Code of Practice

The Geotechnical Division of SAICE

Site Investigation

Code of Practice

The South African Institution of Civil Engineering

JANUARY 2010

PREFACE

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The Site Investigation Code of Practice establishes a standard of "acceptable engineering practice" to assist the construction industry (client, project manager, consultant, contractor) in the planning, design and execution of geotechnical site investigations in southern Africa.

The code has been introduced to the South African civil engineering industry to address shortcomings that have lead to inappropriate investigations being carried out. The code is published as a guide to good practice and is not intended to be prescriptive in its content and recommendations. The recommendations contained herein are based on generally accepted national and international standards and principals, and any deviation from these recommendations should be defended by sound engineering judgement or site specific experience.

Site investigation is a complex scientific process that is vital to any construction project. Inadequate investigation can lead to over-conservatism in design and/or large construction cost overruns. Conversely it can lead to failures during or after construction resulting in damage to property, consequential damages or even loss of life. There are countless examples in industry of investigations that were insufficient or inappropriate for the type and size of development, the prevailing soil conditions and proposed foundation solutions. Often these investigations have been prescribed by budget and/or time constraints (fast tracking), or by inexperience on the part of the client and project manager.

The objective of this code is to recommend a concise and systematic way of carrying out investigations using methods and techniques that are relevant, reliable and cost-effective. In addition to giving guidance to geotechnical practitioners, this guideline should also be used by project managers and clients in the preparation and adjudication of site investigation proposals and tenders.

The document has not been drafted as a comprehensive guideline of investigative methods and should be read in conjunction with the references cited at the end of each section. A bibliography is included at the end of the document for further reading.

Reference:

> **Site Investigation Code of Practice**, 1st Edition, South African Institution of Civil Engineering - Geotechnical Division, January, 2010.

This guideline is endorsed by the following professional bodies:

- South African Institution of Civil Engineering, SAICE
- South African Institute for Engineering and Environmental Geologists, SAIEG

COMMITTEE

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1. INTRODUCTION

1.1 Background

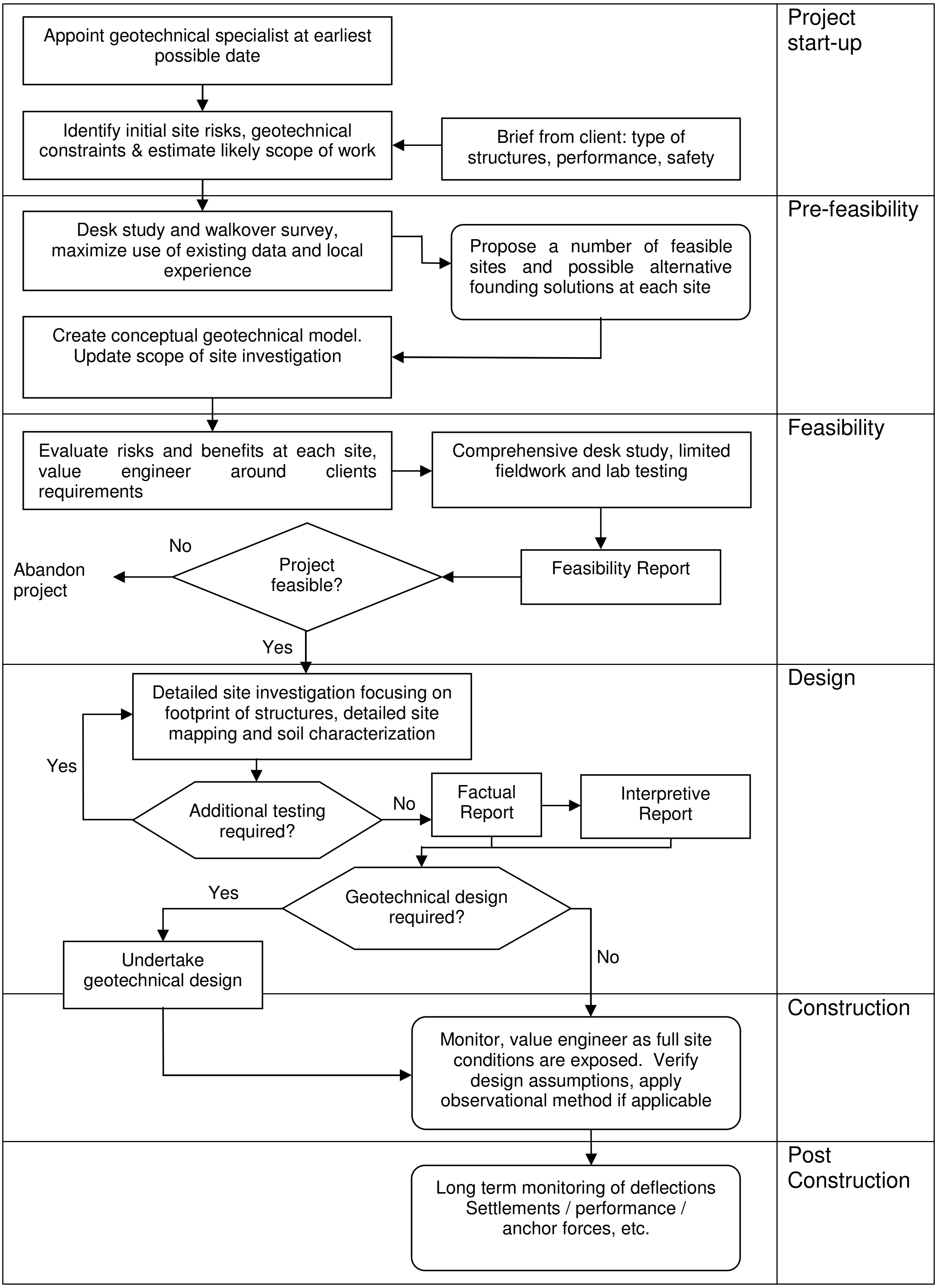
The soil and rock that surround us serve as foundations for our structures, as well as a source of natural construction material that is generally more cost-effective to use than man-made materials. Their inherent variability results in many construction challenges and a project owner/developer is well advised to procure the services of a professional geotechnical consultant to maximise the benefits of constructing on, or using natural materials. The geotechnical consultant should both be qualified and experienced in geotechnical engineering to be able to investigate a site and determine the risk associated with geotechnical constraints and ultimately to design practical and cost-effective foundation or construction solutions.

The state of current practice of site investigation in South Africa is such that it is deemed necessary to implement recommended standards for the industry as a whole. As the scope of work of site investigations covers a very broad range, this document is intended to serve mainly as a guide, with the geotechnical consultant bringing the necessary refinements for each specific project. The emphasis of this document is on bringing “value engineering” back into the minds of those procuring a site investigation and to ensure that site investigation is brought into the main stream of the project planning at the earliest stage possible and not as a last minute “necessary evil”. As unforeseen ground conditions can have enormous cost and programme implications for a project, a well designed site investigation presents an opportunity, at minimal expense, to optimise founding solutions. It is, without exception, more cost-effective to carry out an appropriate site investigation from the start, than to attempt to rescue an inadequate investigation during construction, or worse still, after construction is completed. Adequate and appropriate site investigation by competent persons ensure that the significant risks that lie hidden within the ground, are identified at an early stage in the planning phases, allowing appropriate founding solutions to be budgeted for. These risks may even affect project viability as a whole. The cost of an investigation is often insignificant compared to the cost of over-designed foundations based on minimal information and guessed parameters.

It remains a challenge, and an objective of this document, to convince developers to invest money in a sound foundation. In terms of controlling the risks of over-expenditure on a project, adequate site investigation has the potential to save the client between 10% and 100% on project foundation costs. Hence, it is a well worthwhile spending up to 2% of the project cost on adequate site investigation as an essential investment in financial risk management.

Apart from giving guidance on site investigation requirements, the intension of this document is to highlight the phased investigation approach that is essential to almost any size of investigation. The concept of a single phase ground investigation should be firmly resisted by any geotechnical practitioner, as only once the investigation proceeds can one assess the need or otherwise, for further probing. This is not an open cheque-book approach, but one that clearly highlights that additional investigation of some form is possible, and likely. These variations can easily be dealt with by rates and costs agreed up front for the various investigation techniques. Without this phased approach, shown in Figure 1, investigations and reports are left incomplete and not able to draw proper conclusions. The geotechnical designer must not be left guessing parameters! Sufficient investigation and testing must be carried out for design parameters to be determined with a reasonable degree of confidence, if not from direct test methods then at least by correlations from indirect, but reliable methods. If assumptions are made, these should be clearly stated and allowance made for verification in the construction budget.

Figure 1: Site investigation good practice.



This leads to the next important point, a site investigation is *not complete* without on-site confirmation during construction and allowance must be made during the procurement phase for this. An investigation typically samples only a small percentage of the site. During construction the full site may be exposed, allowing the geotechnical specialist to verify conclusions and to optimise designs on an on-going basis, often saving on programme and cost, or avoiding unnecessary delays as changed ground conditions are timeously identified. This document also highlights the value the geotechnical consultant brings during the construction phase of the development, which is essential when using the Observational Method of design.

1.2 Scope

The objectives of this Code of Practice are to:

- define appropriate standards for site investigations, that are qualitative and not overly quantitative or prescriptive,
- provide a framework for identifying the risks associated with construction activities,
- provide guidance to inexperienced investigators in planning investigations,
- identify appropriate geotechnical investigative methods to be employed,
- serve as a standard for clients to prepare or adjudicate tenders,
- emphasise the selection of critical geotechnical design parameters to be determined, and
- serve as a legal reference of accountability for geotechnical practitioners.

This code is not intended to undermine or restrict sound engineering judgement, local experience, creativity or competition among practitioners.

1.3 Definitions

For the purposes of this code, the definitions given below apply:

"**Aerial photograph interpretation**" refers to the examining of photographic images for the purpose of identifying surface features and exposures, terrain units with similar geotechnical characteristics and geological contact and fault lines.

"**Client**" means the person, organisation or agent/cy that provides the brief for the investigation, commissions the work and pays for it.

"**Competent person**" is defined by the Code of Practice - Geotechnical Engineering, to be published by the Engineering Council of South Africa. The code is currently in draft format, but identifies engineering work reserved for registered persons and defines the level of competence required for the execution of work of varying complexity, specifically in the field of geotechnical engineering.

"**Consultant**" means the individual professional or consulting practice engaged by the client to undertake the site investigation, or is responsible for geotechnical advice and, if required, the geotechnical design.

“**Contractor**” means the person or organisation that undertakes the execution or part of the execution of the geotechnical investigation fieldwork and/or laboratory testing.

“**Geophysics**” refers to the indirect measurement of certain properties of the Earth by quantitative physical methods, especially by seismic, gravity, electromagnetic and radioactivity methods.

“**Geotechnical borehole**” refers to a borehole drilled for the purpose of extracting disturbed or undisturbed samples of soil and rock for profiling and testing and/or to allow in-situ geotechnical tests to be carried out at depth below the ground surface.

“**Geotechnical model**” refers to the description of the nature and the variability of the geology that underlies a site and includes the classification and characterisation of the soil and rock, as well as the ground water. The model typically includes plans, profiles, cross sections and material parameters.

“**Global positioning system**” refers to a device capable of receiving time and special information from a constellation of geo-stationary satellites and translating these to degrees of latitude and longitude and elevation with respect to a universal coordinate system.

“**Hazard**” means a condition or a set of conditions with the potential for initiating an unforeseen result.

“**In-situ test**” refers to geotechnical tests that are carried out on the site from ground surface, in local excavations or in boreholes to determine specific geotechnical parameters by direct or indirect correlations.

“**Laboratory test**” refers to mechanical and chemical tests that are carried out in a controlled environment on disturbed and undisturbed samples of soil and rock recovered from an investigation site for the purposes of geotechnical classification and characterisation.

“**Profiling**” means the description of the soil or rock profile in accordance with accepted norms by the visual inspection of an excavation or by logging the core or chip samples from geotechnical boreholes.

“**Risk assessment**” means the process through which the hazards relevant to a specific activity are identified, a prediction is made of how probable they are (likelihood) and how serious they might become (impact), and decisions are taken on what mitigating actions are required to achieve the project objectives.

“**Risk**” means the combination of the probability, or frequency, of occurrence of a defined hazard and the magnitude of the consequences of the occurrence.

“**Site investigation**” means the phased process by which geological, geotechnical, and other relevant information ,which might affect the construction or performance of a civil engineering structure or building project, is acquired.

“**Site**” means the area or place where the investigation or construction is being carried out.

“**Supervisor**” means the person designated in writing by the contractor or consultant, who is resident on site and whose responsibility it is to supervise the execution of the work.

