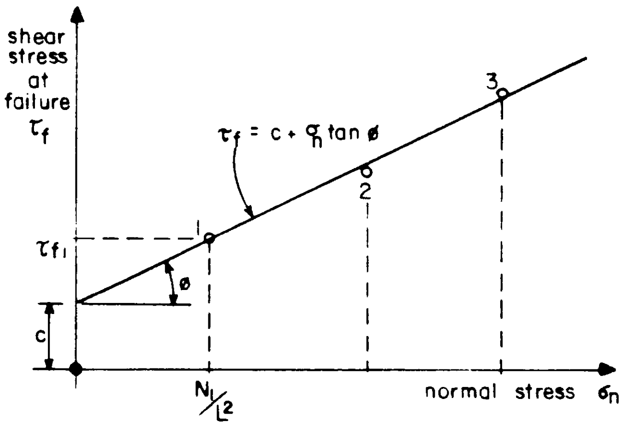


FIG. 6.2.2. MAXIMUM SHEAR STRESS RELATED TO NORMAL STRESS FROM SHEARBOX TESTS. (Coulomb envelope)

6.3 Pinhole test

The pinhole test is in the strictest sense, a test of erodibility rather than of dispersiveness.

The test is detailed by Sherard, et al (1976). Distilled water is caused to flow through a 1 mm diameter hole created in a recompacted specimen of the soil. This water, emerging from an erodible material, will carry a suspension of particles. Water passing through an erosion resistant material will be crystal clear. The test is based purely on visual assessment.

The pinhole apparatus is detailed in figure 6.3.1. Soils were originally classified according to the test results into "Dispersive Soils" (categories D1 and D2) and "non dispersive soils" (categories ND1 to ND4 Table 5). These classes should now rather be taken to read "erodible" and "non erodible" material.

6.4 Crumb test

The crumb test is described by Sherard et al. (1976). No special equipment is required and the advantage of using this test lies in its simplicity.

The procedure entails depositing a few representative "crumbs" or clods (± 6 to 10 mm in diameter) in a beaker of distilled water or a sodium hydroxide solution. For many soils the use of distilled water is as good an indicator as the sodium hydroxide solution. Many soils, however, do not react in the distilled water, but do so in the solution. The reaction is observed after five to ten minutes.

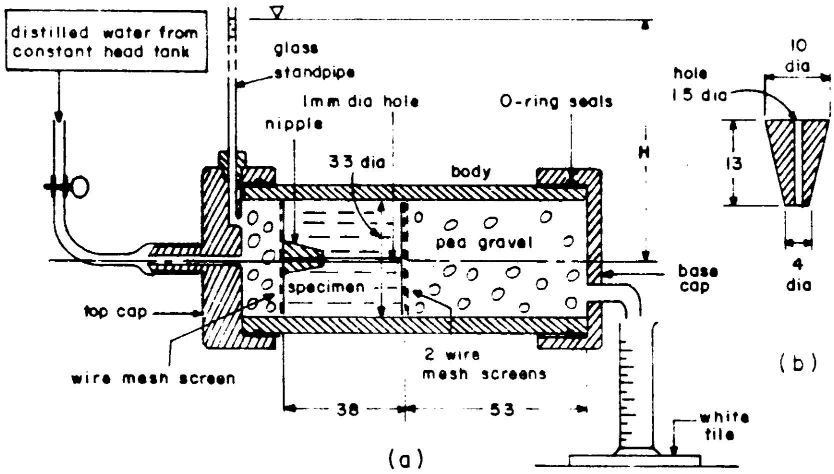


FIGURE 6.3.1. APPARATUS FOR PINHOLE TEST: (a) GENERAL ARRANGEMENT (b) DETAILS OF NIPPLE (DIMENSIONS IN MILLIMETRES)(after Sherard et al,1976)

CLASSIFICATION		HEAD mm	TEST TIME FOR GIVEN HEAD MINUTES	FINAL FLOW RATE ml/sec.	COLOUR OF FLOW AT END OF TEST	HOLE SIZE AFTER TEST
Dispersive	D 1	50	5	> 1,5	Very distinct	> 2x
	D 2	50	10	> 1,0	Distinct to slight	2x
Intermediate	ND 4	50	10	< 0,8	Slight but easily visible	1,5x
	ND 3	180-380	5	> 2,5	Slight but easily visible	2x
Non-dispersive	ND 2	1000	5	> 3,5	Clear or barely visible	< 2x
	ND 1	1000	5	< 5,0	Crystal clear.	No erosion

TABLE. 5: EVALUATION OF PINHOLE TEST RESULTS:

SOURCE	% DISPERSION FOR		
	HIGHLY DISPERSIVE	INTERMEDIATE	SLIGHTLY DISPERSIVE
Sherard (3)	> 67 %	33 to 67 %	< 33%
Ryker (11)	> 35 %		< 35%
Holmgren & Flanagan	> 40 %		< 40 %
Marshall & Werkman	> 50 %	30 to 50%	< 30 %
Decker & Dunnigan (6)	generally > 30 %; depending on soil type > 25 to 40 %	10 to 30 %	< 10 % depending on soil type < 25 to 40%

$$\% \text{ DISPERSION} = \frac{\% \text{ CLAY } (< 5\,\mu m) \text{ DISPERSING NATURALLY}}{\% \text{ CLAY } (< 5\,\mu m) \text{ WITH DISPERSING AGENT}}$$

TABLE. 6: SCS DOUBLE HYDROMETER DISPERSION TEST.

(From Scheurenberg 1980)

The observations are classified into four classes namely :

Class 1 : No dispersion - No sign of colloidal dispersion

Class 2 : Slight dispersion - Bare hint of colloidal cloud on surface of crumb

Class 3 : Moderate dispersion - Obvious cloud of colloids in suspension

Class 4 : Strongly dispersive - Colloidal cloud covers bottom of beaker. In extreme cases, all the water in the beaker becomes cloudy.

According to Elges (1985) the crumb test generally gives a good indication of the potential dispersiveness of soil. The warning is given, however, that a dispersive soil may give a non dispersive reaction using this test method.

SCS Double Hydrometer Dispersion Test

The Soil Conservation Services (SCS) laboratory dispersion test was developed from a method proposed by Volk in 1937 (Elges 1985). The test procedure is described in Head's (1982) "Soil Laboratory Testing" (Volume 2).

Result of a standard hydrometer analysis are compared with those of an analysis conducted without the use of a dispersant and a minimum of agitation. The resultant particle size distribution curves are drawn on the same sheet.

$$\text{Percent Dispersion} = \frac{\%\ \text{Clay}\ (<5\mu m)\ \text{dispersing naturally}}{\%\ \text{Clay}\ (<5\mu m)\ \text{with dispersing agent}}$$

Table 6 indicates suggested interpretations of the test results.

6.5 Flow test

This test involves using the permeameter apparatus. The sample is emplaced in the mould. A head of water is applied to the sample. Flow of water through the sample is permitted to proceed for several days with the permeability being ascertained every twelve hours. The colour of the water emerging from the sample is also monitored. The potential erodibility of the material is thus ascertained.

6.6 Chemical Tests

Clays with a low salt content in the pore water and the presence of exchangeable sodium are highly susceptible to dispersive behaviour.

The basic parameter to quantify this behaviour is the Exchangeable Sodium Percentage (ESP) where

$$ESP = \frac{\text{exchangeable sodium}}{\text{cation exchange capacity (CEC)}} \times 100\ \%$$

Units Me/100 gm of dry soil.

The ESP is often quoted as the criterion for potential dispersiveness with suggestions that the soil is dispersive if the ESP exceeds the value of to 24% (Scheurenberg 1980).

Another parameter commonly used to express the role of sodium where free salts are present is the SAR (Sodium Absorption Ratio) of the pore water. The procedure involves mixing the soil at natural moisture content with distilled water to bring the soil to its liquid limit. The soil is allowed to stand for several hours permitting equilibrium to be established in the soil/water system.

A saturation extract is taken from this saturated soil paste and analysed to determine the quantities of the four metallic cations in solution i.e. calcium, magnesium, sodium and potassium in milli equivalents per litre (Me/litre). The total dissolved salts (TDS) is taken to be equal to the sum of the quantities of these four cations :

$$TDS = Ca + Mg + Na + K$$

$$\text{Percentage Sodium} = \frac{Na}{TDS} \times 100\%$$

The sodium absorption ratio is calculated from the equation :

$$SAR = \frac{Na}{\frac{Ca+Mg}{2}}$$

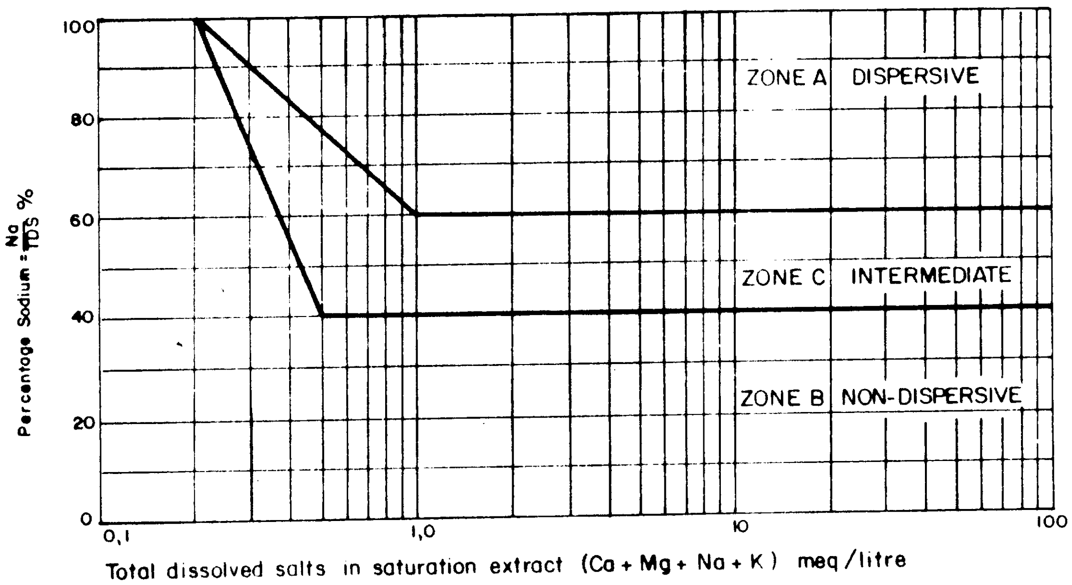
The SAR is a measure of the amount of sodium in the pore water relative to other cations and is the main factor in determining the dispersiveness (Figure 6.6.1). Generally if SAR exceeds one, the clay will be dispersive (Head 1982). The details of this test are given by Sherard *et al.* (1976).

6.7 Triaxial test

Details of the triaxial test procedures are described by Bishop and Henkel (1974).

The type of triaxial test used in this study is the cylindrical compression test. A cylindrical sample is encased in a thin rubber sheath with rigid caps and pistons on both ends and placed in a triaxial cell (Figure 6.7.1). The cell is then filled with a fluid and by application of pressure to the fluid the specimen may be subjected to hydrostatic compressive stress. Shear stresses are created in the specimen by applying additional vertical stress. This additional vertical stress is -

FIGURE. 6.6.1 POTENTIAL DISPERSIVENESS CHART



Reference: Sherard, Dunnigan and Decker: Identification and nature of dispersive soils. Jour Geotech. Div. ASCE Apr 1976

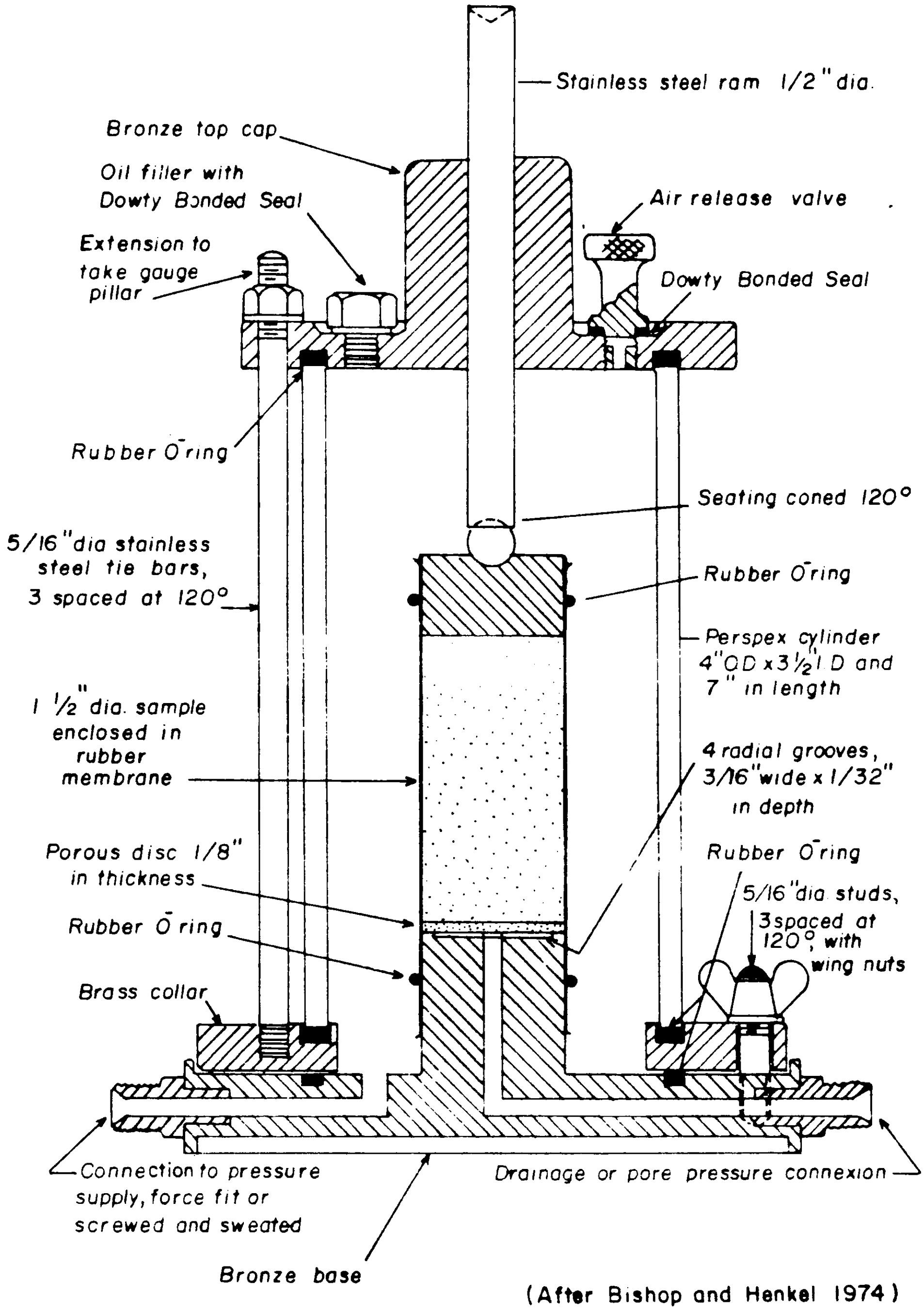


FIG .6.7.1. THE TRIAXIAL CELL.

obtained by applying a load axially through a ram acting on the top cap and is termed the deviator stress. Under these conditions the axial stress is the major principal stress σ_1, while the intermediate and minor principal stresses (σ_2 and σ_3 respectively) are both equal to the cell pressure.