“**Survey**” refers to the act of setting out or recording positions to a specified accuracy and with reference to a defined coordinate system using optical or GPS methods.

"**Test hole**" refers to an excavation of limited extent which is excavated as part of the site investigation, that allows direct and visual inspection of the soil or rock and the taking of samples.

"**Test pit**" means a test hole excavated by hand or using mechanical excavators.

"**Trial hole**" means a test hole of limited cross section in relation to its depth, typically drilled using either mechanical or hydraulic augers.

"**Walkover survey**" refers to a visual, non-intrusive, assessment of an area associated with a site for the purpose of mapping geological exposures and identifying test positions, access restrictions and existing sources of construction materials.

1.4 Abbreviations

Organisations - South Africa

CESA	Consulting Engineers South Africa
CGS	Council for Geoscience
CSIR	Council for Scientific and Industrial Research
CSRA	Committee for State Road Authorities
DCA	South African Drilling Contractors Association
ECSA	Engineering Council of South Africa
GIGSA	Geosynthetics Interest Group of South Africa
NHBRC	National Home Builders Registration Council
PMI SA	Project Management Institute SA Chapter
PMSA	Project Management South Africa
SAFCEC	South African Federation of Civil Engineering Contractors
SAICE	South African Institution of Civil Engineering
SAIEG	South African Institute for Engineering and Environmental Geologists
SANCOLD	South African Commission on Large Dams
SANCOT	South African National Commission on Tunnelling
SANIRE	South African National Institute of Rock Engineering

Organisations - International

ASCE	American Society of Civil Engineers
BSI	The British Standards Institution
CEN	European Committee for Standardisation
CIRIA	Construction Industry Research and Information Association
ISO	International Organisation for Standardisation

Codes & Standards - South Africa

TMH	Technical Methods for Highways, CSIR
TRH	Technical Recommendations For Highways, CSRA

Codes & Standards - International

ASTM	American Standards for Testing Materials, ASCE
BS	British Standards, BSI
EN	Eurocodes, CEN
ICS	International Classification for Standards, ISO

Technical

API	Aerial Photograph Interpretation

BH	Borehole
CPT	Cone Penetration Test
CPTU	Piezocone test
CSW	Continuous Surface Wave testing, Geophysics
CVES	Continuous Vertical Electrical Sounding, Geophysics
DCP	Dynamic Cone Penetrometer
DPL	Dynamic Probe Light
DPSH	Dynamic Probe Super Heavy
DTM	Digital Terrain Model
EM	Electrical conductivity Meter, Geophysics)
GPR	Ground Penetrating Radar, Geophysics
GPS	Global Positioning System
PLI	Point Load Index strength test
PLT	Plate Load Test
PMT	Pressuremeter Test
RMC	Rock mass classification
SPT	Standard Penetration Test
TH	Trial Hole
TLB	Backhoe Loader
TP	Test Pit
UCS	Unconfined Compressive Strength
VST	Vane Shear Test

1.5 Legislation Pertaining to Geotechnical Site Investigations

Mine Health and Safety Act, No. 29 of 1996.

National Water Act, No. 36 of 1998.

Occupational Health and Safety Act, No 85 of 1993.

Housing Consumers Protection Measures Act, No. 95 of 1998.

National Building Regulations and Building Standards Act, No. 103 of 1977.

Natural Scientific Professions Act, No. 106 of 1993.

Engineering Professions Act, No. 114 of 1990.

Minerals Act, No. 50 of 1991.

Construction Regulations, 2003, Regulation Gazette No. 7721, Vol 456, Pretoria, 18 July 2003, **No. 25207**.

1.6 References

Code of Practice - Geotechnical Engineering, (2009), Engineering Council of South Africa, Draft Revision D, July 2009.

2. PLANNING

2.1 Introduction

In the planning of a geotechnical site investigation, it is essential that the objectives of the investigation in relation to the nature of the development are clearly understood. This requires that the geotechnical consultant obtains clear terms of reference from the client regarding phase, scope and detail required for the intended project. From these the consultant can initiate the planning process for the commencement of the geotechnical investigation.

The planning of an investigation is dependant upon a number of factors including:

- nature and complexity of the development,
- stage of development, i.e. phase or detail of investigation required,
- size of the area to be investigated,
- complexity of the geology and
- expected physical and geotechnical constraints associated with the site.

These factors determine the type and extent of investigative methods to be employed to develop a geotechnical model populated with appropriate design parameters. These parameters form the basis for geotechnical design and ultimately construction of the project.

2.2 Objectives of Investigation

The aim of the investigation is to characterise the nature and distribution of the geotechnical properties of the site to permit the acceptable design, construction and operation of the proposed works. The investigation should endeavour to achieve the required technical standards of good practice with maximum economy.

The detail of investigation required is dependant on the stage of the development or project. The information required may initially be on a broad level where limited data is required to allow comparison of a number of alternatives in the selection of the most favourable site. Once a preferred site has been selected, the level of detail and scope of investigation increases as initially the layout of the project is finalised and ultimately the detailed design of the structures and foundations are undertaken. Other categories of investigation may involve assessing a site for temporary works design, remedial design or for quality control and monitoring of existing works.

The site is primarily characterised by the regional geology and geomorphology of the terrain within which it occurs. The departure point for a site investigation is therefore an understanding and description of the regional geology, topography, hydrology, climate, vegetation and seismology. Within this framework a conceptual geotechnical model of the site can be defined by interpolation and/or extrapolation of the geological properties and engineering classification of materials.

The conceptual geotechnical model is further developed and populated by undertaking field and laboratory investigative measures. The complexity and sophistication of the model evolves as successive levels of detail are sought and achieved.

2.3 Development Classes (Categories)

The size of the site for which a geotechnical investigation is to be conducted is dependent on the nature of the intended development. Development projects are classified into three broad categories in terms of spatial extent as follows:

- **Compact** - individual structures or clusters of structures, for example a process factory, building, small dam, quarry, bridge, tower, tank etc.
- **Linear** - roads, pipelines, rail lines, canals, transmission lines, tunnels etc.
- **Large area** - housing estates, mine developments, industrial complexes, power stations, airports, harbours, large dams etc.

The scope of the investigation is further influenced by the complexity of structure, nature and magnitude of loading, sensitivity to settlement or development intended. The following classes are recognised:

- **Minor structure** - single storey buildings, steel structures and machines that are generally not sensitive to settlement.
- **Standard** - multi-storey buildings, commercial and retail complexes, light industrial structures, warehouses, showrooms, communication masts, bridges, small dams and reservoirs etc.
- **Complex** - heavy industrial complexes, high rise structures, large reservoirs, dams, power plants, airports and harbours etc.
- **Exceptional** - facilities associated with nuclear power generation, hazardous waste disposal, military installations and testing facilities etc.

2.4 Levels of Geotechnical Investigation

The required level of detail of a geotechnical site investigation is often dependent on the stage of the project development. The level of detail of investigation generally increases with each consecutive phase and is aimed at developing the geotechnical model of the site sufficient for planning, design and implementation.

A typical major civil engineering project will go through all the stages of investigation (with separate contracts) to provide the required level of detail of information at appropriate times throughout the development of the project. With smaller projects the principals of a phased investigation should still be implemented, although a single investigation contract is typically awarded.

The following stages of investigation apply:

- **Pre-feasibility** - desk study of available information and site walkover.
- **Feasibility** - comprehensive desk study and limited intrusive investigations (test pitting).
- **Tender design or Basic engineering** - geophysics, test pits, trial holes and limited boreholes with laboratory classification testing. A second round of investigations may be required to examine anomalies or uncertainties that emerge during the first round. This level is usually required for bankable feasibility studies.

- **Detailed design** - detailed intrusive investigations based on the development layout including boreholes, in-situ testing and advanced laboratory testing. Large scale trials may also be undertaken, e.g. test piles, pump tests, preload embankments etc.
- **Construction** - monitoring and additional testing during construction ensures that the geotechnical design criteria are being achieved. This phase of investigation also allows an appraisal of a much larger representation of the site geology often exposed during earthworks and foundation construction than is possible during earlier investigations. This is an often neglected part of the investigation process.
- **Post construction** - monitoring of the structure after construction provides valuable information in assessing the validity of the geotechnical model and the adequacy of the investigative methods. It also affords an opportunity to detect and remedy deficiencies, preferably before major damages are incurred.
- **Remedial** - forensic investigations attempt to identify the cause of failure or inadequate performance of structures and provide additional information to recommend appropriate remedial measures.

2.5 Appropriate Methods of Site Investigation

A site investigation will typically encompass the following elements:

- **Desk study** - the desk study should include a study of published geological and topographic maps, aerial photographs, ortho-photographs, geo-hydrological maps or any other relevant data from previous work on and around the site. In addition it is considered advisable that a site inspection or walkover survey be carried out.
- **Surveys** - land surveys are conducted to create a topographical model of the site or to set-out and record test positions or other pertinent features.
- **Test holes** - these are excavated and profiled in-situ to develop the site stratigraphy, identify seepage behaviour, appraise slope stability for excavations and to sample for laboratory testing. Test holes are a relatively cost-effective means of investigation that provide valuable information.
- **Boreholes** - allow an assessment of the stratigraphy at depths beyond the reach of test holes and in difficult ground conditions. Boreholes also provide a means for carrying out certain in-situ tests and sampling using coring tools and thin-walled push-in type samplers. Drilling spoils and core samples from boreholes can be logged and tested to further develop the geotechnical model of the site. Core drilling is more expensive and time consuming than test holes or percussion drilling, but is often the only means of obtaining geotechnical information at depth or in difficult ground conditions. Exploration drilling, although less expensive, should never be substituted for geotechnical drilling.
- **In-situ tests** - attempt to measure geotechnical parameters on the site by direct or indirect means. A host of tests are available to the geotechnical consultant, each suited to specific ground conditions and providing information on a range of geotechnical parameters.
- **Geophysical methods** - offer a quick, non-intrusive and cost-effective means of exploring subsurface conditions in plan or in section. These can be used to map variations in geology and structural features such as fracture zones or fault zones and provide information for the design of earthing requirements and corrosion

protection measures. Geophysical methods are also used to optimise the positioning of further test points, e.g. boreholes.

- **Laboratory tests** - offer the most practical and accurate means of classifying and characterising geo-materials, provided that representative, and in some cases undisturbed, samples can be obtained and tested.

2.6 Requirements

It should be emphasised that all investigations are point specific and with the data obtained being confined to the point or volume investigated. Whilst some commentators indicate that an investigation ratio of 1:500,000 is usual, i.e. 1m^3 of material is investigated for every 500,000m^3 affected by the structure, this ratio or any other rule of thumb should not be followed blindly and it is advised that each investigation should be handled on its own merits.

Considering the investigation category and stage of investigation, Table 1 presents typical guidelines for the density of geotechnical data points required for various developments or project types. Data points refer to one or more site investigation methods, e.g. test holes, boreholes and in-situ tests at a specific location, selected to suit the site geology and the nature of the development.

Comments related to the use of Table 1:

- The table refers to investigation data points without reference to specific techniques or methods. The appropriate type of investigation, e.g. test pit or borehole etc., will depend on the geological conditions and on the expected engineering solution, e.g. piled foundation, soil nailed lateral support, etc.
- In addition to the broad category of development, the minimum required density of data points will also depend on the complexity and variability of the geology and topography, the type, size and complexity of the proposed structures, the availability of existing site information and on the experience of the consultant on the site or adjacent to the site.
- Extrapolation, and even interpolation, between investigation points should only be undertaken with care and an awareness of the variability which is likely to be encountered in practice.
- This code of practice generally applies to site investigations for surface and near surface developments. For tunnelling and deep excavations, investigations should be designed in accordance with the ISRM’s recommendations on site investigation, referenced at the end of this chapter.
- This table is not fully comprehensive in dealing with specialised developments such as hazardous waste sites, pressurised tunnels, large underground caverns, underground mining, cemeteries, etc. These developments require close cooperation and input from specialist geotechnical professionals in planning and designing appropriate investigations.

To incorporate all of the above variations in this document is beyond its intended simplicity and practical use. It is expected that clients and their project managers are sufficiently conversant in site investigation practice to prescribe or adjudicate in these matters. If this is not the case, they should seek specialist advice.