Connections at the ends of the sample permit either the drainage of water and air from the voids in the soil or the measurement of the pore pressure under conditions of no drainage. The drainage of water from the specimen is measured by a burette.

There are three conditions under which shear tests may be performed. Generally the application of the all round pressures and of the deviator stress, form two separate stages of the test. The three conditions under which the tests are classified depend on the conditions of drainage obtaining during each stage.

i) Unconsolidated - Undrained Test (UU or Quick Test). No drainage is allowed during application of confining pressure σ_3. No dissipation of pore pressure is allowed to occur. No drainage is allowed during the application of the deviator stress.

ii) Consolidated - Undrained Test (Cu Test). Drainage is permitted during the application of the all round stress, so that the sample is fully consolidated under this pressure. No drainage is allowed during the application of the deviator stress.

iii) Consolidated-Drained Test (CD or Slow Test). Drainage is permitted throughout the entire test, so that full consolidation occurs under the all round stress and no excess pore pressure is set up during the application of the deviator stress. In carrying out drained tests on soils of low permeability sufficient time must be allowed for the excess pore pressure to dissipate. The rate of testing therefore depends on the coefficient of consolidation.

To obtain Mohr's envelope, several triaxial tests should be performed on specimens of the same soil using various confining (cell) pressures σ_3.

6.8 Atterberg Limits

Atterberg Limits are indices useful in characterising assemblages of soil particles. The limits are based on the concept that a fine grained soil can exist in any of four states depending on its water content. A soil is a solid when dry and upon the addition of water, proceeds through several stages namely the semi-solid, plastic and liquid phases. The moisture contents at which the soil passes from one stage to the next is known as the consistency limits or Atterberg Limits. The tests to determine these limits are conducted on material passing through the 425 μm BS test sieve. The moisture content of a soil is defined as the ratio of the weight of water to the weight of solids in a given volume.

Liquid Limit (LL)

The liquid limit is the minimum moisture content at which the soil will flow under its own weight. The procedure for determining the liquid limit is detailed in the British Standards 1377 of 1975 Test 2 (B).

The liquid limit is determined by measuring the water content and the number of blows required to close a groove of specific width for a specified length in a standard liquid limit or Casagrande device.

A cake of wet soil is placed in the circular brass dish and a groove is cut in it with the grooving tool. By rotating the handle of the device the dish is raised to a height of 1 cm and then falls freely on a block of hard rubber. Rotation is effected at a rate of two blows per second until the groove closes over a length of 13 mm. The number of blows is recorded. The soil is said to be at its liquid limit when 25 blows are required to close the gap. A graph of the moisture content versus number of blows can be plotted after several attempts. The moisture content corresponding to 25 blows can then be read off.

6.9 Plastic Limit (PL)

The plastic limit is defined as the minimum moisture content at which a soil can be rolled into a thread 3 mm in diameter without breaking. The procedure for determining the plastic limit is described in British Standards 1377 (1975), Test 3.

A wetted sample of about 20 g (passing the 425 μm sieve) is rolled with the palm of the hand on a glass plate into a thread of about 3 mm in diameter. The thread is folded and rolled repeatedly until it begins to crumble. The moisture content of the crumbled sample is then determined as the plastic limit.

6.10 Plasticity Index (PI)

The Plasticity index (PI) is a measure of the moisture content range over which a soil behaves plastically and is the difference between the liquid and plastic limits.

$$PI = LL - PL$$

6.11 Linear Shrinkage

The linear shrinkage percentage indicates the change length of the sample over the original sample length as a consequence of dessication.

Percentage of Linear Shrinkage

$$= \left(1 - \frac{\text{Length of oven dry specimen}}{\text{Initial length of specimen}}\right) \times 100$$

The procedure for determining the linear shrinkage value is described in Test 5, British Standards 1377 (1975). The basic procedure entails mixing the sample of soil with distilled water into a smooth homogenous paste. This paste is then emplaced in the standard mould, smooth with the top of the mould. Air drying is initially permitted, followed by oven drying at temperatures from 60°C to 65°C until shrinkage has ceased and then at 105°C to 110°C to complete the drying process. The final length of the soil bar is then ascertained.

6.12 Specific Gravity

Specific gravity is a number that expresses the ratio between the mass of a substance and the mass of an equal volume of water at 4°C. Thus a mineral with a specific gravity of two, weighs twice as much as the same volume of water.

The test procedure is given in Test 6, British Standard 1377 (1975).

6.13 Grading

Mechanical analysis is carried out in two stages :

i) separation of the coarser fractions by sieving on a series of standard sieves

ii) the determination of the proportions of finer particles by fine analysis.

The standard method of obtaining the particle size distribution is to first wash out the fine material (silt and clay sizes) and then to dry and sieve the larger sizes. Fines analysis is then conducted on the clay and silt. An alternative favoured method is to sieve the whole sample of soil in its dry state, without washing.

Wet sieving entails separation of all silt and clay from the sample without loss of any fine sand. ($<75 \mu m$ or 0,075 mm). The fine material less than 75 μm is washed to waste and the larger faction is retained, dried and sieved. (BS 1377 of 1975. Test 7A).

Dry sieving entails drying the entire sample and passing it through the specified nest of sieves without any of the fine material being extracted. Material retained on each sieve is weighed (BS 1377 of 1975. Test 7A).

Fines analysis

The so called standard or subsidiary methods of determining the grading of fines is specified in British Standards 1377 (1975), Tests 7(c) and 7(d).

In both methods a suspension of fine particles is produced according to the specifications. Dispersants are used to ensure deflocculation. The suspension is brought to a standard temperature of 25°C in a water bath. The cylinder containing the liquid is thoroughly agitated and set up vertically in the water bath. At stop watch is then started.

The standard method then entails drawing off three samples by a special pipette at specified time intervals which relates to the particle diameter and to the specific gravity of the particles being tested. The times given in BS 1377 relate to 0,02, 006 and 0,002 mm size particles. Each of the pipette samples taken contains only particles of a smaller size than those specified. Thus the "percentage passing" can be calculated and a grading curve plotted for the fines.

The subsidiary method involves determining the SG by means of a hydrometer. Readings are taken at 1/2, 1, 2, 4, 8, 15, 30 minutes and at 1, 2, and 4 hours after the start of sedimentation. Relating the specific gravity of the suspension to the values of particle sizes remaining in suspension at that time is usually carried out by a nomogram based on Stoke's Law.

6.14 Determination of moisture content

The standard method (BS 1377 (1975) Test 1) entails placing the soil in a glass weight bottle. The bottle with contents of known mass is then placed in an oven maintained at 105 to 110°C until no further mass is lost. The difference between the original and final weighings represents the mass of water evaporated.

M_1 is mass of container (g)
M_2 is mass of container and wet soil (g)
M_3 is mass of container and dry soil (g)

$$\text{Moisture Content } (w) = \frac{M_2 - M_3}{M_3 - M_1} \times 100\%$$

Permeability

Permeability of a soil is defined as the rate at which a fluid (usually water) under pressure can diffuse through the voids in a soil.

6.15 Permeability Tests

The falling head permeater test is the more suitable test for fine sands than the constant head permeater test. Due to the finer nature of the wad the falling head method is utilized.

The test procedure and related theory is detailed by Head (1982). In this device the cylinder containing the sample is fitted with a cap and stand pipe. The apparatus is filled with water up to a mark on the standpipe. The stopcock is opened and water is allowed to percolate through into the container at the base until the level of the standpipe has dropped to a second mark (H_2) from original level (H_1). The time taken for the water level to fall this distance is observed (Figure 6.15.1).

During a time interval t the water level drops H i.e. the vertical coefficient of permeability is defined as follows :

$$kv = \frac{d^2 . L}{D^2 (t_2 - t_1)} \quad \frac{Ln\ H_1}{H_2}$$

where L = length of sample

D = diameter of standpipe

d = diameter of sample

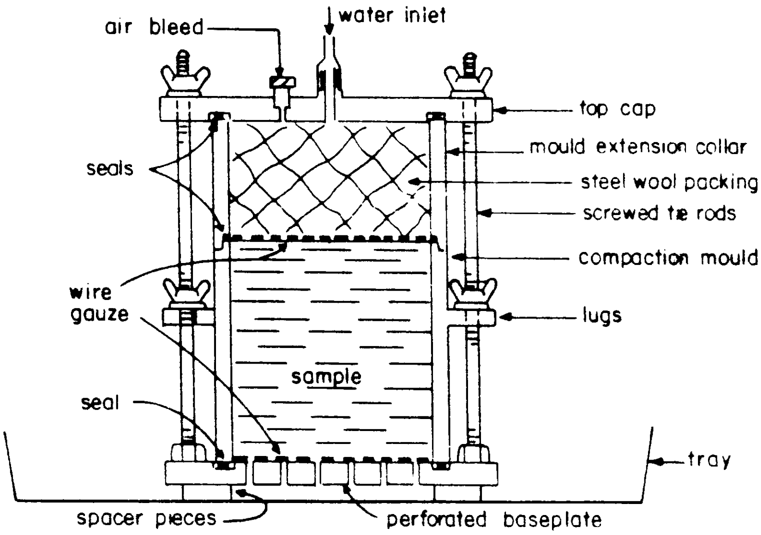


FIGURE 6.15.1. ARRANGEMENT FOR FALLING HEAD PERMEABILITY TEST IN COMPACTION MOULD.

FIELD TESTS

6.16 Shear vane

The vane test has been used to determine the undrained shear strength of the wad. These tests have been conducted utilizing a portable hand shear vane. The tests have been conducted in the exposed walls of test pits.

The test basically consists of placing a four bladed shear vane in the undisturbed soil and rotating it to determine the torsional force required to cause a cylindrical surface to be sheared by the vane. The shear vane utilised in this study is calibrated to directly convert the force to a unit shearing resistance of the cylindrical surface.

The assumption made in the vane test is that the maximum value of torque is used, which means that the shear strength is computed from one reading only.

6.17 Bearing test

In situ loading tests involve measuring the applied load and penetration of a plate being pushed into a soil. In soils the test is carried out to determine the shear strength and deformation characteristics of the material beneath the loaded plate.

The test is usually carried out under a series of maintained loads. The ground is allowed to consolidated before a further increment is applied. This test method yields the drained deformation characteristics.

The general principles, limitations, test arrangement, analysis of results and the interpretation of the results of the plate load test or bearing test are discussed in British Standards, BS5930 of 1981 : Code of Practice for Site Investigations.

The test is subject to scale effect. Several plate sizes and shapes are used. The choice of plate depends on the problem being studied. Circular plates range in size from 150 mm in diameter to 1000 mm in diameter. The plate must be rigid and the vertical loading may be achieved by kentledge, tension piles or ground anchors. The penetration of the plate should be measured at the centre and edge of the plate. The displacement of the plate is related to an independent and fixed datum.

The load is usually applied in equal increments with each increment being maintained until all movement of the plate has ceased or an acceptable low rate of increase has been reached. The increments are continued up to some multiple of the working load, up to failure or to full available load. Cycles of unloading and reloading may be carried out at various stages in the test to obtain an indication of amounts of reversible "elastic" and irreversible" deformation.

The penetration of a rigid circular plate on a semi infinite plane surface applies

$$S = \frac{\pi q}{4} B \frac{(1 - V^2)}{E}$$

where E is the elastic modulus

q is the pressure applied to the plate

S is the settlement of the plate

B is the diameter of the plate

V is Poissons ratio

Chapter 7 : Geotechnical Properties of Wad

The engineering properties of a soil depend on the composite effects of several interacting and often interrelated factors. According to Mitchell (1976) these factors may be divided into two groups, namely, compositional and environmental.

Compositional factors determine the potential range of values for any property and can be studied using disturbed samples. The important factors included here are :

i) Types of minerals
ii) Amount of each mineral
iii) Type of adsorbed cations
iv) Shape and size distribution of particles
v) Pore water composition

Environmental factors will determine the actual value of any property. Undisturbed samples or in situ measurements are required for this study. Environmental factors include the following :

i) Water content
ii) Density
iii) Confining pressure
iv) Temperature
v) Fabric
vi) Availability of water

The quantitative prediction of wad behaviour completely in terms of compositional and environmental factors is a difficult objective for the following reasons :

i) The compositions of the wad and ferroan soils are extremely complex.

ii) Determination of the soil composition is difficult. Wad is an amorphous mineral substance, hence extremely difficult to quantify in terms of its contribution to the makeup of a wad soil. Compositional variations may occur over very short distances in the soil.

iii) Physical and chemical interactions may occur between different phases and constituents of the wad.

iv) Past geological history and the present in situ environment are difficult to simulate in the laboratory.

v) Physio-chemical theories for relating quantitively composition and environment to properties are inadequate.

Despite these difficulties, examination of both the compositional and environmental factors is useful for a better understanding of the gross behavioural characteristics of wad.

As discussed in chapter 5 of this text, the wad may, on a visual basis be subdivided into two broad groups. Macroscale fabric is the basis of this subdivision. This grouping must be seen as a first, elementry and gross subdivision. The fabric, manifest in the wad, is considered to be the primary factor influencing behaviour, while compositional differences are considered subordinate. This assumption is of course a simplification of the complex interrelationships of compositional and environmental factors sketched above.

Soil materials possessing similar fabrics e.g. laminated wad and laminated ferroan soils display compositional differences. Visually, on the macroscale, the two materials appear similar but on the microscale, compositional differences may result in differences in concentrations of solubles and insolubles. These differences will in turn have an influence on the porosity and void ratio of the material developed. The void ratio is, of course, one of the factors determining the manifest fabric. As discussed earlier, the laminated soil inherits the superimposed laminated fabric from the parent rock. As the soil "matures" and leaching progresses, embayments and voids are opened in the material. The rate of leaching and the manifest changes from continuous 'sheets to sheetlets' will be determined by the differing compositional and environmental factors influencing the respective soil types. The differences include variations in the composition of the soil, pore water and percolating water compositions etc. Visually, and on a coarse scale, the wad and ferroan soil may display the same laminated fabric but on a microscale, irregularities and differences arise. No soil is homogenous, even on a scale of millimetres. Consequently a range of geotechnical properties are noted for apparently similar materials within the same fabric grouping.

Environmental factors such as fabric, tend to determine the order of the geotechnical properties noted, while the compositional factors determine the range.

In excess of one hundred and fifty wad profiles have been examined and many samples extracted. Relationships between the nature, form and spatial arrangement of macrofabric features and laboratory measurements of the geotechnical properties of the soils have been established. It is of importance to note that the use of macrofabric data and suggested relationships with measured properties are meant to aid in the formulation of an initial perspective concerning the potential stability of the subsurface residual material and to facilitate the selection of appropriate sampling and testing techniques. The intention is not to replace these tests but merely to create a gross impression of potential behavioural characteristics. The test results discussed in this text pertain to soils in which the inherited fabric was relatively undisturbed and readily identifiable.

7.1 Effects of primary features (fabric)

Fabric affects a range of geotechnical properties particularly the permeability, shear strength, compressibility and consolidation. The macrofabric features in the laminated wad induce a degree of anistropy with the maxima or minima either in the plane of the lamallae or perpendicular to them. Obviously the orientation, distribution and nature of the lamellae will determine the magnitude of the influence that these features will have on the soil mass properties. The laminated wad exhibits a two-dimensional anistropic behavioural pattern with limits determined simply by testing along and across the laminations.

The minimum direct shear strength, drained or undrained, at any consolidation stage lies along the intra lamellae zone possessing the weakest bonding. This observation is supported by shear box tests with laminations orientated parallel to the shearing direction. The upper limits of drained and undrained shear strength parameters are expected to be orientated across the plane of the layering.

7.2 Effects of secondary features (fissures)

The secondary features or fissures superimposed on the soil mass serve to further complicate the assessment of properties. The nature and orientation of fissures sets may differ, thus producing three-dimensional anisotropy of geotechnical properties. This anistropic effect pertains particularly to the drained and undrained shear strength parameters, permeability, and to a lessor extent compressibility.

Compressibility, consolidation and permeability are generally influenced by the fissure fill material thickness, if any is present, the applied stress levels and continuity.

Field and laboratory tests conducted on fissured laminated wads, in which the fissures are closed or filled with clay, yield permeability values in the low to very low range (Table 7). Adapted constant and variable head permeability tests have been conducted on openly-fissured laminated wads. The test results reflect a susceptibility to erosion. Similar results have been obtained from tests conducted on openly-fissured massive wad samples.

7.3 Effect of secondary calcification + silicification

Scanning electron microscope studies of wad samples of a "brittle" nature, reveal secondary calcification or even silicification. The term "brittle" is used due to the phenomenon of the sample shattering as a consequence of a hammer blow. The secondary calcification is manifest along sheetlet contacts in embayments and around sphere contacts (Plates 1 and 2). The effect that this cementing has on test results must not be underestimated. The reinforcing effect of the cement serves to influence plate load, consolidation, triaxial and shear box test results. Very high E modulus values are obtained from tests conducted both parallel and perpendicularly to lamination at both natural moisture content and under saturated conditions (Table 7). Several of the tests conducted on this cemented wad produced a settlement of less than 1,9 mm when loaded up to 508 kPa under saturated conditions. Alternatively 90 mm of settlement was obtained, on a wad not displaying this secondary silification, under saturated conditions loaded to 508 kPa.

TABLE 7.

GEOTECHNICAL PROPERTIES OF WAD

TEST		WAD TYPE: RESIDUAL SOILS No REWORKING To PARTIAL REWORKING — LAMINATED WAD		MASSIVE WAD		No. of Tests
TYPICAL GRADING		CLAYEY SILT TO SANDY SILTY CLAY		SANDY CLAYEY SILT		
		Min.	Max.	Min.	Max.	
ATTERBERG LIMITS	LIQUID LIMIT	28	113	27	136	66
	PLASTIC LIMIT	22	154	21	125	
	PLASTIC INDEX	3	26	11	27	
LINEAR SHRINKAGE		1	11	2	11	66
SPECIFIC GRAVITY		2,2	3,10	1,94	3,0	66
DENSITY kg/m³	BULK	373	1686	664	1826	49
	DRY	220	1221	406	1516	49
% NATURAL WATER CONTENT		13	172	13	167	49
DEGREE OF SATURATION %		21	98	22	100	49
1/Mv	MPa	0,6	58	1,9	28	49
COMPRESSION INDEX		0,1	6,7	0,19	5,1	49
OCR		1,1	7,8	0,8	9,8	49
VOID RATIO	eo	1,3	16,6	0,97	6,2	49
POTENTIAL VOLUME CHANGE	50 KPa	< 1%	1-5%			26
	80 KPa	< 1%	1-5%	< 1%	10-20%	
TRIAXIAL TEST	C' KPa	23	63	4,0	53,0	16
	Ø' DEGREES	21	25	23,0	29,0	
	C KPa	26	74	1,0	65	
	Ø DEGREES	15	19,3	21,5	33,3	
SHEAR BOX	C KPa	0	82	0	30	13
	Ø DEGREES	18,5	53	24	33,5	
SHEAR VANE	KPa	38	74	4	60	26
E PLATE LOAD VERTICAL	E INITIAL MPa	60*1	589*1			41
	E FINAL MPa	24*1	100*1			
E PLATE LOAD HORIZONTAL	E INITIAL MPa	0,1*2	27*2			
	E FINAL MPa	0,5*2	7,2*2			
PERMEABILITY		VLP	IP	LP	VLP	20
DISPERSIVENESS	CRUMB TEST	CLASS 1.	CLASS 3.	CLASS 1.	CLASS 2.	35
	SCS TEST	NOT DP.	SLIGHT DP.	NOT DP.	SLIGHT DP.	
	ESP TEST*3	NOT DP.	INTERMED.			
500 mm head	PINHOLE TEST			CLEAR	CLEAR	
	FLOW TEST	NO DISCL	MD DISCL	NO DISCL*5	MD DISCL*5	

*1 SECONDARY SILICIFICATION *2 MINOR SECONDARY SILICIFICATION

*3 TEST FROM WAGNER 1982

7.4 Discussion of the test results

A summary of the geotechnical properties determined for laminated and massive wad is given in Table 7. These test results will be discussed individually. It must be noted that the sampling and preparation of specimens will have caused disturbance of the soil, altering some of the properties.

Grading

The massive or non-laminated wad grades primarily as a sandy clayey silt. A clayey silt or silty clay description aptly characterises the laminated wad. The greatest percentage of clay present in a sample is 48, noted in a laminated wad.

An important factor affecting the behaviour of the material is the clay component. This component consists of clay size particles of both quartz and clay minerals. The clay mineral particles may, however, grade as particle sizes greater than 2 microns. The clay phase of the wad may therefore exert an influence far exceeding its apparent relative abundance in the soil. These clay minerals may also occur as particles of such a small size that the physio-chemical interactions with each other and with the water electrolyte phase of the soil may be great.

Atterberg Limits and Linear Shrinkage

A maximum plastic limit of 136 percent and a maximum liquid limit of 151 percent has been recorded for the laminated type material and maximum of 125 and 136 percent respectively for the non-laminated material (Table 7).

These high values may be related to the fine nature of particles (silt and clay size) and thus the high specific surface area manifest in these soil types. A much higher percentage of water will thus be required to take the material to these critical behavioural limits.

Some samples tested indicate a high plastic limit yet the grading analyses show low percentages of clay size particles present in the material. One of two explanations may be applicable.

i) The clay mineral assemblages present in the samples namely chlorite, kaolinite and montmorillonite are occurring in a size range greater than 2 microns.

ii) The traditional dispersants used during the grading analysis tests i.e. sodium silicate, hexametaphosphate and sodium oxalate are not functioning as they should and clay particles remain as flocculated clusters greater than 2 microns.

The latter is the more plausible explanation.

Fine grained flocculated particles may thus not be affected by the dispersing agents hence settling out of the solution in the hydrometer as coarse particle assemblages. Failure to deflocculate the particle assemblages will result in an incorrect assessment of the fine (silt and clay) particle size distribution being made.

The range of linear shrinkage values obtained may be related to the composition of the clay minerals. If the 1:1 lattice minerals such as kaolinite predominate, little shrinkage is observed. The predominance of the 2:1 lattice clay minerals in the clay particle size fraction, in particular, results in the material as a whole displaying linear shrinkage values of up to eleven per cent.

Alternatively the manifestation of relatively high linear shrinkage values may be attributable to the development of strong negative pore pressures and the attraction of adjacent particles towards each other by surface tension. The drying shrinkage of the fine-grained wad is thus determined by the particle movements as a consequence of negative pore water pressures developed by capillary menisci. The multitudes of smaller voids developed as a consequence of the remoulding of the wad allows large capillary stresses to develop. It is of importance to note that the shrinkage is observed in remoulded samples in which any secondary cementing and the inherited soil structure would be destroyed and the particles rearranged. An unremoulded wad in profile, possessing secondary cementing may not display this shrinkage on dessication. The cement may, if present, serve to resist the influence of the capillary stresses.

The effect of the shrinkage with dessication is that the wad appears "blocky" on a scale of millimetres.

Density

The laminated and non laminated wad type may possess low dry densities. Values as low as 220 and 406 kg/m^3 respectively have been obtained (Table 7). Wagener (1982) records a low dry density value of 225 kg/m^3 and Roux (1981) notes a value of 80 kg/m^3. These are extremely low values and indicate the very porous nature of the material. The leaching process proceeds while the remaining material or insolubles occupy the volume of the original dolomite. This phenonenon has been clearly viewed at shallow depth in the soil profile. The fabric and structure of the original rock can sometimes be traced laterally and vertically into the residual low density soil. This situation is observed where a very young soil exists near the upper bedrock surface and consolidation has been limited.

Distortion or reworking is noted where greater overburden pressures has resulted in collapse and consolidation of the extremely low density material.

Natural Water Content and Degree of Saturation

The natural water content of the laminated and non laminated wad varies from very low values, in the region of 13 per cent to high values of 172 per cent and 167 per cent respectively for laminated and non laminated wad (Table 7). The corresponding degrees of saturation are near 100 per cent. These similarly high values reflect the porous nature of these materials. Wagener (1982) has recorded in situ moisture content values in the range from 11 to 264 per cent with the degree of saturation ranging from 29 per cent to 99 per cent. An almost saturated soil with a void ratio greater than one contains a greater volume of water than solids and in these residual dolomitic soils, void ratio's greater than one are more the rule than the exception. Void ratio's up to sixteen have been noted.

Emphasis, in previous studies of wad composition and geotechnical properties has almost entirely been on the mineralogy and structure of the solid phase with very little regard for the properties of the liquid phase.

The concept of effective stress postulates that volume change and strength behaviour depend on the stresses carried by the solid grain structure and that the water is a neutral phase. In a porous soil with a void ratio of sixteen and degree of saturation of near a hundred per cent, the nature of the pore fluid, its composition and its interaction with the soil particles can be expected to influence the physical and physio-chemical behaviour of the material as a whole.

The high natural water contents may be ascribed to :

i) The high specific surface area of the fine grained material particles, permitting a high percentage of hygroscopic water to be held.

ii) The porous nature of the material permitting space for taking up of interstitial or free water.

The wad removed from in situ has been noted to behave like a sponge, expelling fairly large quantities of water on compression.