Table 1: Typical guidelines for various stages of site investigation

Category	Development	Phase	Data points	Special Considerations
Compact	Building (Brick or Concrete)	Feasibility	1 per structure	
		Design	3 per structure	Settlement sensitivity of finishes
	Factory (Steel Frame)	Feasibility	2 per ha	
		Design	4 per ha or 4 per structure	Crane & floor requirements
	Quarry or Borrow Pit	Feasibility	1 per 5ha	
		Design	2 per 1ha	
	Tower or Mast	Feasibility	1 per structure	
		Design	1 per 25m^2	
	Reservoir	Feasibility	1 per structure	
		Design	1 per 100m^2	
	Bridge	Feasibility	1 per abutment	
		Design	2 per abutment 1 per pier	
	Substation	Feasibility	2 per ha	
		Design	4 per ha	
Linear	Pipeline	Feasibility	1 per km	
		Design	4 per km	
	Road/Rail/Conveyor	Feasibility	2 per km	
		Design	5 per km	
	Canal	Feasibility	1 per km	
		Design	4 per km	
	Power Transmission	Feasibility	1 per km	
		Design	4 per km	
	Tunnels	Feasibility	2 per km	
		Design	5 per km	
Large	Housing Complex	Feasibility	1 per ha or 1 per structure	GFSH & NHBRC requirements SANS10400 SAICE Code of Practice Van Rooy & Stiff (2001)
		Design	2 per structure	
	Harbour	Feasibility	1 per 5ha	
		Design	4 per ha or 5 per structure	
	Airport	Feasibility	1 per 10ha	
		Design	1 per ha or 5 per structure	
	Industrial complex	Feasibility	1 per ha	
		Design	10 per ha or 5 per structure	
	Power Plant	Feasibility	1 per ha	
		Design	10 per ha or 5 per structure	
	Dam	Feasibility	1 per 25ha basin 5 per km wall	Also dependent on the category of dam
		Design	1 per 10ha basin 10 per km wall	
Special	Dolomite stability	Feasibility	1 per structure	Council for Geoscience requirements Buttrick et al.
		Design	4+ per structure	
	Undermined Land	Feasibility	1 per ha 4 per km	Geophysical methods
		Design	2 per structure	

2.7 Client Specified Requirements

The client may have project specific geotechnical specifications and design criteria related to the proposed development. Such specifications and criteria can have an influence on the planning of an investigation. It is, therefore, paramount that the consultant obtains clarification from the client before the investigation plan is finalised.

In addition, investigations should also be carried out within the context of local or international standards and codes as specified by legislation or by the client in the terms of reference. The adoption of a particular code or standard may have a significant impact on the responsibilities of the consultant and the scope of work of the investigation. An attempt should always be made to select methods and standards that are applicable to the geological conditions and that are readily available in the local market.

The client should also specify or request method statements of the proposed investigative methods. A method statement outlines the equipment and procedures associated with a particular investigative method and should be referenced to recognised local or international standards. These method statements form the basis for quality control verification during the execution of the investigation, both for the client and for the main geotechnical contractor.

2.8 Extent of Investigation

The lateral extent of the investigation is generally limited to the allocated site boundaries, but should be sufficient such that the surrounding conditions will not have a material effect on the performance of the development and *vice versa*, e.g. lateral support of deep basements affecting neighbouring properties.

The depth to which the investigation must be carried out is dependent on the depth of influence of the structures and foundations, as well as the sub-surface stratigraphy, specifically the extent of the compressible zone. In this regard the following guidelines should be considered:

- **Spread footings** - investigate to a depth of at least twice the expected foundation width below founding depth, or to the level of bedrock with a consistency of soft rock or better.
- **Deep foundations** (piles) - investigate to three diameters below the pile tip for individual piles, to the width of the pile group below the founding depth of the group, or to at least 5m into bedrock with a consistency of soft rock or better.

Where investigations are stopped in a competent horizon, either pedogenic rock or bedrock, the consultant should be reasonably confident that these are not underlain by soft soils within the depth of influence of foundations. Examples of such “incompetent” bedrock include dolomitic ground (pinnacles), “floaters” in a residual profile or preferential weathering in bedded sedimentary rock. In these cases, selected exploratory boreholes should be extended to greater depths, or provision be made in the design of foundations to carry out proof drilling beyond the founding depth of the foundations.

2.9 Parameters Required

The level of investigation and sophistication of the geotechnical model will determine whether material classification and/or material characterisation is required. The objective of material classification is to categorise representative soils from the site stratigraphy into standard classes with similar engineering properties and behaviour. Classification is done on disturbed samples and generally comprises indicator and compaction testing. Material characterisation requires undisturbed representative samples to determine the in-situ state of the soil and rock (stress, density & structure), as well as specific material parameters of strength and compressibility for use in design calculations. If undisturbed samples cannot be obtained, samples can be reconstituted in the laboratory to represent the in-situ state, alternatively in-situ field testing could be considered.

Typical parameters from a geotechnical investigation will include the following:

Classification: Soil

- Grading properties (75mm to 2µm)
- Atterberg limits
- Maximum compacted density and optimum moisture content
- California bearing ratio
- Corrosivity
- Erodibility

Classification: Rock

- Unconfined compressive strength
- Joint characteristics
- Rock mass classification

Characterisation - State

- Specific gravity
- In-situ density & moisture content (void ratio)
- Permeability
- Collapsibility, heave and swell potential

Characterisation - Strength and Compressibility

- Shear strength
- Compressibility
- Consolidation and creep properties

2.10 Plans and Drawings

Most categories of investigation will require drawings supplied by the client to plan for the geotechnical investigation. In the early stages of development these should include:

- Surface and sub-surface layout showing existing infrastructure, services and servitudes

- Proposed development layout plans
- Existing topographical survey data

During later stages, the following additional information could be added:

- Detailed topographical surveys and digital terrain models
- Earthworks plans and materials management
- Roads, as well as hardstand, lay-down and parking areas
- Structure location and proposed foundations

Drawings should as a minimum indicate the following:

- Scale and orientation (north arrow)
- Coordinates system and grid, referenced to a defined local or international system or datum
- Reference point/s for on-site verification.

2.11 Special Considerations

Certain sites may be underlain by specific known problem soils / rock and conditions that require specialised investigation techniques. These may include the following:

- Dolomitic terrain
- Undermined land
- Landfill/backfilled sites
- Expansive soils
- Collapsible soils
- Highly compressible soils
- Dispersive soils

In the planning stages of the investigation, these “problem soils” should be identified from published geological maps or literature and catered for by the investigation methods.

2.12 Other Factors

Health, Safety and the Environment - Geotechnical investigations have to comply with legislation, mostly the requirements of the Occupational Health and Safety Act (Act 85 of 1993) and the regulations accompanying this act, as well as the Mines Health and Safety Act (Act 29 of 1996). In addition, it is the responsibility of the client to obtain any project or site specific SHE specifications and to make these available as part of the request for proposal documentation. It is also advisable that the geotechnical contractor prepares a project specific SHE Plan to be approved by the client prior to the commencement of fieldwork.

Site access - It is the client's responsibility to obtain the necessary permissions to access the land. This may include obtaining the necessary way leave permissions to work within or in close proximity to erf and road/rail servitudes, as well as permission form land owners.

Presence of existing services - It is the client's responsibility to obtain and indicate the presence of existing services on the site prior to the commencement of fieldwork. This aspect is particularly crucial with respect to fuel lines, gas lines, telecommunication lines and major electrical and water reticulation lines. It is also the client's responsibility to apply for and obtain the necessary excavation and/or way leave permits.

Security - Allowance should be made to provide security for equipment and personnel in certain areas. For example, employing security guards on a project where drilling equipment is left overnight on an unprotected site.

Socio-political considerations - A site may be located in an area which is socio-politically sensitive. That is, it may be paramount that the local community be informed by the client of the need to undertake a geotechnical investigation and the extent and nature of such an investigation.

Environmental sensitivity - The investigation must conform to national and provincial environmental legislation, or local authority by-laws that may have relevance to the execution of the investigation.

Proximity to roads/railways/waterways - If fieldwork needs to be conducted immediately adjacent to roads/railways/waterways then safety aspects must be taken into account. This would affect the personnel working on site and the general public in proximity to the site. Potential hazards in this regard may include dust pollution, spillages, traffic, strongly flowing rivers etc. Appropriate precautionary measures will then have to be implemented.

2.13 Follow Up During Construction

In the course of a geotechnical investigation, investigative test pitting, drilling or testing is done at selected positions across the site. The density and spatial distribution of these positions represent what is considered to be sufficient to adequately characterise the site and develop a geotechnical model. The model includes an interpolation or extrapolation of the conditions encountered at each test position and will require verification during the construction phase of the project.

The planning of a geotechnical investigation must, therefore, make provision for monitoring and observations during the construction phase of the project. This is undertaken to verify that the conditions encountered during construction, conform to the geotechnical model in broad terms. In this regard the application of the Observational Method may be of use, refer Section 6.4. This method requires that specific parameters or characteristics of the site are monitored and that the necessary corrective actions are implemented to accommodate the design criteria.

2.14 Programme

As part of the planning of a site investigation the client will typically require a programme from the geotechnical practitioner. That is, a breakdown of the various elements of the investigation in terms of a time frame to complete each element. The compilation of the programme needs to take into account the following factors.

- The client's general programme requirements. More often than not, the time required to complete a geotechnical investigation will exceed the client's expectations. In this case, both parties will have to negotiate a reasonable programme by amending the scope of work and/or allocating additional resources.
- The project manager may resort to fast tracking tactics to meet the requirements of developers and investors. Fast tracking should never compromise the quality of the geotechnical investigation.
- Health, safety and environmental considerations. The fieldwork programme will be dependent on securing approval from the relevant SHE authorities. Sufficient time should be allowed for induction processes, medical certification and the compilation and approval of SHE documents, including method statements and risk assessments.
- The availability of plant, equipment and laboratory facilities.

2.15 References

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3. PROCUREMENT

3.1 Background

The purpose of this chapter is to provide clients or their agents with guidance on the procurement of a site investigation.

Broadly speaking, there are two major components to any site investigation. These are professional advice (provided by the consultant) and contracted services (provided by drilling contractors, plant hire contractors, geophysicists and testing laboratories).

Few South African companies have the capability of providing both the professional and contracting components of an investigation. The most common way of procuring a site investigation is to appoint a consulting geotechnical engineer or engineering geologist who will plan the investigation, appoint subcontractors for drilling and testing, supervise the fieldwork, analyse the results and produce reports on the findings of the investigation. In the case of larger investigations, the client may elect to appoint the drilling and testing contractors directly to lessen the financial burden on the consultant.

Due to the particular nature of professional obligations and liability, it is preferable that the consultant should be appointed directly by the client.

3.2 Budget and Schedule

Ground related problems generally have a disproportionate effect on the cost and progress of a project, since problems occurring at an early stage of construction will often lead, not only to additional costs of putting things right, but also to irrecoverable delays, which are themselves costly (Clayton, 2001).

In order to manage the geotechnical risks on a project, sufficient time and money should be included in the project planning for an adequate investigation to be carried out.

3.2.1 Time required

Depending on the nature of the project, a site investigation can take anywhere from a few days to a year or more to complete.

Investigations for simple structures of non-problematic sites, requiring only a qualitative assessment of the soil profile can be completed in a matter of days. The period required for investigation of larger structures and/or difficult soil conditions will depend on a number of factors including:

- Procurement procedures.
- Time required for mobilisation of personnel and equipment.
- Safety, health, environmental and quality assurance requirements.
- Access to land, particularly where weather or seasonal crops play a role.
- Time required for execution of the investigation.
- Laboratory testing, including availability of equipment and time required for tests especially those concerned with the measurement of consolidation parameters in low permeability materials.

Ideally, geotechnical input to the project should be obtained as early as possible in the project. Key inputs include the likely scope of the investigation and the period of time required for its execution. The programme should also allow for incorporating the findings of the investigation into the design, or for additional investigation of problem conditions identified during the investigation. On major projects, ongoing exchange of information between geotechnical and design personnel is encouraged, rather than waiting for the completion of the final report before such interaction occurs.

All too often, the scope of the investigation and the adequacy of the findings are compromised by leaving insufficient time in the programme for the execution of the necessary investigation. This is particularly true for advanced laboratory testing, which could take several months to complete.

On major projects, the client would be well advised to include a geotechnical specialist on the project team from the outset to ensure that adequate provision is made for site investigation in the project programme and budgets.

3.2.2 *Cost of investigation*

The cost of the investigation varies according to the complexity of the project, the nature of the ground conditions and the level of acceptable risk.

There can be little doubt that the risk to the project is increased by inadequate provision being made for site investigation. The financial risk is graphically demonstrated in Figure 2.

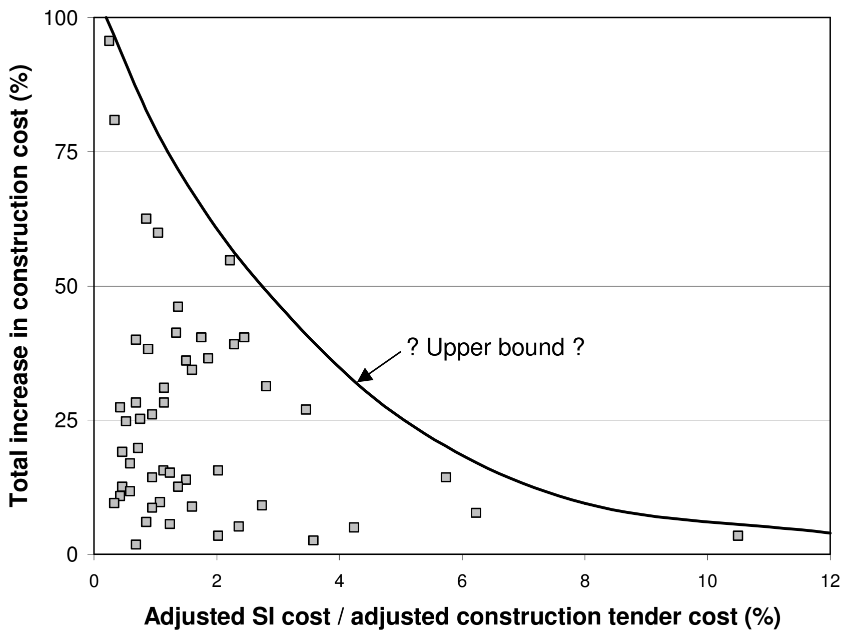

Figure 2: Cost overruns as a function of expenditure on site investigations for United Kingdom highway projects (Mott MacDonald and Soil Mechanics Ltd, 1994)

Over the years, the provision made for site investigation costs in the project budget has tended to decrease. This is partly the result of failure on the part of clients and project managers to recognise the value to the project of adequate geotechnical data and the risks posed by inadequate site investigation. It is compounded by the mistaken belief that responsibility for unforeseen ground conditions can be passed on to the designer or the contractor simply by including the necessary clauses or disclaimers in the contract documents. At the end of the day, the site belongs to the client and the client must bear the costs of executing the project in a manner compatible with the conditions present on the site. The most cost-effective way of doing this is to ensure that adequate geotechnical information is available to facilitate the selection, design, pricing, programming and execution of the works in the most appropriate way from the outset. Failure to do so leads either to the adoption of conservative assumptions regarding the soil conditions or the adoption of inappropriate or unsafe solutions, both of which have severe cost implications.

Clayton (1995) reports that in the 1940's the cost of site investigations "for fair sized works" was typically about 1% to 2% of the cost of the main work. In his 1972 Rankine Lecture, Rowe provided the following table of investigation costs (reproduced from Clayton, 1995).

Table 2: Site investigation costs as a percentage of project costs

Type of Work	% of capital cost of works	% of earthworks and foundation costs
Earth dams	0,9 - 3,3	1,1 - 5,2
Embankments	0,1 - 0,2	0,2
Docks	0,2 - 0,5	0,4 - 1,7
Bridges	0,1 - 0,5	0,3 - 1,3
Buildings	0,1 - 0,2	0,50- 2,0
Roads	0,2 - 1,6	1,6 - 5,7
Railways	0,6 - 2,0	3,5
Overall mean	**0,7**	**1,5**

It is a sad reflection on the profession that the amount of money spent on investigation, testing and professional fees after problems have occurred on a project frequently eclipse the amount spent on the original investigation.

It is also not uncommon for a greater portion of the total construction budget to be allocated to "decorating" public areas with high quality finishes than the geotechnical investigation. Those very same, highly visible, finishes are then often the first to show the impact of the "hidden" ground conditions.

3.3 Selecting a Consultant

3.3.1 Basic requirements

The client may appoint either an individual professional or a specialist geotechnical consulting practice to undertake the site investigation. Prospective consultants may be asked to provide detailed personal Curriculum Vitae for the lead professional and team members, a statement of the firm's size, year of establishment, client base, experience with similar projects, quality assurance programme, commercial affiliations, financial standing and professional indemnity insurance cover.

The professional appointed to lead the investigation should be a competent geotechnical practitioner as defined by the Engineering Council of South Africa.

3.3.2 Obtaining proposals and prices

A number of methods may be used to obtain proposals and prices for a geotechnical investigation:

a) Sole source

A trusted consultant is requested to prepare a scope of work and submit a budget for an investigation based on an understanding of the client's requirements. This was the "traditional" method of procuring an investigation and remains a popular method in cases where a specific consultant has specialised expertise or understanding of the client's particular requirements. There is often a long term relationship between the client (or his agent) and the consultant.

The responsibility for determining the scope of the investigation is left to the discretion of the consultant, or decided upon in discussions between the consultant and the client.

The main advantage of this procurement method is the speed with which proposals can be obtained and the investigation started. In addition, contracts placed in this way are less likely to result in claims for additional work as the consultant will endeavour to preserve his status as supplier of choice.

The main disadvantage is that the client receives only one bid for the work and may not be paying the lowest price for the investigation. In addition, such appointments are often made by exchange of correspondence and no formal conditions of contract exist that can be relied on should a dispute arise.

b) Solicited proposals

This is similar to the "sole source" procurement method except that a small number of selected consultants, often registered on a preferred vendor list, are requested to prepare proposals.

The main difficulty with this method is that various consultants' perceptions of the scope of the investigation may vary widely, or the scope of work may be manipulated to gain advantage over a competitor. This makes it difficult for a "lay" client to adjudicate the bids received, particularly with regards to divergent technical proposals. It also places the client's agent in a difficult position when the consultant preferred on technical grounds has not submitted the lowest price.

c) Competitive tender

Tenders are invited from all (or selected) consultants for undertaking a defined scope of work under defined conditions of contract. This method is often preferred by state organisations or large corporations who are required to abide by laid down procurement procedures. It is also a route frequently chosen by foreign clients who have no way of assessing the relative competence of the various consultants within the local market and who want to procure an investigation that conforms to design criteria and methods that they are used to.

The main disadvantage of this method is that the client or the client's agent may have insufficient expertise to define the required scope of work. This often leads to inappropriate methods of investigation which are incapable of yielding the results required for the project. Another danger lies in a foreign client's lack of understanding of local conditions and the request for a specific scope of work that the client is familiar with, but which is inappropriate for local conditions. An example would be specifying sophisticated in-situ tests for soft saturated European clays in the stiff partially saturated residual clays of sub-tropical Africa.

Appointments are often made on the basis of price alone as the scope of work and contract conditions are common to all bidders. Although cognisance may be taken of the professional competence of a particular consultant, this is difficult to quantify. In such cases, the client may end up paying more in claims for unforeseen ground conditions and additional construction costs than was saved on the cost of the investigation.

3.3.3 Selection criteria

The criteria applied in the selection of a consultant may be divided into two categories, professional competence and contractual / commercial criteria.

- Professional Competence:
  - Established expertise and reputation in the industry
  - Experience with projects of a similar nature
  - Knowledge of local geology
  - Adequacy of proposed investigation scope and methods
  - Ability to add value to the project
  - Availability of skilled personnel
- Contractual / Commercial:
  - Cost of services
  - Abnormal limitation of liability
  - Level of Professional Indemnity cover
  - Investigation programme (resources)
  - Socio-economic requirements, e.g. economic empowerment legislation

Although both sets of criteria must be considered in parallel, no contractual / commercial advantages can ever justify appointing a consultant who does not have the required skills and resources, or accepting a proposal that cannot adequately fulfil the requirements of the investigation.

3.4 Appointment of the Consultant

The appointment of a consultant should always be in writing. The appointment may vary from a simple letter of acceptance of the consultant's proposal to a detailed contract document.

There are a number of standard conditions of contract that may be used to define the contractual relations between the parties. These may be supplemented with client-specific conditions of contract and/or variations to the standard conditions.

As indicated in Section 3.1, most geotechnical investigation contracts are concluded with individual professionals or geotechnical consulting practices, rather than with a site investigation contractor. As such, it is appropriate to carry out this work under a "professional services" contract rather than a construction contract.

The following are the most commonly used conditions of contract for professional services:

- **New Engineering Contract: The Professional Services Contract**, Third Edition, June 2005. Institution of Civil Engineers, London. Thomas Telford Limited, London.
- **FIDIC Client - Consultant Model Service Agreement**, Fourth Edition, 2006. International Federation of Consulting Engineers, Paris.
- **CIDB Standard Professional Services Contract**, Second Edition, September 2005. Construction Industry Development Board, Pretoria.
- **SAACE Form of Agreement for Consulting Engineer Services**, July 2003. Consulting Engineers South Africa (CESA), Johannesburg.

The use of standard conditions of contract considerably reduces the amount of work required in the issue of enquiries by the client or the preparation of bids by the supplier. Most of these documents define the duties of the professional supplier and make provision for limitation of liability, payment conditions and settlement of disputes.

3.5 Remuneration of the Consultant

The method of remuneration is generally agreed between the client and the consultant. The most popular methods of remuneration are described below.

3.5.1 Time and cost

Under this remuneration model, the consultant provides a cost estimate for a defined scope of investigation, together with rates for professional services and disbursements. The consultant then invoices the client based on the actual hours and disbursements expended in the execution of the work. The bid submitted by the consultant is based on an estimate of the quantities at tender stage and the final price may be more or less than the estimated amount. The risk of cost overruns rests with the client.

Disbursements such as plant hire, laboratory tests, etc. may be charged either at fixed rates or at cost. Consultants charge a handling fee of between 5% and 15% for externally procured services, or require an upfront payment for these services.

The main advantage of this model is that it is easy to accommodate changes in the scope of the investigation. The main disadvantage for the client is the cost of the investigation is not fixed and could exceed the initial estimates or worse, the approved budget.

Progress payments are generally made at regular intervals, typically monthly, according to the value of the completed work.

3.5.2 Lump sum

Under a lump sum contract, the client and consultant agree to a fixed, lump sum cost for a given scope of work. The lump sum price may be subdivided into interim amounts to be paid when specific milestones are reached. The risk of cost over-runs rests with the consultant. The client is, however, at risk if the scope of work changes and no rates are included in the agreement from which the value of the additional work may be determined.

Variations on the lump sum model include:

- a lump sum contract for professional fees and re-measured disbursements, or
- a lump sum contract with rates for additional work.

3.5.3 Percentage fee

A percentage fee contract is one where the consultant is paid an agreed percentage of the cost of the works. This type of contract is generally used where the consultant provides ongoing services of similar nature to the client on projects of various sizes.

Progress payments may be made according to an agreed formula on reaching specific milestones.

3.6 Consultant's Liability and Insurance Requirements

In terms of most professional services contracts, the consultant is obliged to perform the agreed scope of work with reasonable care, skill and diligence in accordance with accepted professional norms in the industry. Should this obligation be breached, the consultant may be held liable for rectification of the arising defects and any damage suffered to the extent specified in the contract.

Most professional services contracts limit the liability of the consultant to an agreed amount as specified in the contract, or to a multiple of the fees paid to the consultant, typically one or two times the fee excluding disbursements.

The period of liability is typically limited to three years after completion of the consultant's contract. The contract generally obliges the consultant to have professional indemnity insurance in place to cover the limit of liability plus costs.

Any limitation placed on the scope of the investigation by the client could reduce the consultant's liability and should be avoided.

It is not reasonable to expect the site investigation consultant, who generally plays a relatively modest role in the overall project, to accept unlimited liability, or a limitation of liability based on the overall value of the project. If the client requires protection beyond the limits of liability typically specified in a professional services agreement, consideration should be given to taking out a project-specific professional indemnity insurance policy that covers all professionals involved in the project. In such instances, it is common practice to set the limit of the consultant's liability to the deductible under this project-specific policy.

3.7 Data Included in the Enquiry

The adequacy of the investigation can be enhanced and the likelihood of disputes/claims reduced if certain essential data is provided by the client to assist the consultant in assessing the scope of the investigation and the cost thereof. This includes:

- **Site description** - site location, accessibility, existing infrastructure and services, vegetation, trafficability, etc.
- **SHEQ requirements** - access restrictions, safety, health, environmental and quality assurance requirements including all client specific or site specific requirements.
- **Nature of the development** - size, loading, movement tolerances, design life, etc.
- **Purpose of the investigation** - site selection, feasibility, detailed design, etc.

3.8 Technical Specifications

Apart from this code, there are no national standards or codes of practice that set out requirements for site investigations. There are, however, a number of technical specifications and codes published by CEN, BSI & ASCE that have a bearing on the execution of such work. A list of these documents is contained in the bibliography to the code.

For such specifications or codes to apply to a particular investigation, they should be specifically referenced in any agreement concluded between the client and the consultant.

3.9 Legal Requirements

Apart from needing to obtain information on which to base the design of the works or to advise a potential contractor of the expected geotechnical conditions, site investigations are required by law.