The potential for liquifaction of the wad is apparent when examining the available information concerning the void ratio's, degrees of saturation and microscopic fabric of many of the samples. Saturated wad in profile has been noted to "squirt" when a blow is struck with a geologic pick. This behaviour has been noted particularly in the capillary zone occurring above the watertable. The capillary zone may encompass a substantial portion of the wad profile above the watertable. Capillary rise and degree of saturation vary markedly above the watertable due to the complexity of the wad structure. The soil particles are irregular in shape and vary widely in size. The voids may form continuous but extremely tortuous 'tubes' with narrow and bulbous sections occurring eratically. It is the wad that occurs within the saturated portion of the capillary rise zone or below the watertable that may be susceptible to liquifaction.

The author has difficulty in providing a logical explanation for the fact that samples may, in some instances, be recovered from potentially unstable wad profiles within the capillary rise zone, without liquifaction being induced. A possible explanation is that secondary cementing provides adequate additional strength to the material to sustain the shock loading associated with the blows of a hammer.

Void Ratio's

The average void ratio values for the laminated material appears to be more than double that for the non laminated wad. The mean void ratio for the former is in the region of 5,1 and that of the latter in the region of 2,3. The highest void ratio recorded is 16,6 (Table 7). Wagener (1982) indicates that he has recorded void ratio's in the range 0,9 to 11,2. As previously discussed, the high void ratio's may be attributable to the process by which the residual soil development occurs. The leaching process results in the breakdown and removal of primary minerals while the insoluble constituents remain behind, occupying the original rock volume. Numerous voids are thus developed within the residual soil. The laminated wad inherits its fabric of sheetlets from the laminated parent rock characterised by preferentially orientated elongated grains. This laminated residual dolomite soil clearly displays extensively developed embayments, passages and irregular voids when examined under the scanning electron microscope. These features are, however, not interconnected, resulting in a high porosity but a low permeability.

Collapse Tests : Assessment of Potential Volume Change

Twenty six modified oedometer tests were conducted on both wad types. The test method employed is a modification of the Jennings method (1981). Saturation is effected at loads of 50 kPa and 80 kPa instead of the recommended 200 kPa proposed by Jennings (1981). Wagener (1982) used these values and similar loads of 50 kPa and 80 kPa have been adopted to permit comparison of results. Samples tested in this manner were taken at shallow depth to ensure that the applied stress exceeded the overburden pressure. The results obtained confirm Wagener's (1982) findings noted at low loads (Table 7). Very little, no sudden or dramatic collapse settlements were observed on the majority of samples.

The laminated material under the worst circumstances reflects a potential volume change of one to five percent but on average less than one percent. A potential volume change of ten to twenty percent is the worst category noted for the non laminated material but on average a potential volume change of less than five percent characterises the behaviour. Dramatic or collapse settlement can, however, be expected to characterise the behaviour of this material at higher loads as is confirmed by the plate load tests.

The fabric of the laminated material consists of fine sheets. Although this material possesses low dry densities and high void ratios, the voids are not continuous and are "bridged" by sheets. Orientation of the sheets on the microscale plays a large role in the manifestations of behaviour on the macroscale. Even on saturation, the fine sheets, when loaded perpendicularly to laminations, are extremely competent and are able to support the imposed loads. Geometry prevents the material from slipping into a more dense packing. However, if the sheets are orientated parallel or at an angle to the plane of loading, the sheets may slide over one another, undergo structrual damage and confinement while falling into a denser packing on wetting up. A loss of shear strength thus occurs along the sheet contacts. Secondary cementing present in some of samples will, to a certain extent, negate this effect. The cement will impart strength to the material even if some loss of shear strength occurs.

The massive or non laminated material is characterised by a fabric consisting of fine sheets stacked on each other. Wetting up does in certain instances, as stated above, result in collapse. This collapse as a result of saturation under constant total stress is an apparent contradition to the principle of effective stress. The addition of water decreases the (negative) pore water pressure operative in partially saturated soil and reduces the effective stress. The apparent anomaly of volume decreases instead of increase under decreased effective stress results because of the application of continuous concepts to a phenomenon that is controlled by particulate behaviour.

The massive wad possesses the following properties :

i) An open fabric as indicated by the void ratio
ii) Very low bulk and dry densities
iii) A partially saturated fabric
iv) Secondary cementing
v) A high enough total stress ensuring that the structure is metastable.

When water is added to the wad, the effective stress will be reduced, a loss of shear strength occurs and hence particle the contacts may fail in shear (Figure 7.4.3). In addition, some of the fines constituting the secondary deposits may be washed out.

Resultant collapse settlements may be large, even at low imposed loads. The high void ratio's and low dry densities indicate the magnitude of densification that may occur. Secondary silicification or calcification serves to render the material more competent even under the influence of greater imposed loads on saturation.

Elastic Moduli $\left(\frac{1}{Mv} \right)$

Elastic moduli were calculated from the e - log p (void ratio versus log pressure) curves in the pressure ranges po to (po + 50) kPa. The values so obtained range from 0,6 to 58 MPa for laminated wad (perpendicular to fabric) and 1,9 to 28 MPa for the non laminated material. The mean values are 13,2 MPa and 8 MPa respectively (Table 7). The low values may possibly be attributable to sample disturbance or to the presence of secondary features. Any secondary features (i.e. discontinuities), present in the small sample will have a dramatic effect on the results.

The higher values from 28 MPa to 58 MPa characterise the type of behaviour to be expected from a stiff or dense soil. Both wad types are not dense but may possess a stiff consistency. This stiffness may be attributed to the secondary cementing noted in many of the samples or to the presence of a high percentage of clay.

Wagener (1982) notes that there is no correlation between the density of wad and the elastic modulus; low dry density materials often having a higher modulus of elasticity. This phenomenon may be attributable to the effects of the following :

i) Secondary cementing which imparts great strength to the materials, even those with a high void ratio and low dry density.
ii) The high natural moisture content and degree of saturation which must have a profound influence on the behaviour of a material with a high void ratio.

Compression Index (Cc)

The compression index results obtained from forty nine tests indicate that the range of values for laminated wad is from 0,1 to 6,7 and for massive wad from 0,19 to 5,1 (Table 7). These values indicate a high compressiblity for both types of wad when one considers that most clays have a compression index less than 0,5.

The compression index will be influenced by the fabric of the wad. In the absence of grain crushing, which may be important in granular soils at very high pressures, compression will involve shear at the interparticle contacts. Resistance to shear, which will affect the rate of compression, depends on the arrangement of the particles, the particle assemblages and on the forces holding them together.

Compression of the laminated wad is dictated by the orientation of the sheets or lamellae to the applied stress. If the laminations are perpendicular to the applied stress, the fine sheets serve to 'bridge' the voids and the material will undergo compression associated with structural damage. However, if the sheets are orientated in the plane of the applied load, the compression will be associated with shear failure along sheet surface contacts. The cohesive strength, consisting of Van Der Waal's forces and secondary cementing and the friction between the sheets must be overcome. If any open secondary features are present in the plane of the applied stress compression will occur rapidly.

The massive wad is not anisotropic, consequently orientation of the applied stress is not a critical factor. Compression will entail a loss of shear strength at the particle contacts (Figure 7.4.1).

Thus for both wad types, compression results mainly from decreases in the size of intercluster or interaggregate voids.

Coefficient of Volume Compressibility (Mv)

The coefficient of volume compressibility is defined as the change in volume per unit volume change per unit change in pressure as a result of consolidation due to that pressure change. The mean Mv value obtained for laminated wad is 0,08 m^2/MN with the range 1,67 to 0,02 m^2/MN. Massive wad displays values in the range 0,53 to 0,04 M^2/MN. These values indicate the potential volume compressiblity of the wad calculated in the range po to (po+50) kPa (Table 7).

The amount of compression to be effected in the wad will depend on the compositional and environmental factors. The following factors play a

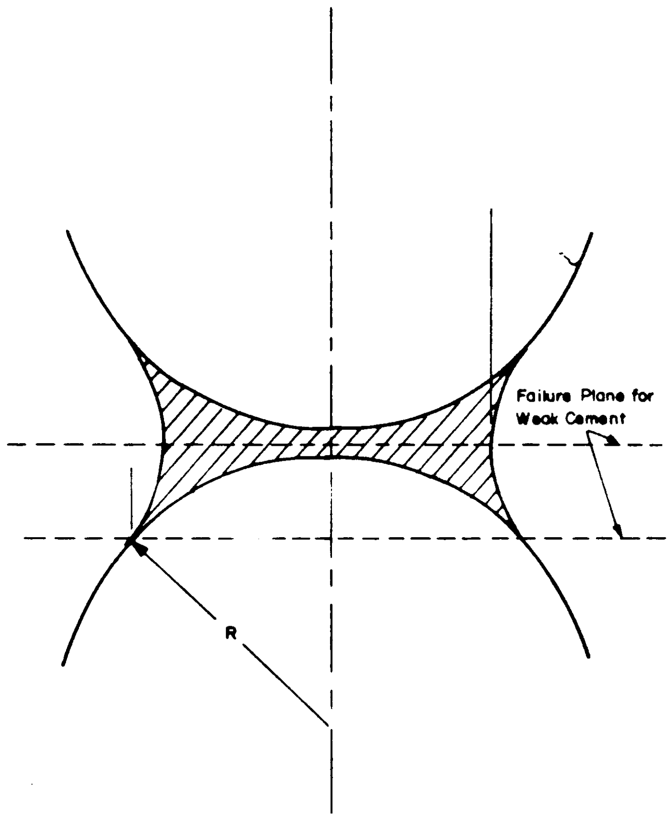


FIG. 7.4.1. CONTACT ZONE FAILURES FOR CEMENTED SPHERES.

role in resisting volume change in the wad :

i) Physical interactions :

Physical interactions include bending, sliding, rolling and crushing of soil particles. Hence the wad's ability to resist structural damage is of importance. The secondary cement, if present, will play a large role in strengthening the resistance of both types of wad to volume changes. Particle bending is important in the case of the laminated wad with its platy particles.

ii) Chemical precipitates :

The chemical precipitates, namely the secondary silica and calcite serve as cementing agents between the particles.

iii) Fabric :

Both types of wad have very open structures, with the high void ratio's reflecting this characteristic. The potential for densification is thus great but the orientation of the fabric to the applied stress is critical, especially in the case of the laminated wad. This aspect has been discussed at length in the section on compression indices.

iv) Stress history

The overconsolidated wad is usually less compressible than the normally consolidated wad. Any past stress influence would have served to densify the material.

Overconsolidation Ratio

The overconsolidation ratio values range from 0,8 to 9,8. Very few values, however, are less than unity with the average values, based on forty nine results, being 5,5 for massive wad and 3,9 for the laminated material (Table 7). The pre-consolidation pressures were determined by the Casagrande Method (Lambe and Whitman 1969).

It must be borne in mind that there are phenomena other than overburden pressures than can produce a pre-consolidation effect. Dessication of wad occurring near the surface in dry weather causes a large suction and therefore a large, positive effective stress. Dessication therefore nearly always results in the upper one or two metres of such material being over-consolidated. This wad will therefore indicate a high pre-consolidation pressure that in fact has never been applied to the soil. Therefore the cause of these high pre-consolidation pressures in such materials is not due to an externally applied load but rather due to an equivalent internal tension induced by negative pore pressures. A fall and subsequent rise of the watertable within a zone of wad in the soil profile may cause slight overconsolidation. The drawdown will cause an increase in effective stress followed by a fall in the effective stress as the watertable rises.

In addition, secondary deposits of calcite or silica will serve to increase the overconsolidation ratio noted. The more strongly cemented samples will display a greater resistance to deformation and volume change, hence providing greater Pc values.

Plate Load Tests

A number of vertical and horizontal plate load tests were executed in large diameter auger holes and test pits. The test pits were excavated by means of a Liebher 941 excavator, sometimes to a depth of 5 metres. The excavation so created was large enough for the machine to be driven into it. The machine then served as a reaction for conducting vertical plate load tests.

Extremely high modulus values have been obtained on the materials of brittle consistency. The imposition of large loads with little deformation may be attributable to the secondary cementing which serves to strengthen the material. Low values, even as low as the E values for polystyrene have been obtained during horizontal testing of these laminated materials. These tests were conducted on materials of stiff to soft consistency with the loads being applied parallel to the laminations. The fine sheetlets, if not cemented by secondary deposits, will yield more readily under stress. Secondary features provide planes of weakness along which the material may readily yield. Large deformations may thus occur at low stress increments. Wagener (1982) has calculated elastic moduli values ranging from 7 to 54 MPa in the po to (po + 50) KPa pressure range.

Initial vertical deformation moduli ascertained perpendicular to the laminations, range from 60 MPa to 589 MPa (Table 7 and Figures 7.4.2 and 7.4.3). There are many values which are higher than this, with the material reflecting inelastic behaviour. During the execution of several tests no deformation was noted under the influence of several increments of load as high as 93 kPa. Two or three independent dial gauges were used to monitor deformation hence the dial gauges could not have malfunctioned. The two sets of plate loading equipment were also checked to ensure that the equipment was in working order (Figure 7.4.2).

Deformation modulus (final vertical) values range from 24 MPa to 100 MPa. The E (initial horizontal) values range from 0,1 MPa to 27 MPa. Deformation modulus (final horizontal) values occur in a range from 0,5 to 7,2 MPa. These deformation moduli results thus range from values which are associated with wad of very soft consistency to material of extremely stiff consistency.

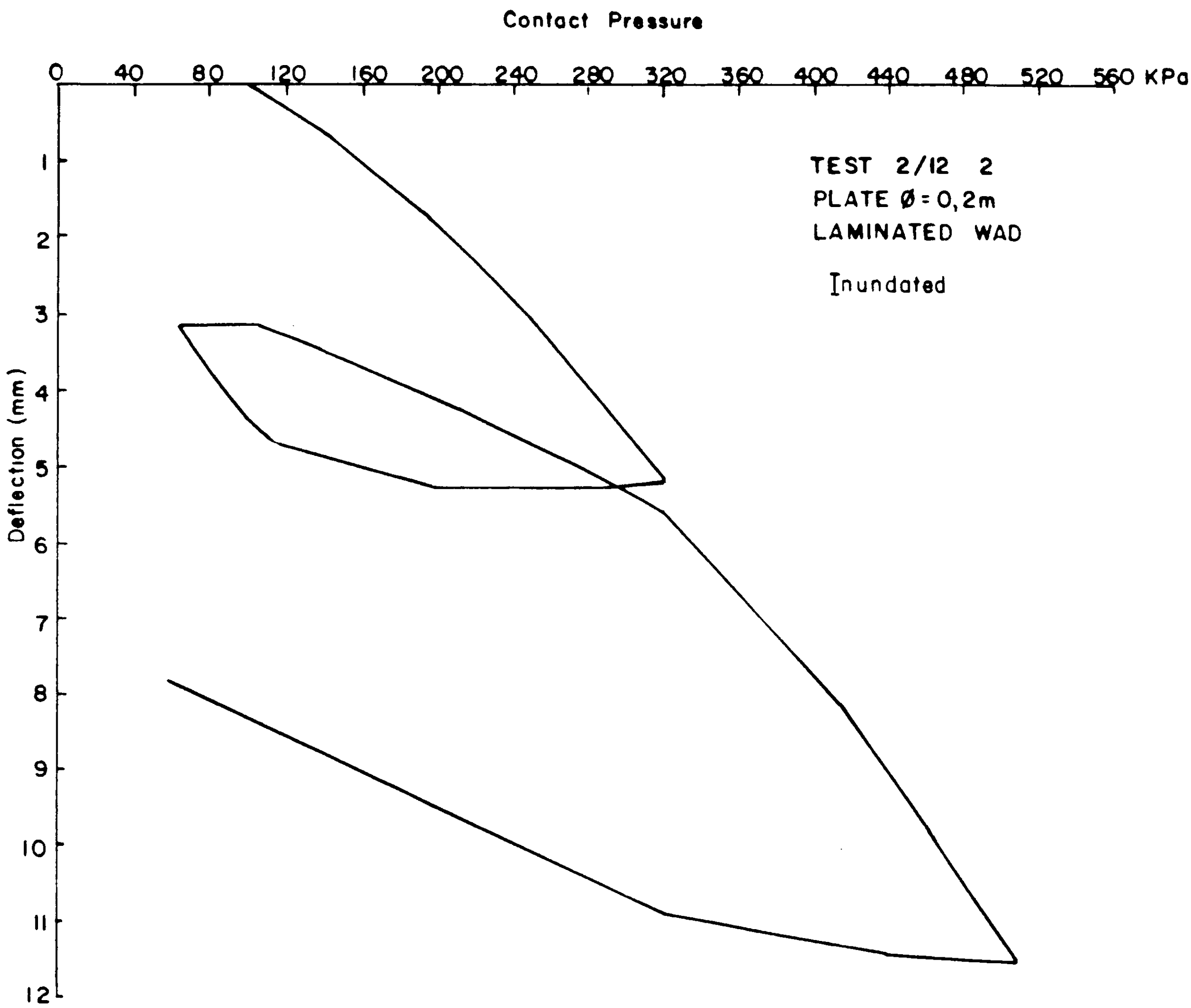


FIG. 7.4.2. A TYPICAL PLATE LOAD TEST RESULT.

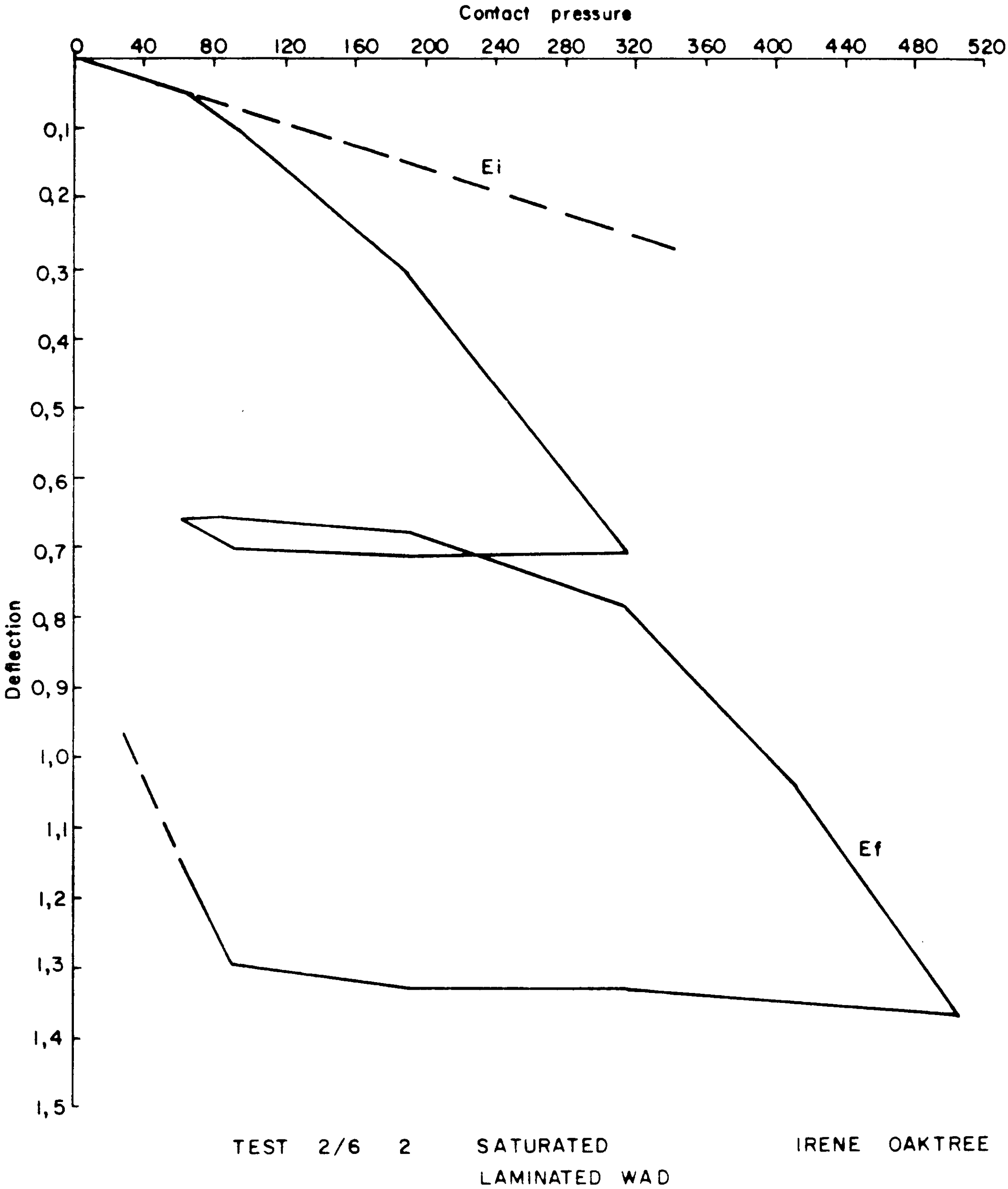


FIG. 7.4.3. PLATE LOAD TEST RESULT FOR LAMINATED WAD.

Permeability

The non-reworked, intact laminated wad tends to have a low to very low permeability and the massive material a low permeability. The smaller particles but high void ratios tends to be a contradictory factor in the assessment of the permeability. Permeability, will, of course, depend on particle size, void ratio, fabric and degree of saturation. The fabric in turn usually depends on the void ratio, leading one to develop the expectation of a high permeability. This expectation is, however, not fulfilled.

Passages, voids and embayments are extensively developed and clearly visible under the scanning electron microscope. These features are, however, either truncated or interconnected in a highly tortuous manner, resulting in a high porosity but a low permeability. The secondary deposits of amorphous silica and calcite may serve to further reduce the permeability. The non-laminated massive wad, characterised by spheres on the microscale, appears to have an "open" fabric despite, in some instances, much secondary cementing. The material appears porous, but the voids are not interconnected thus producing a low permeability.

Hence within the wad material, percolating water cannot achieve the critical velocity and seepage forces required to overcome the hydrodynamic stability of the particles leading to internal erosion or piping.

Secondary features, including bedding planes and discontinuities inherited by the non-reworked soil mass, may serve to increase the permeability if they are not filled with clay. These clay deposits indicate water movement in the past. The material is thus characterised by a low permeability but the soil mass as a whole may be more permeable and erodible due to the presence of inherited fissures which are open.

Dispersiveness

The samples of both material types tested for dispersiveness rendered results predominantly indicating that the material is non-dispersive. The material is thus erodible but non dispersive. The flow test results indicate increasing permeability with time reflecting a susceptibility to erosion.

Only four samples, have been noted to indicate potentially dispersive behaviour. These samples were retrieved from the Oaktree Formation. This behaviour was noted during the execution of grading tests utilizing the hydrometer method. The hydrometer method for fines analysis entails dispersing the wad utilizing a 100 ml solution of sodium hexametaphosphate. The sample plus 100 ml solution are shaken in the centrifuge for four hours. The sample passing through the 63 m sieve was placed in the 1000 ml measuring cylinder. The tests were conducted according to the British Standards 1377 (1975) Test 7 (D). The solution retained its murky or muddy appearance for two and a half weeks. The four measuring cylinders were not disturbed in any way during this time period. This behaviour may be attributable to the electrical charges on the particles. Table 2, results T, U, V, W gives the XRF-analyses of these materials.

Flow tests were conducted on samples of both types of wad. The tests were conducted using the permeability apparatus with a constant 1,5 m head of water. Water was permitted to flow through the sample for several days with the permeability being ascertained approximtely every twelve hours. The water flowing from the sample was scrutinised to ascertain if discoloured in any way.

The results of these flow tests are interesting. During the execution of these tests it was noted in some samples that the permeability of the wad would increase and then stabilize. The stabilization may be attributed either to the eroded material eventually clogging up drainage paths within the sample or the sieve at the base of the sample.

Both types of wad generally have a low permeability of the order of 10^{-7} m/s. As discussed in the previous section, the passages within the soil are truncated and highly tortuous while secondary deposits, indicating past movement now serve to further inhibit flow. The percolating waters must therefore follow a highly tortuous flow path constantly being hindered and hence unable to achieve the critical flow velocity required to overcome the hydrodynamic stability of the particles. Any particles dislodged would quickly clog up the flow paths. The wad material therefore appears to be hydrodynamically stable, i.e. non-erodible, particularly the laminated wad.

The introduction of secondary features such as fissures, however, may alter the assessment entirely. The presence of these secondary features may encourage the erosion process. Those fissures which are open or filled with red soil will permit the percolating water to achieve the critical velocity required to overcome the hydrodynamic stability of the particles filling the fissures (Plate 7). Firstly the red soil in the fissures will be borne away. The erosive action of the water will then be increasing, permitting wad particles to be dislodged from the fissure walls. The seepage force of the moving water will then be applied to the soil skeleton and the erosive process will grow. Clay filled fissures indicate possible flow and movement of material in the past. This clay would serve to inhibit water percolation.

Chapter 8 : General Discussion : Contribution of Wad to Stability ASPECTS and the Comprehensive Description of WAD.

During the execution of a stability investigation for sites on dolomitic terrain, attention is focussed on the overall geology and the groundwater position in the subsurface profile.

When examining the geology, particular attention must be paid to the presence and position of wad in the profile. Wad has always been viewed with a negative bias and the tendency has been to assume that the material possesses only poor behavioural characteristics. Investigations have tended to concentrate on the nature of the material overlying and underlying the wad. This tendency is clearly mirrored in the classification systems developed to assist in the process of zoning a dolomitic terrain. These classification systems by Weaver (1979), Venter (1981) and Van Rooy (1984) have tended to be based on the geological context in which the wad occurs. The nature and properties of the wad or ferroan soil are usually ignored or treated in a subordinate manner. As a consequence of overconservative reaction and assessment, much valuable ground has been designated as unsuitable for development.

A study of site investigation reports from a number of reputable consulting firms over the past few years has emphasised the inadequacies in the descriptions of wad. Jennings et al. (1973) emphasised that the reliable description of soils as they occur in the field is the key to the first assessment of engineering properties (Table 8).

Particular attention needs to be paid to the fabric description and to the degree of secondary cementing and of reworking. Wad fabric examination may prove so essential for engineering appreciation of a site that it should dominate the way the stability and foundation investigations are executed. Failure to distinguish between the wad types may be traced to a lack of detailed fabric examination during the investigation.

The identification of wad type on the basis of fabric is essential to the assessment of the stability of a site. Knowledge of the wad or ferroan soil types will provide the engineering geologist or geotechnical engineer with an initial perspective of the site as regards the potential for doline or sinkhole formation, collapse settlement or the competence of the material.

Gaining access to suitable representative samples may prove difficult. Foundation investigations will, of course, encompass an assessment of the upper profile material. If wad occurs in this zone, access, assessment and sampling will easily be achieved by utilizing a backactor or large diameter auger.