3.9.1 Occupational Health and Safety Act

Geotechnical investigation is regarded as a construction activity and is governed by the Construction Regulations (2003) of the Occupational Health and Safety Act (Act 85 of 1993). The Regulations contain requirements pertaining to both the procurement and execution of an investigation. The latter are dealt with in Section 4 of this Code.

> *Clause 9(2)(c)(i)* requires the Designer to ensure that a “geo-science technical” report is made available to the Contractor. Effectively, this requires the client to carry out a geotechnical investigation on any construction site or to require that this be done by the client’s appointed designer, or by the contractor in the event that design forms part of the contract.
>
> *Clause 4(1)(a)* requires the client to prepare health and safety specifications for construction work, which includes the performance of a geotechnical investigation. *Sub-clause (h)* requires the client to ensure that potential contractors have made provision in their bids for health and safety measures during the construction process.

In terms of the Act, the client is regarded as an Employer and, as such is presumed-in-law to be responsible for any unsafe act by any of his employees, including any consultant (or contractor) appointed by the Employer to conduct a site investigation. There is, however, a provision in *Clause 37(2)* that allows the Employer to conclude a written agreement with the consultant (as a mandatory) acknowledging that the consultant is an employer in its own right with duties as defined in the act. In doing so, the Employer can avoid such presumption.

3.9.2 Housing Consumers Protection Measures Act

The Housing Consumers Protection Measures Act (Act 95 of 1998) provides for the establishment of a national home builder's registration council known as the NHBRC, the registration of Home Builders and the publication of a Home Building Manual setting out the technical requirements with which the Home Builder must comply.

Part 1, Section 2, Clause 2.5 of the Home Builders Manual requires the Home Builder to appoint a Competent Person to classify individual sites in accordance with a laid down classification system. In the context of this clause, a Competent Person is defined as a person registered in terms of the Engineering Professions Act (act 114 of 1990) or the Natural Scientific Professions Act (Act 106 of 1993) and holding the professional indemnity insurance prescribed by the NHBRC.

3.10 References

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4. EXECUTION

4.1 Background

As discussed in Section 2, the execution of a geotechnical investigation progresses through a number of logical and consecutive stages:

- **Pre-feasibility** - typically non-invasive, comprising a desk study using existing information followed by a walkover site inspection.
- **Feasibility** - usually for the selection of a preferred site from a number of alternatives, or the assessment of the viability of a proposed site. The approach would typically include a detailed desk study, broad verification of geology by limited intrusive investigations and laboratory classification testing.
- **Tender Design** - investigations to provide information for contractors to be able to define a scope of work, draw up a bill of quantities and price a project for tender purposes. More extensive intrusive investigations and laboratory testing is required, possibly also in-situ testing.
- **Design** - these investigations focus on individual structures and their associated loads and settlement criteria. Investigations typically include detailed site mapping incorporating geophysical surveys, extensive characterization of the founding conditions by means of test holes, boreholes, as well as in-situ testing. Laboratory testing includes material classification, as well as characterisation to determine specific geotechnical parameters for use in design calculations and modelling.
- **Construction** - comprises the recording of “as built” founding conditions, as well as monitoring to verify design assumptions and to measure critical parameters with reference to predetermined “trigger” levels.
- **Post-completion** - continued monitoring and inspection at intervals determined by design requirements.

For various reasons, dictated by specific project needs, not all of the above stages will necessarily be incorporated. However, the general principle of progressively more detailed investigation must, however, be followed with each stage culminating in recommendations for the following. While for greenfield sites it would be possible to commence with pre-feasibility or reconnaissance level investigations, this is not necessarily required in the case of brownfield sites, where existing information may suffice, or existing development might severely inhibit the ability to conduct certain stages of investigation.

4.2 Investigation Stages

Each of the investigation stages is examined in this section from a perspective of the incremental generation of information, site safety, the cost of investigative measures and time requirements.

The consultant should at all times be mindful of developing or improving the geotechnical model of the site, which ultimately forms the blueprint for design. Each consecutive phase of the investigation brings more detailed information to this model and should be planned and executed to address the specific requirements of the design philosophy.

4.2.1 Pre-feasibility

Various sources of information exist which may be used during the desk study that form part of the pre-feasibility stage. These include, amongst others, geological and topographical maps, aerial and satellite imagery, as well as various other publications on the geology and engineering geology of southern Africa. Additional information may also be readily available from past developments on or nearby the site. This may take the form of personal accounts, geotechnical or other reports, drawings or photographs.

The pre-feasibility investigations should conclude with a conceptual geotechnical model of the site.

a) Geological maps of South Africa

Probably the first step would be to consult the 1:250,000 regional geological maps of South Africa that are available from the Council for Geoscience. More detailed geological maps at a scale 1:50,000 are available for selected urban areas. These maps are supplemented by explanatory booklets, which are most useful in providing background to the formations encountered in various areas.

The South African Committee for Stratigraphy (1980) handbook, is also a handy reference to ascertain the rock types which would underlie the site at depth.

b) Aerial photographs

Once the geology of the area is identified it may be necessary to conduct an API for identification of inter alia lineations, land forms and facets, drainage features, unstable slopes, possible borrow areas and wet or waterlogged areas.

Overlapping stereo pairs of aerial photographs usually at a scale varying between 1:10,000 to 1:50,000, may be obtained by consulting the Chief Directorate: Surveys and Mapping of the Department of Land Affairs, Aerial Photo Division located in Bosman Street, Pretoria or Mowbray, Cape Town. Photographs are available for online ordering from the Mowbray office.

c) Topographical maps

Topographical maps are available for most areas in South Africa at a scale of 1:50,000, either in hard copy or electronic format, while much information may be gleaned from GPS (e.g. Garmin’s Garmap suite of street, topographic and waterways maps) or online-based information systems (e.g. Google Maps).

Topographical maps are available form the Chief Directorate: Surveys and Mapping.

d) Ortho-photographs

These are available at a scale at 1:10,000 and unlike aerial photographs, have been corrected for distortion over the full area of the photograph. Contours from these and similar maps are useful to create a first-order digital terrain model (DTM) of the site.

Ortho-photographs are available form the Chief Directorate: Surveys and Mapping.

e) Satellite imagery

The availability of online satellite images of all portions of the earth makes this tool particularly useful especially during the initial stages of a project for identification of major geological or topographical features. Whilst basic images are available to all, high resolution images may have to be purchased. Digital images may be exported in electronic format for use in reports or as background information on plans or maps.

The latest imagery from Landsat 7 includes images in selected frequency bands that highlight certain properties of the surface of the earth including thermal contrasts, vegetation, urban development etc.

Online resources such as Google Earth have become handy references for satellite images. However, the photographs may be dated and the resolution limited.

f) Publications on the geology of South Africa

The four volumes on the engineering geology of South Africa by A.B.A. Brink (1979, 1981, 1983 and 1985) form an invaluable source of general and, in some cases, site specific information on the geology of the sub-continent focussing on the engineering properties and behaviour of construction materials.

Another handy reference is *The Geology of South Africa* by Johnson et al. (2006).

g) Seismicity

The level of amplification induced in structures by seismic events is primarily influenced by the nature and magnitude of the seismic impulse, e.g. magnitude and epicentre of an earthquake, but also by the dynamic stiffness properties of the rock mass and regolith and of the particular structures.

The frequency response curves for use with structures founded on various strata are best handled by competent seismic engineers well versed in these aspects (see Pinto 2003) and the SANS 10160 National Standards. Early work on the seismicity of southern Africa by Fernandez and Guzman (1979a and b) which did not account for the effects of mining induced seismicity, has been considerably updated by Fernandez and du Plessis (1992), as well as Kijko et al. (2003) to include these influences. This has the effect of predicting much higher seismic design accelerations in those areas of Gauteng and Free State affected by mining activity.

h) Walkover Survey

If the site is reasonably accessible, a walkover survey or inspection of the site forms an essential part of the pre-feasibility investigation. Cost and time associated with a walkover survey are minimal. Safety is generally not a consideration unless the site is under construction, forms part of a working plant, or is situated within the confines of transport routes such as road or rail. The survey should ideally be preceded by an API to identify points of geological interest or importance. During the survey, attention should be given to:

– **Site accessibility**
– **Geological exposures** - rock outcrops, cuttings, borrow pits and quarries
– **Topographic features** - gradient, drainage, etc.

– **Vegetation** - natural or cultivated, indicator species, etc.

These observations should be noted and preferably photographed. In addition to a visual assessment, the walkover survey also affords an opportunity to observe adjacent sites and developments and to engage in discussions with local land owners or developers.

Inspection of road and rail cuttings or existing excavations such as borrow pits and quarries may be used to confirm the regional geological setting, while the condition of existing buildings, fills and roads may provide indicators to problems such as heave, settlement and slope instability. Variations in the local vegetation are often indicators of changes in stratigraphy or sub-surface moisture.

If the site is not readily accessible due to remoteness, security concerns or socio political sensitivity, the walkover survey would probably form part of the feasibility stage.

4.2.2 Feasibility

During the feasibility stage all available information should be consulted and followed by limited intrusive investigations. The client may require that the investigation is planned to allow project budget costing within a defined accuracy, e.g. ±15% bankable feasibility investigation.

This phase is probably the largest generator of information per unit of input and probably comprises no more than 20% of the cost of the total geotechnical investigation. Provided well-indexed maps are available and the necessary references are at hand, this phase of the investigation should also take no more than 20% of the total time expended.

a) Intrusive Investigations

Limited intrusive investigations may be required to supplement or verify the information gathered from maps, photographs or publications. These investigations could be undertaken concurrent with a walkover survey and present the first opportunity to add direct physical information to the geotechnical model.

The investigation may be in the form of test pits to facilitate in-situ profiling and sampling. However, for large and complex developments, exploratory drilling and/or auger trial holes may be considered. Laboratory classification testing is carried out on selected representative samples.

Prior to undertaking excavation and profiling on a site, permission must be obtained from the Client to carry out the necessary excavation works. For industrial facilities, this will generally be in a form of an excavation permit. Along transportation routes (road & rail) a way leave application will have to be lodged with the authorities. In other developments, an appointment letter from the Client may suffice. The permission is required mainly to ensure that existing services are not affected or damaged during the investigation.

Care must be exercised when undertaking intrusive investigations to limit damage to the environment. This is particularly applicable at feasibility stage where the investigation may be for site selection purposes where one or more of the sites remain undeveloped.

4.2.3 Tender design (Factual Report)

In order to compile a factual report or geotechnical data pack for tender purposes, a substantial amount of fieldwork, possibly in-situ testing and laboratory classification testing will be required. Such a report details the findings from the feasibility study and in addition the methods used and the raw data from non-invasive and invasive techniques supported by laboratory classification testing.

This phase is also a large generator of information, but input costs are high and may comprise up to 80% of the total cost of the investigation due mainly to the high cost of geotechnical drilling. Typically 60-80% of the time taken on the geotechnical investigations is expended over this stage.

a) Health and safety

The Occupational Health and Safety Act stipulates minimum requirements for aspects such as the preparation of a site safety plan, risk assessments, method statements and protection of the environment. It may be necessary for larger investigations that this aspect is outsourced to experts, but mostly they will be handled in house. Larger projects may also warrant the appointment of a full time site safety officer.

If the investigation programme is expected to exceed 30 days, or involve more than 300 person days, the consultant shall, before carrying out the investigation, notify the provincial director in writing. This is to comply with Construction Regulation *clause 3.(1)(b)*.

Entering test holes for the purposes of profiling and sampling, exposes the geotechnical practitioner to high risks that must be evaluated (risk assessment) and mitigated (signed off) by a qualified and experienced professional. The guidelines as given in the SAICE code of practice: "The safety of persons working in small diameter shafts and test pits for geotechnical engineering purposes" must be strictly followed.

b) Quality Assurance

The consultant must be aware of the quality requirements of the client. Here a quality plan and checklists will prove invaluable.

4.2.4 Investigation for detailed design

The main objective of this phase of investigation is to provide the designer/s with site specific, and sometimes structure specific, geotechnical parameters. The investigations should also be aimed at gathering sufficient information to allow the consultant to provide recommendations for site preparation, earthworks and the founding of structures. During this phase the factual geotechnical data is interpreted and used to generate design parameters to allocate to the geotechnical model of the site. Additional fieldwork and laboratory testing may be undertaken to improve the geotechnical site model and to investigate specific structures associated with the development.