During the stability investigation, it is essential that wad occurring in the crucial part of the soil profile i.e. just above the dolomite bedrock, is carefully scrutinised. If this zone occurs at shallow depth, access will be gained by large diameter augering and an assessment will easily be made. However, the pneumatic percussion drilling method is used if this zone is located at a depth beyond the reach of a large diameter auger. This drilling method usually results in the destruction of the soil fabric by the shearing and hammering action. In some instances small fragments of identifiable material are retrieved. No information concerning the crucial secondary features is, however, obtained.

Where the convential methods, mentioned above, are not feasible, a simple tube sampler attached to the rods of a pneumatic percussion drill merits consideration. When a borehole intercepts wad, drilling is interrupted to permit the tube to be attached to the drilling rods and to be forced into the wad. Alternatively, an overall perspective of the subsurface profile on a site may be obtained during an initial drilling programme. Several suitable localities can then be selected, adjacent to existing boreholes, for the boring of sampling holes. The adjacent holes provide the basic information concerning the subsurface, permitting selection of appropriate sampling depths. The only purpose of this operation would be to gain an impression of the fabric of the material permitting identification. Identification allows an initial perspective of the potential stability to be formulated. The obvious disadvantages are the cost implications, sample disturbance and damage to sampling tubes when chert and dolomite boulders, floaters and rock are intercepted.

The description of wad samples recovered from pneumatic percussion boreholes requires attention. Unfortunately the retrieved samples are disturbed. Occassionally, however, small fragments of wad are obtained permitting fabric identification.

The essential descriptions included are colour and soil type. Typical descriptions of wad are as follows :

"Dark brown sandy clay (70%) with wad (30%)".

"Light and dark grey CHERT with minor amounts of dark grey clayey silt (wad)".

Percentages of clay and wad respectively are often cited. This practice is questionable as wad grades predominantly as a silty clay or clayey silt and is retrieved in a totally reworked form. The material which we refer to as "wad" locally, consists predominantly of quartz and subordinate amounts of manganese and iron oxides and hydroxides. Although fine shale layers present in the wad may be mixed in with the wad during the drilling process giving the material a more clayey appearance, noting the clay content is of importance as a clayey material will be less susceptible to erosion.

The description of the wad, in profile, must be executed according to the recommended standard method, (Jennings et al. 1973). Certain additions and adaptations to the system are, however, proposed. If this adapted system is properly utilized, the soil profile will provide the engineering geologist or geotechnical engineer with the basic information for the approximate quantitative assessment of the properties of the wad (Tables 8 and 9).

The suggestion is made that the soil descriptors are utilized as follows: (Table 9).

i) Moisture Condition

The description of the moisture condition of the wad should be completed in terms of the standard as proposed by Jennings et al. (1973).

ii) Colour

The observer must pay particular attention to the colour of the material. The manganese rich samples tend to be extremely dark in colour namely black or bluish grey. The iron rich material will tend to bear a reddish or purplish tinge, for example, a purplish brown colour.

iii) Consistency

Consistency is a measure of the hardness or toughness of the soil and is an observation based on the effort required to dig into the soil or alternatively to mould it in the fingers (Jennings et al. 1973). Consistency is, in fact, a rough measure of shear strength.

The description of the consistency of the wad may be completed according to the proposed terms of the MCCSSO system (Jennings et al. 1973).

CONSISTENCY OF GRANULAR SOILS	
Very loose	Crumbles very easily when scraped with geological pick.
Loose	Small resistance to penetration by sharp end of geological pick.
Medium dense	Considerable resistance to penetration by sharp end of geological pick.
Dense	Very high resistance to penetration of sharp end of geological pick-requires many blows of pick for excavation.
Very dense	High resistance to repeated blows of geological pick-requires power tools for excavation.

CONSISTENCY OF COHESIVE SOILS	
Very soft	Pick head can easily be pushed in to the shaft of handle. Easily moulded by fingers.
Soft	Easily penetrated by thumb; sharp end of pick can be pushed in 30-40 mm, moulded by fingers with some pressure.
Firm	Indented by thumb with effort; sharp end of pick can be pushed in up to 10 mm; very difficult to mould with fingers. Can just be penetrated with an ordinary hand spade.
Stiff	Penetrated by thumb-nail; slight indentation produced by pushing pick point into soil; cannot be moulded by fingers. Requires hand pick for excavation.
Very stiff	Indented by thumb-nail with difficulty; slight indentation produced by blow of pick point. Requires power tools for excavation.

ORIGIN
Residual
Transported 1. Talus 2. Hillwash 3. Alluvial 4. Lacustrine 5. Estuarine 6. Aeolian 7. Littoral
Pedogenic

MOISTURE CONDITION
Dry
Slightly Moist
Moist
Very Moist
Wet

COHESIVE STRUCTURE
Intact
Fissured
Slickenside
Shattered
Microshattered
Others

SOIL TYPE
Boulders
Gravel
Sand
Silt
Clay

TABLE : 8 : THE DESCRIPTORS OF THE MCCSSO SYSTEM.

TABLE 9. STRUCTURE SPACING

SPACING IN mm	DESCRIPTION FOR JOINTS, FAULTS, OR OTHER FRACTURES
Greater than 1 000	Very widely (fractured or jointed)
300 - 1 000	Widely
100 - 300	Medium
30 - 100	Closely
10 - 30	Very closely

After Core Logging Committee (1970)

Wad predominantly grades as a silty clay or a clayey silt hence the terms applied to cohesive soils will primarily be used.

iv) Structure

This descriptor embraces information concerning the primary fabric and the presence or absence of secondary fissures.

Description of the primary features :

The primary feature of the wad may be described in the following terms:

"Laminated". The residual soil displays the structure of the parent dolomite from which it is derived, namely a laminated dolomite. The layers in the soil are extremely fine but are discernable to the naked eye. (Refer to Chapter 5).

"Non Laminated or Massive". This residual soil displays a fabric inherited from a massive or non laminated dolomite. This material displays no form or distinguishing features on the macroscale. (Refer to chapter 5).

Description of secondary features :

Several important factors must be noted with respect to the secondary features namely :

i) The absence or presence of fissures
ii) The spacing of the fissures
iii) Predominant orientations of the fissures
iv) Separation of the fissure planes.
v) The type of fill material, if any, in the fissures.

As regards the spacing and separation of the fissures it is suggested that the discriptors proposed by the AEG (1970) be utilized (Table 9).

v) Soil Type

Description of the residual soils must be executed according to the standard method (Jennings et al. 1973). The material will thus primarily be described as a clay silt or silty clay.

vi) Origin

It is extremely important to accurately distinguish between the residual unreworked wad and the reworked wad, and the residual and transported wad as the nature of the material will adversely affect the behaviour characteristics. Distinguising between residual unreworked massive wad and transported wad may be problematical if no pebble marker or secondary features are discernable in the profile. Indicators of reworking might be "floaters" of laminated or massive wad in the reworked mass (Plate 13) and extensively developed bioturbation features.

vii) Cementing

A further additional descriptor is proposed. The terms "poorly cemented, partly cemented and well cemented" should be utilized. "Well cemented should be incorporated in the soil profile description of those materials displaying a "brittle" nature. The wad of a brittle nature "shatters" or explodes when struck with a geological pick. The importance of taking cognisance of this behaviour must be underscored. Scanning electron microscope studies indicate that secondary cementing is manifest in the wad material displaying this behaviour. A hammer blow results in the transmission of a shock wave through the wad. The cement fails and the wad explodes as energy is released.

This well cemented or brittle wad is found to support loads of up to 90 kPa without yielding.

The suggested descriptor sequence is summarised as follows:

Moisture Content

Colour

Consistency

Cementing

Structure

Orientation of fissures

Fissure filling, if any

Soil Type

Reworking

Origin.

An example of a comprehensive description of a ferroan soil type would be as follows :

Moist, purplish brown, stiff, well cemented, intensely fissured laminated silty clay (ferroan soil). Fissures: 1 fissure set vertically inclined with clay filling. Laminations horizontally orientated. Fine chert layers ± 1 mm thick at ± 40 cm intervals. Residual soil derived from laminated dolomite. Little reworking by bioturbation. Roots.

Successive beds of shale and wad may be noted in a profile. On a scale of tens of centimetres it might be argued that the wad appears laminated. The wad in such a situation may, however, be of the massive type. The parent rock would have consisted of massive or non laminated dolomite with shale intercalations. The presence of these shale layers must not be permitted to interfere with the classification of the wad material itself. A typical description could be as follows:

Moist, black, soft, poorly cemented, medium fissured, massive clayey silt (wad) with widely spaced horizontally orientated shale intercalations (± 2 mm thick). Fissures : 1 fissure set nearly vertically inclined with a red soil filling. Residual soil derived from a massive dolomite. Partial reworking by bioturbation. Roots.

The correct identification of wad type may influence every aspect of a site investigation as follows :

i) Dolomite Stability Investigation :

During this phase of an investigation an assessment must be made of the contribution wad may make to the potential stability or instability of a site.

A visual assessment of the wad may be made by trenching or large diameter augering. Where these methods are not feasible a simple tube sampler attached to the rods of a pneumatic percussion drill merits consideration. When the borehole intercepts wad, drilling is interrupted to permit the tube to be attached and to be forced into the wad. The only purpose would be to gain an impression of the fabric of the material and hence permit identification. Identification would permit an initial perspective of the stability to be formulated.

Generally residual wad soils are non dispersive but erodible. The soil mass may posses a high void ratio but the voids appear to be poorly interconnected, in a tortuous manner, resulting in a low permeability. The permeability of the soil mass as a whole is determined by the nature of the fabric and fissures. Inclination and openness of laminations, bedding planes and fissures and the nature of fill material are of particular relevance (Figure 8.1).

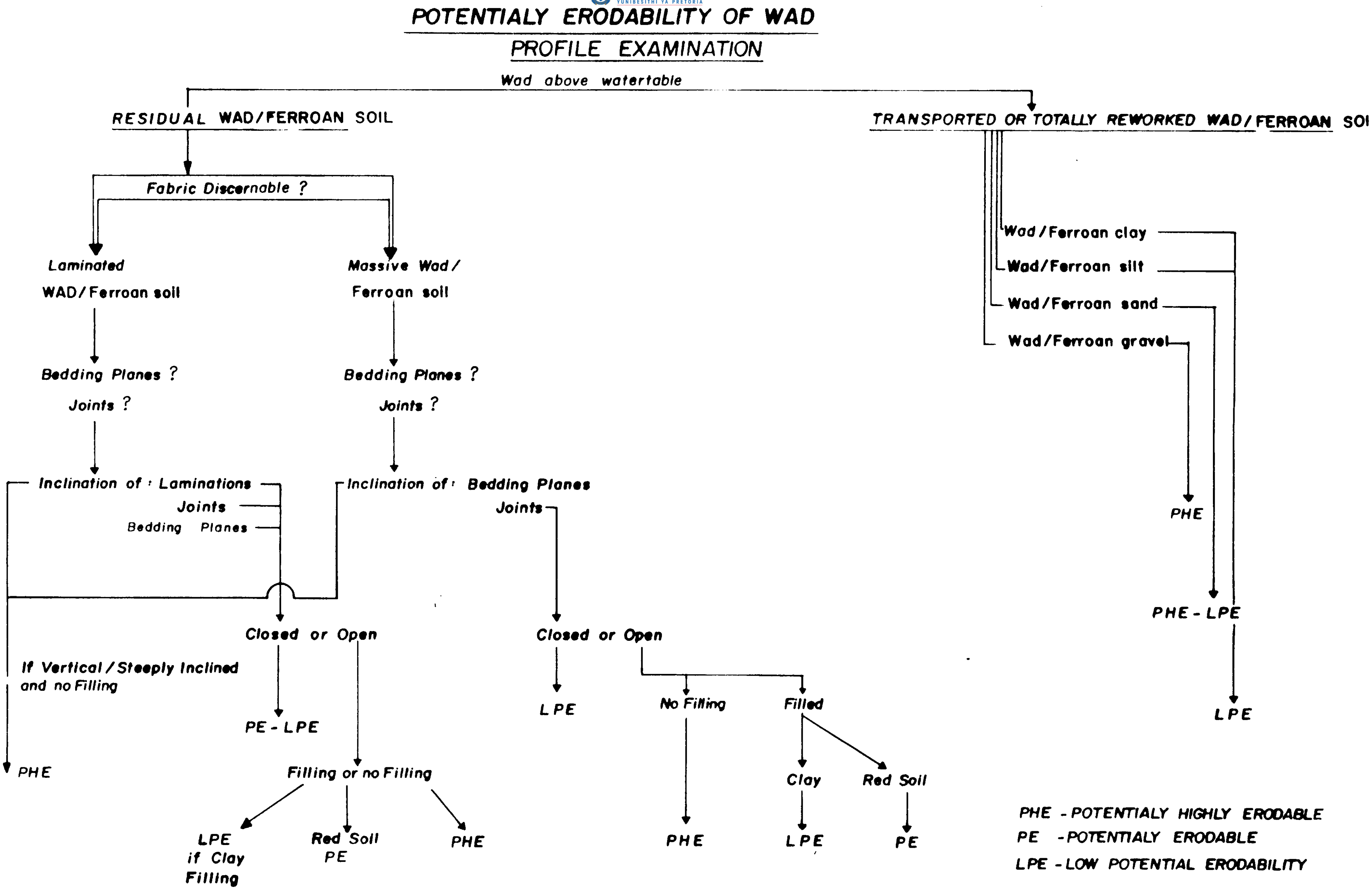


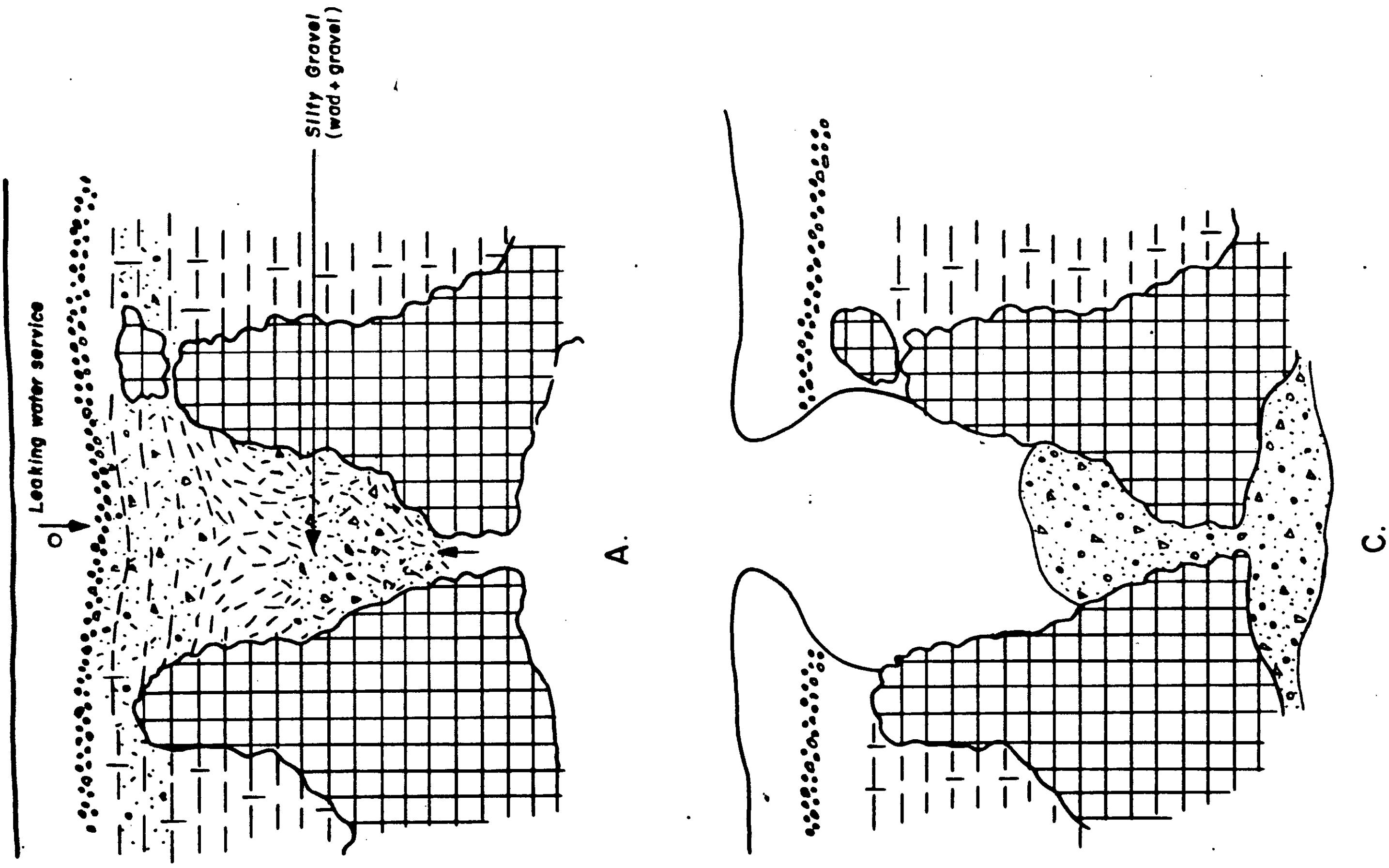
FIGURE 8.1. THE CONTRIBUTION MADE BY WAD TO POTENTIAL STABILITY OR INSTABILITY GIVEN THE OTHER INTERDEPENDENT CONDITIONS FOR SINKHOLE FORMATION.

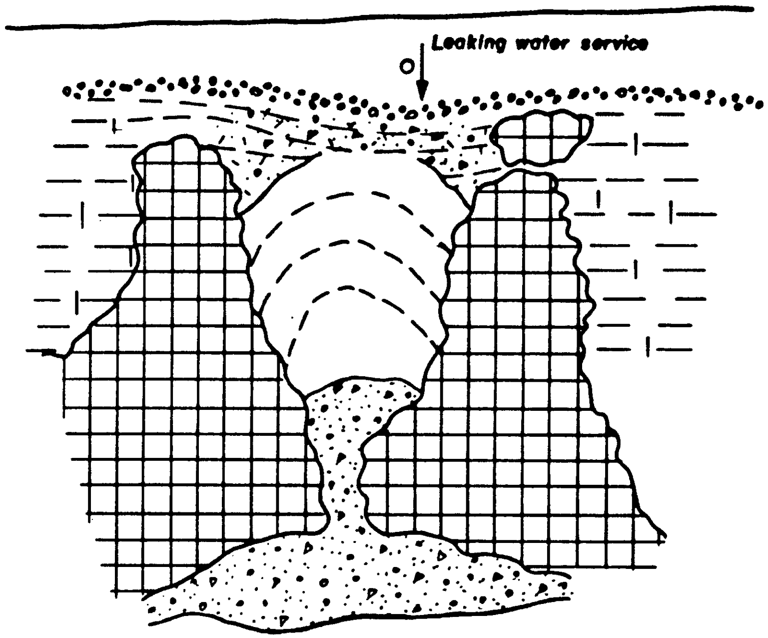
Jennings et al (1965) list the following interdependent conditions necessary for sinkhole formation :

i) Adjacent rigid material to constitute abutments for the roof of a void
ii) Arching must develop in the residuum
iii) A void must be developed below the arch in the residuum
iv) A reservoir must exist below the arch to accept material which is removed to enlarge the void substantially
v) Once a void of appropriate size is established, a disturbing agency must induce collapse. The void migrates upwards. A common agency is water in the arch material.

The author believes that the process of sinkhole formation is extremely complex involving many interrelated and interdependent conditions and mechanisms. These factors listed above are but a few of many conditions potentially contributing to sinkhole formation. Accepting the conditions listed above, the nature of the material between the abutments as well as the overlying material will determine the susceptibility to sinkhole formation. Consider two mechanisms of sinkhole formation (Figure 8.2 and 8.3).

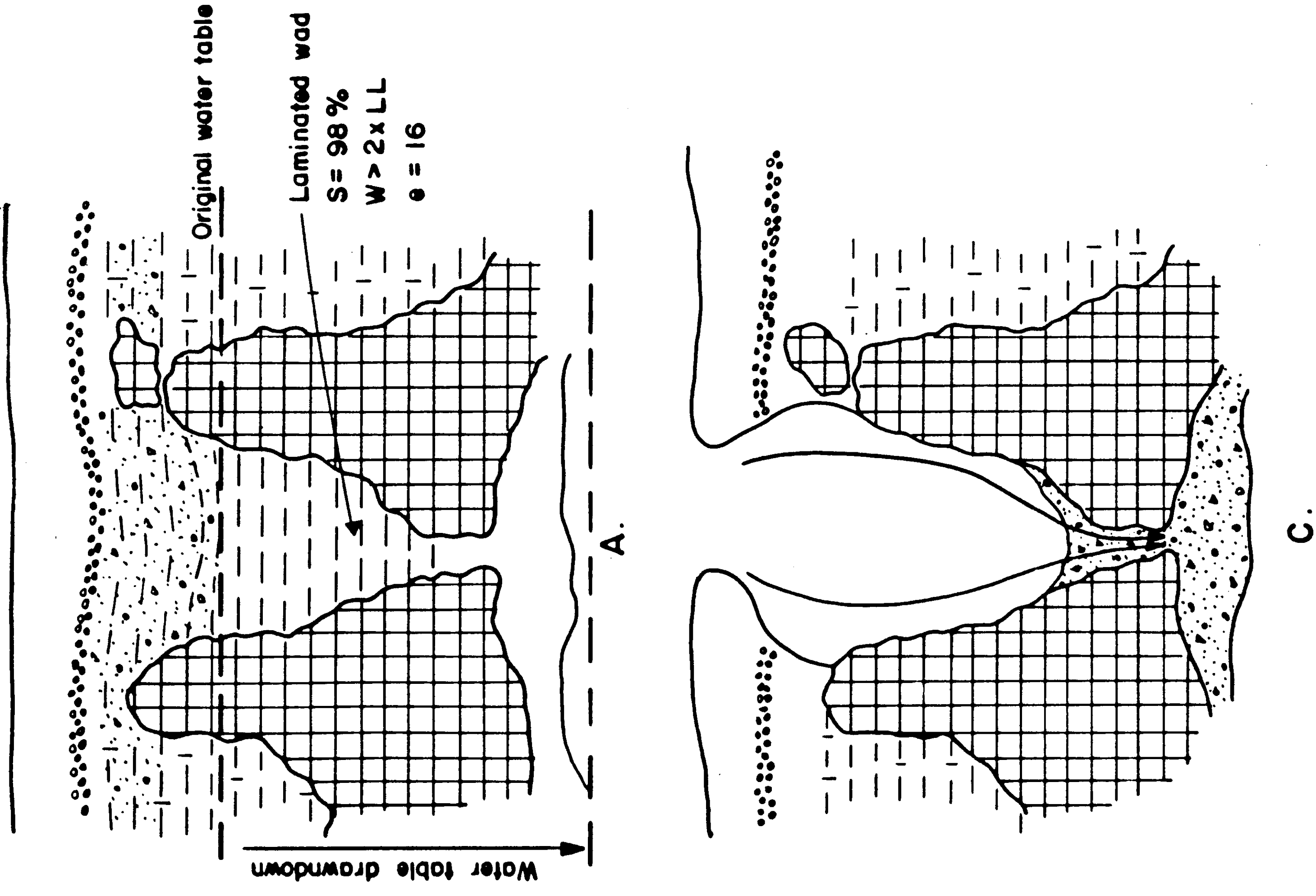
Firstly sinkholes developing as a consequence of leaking services etc. Water from a leaking service for instance, would percolate downward achieving the critical seepage force required for erosive activity. This erosion would initiate the movement of material down the throat and into the reservoir. Erosion and loss of shear strength by the residuum causes the void to grow in size and the arch migrates upward. (Figure 8.3). The wad therefore is located in the critical part of the profile above the watertable and the erosion thereof serves as the triggering mechanism. The upper part of many soil profiles, associated with the sinkholes in the area south of Pretoria, consist of highly permeable material. This reworked material is constituted by chert rubble and wad and could be described as a silty gravel.

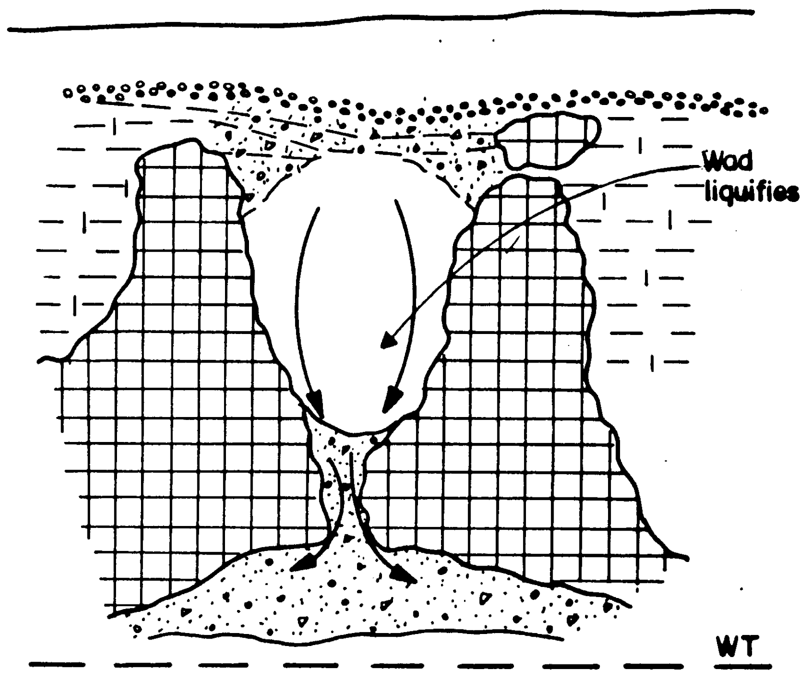

Leaking water service
Silty Gravel
(wad + gravel)
A.
C.



B.

FIGURE 8.2: MECHANISM OF SINKHOLE DEVELOPMENT. DIAGRAM A: FERROAN SOIL HAS BEEN REWORKED TO SUCH AN EXTENT THAT THE ORIGINAL FABRIC HAS BEEN DESTROYED AND THE MATERIAL NOW POSSESSES A HIGH PERMEABILITY. PERCOLATING WATERS ACHIEVE THE SEEPAGE FORCE REQUIRED TO OVERCOME THE HYDRODYNAMIC/STABILITY OF PARTICLES. DIAGRAM B: HEADWARD EROSION PROCEEDS. DIAGRAM C: SINKHOLE FORMS.


Original water table
Laminated wad
S = 98 %
W > 2 x LL
e = 16
Water table drawdown
A.
C.



B.

A. Drowdown of water table results in a mass of saturated wad located in a critical portion of the profile. The wad has the potential to liquify.

B. An external dynamic load such as an earth tremor associated with mining activity causes the wad to liquify. The wad mass moves rapidly into the recepticle overlying more competent layers result in arch formation.

C. If no competent material overlies the mobilized wad the resultant cavity will "day light" immediately constituting a sinkhole.