This is the most important phase as the factual data is converted into design parameters and guidelines. The cost of this phase of the investigation, even though it is the most important, is usually small and may well be less than 10% of the total for many projects. Typically less than 10% of the total time is expended on this phase of the project. The exception to the above, is when challenging ground conditions are encountered or where challenging structures are involved. For these applications, empirical or “recipe” design approaches are insufficient and the consultant may have to resort to advanced analyses, numerical methods, large scale testing and full scale trials to determine appropriate design parameters and founding or construction solutions.

a) The design philosophy

There are two design philosophies that can be adopted to ensure a safe and serviceable geotechnical design. The first is the traditional limiting equilibrium or working stress philosophy that relies on a global lumped factor of safety against failure and occasionally for serviceability. More recently, geotechnical design has followed structural design in adopting a partial factors of safety and limit states design approach. The choice of philosophy may be regulated by law (e.g. application of Eurocode 7 in the UK from 2010), stipulated by the client or selected by preference by the consultant.

Characteristic values of design parameters can be derived using statistical methods and defined confidence levels. However, considerable experience is required when using statistical concepts in geotechnical engineering. A simple averaging of values does not properly account for the variability of the parameter, or for parameter inter-dependencies. It is common practice to model natural phenomena using the normal probability distribution. This assumption simplifies the manipulation of statistical data and the prediction of confidence levels where the average and median values coincide. Geotechnical data, however, do not always conform to a normal distribution, and even if it does, the distribution is likely to be “flat”, i.e. with a larger degree of variability. Skewed probability distributions result from the fact that most geotechnical parameters cannot assume a negative value, e.g. friction angle, stiffness, permeability etc. Finally, the sample size of geotechnical data is usually quite limited, which makes statistical interpretation less reliable.

Where large volumes of data are generated it is appropriate, with cognisance of the above precautions, to represent the data using sample size, average value, standard deviation, range and possibly outliers. These statistical values are particularly useful if they are used to carry out sensitivity analyses during the design process. Statistical data can best be presented graphically, either in the form of probability density distributions or possibly box and whisker plots. These at least provide some indication of the nature of the distribution of the data.

The design philosophy can allow for the application of the Observational Method, refer Section 6.4. This approach calls for developing the base design using the most likely values for the geotechnical parameters based on the information available, not necessarily a conservative selection based on the variation in data. The designer has to identify the shortcomings in the data and in the predicted geotechnical behaviour. These lead to the derivation of a plan of monitoring during construction to identify critical limits that will trigger the implementation of preconceived contingency actions.

b) Design parameters

In the selection of appropriate design parameters, the consultant has to consider the type of structure (applied loading, dynamics and settlement criteria) and the nature of the geology (stratigraphy and stress history). These parameters should also account for the in-situ state of the geo-materials (e.g. normally consolidated vs. over consolidated), as well as soil-structure interactions (e.g. drained vs. undrained behaviour and strain levels).

There are two classes of geotechnical parameters. On the one hand there are fundamental parameters that depend only on the properties of the material constituents and are independent of the in-situ state and structure of the material.

These parameters are typically determined from basic testing on disturbed or reconstituted samples. However, they require sophisticated analysis and design calculations to take account of stress history, applied stress paths and the effects of structure and fabric. The critical state or steady state effective angle of friction represents an example of a fundamental strength parameter. On the other hand there are parameters that, in addition to the material constituents, are influenced by the in-situ state and the structure or fabric of the material. These parameters are typically determined from advanced testing that model the structural loading on high quality undisturbed samples that preserve the in-situ state of the material. The resulting parameter has encoded within its numerical value all of the behavioural aspects associated with the in-situ material under the intended loading. These parameters can, therefore, be used in relatively simple design calculations. An example of such a parameter is the tangent Young's modulus of a material, determined from an undisturbed sample that was loaded across the relevant stress increment.

It is essential that the consultant liaises with the design team during this phase of investigation to ensure that appropriate design parameters are determined and that these parameters are understood and correctly used by the designers. A typical misunderstanding arises from the request for a "*modulus of sub-grade reaction*" from the structural designers. These moduli are then universally applied in design calculations, often using structural design software or finite element packages. The fact is that the modulus of sub-grade reaction represents a higher order "lumped parameter" that allows quick settlement estimates for a specific foundation (size, shape and depth of founding) on a specific stratigraphy (layer depths, moduli etc.). Using this parameter for a different foundation, stratigraphy or worse still, in a finite element analysis is fundamentally wrong.

4.2.5 Construction monitoring

Many projects require that the results of the various recommendations made in the geotechnical design report are verified during the construction stage. This may, for example, include verification of:

- the founding depth of piled foundations,
- the bearing capacity of a founding horizon for spread footings,
- the classification and selection of materials encountered on site,
- the deflection of a laterally supported wall, etc.

The importance of this phase cannot be over-emphasised as the whole of the structure foundation is exposed during construction and recommendations made in the geotechnical reports may have to be altered or even reversed based on the available evidence. If conditions on the exposed site turn out to be more favourable than indicated by the site investigation, the design may possibly be altered with significant cost saving.

Construction monitoring forms an integral part of the Observational Method of design, during which the design assumptions are verified and contingency plans implemented based on the design limit levels.

4.2.6 Post completion

Post-completion surveys may be required to validate long term or post construction design assumptions and to ascertain to what extent the construction process has influenced the subsurface conditions. These typically take the form of deflection measurements either directly, or with remote and electronic methods.

In many cases the final deflections only occur after many years of service and hence measures must be put in place in the design and construction stage such that these long-term measurements may be made.

Measurement may be as simple as installing a level target onto a critical element. Recently, however, electronic measuring devices embedded within or onto a structural member have become more widely used in practice. A variety of sensors are available including strain gauges, inclinometers and pressure transducers and in some applications the output is linked to a cellular device that transmits data real time to the person responsible for monitoring.

These measurements may be used during the early life of a major structure to bring about cost-saving modifications, or they may indicate shortcomings in the design process that form the basis of updates to codes, standards and guidelines.

Certain legislative requirements might enforce regular post-construction monitoring, e.g. the Dam Safety Legislation section 123(1) of the National Water Act 1998, Act 36 of 1998.

Whatever the reason, the value of post-completion surveys cannot be overstated.

4.3 Field Investigation Methods

This section briefly discusses several methods that are used routinely to investigate sites for geotechnical purposes. These generally have to be carried out in accordance with standard procedures. There are a limited number of South African geotechnical investigation standards and codes available:

- TMH1 for laboratory testing
- CSRA specifications for drilling
- Lateral Support Code

Unfortunately these codes have not been maintained and are generally specific to road construction.

There has recently been a drive to adopt Eurocode 7 in South Africa. Eurocode 7 parts 2 and 3, are highly comprehensive documents detailing the requirements and evaluation of laboratory and in-situ investigations. Eurocode 7 refers to a number of execution standards that detail the procedures of these test methods.

Apart from the Eurocodes there are several authoritive standards publications on site investigation methods including those advocated by ISO, BSI and ASCE, as well as a number of international conferences dealing with the subject.

4.3.1 Methods of investigation

a) Non-intrusive methods:

- **Geophysics** - comprises indirect methods for the detection or inference of the presence and position of geological structures, as well as the imaging or mapping of the physical properties of the earth.

- **Remote sensing** - the small or large-scale acquisition of information on the properties of the earth's surface by the use of sensing devices that are not in physical contact with the earth.

b) Intrusive methods:

- **Test holes** - for the purposes of in-situ profiling, sampling and the appraisal of excavatability, slope stability and visual assessment of groundwater seepage.
- **Geotechnical drilling** - principally for the recovery and logging (description) and testing of samples of cohesive soils and rock using rotary core drilling methods. Also for carrying out in-situ tests at depth and the recovery of high quality undisturbed samples using various push-in type samplers.
- **Percussion drilling** - for the recording of drilling parameters and recovery of chip samples for logging.

c) In-situ test methods

- **Penetrometers** - various penetrometers are available to record the resistance to penetration and many other soil parameters while pushing or driving a device into the ground from surface. Some are hand operated, while others require mechanical hammers to drive, or hydraulic systems to push the devices into the ground.
- **Borehole probes** - these devices are lowered into a borehole to carry out specific tests on the material in the sidewall, or immediately below the base of the borehole. Examples include penetration tests (SPT), cavity expansion tests (PMT and Goodman Jack), shear tests (VST & borehole shear test), and permeability tests (pump and packer or Lugeon tests).

d) Laboratory methods

Laboratory tests are carried out on disturbed or undisturbed samples recovered as part of the fieldwork investigations. These tests are carried out in a controlled environment, using standardized equipment and procedures and provide quantitative data for material classification, as well as characteristic parameters for design.

Apart from standards and conference proceedings, these methods are well described by:

- CIRIA publications
- Clayton, C.R.I., Mattthews, M.C., and Simons, N.E. (1995), **Site Investigation**, 2nd Edition, Blackwell Science.
- Head, K.H. (1984), **Manual of soil laboratory testing**, Volumes 1 to 3, London: Pentech Press Limited.

Methods that are used routinely in South Africa are briefly described in the following sections.

4.3.2 Geophysics

The list of techniques is many and varied, but the most common are:

- Reflection and refraction seismic surveys
- Magnetic surveys
- Gravity surveys
- Resistivity surveys
- Continuous Surface Wave tests
- Electromagnetic surveys
- Ground penetrating radar surveys
- Infrared, radiometric and light detection and ranging (LIDAR) surveys.

In broad terms reflection and refraction seismics are used in the detection of consistency boundaries, i.e. between soft (soils) and hard (rock) material. Surface wave seismics are used to record a profile of small strain shear stiffness variation with depth. Magnetics, gravity surveys and wire line logging are used in the delineation of mineral resources or ore bodies in the mining industry and for identifying cavities in soluble rock formations. Conductivity and resistivity surveys are mainly used for corrosivity studies and to assist with the design of grounding for power plants and substations. They are also useful in detecting moisture variations and geological discontinuities.

Geophysical surveys should be carried out and reported on by a specialist geophysics contractors. It is also advisable to include the geophysicist during the planning of the geotechnical investigation to ensure that the most appropriate technique and spacing or frequency of tests is selected for the particular geological setting and in terms of the requirements of the development.

4.3.3 Test pits and trenches

Test pits are typically excavated to a maximum depth of 5m using a tracked excavator or TLB. Considerations include:

- **Access and mobility** - a TLB or wheeled excavator can move around readily between widely spaced test positions and across existing surfaced roads etc. A low-bed may be required to move tracked excavators between sites and sometimes even between test positions on a site. On larger investigations an excavator may be used to dig test pits *on-the-run*, whereas a TLB follows to close-up the pits that have been completed.
- **Stratigraphy** - an excavator equipped with a rock bucket or ripper may be required to penetrate well developed pedogenic horizons that occur at shallow depth and potentially overly soft residual soils.
- **Depth of investigation** - a TLB is well suited to explore depths of up to 3m, whereas an excavator is required to extend test pits up to 5m deep.
- **Excavatability** - SABS 1200D - 1988 Earthworks provides a specification for excavation classes based partly on the use of an excavator with a minimum flywheel power of 0,1kW per mm width of tined bucket. By selecting a machine of similar power, the material on site can easily be classified for excavatability.

Conditions deeper than the base of the hole may conveniently be assessed by conducting hand operated cone penetrometer tests. These typically extend to a depth of 1m to 2m in the case of a DCP, or up to 6m using a DPL.

Test pits are usually excavated as small as practical. However, when investigating dolomitic terrain or highly variable conditions, it is advisable to extend these to trenches of 10m to 20m long. A description of the material variability in these trenches and a visual representation thereof, provide a valuable record for earthworks and foundation design.

For safety it is highly recommended that when a trench or test pit is occupied, a person is in attendance at the surface, monitoring sidewall stability and watching over the person working in the excavation.

Profiling of test holes in South Africa is done exclusively in accordance with the recommendations of Jennings et al. (1973), see also Brink & Bruin (2002).

4.3.4 Auger holes

An auger piling machine is typically used to drill a 750mm diameter vertical shaft for inspection. The hole is profiled and sampled by lowering a person down the hole in a bosun's chair. Light may be required in deep holes and this is usually provided by sunlight from a surface mirror, or a light attached to the hard hat of the logger.

Care should be taken not to descend below the level of water seepage. If holes appear unstable, it may be necessary to log from the spoils retrieved from the auger flight, but this requires that the geo-practitioner responsible for logging is on site to assess the ground stiffness from the machine penetration characteristics, i.e. the torque capacity of the machine conducting the augering.

Depths reached may not only be limited by the reach of the auger, but more typically by the amount of sidewall collapse, usually below the water table. As a rough guide it is probably unlikely that in-situ profiling would take place deeper than 20m.

Auger drilled pile sockets may have to be inspected and logged as part of the construction investigation phase. In this case the hole may have to be temporarily cased to the level of stable ground, or to cut off seepage inflows, to allow the logger to descend safely into the rock socket.

4.3.5 Rotary core drilling

For geotechnical purposes NX sized boreholes are most common. Here a double barrel core tool (NWD4) is typically used, resulting in approximately 50mm diameter core and generating a borehole of 76mm diameter. Drillers will often prefer to use a single barrel TNW core tool in rock, which allows a 3m drill run as opposed to the 1,5m run with NWD4. However, this should be strongly discouraged as the core extraction process often results in excessive core breakage. It is not uncommon for the driller to hit the TNW barrel with a heavy hammer to release the core. Where difficult drilling conditions prevail, a triple barrel core tool (HMLC) may be used, which drills a 100mm diameter borehole and recovers approximately 60mm diameter core.

Boreholes are stabilised using a short length of temporary casing at ground surface and a bio-degradable synthetic drilling mud. In addition to stabilising the borehole sidewalls, the circulating drilling mud also facilitates removal of the cuttings. Where the upper horizons comprise loose unconsolidated material the borehole is generally advanced using wash boring techniques to install temporary casing, or by augering.

Cores are extracted into plastic sheaths and placed in boxes or trays for later logging to a standardised procedure (Brink and Bruin, 2002). Photographs of the core boxes are taken during the logging process.

In soft cohesive soils, undisturbed samples may be recovered from the borehole using thin walled push-in tube samplers. Clayton et al. (1995) give guidance on the use and design of tube samplers for geotechnical investigations.

Standard penetration tests are generally a requirement in boreholes and are usually conducted at 1,0m to 1,5m intervals in both non-cohesive and cohesive materials. Other tests that are not routinely specified include vane shear tests (Blight 1970) and pressuremeter tests (Mair & Wood 1987).

It is standard practice to install simple standpipe piezometers in selected boreholes once the drilling has been completed and the borehole flushed with clean water. These piezometers can be monitored to establish the depth of the permanent water table on site. Water levels should be determined with care and allowance made for these levels to stabilise. Even then it is advisable to pump or bail some water from the piezometer to verify that it recovers to the stable level.

Geotechnical drilling, as opposed to exploration drilling, is a laborious process that requires the core tool to be removed after each drill run of 1,5m to 3m. Successful recovery relies on experienced operators and full time supervision by a geologist or engineering geologist. In South Africa, common practice is to allow the driller to provide the full service with only itinerant supervision from the consultant.

The core should be logged as soon as possible after recovery and preferably before the core is transported off site. Alternatively the core must be protected by wrapping and sealing the core in plastic sleeves.

The borehole log includes information on the method of drilling, in-situ tests carried out, recovery of material and core, RQD, fracture frequency, samples taken, water table depth and a profile description including logging of the joint properties in the rock mass.

4.3.6 Percussion drilling

Percussion drilling provides a method by which a rapid borehole can be formed in a variety of soils and rock, whilst recording drilling parameters and providing disturbed samples (chips) of the cuttings for logging.

In South Africa, percussion drilling is usually carried out using down-the-hole air percussion hammers, either by open-hole or by Odex/Symetrix methods that install temporary or permanent casing as part of the advancement of the borehole.

By using instrumented drilling rigs (e.g. Jean Lutz instrumentation), the following parameters can be monitored and recorded during the drilling process: time, depth, holding pressure, weight on bit, torque, drilling pressure, air loss and ground water strikes.

Drilling chip samples are collected for each meter advanced and placed in marked plastic bags to be logged according to the recommendations of Brink and Bruin (2002).

4.3.7 Standard penetration test (SPT)

As for the DPSH this test is also done by measuring the number of blows from a 63,5kg hammer dropping 760mm to advance a standard split spoon sampler through 6 increments of 75mm. The upper 150mm is considered “disturbed material” and these blow counts are ignored. The number of blow counts for the remaining 300mm is reported as the SPT N-value.

A compressed and disturbed sample may be retrieved from the sampler for logging and for laboratory classification testing. In hard driving conditions that is likely to damage the spoon sampler, a cone similar to the DPSH cone can be fitted.

Standard practice is to terminate the test and record refusal if the blow counts exceed 50 blows per 150mm penetration. However, some practitioners are now requesting the blow counts to be recorded up to values of 200 when penetrating very soft and soft rock.

This test has been used for many decades and a vast data base of correlations between SPT N-value and other soil parameters have been established (Clayton 1993).

When carrying out the SPT in loose non-cohesive soils, care should be exercised when drilling and especially when extracting the drill string to minimise disturbance of the material to be tested. Unrealistically low values are common in these soils.

4.3.8 Dynamic cone penetrometer (DCP)

The DCP test comprises a 20mm diameter (60° apex angle) cone that is driven into the ground using a sliding hammer of 8kg mass dropping through a distance of 575mm. During the test the cone penetration is recorded after single or multiple hammer blows.

The test is continued to refusal or to a depth of 1m with the option to extend the test to a depth of 2m by attaching an extension rod.

The DCP N-value or penetration rate is calculated as the average penetration of the cone in mm per blow over each increment of measurement. The penetration rate is usually plotted on a graph of rate (mm/blow) versus depth (m).

The test is extensively used to classify in-situ road sub-grade materials (TRH4) and well established correlations have been derived to calculate the in-situ CBR (Kleyn 1984). There are correlations to estimate allowable bearing capacity and stiffness for foundation design, but these should be used with caution and preferably site calibrated.

4.3.9 Dynamic probe super heavy (DPSH)

DPSH equipment used in SA consists of a weight of 63,5kg dropping 750mm onto a string of rods with a 50mm diameter (20cm^2 projected area), 90° apex angle, disposable cone at the front. The result of the test is presented as a graph of the number of blows required for each 300mm penetration (DPSH N-Value) against depth.

The test is continued to refusal when more than 80 blows are required for 300mm penetration. Once the DPSH has met refusal, the detachable cone allows the drill string to be retracted 600mm to 1m and re-driven without the cone. This re-drive allows direct measurement of the friction on the rods at the refusal depth. The blow-counts for the entire penetration profile can then be corrected for rod friction by applying incremental adjustments that start from zero at ground surface and increases linearly with depth to equal the re-drive value at the termination depth.

Provided that the hole remains stable and open once the test has been completed, a simple standpipe piezometer can be installed. These piezometers can be monitored to establish the depth of the permanent water table on site.

4.3.10 Cone penetration tests (CPT & CPTU)

During a standard cone penetration test (CPT) a probe with a conical tip and tubular sleeve is hydraulically pushed into the ground and the force required for this penetration is measured. The total force of penetration is converted into the cone or tip resistance and the sleeve friction resistance respectively. This differentiation can be made by mechanical means, i.e. by driving the tip and sleeve separately using duel rod systems, or by fitting appropriate electronic sensors to the tip and sleeve. The results are typically presented as tip resistance, sleeve friction and friction ratio (tip to sleeve) with depth of penetration.

The piezocone (CPTU) differs from the CPT in that it is equipped with a porous disc and pore pressure transducer located just behind the cone tip. As with the CPT the cone tip and friction sleeve resistances are recorded, usually electronically, but at the same time also the pore pressure response at the porous disc position. One of the greatest advantages of the CPTU is the ability to record the dissipation of the excess pore water pressures around the cone tip at the end of each rod change, usually 1m intervals. The dissipation data can be used to determine the consolidation parameters for the soils, as well as the nature of the seepage regime in the test area, especially the depth of the phreatic surface.

The CPT and CPTU penetrometers have limited application in soils that are dense/stiff or gravely. It has found major application in the investigation of tailings impoundments and fine grained alluvial sediments.

The data from the CPT and CPTU can be used to classify and characterise soils and the publications by Meigh (1987) and Lunne et al. (1997) are probably the most comprehensive in this regard.

4.3.11 Others

A variety of other techniques may be available, but are rarely used in South Africa. These include the Goodman jack, pressuremeter, dilatometer, seismic piezocone, enviro-cone and others.

4.4 Field Trials

An often overlooked aspect of site investigation practice is the execution of large scale to full scale field trials, including large diameter plate load tests, pile load tests, impact compaction trials, trial embankments (heave/settlement) etc.

These trials are often resorted to where traditional methods are either unsuited, or do not cover a sufficient “sample size” of the material to be investigated. Trials can be undertaken to characterise site conditions as part of the investigation process or during construction, or to verify design assumptions.

The planning, design, construction, instrumentation and interpretation of field trials should be undertaken by a specialist geotechnical practitioner with due consideration of time and scale effects, as well as differences in ground conditions between the trial site and the actual site of construction.

4.5 Laboratory Testing

Virtually all site investigations require laboratory tests, and these are generally grouped into classification tests and characterisation tests. Classification tests assist with the spatial development of the geotechnical model, whereas characterisation tests quantify the engineering behaviour of the soil and populate the model with design parameters.

Results obtained from laboratory testing should be evaluated for credibility and gross errors by experienced practitioners and compared with existing data and published case histories to ensure reliability. Interpretation of laboratory test results require considerable experience and engineering judgement. Determination of a design parameter by simply averaging the results from a suite of laboratory tests may not be suitable.

The appropriate amount of laboratory testing depends on the complexity and perceived geotechnical risk of projects. Generally, as the complexity and risk increase, more and more advanced laboratory testing is required. The AGS Guide (1998) suggest that for a typical project the cost for laboratory testing ranges between 12% and 15% of the total cost paid to the site investigation consultant / contractor.

4.5.1 Sampling

Appropriate sampling techniques should be employed to obtain soil specimens for laboratory testing. Soil samples are usually taken to confirm visual descriptors and provide parameters for design. It is thus imperative that they represent the various horizons encountered on site and that no mixing occurs.

For classification tests disturbed samples are adequate. Characterisation tests require the soil structure to remain intact and require more advanced sampling techniques such as block sampling, thin wall tube sampling or core sampling.

a) Disturbed samples

These samples are retrieved in a disturbed state usually by hand excavating from a test hole sidewall, by retrieval from excavated spoils, from SPT samples and from borehole core. Samples are stored in sealed plastic bags to preserve moisture conditions. Bags must be robust and have durable labels for identification.

Disturbed samples for indicator classification testing are usually 1kg to 5kg in size, whereas samples for compaction and material use testing are usually in excess of 60kg.

b) Undisturbed samples

Undisturbed samples are retrieved as carefully as possible such that the in-situ state and properties are maintained. If the site conditions allow surface excavations, it is preferable to take block samples by removal from the excavation sidewall or possibly from the base of an excavation. Upon removal, the sample is immediately wrapped with a protective lining. Multiple layers of aluminium foil and thin plastic wrap have been shown to best prevent moisture loss and preserve the integrity of the sample (Heymann & Clayton 1999). It is usual to indicate the direction of the sample so as to avoid any problem with anisotropy. Transportation and storage of block samples must be conducted with due care.

Tube sampling may also be used to retrieve undisturbed samples from boreholes, but this is usually restricted to softer cohesive horizons. The tubes are sealed with wax at the top and bottom.

The size of sample is governed by the sampling tool or by the size of specimen required for testing. The effect of fabric features such as joints, fissures, layering and laminations also affect the size of the required test specimen. Parameters such as strength, stiffness and permeability are strongly influenced by these fabric features and in general specimens should be large enough to measure the mass behaviour such that appropriate quantitative parameters are obtained.

4.5.2 *Classification tests*

Classification tests are relatively inexpensive and include moisture content, plastic limit, liquid limit, shrinkage limit, linear shrinkage, particle size distribution, particle density, unconfined compressive strength, as well as durability and chemical tests. The results are used to confirm soil description during the field investigation and quantify variations in the ground profile both laterally and with depth. Compaction tests are also used to classify materials for construction purposes, e.g. terracing fill. Soil classification can be used to predict engineering behaviour and estimate design parameters using established correlations. This assumes that materials that fall into a particular class will all behave similarly. Such correlations should be used with caution and only for the material and conditions for which it was developed.

4.5.3 *Characterisation tests*

Characterisation tests attempt to quantify the engineering behaviour of the soil and rock and to determine the in-situ state of these materials. Examples include testing for shear strength, compressibility, consolidation, collapse and heave, as well as permeability and density. These tests are more expensive and time consuming than classification tests and the type, complexity and number of tests required will strongly depend on the nature of the project.

4.5.4 *Testing standards*

Various standards give guidelines on the details of laboratory testing. In South Africa, TMH 1 (1986) was published to control the testing of road construction materials and forms the basis of routine classification tests.

More sophisticated testing is addressed in EN 1997-2: 2005, BS 1377, and various ASTM, ISO and ISRM publications.

The three volume publication by K.H. Head (1986) is a very handy reference that details both the theoretical background and the practical execution and interpretation of standard laboratory tests.