8.3 A PROPOSED MECHANISM OF SINKHOLE FORMATION.

The water percolating through this mass is able to achieve the critical velocity required to overcome the hydrodynamic stability of the particles. The seepage force of the water is thus great by the time it reaches the in-situ unreworked wad lower down in the profile and in the throat of the potential sinkhole. The nature of this material will determine if the process may be checked or whether it may proceed (Figure 8.2).

The soils which are potentially highly erodible and the presence of which should cause concern are laminated and massive wads with open joints or joints filled with red sandy silts and silty sands, ferroan sands and particularly ferroan or wad gravel (Figures 8.1, 8.2 and 8.3).

The author believes that sinkholes in dewatered areas may be associated with the process of liquifaction. This study has shown that many wads are in a metastable state with the potential to liquify given externally induced dynamic loading. The high void ratio's, as high as 16, the high natural moisture contents (sometimes twice the liquid limit), and the high degree of saturation indicate the potential susceptibility of this material to liquifaction.

This wad must be located in the critical position in the profile, namely in the throat region. Given the other preconditions for sinkhole formation, particularly a recepticle for the material to flow into and the wad located below the watertable or in the lower capillary rise zone in a fissure, mobilization would result in the formation of a sinkhole. The wad would transmit a dynamic load causing the pore pressures momentarily to surpass the stabilizing forces, such as the van der Waals forces, resulting in a change in state and mobilization. The mobilized material would rush into the grike or throat and into the recepticle. The overlying material would also be destabilized and mobilized, being drawn down into the throat.

No arching would occur in an overburden consisting of reworked wad and chert rubble, wad gravel or any loose material, only mass movement. This mobilization and mass movement would occur in a matter of seconds. The energy source for the dynamic load could be earth tremors possibly associated with mining activity, or a passing train. This is a proposed mechanism for the formation of the extremely large sinkholes.

If a competent layer of material overlies the mobilized wad, a roof would be created in which arching would continue to occur until the feature eventually 'daylights'.

The recepticle for the mobilized material in both man induced and naturally occurring sinkholes need not necessarily be located immediately below the manifest sinkhole. The flow path for moving water is not only vertical but also possess a lateral component due to the utilization of the tortuous passages in the soil.

The permeability of the soil may be viewed in terms of the primary and secondary permeabilities. The former refers to the tortuous paths in the wad material and the latter refers to discontinuities such as fissures which may be present in the residual soil mass.

Excessive artifical drawdown of the watertable will result in the rapid removal of water from the discontinuities in the rock and in the residual wad. The water in the voids of the wad will not drain out as rapidly due to the low permeability of the soil material. The wad may be in a metastable state with a high void ratio and a moisture content exceeding the liquid limit of the soil. The rapid artificial drawdown of the watertable would serve to further compound the potential instability of the soil mass. An enormous mass of water is left above the receding watertable creating a "drag effect" on the soil skeleton. Any applied dynamic load or shock such as an earth tremor would trigger the process of liquification. The result of this process would be the instantaneous mobilization of the soil mass.

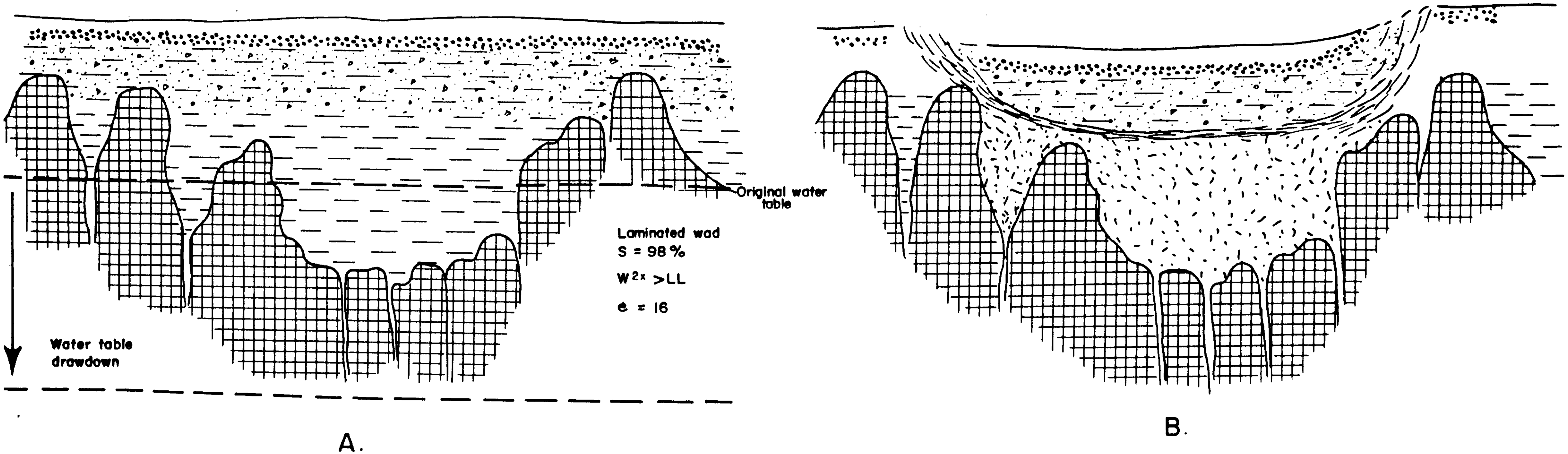
Should a recepticle be present to receive the mobilized mass, a sinkhole may result immediately or with time. A cavity so created could arch in a competent material resulting in a gradual migration of the feature to the surface by ravelling and collapse. If no recepticle is present the wad may on liquification simply fall into a denser state and hence occupy a smaller volume. The manifestation at surface would be a doline (Figures 8.3 and 8.4).

ii) Foundation Investigation

The validity of investigations executed with field and laboratory tests, rests solely on the quality of samples obtained and on how representative they are of the soil structures from which they are taken.

Rankine analysed an element of loose earth and applied his findings to the prediction of mass behaviour (Rowe 1972). His steps are followed when samples are taken and specimen tests are made. But unless the specimens are sufficiently representative of the strata and their structure, prediction of performance can be completely erroneous.

It is essential in conducting an investigation on a site underlain by wad to identify, describe and record the fabric type. Subsequently all tests in the field and laboratory must be conducted taking cognisance of the fabric. Examination of many investigation reports pertaining to such sites indicates a failure to take cognisance of the existence of different types of wad or ferroan soils. The term "wad" is used loosely to describe what must essentially be a range of material types with possibly widely divergent properties.



A. Water table artificially lowered. Wad has potential to liquify.

B. An external dynamic load such as an earth tremor causes the wad to liquify. No recepticle is available to receive the mobilized material. The mass merely settles into a denser state as the water seeps out. The manifestation on surface will be a doline.

FIG. 8.4. A PROPOSED MECHANISM OF DOLINE FORMATION.

Chapter 9 : Conclusions and Recommendations

Two principal types of weathering product of dolomite rock have been identified in the study area, namely wad and ferroan soil. These respective groups of materials may be subdivided into laminated or massive wad and laminated or massive ferroan soils on the basis of the fabric they display.

The geotechnical properties of the different wad/ferroan soils have been ascertained through laboratory and field testing. Relationships between the natural form and spatial arrangement of these macrofabric features and laboratory measurements have been examined. The influence of secondary features or fissures imposed on these soils have been considered.

Wad is noted to possess both poor and very positive behavioural characteristics. A wide range of values have been obtained from the various tests conducted to characterise the behaviour of the wad. This variation in characteristics is a reflection of the influence of environmental and compositional features.

The assessment of the wad requires that particular attention is paid to fabric description and to the degree of reworking. Wad fabric examination may prove so essential for the engineering geological appreciation of a site that it should dominate the way a stability and foundation investigation is executed.

The following results summarise the important behavioural characteristics of the wad :

a. Both laminated and massive wads grade predominantly as silts or clays.

b. The void ratio always exceeds one.

c. The natural moisture content often exceeds the liquid limit.

d. Dry and bulk density values are predominantly low.

e. Almost all the recorded overconsolidation ratio values, for both types, exceed one.

f. Many wad materials particularly those of a "brittle" nature may bear substantial loads with little deformation.

g. The laminated and non-laminated wad material may have a low permeability but secondary features serve to increase the permeability of the wad mass.

h. The material may be erodible but not dispersive.

The information reported in this text indicates that the study of the materials termed wad or ferroan soils has only been initiated. Further attention must be paid to the points listed below. The author is essentially continuing with the study of these aspects.

1. The classification of the wad and ferroan soils on the basis of fabric, as developed in the study area south of Pretoria must be tested in the other dolomitic areas of the West Rand, East Rand, southern Johannesburg and eastern Transvaal. Initial studies by the author indicate that the same types of wad are manifest elsewhere.

2. More detailed studies of the geochemical makeup and development of ferroan soils and wad are required. Consequently, the differences in behavioural characteristics associated with material with the same macrofabric but differing chemical makeup must be determined. Any detailed study into the geochemistry must be initiated using materials which are intact or non reworked. This will permit classification and permit the material to be related to a parent rock. Once the geochemistry of the intact residual soils has been completed, a study of the reworked materials could follow.

3. A study should be made of the possible contributions that wad and ferroan soils and gravel make to sinkhole formation.

4. Liquifaction of wad must be researched, as must the possible contribution that this mechanism may make to sinkhole and doline formation. The author has embarked on such a study in the ongoing research of these materials.

5. Future research of the geotechnical properties of these materials must include specialized studies including studies of the effects that the anisotropic nature of the material has on the behavioural characteristics. Detailed comparisons of properties determined perpendicular and parallel to fabric can be made.

   Another important aspect to be examined is the comparison of behavioural characteristics of the intact unreworked wad with those of the reworked or remoulded materials. The determination of the range of geotechnical properties that the remoulded materials display and the effects that remoulding has on the properties such as shear strength, permeability etc. should be attended to.

6. The inorganic dispersing agents being used for grading analyses of fines in the hydrometer, namely sodium hexameta-phosphate, sodium carbonate, sodium oxalate and sodium silicate may not be effective. Attention should possibly be paid to the use of organic dispersing agents. This is a matter that would most adequately be dealt with by a colloidal chemist.

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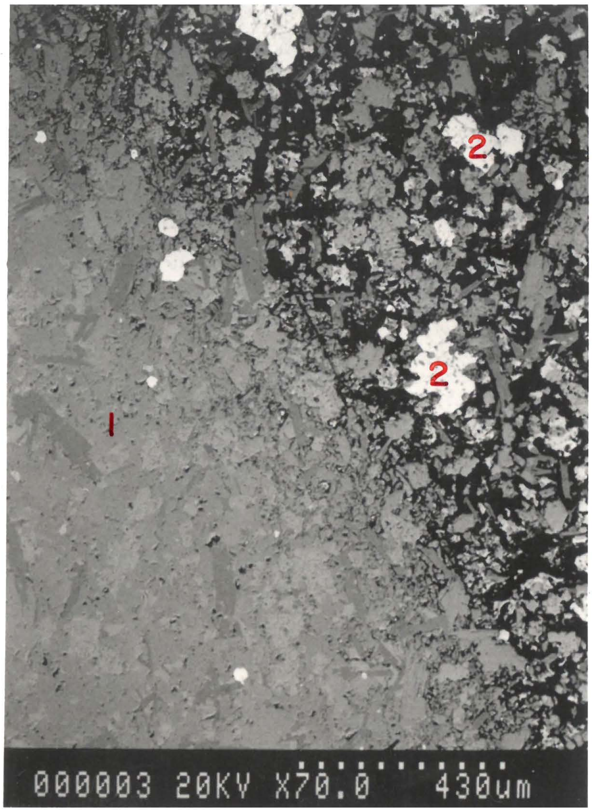
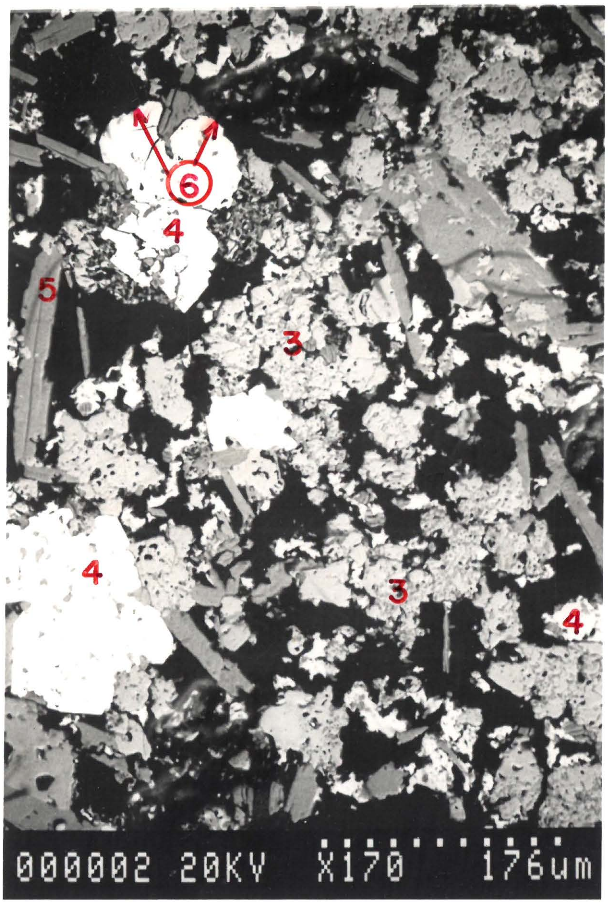


1. Dolomite

2. Partially Leached Dolomite



3. Tremolite
4. Hematite
5. Biotite
(6) Void

PLATES 1 and 2 SEM PHOTOGRAPHS OF A SAMPLE DEPICTING THE WAD / DOLOMITE CONTACT.