4.6 Supervision and Quality Control

The profiling of test pits and auger trial holes and the logging of borehole samples should be undertaken or at least be supervised by a qualified and experienced geotechnical practitioner, preferably a geotechnical engineer or engineering geologist. In fact, the OSH Act and Construction Regulations dictate that no person is allowed to enter an unsupported excavation deeper than 1m[1], except if a competent person in excavations has approved and signed-off the excavation in writing. A certain amount of experience is necessary before a geo-practitioner becomes skilled in the art of profiling and logging. Here it is recommended that young or inexperienced profilers be trained “hands-on” by those with many years of experience. For field profiling, the publication by Brink and Bruin (2002) is invaluable.

Supervision and quality control are required during all stages of the geotechnical investigation. Unfortunately the lack of professional resources in South Africa, often dictates that only itinerant site supervision by the consultant is possible. This is especially

1 By inference from Construction Regulation 3(1)(b)(ii).

true for sub-contracted services such as drilling, geophysics and specialist in-situ testing, where the consultant relies on the sub-contractor to provide a foreman or site agent with the required skill and experience to take responsibility for the supervision of the sub-contracted works. However, the consultant should be mindful of the contractual or legislative requirements with regard to supervision and quality control. Certain high profile or difficult projects may warrant full-time independent supervision for drilling and field testing.

The results of laboratory tests is probably the most widely used set of information for design purposes. It is imperative that good quality control measures are implemented to ensure that the results obtained from laboratory tests are credible and reliable. Although full time supervision of laboratory testing is not advised, it is well worth a visit from the consultant during the execution of the testing. This ensures that both parties are satisfied that the necessary quality assurance has been carried out to ensure high quality results. In addition to quality control measures, accredited laboratories should carry out tests in accordance with locally and internationally acceptable standards and codes of practice. The laboratory supervisor and technicians should be conversant with the various standards to ensure accuracy and reproducibility of the results. Furthermore, the equipment used by the laboratories must be calibrated at regular intervals, the same holds for test equipment used on site.

4.7 Specialised Investigations

The methods of investigation described above are applicable to a wide variety of development types. However, there are a limited number of developments that may require additional or specialised investigations. These developments typically range from hazardous waste disposal sites to nuclear facilities and include the development of highly seismic active areas to sites underlain by dolomitic ground etc.

The type of additional investigation required will depend on the nature of the development and associated risk and will either be specified by the Client or selected by the consultant. In some instances, a specialist in the relevant field (e.g. seismics) may be required to undertake a portion of the investigation or assess the suitability of the investigation for the proposed development.

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5. REPORTING

5.1 Background

This chapter deals with the presentation of the geotechnical site investigation information in a logical and orderly manner. The geotechnical investigation report (also referred to as *the report* in this document) is the medium used to present the geotechnical model including site conditions, stratigraphy, material classification and characterisation, geotechnical parameters, as well as recommendations for site preparation earthworks, foundation design and construction.

The geotechnical site investigation report should not be confused with the geotechnical design report. The latter presents the design approach, assumptions, methods of calculation and the results and verification of the design calculations taking into account both the safety and serviceability requirements for structures associated with the project.

Site investigation projects have the objective of providing specific information on subsurface soil, rock, and water conditions. The importance of preparing an adequate geotechnical report cannot be overstressed. The information contained in this report is referred to often during the design period, construction period, and frequently after completion of the project (e.g. for resolving claims). The report should therefore be clear, concise, complete, autonomous and accurate.

The report can be compiled as a single document or in two parts: (1) factual information and (2) interpretive information. The size of project, programming requirements or the client's preference may dictate the structure of the document, e.g. in some cases the client may wish to issue all the factual geotechnical data as part of the design/construction tender documentation, while keeping the interpretive part to assist with the adjudication of tenders.

The factual report could form part of a tender document and, together with the site inspection, should provide the contractor with sufficient information to submit a realistic bid for the construction of the works. In addition, it will give the contractor an indication of anticipated geotechnical constraints and enable him to select the most appropriate equipment and techniques for carrying out the construction.

The structure of the geotechnical report is discussed in the sections that follow.

5.2 Introduction

The Introduction typically comprises:

- **Terms of reference** - define the context of the investigation and provide details of the client, the project and the brief to the consultant. The contractual arrangement between the client, consultant and any sub-contractors is referenced, as well as correspondence or decisions pertaining to the investigation made prior to and during the investigation.
- **Abbreviations & symbols** - list commonly used abbreviations and symbols (and their units) to assist with the reading and interpretation of the report.
- **Purpose and scope** - stated to resolve any ambiguities with regard to the use and application of the report. The level or phase of investigation, refer Section 2.4, should be clarified, as well as any deviations or exclusions from the client's original specification.

- **Nature of the development** - defines the size and type of development and structures, as well as requirements with regard to loading, deformations and any other relevant specifications or limitations. This forms an essential part of any geotechnical report and prevents the misuse of the information and recommendations in applications for which they were never intended.
- **Reference documents** - provide a list of the project specific references used in the planning, execution and reporting of the investigation. Typically the list includes references to maps, photographs, reports, drawings, specifications etc. References to general publications, standards, methods, etc. that are available in the public domain are often included as footnotes where they are applicable in the body of the report. References should be made in accordance with a recognised method, e.g. the Harvard method.

5.3 Factual Information

Factual information includes all of the site and investigation data gathered as part of the desk study, fieldwork and subsequent laboratory testing and comprises the bulk source of information for the geotechnical site model.

5.3.1 Site description

The description of the site should include:

- Location
- Current land use including known services
- Accessibility
- Trafficability
- Topography and drainage
- Vegetation
- Climate

Where possible the abovementioned descriptions should be supplemented by photographs, figures and maps.

5.3.2 Description of geology

A description of regional and local geology (lithology and expected stratigraphy), identifying general characteristics and expected geotechnical constraints.

5.3.3 Description of field and laboratory investigations

This part of the report should include a comprehensive discussion of the type of investigative methods employed, including:

- date of execution,
- number and locality of tests,
- test procedures,

- equipment used,
- limitations e.g. depth of exploration, and
- relevant observations.

The data is generally presented in its raw format without interpretation, classification or characterisation, but may be summarised in table or graph format for ease of reference.

Profile records, tests results, and other supplementary data are usually presented in appendixes.

5.4 Interpretive Information

This section of the geotechnical report presents an interpretation and discussion of the factual data, highlighting geotechnical constraints/flaws relevant to the proposed development.

The geotechnical site model is completed herein and populated with design information. As far as practical, the model should be presented in tabular or graphical format including geotechnical drawings (stratigraphy plans, geological sections, GIS database etc.). The site model should present appropriate geotechnical design parameters for the calculation of allowable bearing capacity and foundation settlement as a minimum. The consultant should provide a measure of the confidence in these parameters, either on a statistical basis (i.e. a *cautious estimate* as proposed by Eurocode 7), or based on experience and judgement.

In South Africa it is common practice to include basic recommendations for site preparation earthworks and practical founding solutions for typical structures associated with the proposed development. These are not design recommendations, but are intended to provide early guidance and a stepping stone for the design phase.

The level of interpretation and the detail of the geotechnical model will be governed by the level of investigation and phase of progress in the execution of the development.

5.4.1 Site stratigraphy

The soil and rock profile descriptions are used to compile the site stratigraphy, showing spatial variation in representative soil and rock horizons, as well as groundwater.

5.4.2 Materials

The accumulated factual data on the site materials, as determined by the field and laboratory investigations, are used to classify and characterise materials in terms of their engineering properties and behaviour including construction usage, strength, compressibility, consolidation etc.

The information should be evaluated statistically where possible to give an indication of their variability and reliability. As a minimum the range, mean and standard deviation of parameters should be provided where samples sizes of five or more data points are available.

5.4.3 Identification of geotechnical constraints

The interpretive report should include the identification and discussion of geotechnical constraints and flaws related to the following as identified by Partridge et al. (1993) and the series of papers on problem soils published in 1985 in the SAICE Journal:

- Collapsible soils
- Expansive soils
- Highly compressible or "soft" soils
- Erodible & dispersive soils
- Liquefiable soils
- Instability in areas of soluble rock (e.g. dolomite)
- Undermining
- Groundwater levels and seepage
- Corrosivity of groundwater and water extracts from the natural soils
- Steep slopes and unstable natural slopes
- Excavatability
- Seismicity
- Flooding

Fatal geotechnical flaws which would limit the proposed development should be clearly identified and stated.

5.4.4 Basic design recommendations

The consultant can interpret the investigation results and provide basic recommendations regarding the following:

- **Site preparation** - site clearing.
- **Temporary works** - construction platform, temporary roads, lay down areas, trenches, excavations and stockpiles.
- **Earthworks** - terracing, material usage, site roads, paved areas, excavations (lateral support) etc.
- **Foundations** - suitable foundations, depth of founding, allowable bearing capacity, and expected settlement.
- **Special precautions** - aggressive ground water, seismicity, drainage etc.

5.5 Additional Work

Depending on the phase of investigation the geotechnical report should conclude with recommendations for further investigations to be undertaken to address any shortcomings in the available data.

This should not be seen as a deficiency in the investigation process, but rather a means to address unforeseen conditions in a timely manner.

5.6 Validation During Construction

Additional investigations or at least an assessment of the ground conditions exposed during construction can often result in significant construction cost and time savings.

The geotechnical report should outline a philosophy to verify and refine the geotechnical design during construction and include:

- Strategies for refinement of the geotechnical model, e.g. foundation and excavation mapping, data collection and interpretation during construction.
- Strategy for monitoring and interpreting structural behaviour during construction and updating design applications.
- Quality control relating to data for verifying specific assumed design parameters.

These same strategies can be applied post-construction.

5.7 Annexures

The list of annexes to the geotechnical report varies in accordance with the nature and complexity of the report, but typically should include:

- Land survey reports
- Geophysical survey reports
- Test hole profiles and borehole logs
- In-situ test results
- Laboratory test results
- Drawings

5.8 Quality Assurance and Document Control

5.8.1 Review and approval of reports

As a minimum quality assurance requirement, all reports must be reviewed by a professional geotechnical practitioner. The report must also be approved by a principal of the consultancy. A record of the review and approval should be kept which should be signed by the author, the reviewer and the principal. This is generally in the form of a document approval page.

In the case of a sole practitioner where such review is not possible, the client may elect to have the report reviewed by an independent professional. Under these circumstances, professional ethics require the independent reviewer to advise the consultant that such a review is being undertaken. This is generally done through the client.

5.8.2 Revision and issue records

All revisions to the report should be recorded on a “Record of Revisions” sheet included in the report. This record should include the revision number, the nature of the revision, the date and the name or initials of the person who revised the report.

A record should also be kept of all issues of the report. This should include the date of issue, to whom the report was issued, the revision number of the issued report, the number of copies and the format of the report (electronic or hardcopy). Electronic versions of the report should be issued in a non-editable format.

5.8.3 Storage and archiving of reports and supporting documents

All supporting documents, including investigation records, test results, etc. should be kept by the consultant for a minimum period of three years after completion of the project.

A hard copy and electronic copy of at least the latest revision of the report should be kept on file or in archives for as long as practically possible.

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6. VERIFICATION DURING CONSTRUCTION

6.1 Introduction

This chapter discusses additional geotechnical investigations or checks that are routinely carried out during construction or even post-construction. The purpose of these is to verify that the information contained in the geotechnical report accurately represents the ground conditions on site.

Verification impacts on all parties to the development:

- The consultant may wish to verify the geotechnical model and satisfy himself that his investigation identified all the salient features of the site such as intrusions, contact between various strata, adequacy of founding levels, groundwater levels etc.
- The designer should verify that his design parameters are realistic and that the structure will perform as intended. He may also be responsible for approving foundation conditions etc. during construction.
- The contractor has to assure the client that his works and materials comply with the construction specification. Verification testing can also form the basis for claims of changed ground conditions.
- The client may wish to confirm, once construction is complete, that his operation of the development is not adversely affecting the performance thereof.

This chapter addresses some of the techniques that are available for the verification and, where necessary, modification of the geotechnical model and design.

6.2 Risk

The nature of geotechnical investigations and reports is such that they provide discreet information at test locations, which is used to develop a geotechnical model of the site. Parameters are then assigned to the model and used to design foundations, road layer works, lateral support works etc. Due to the variability of ground conditions over any particular site, the information contained in the report and model may not necessarily represent the conditions across the entire development site. As such, there is always the risk of encountering unexpected or changed ground conditions to that originally allowed for in the design. In the worst case, the geotechnical investigation may fail to adequately locate a salient feature that may alter the design and performance of the proposed structure, e.g. a weathered dyke or solution cavity.

Regular inspection and monitoring during construction is strongly recommended primarily to track and record deviations in the actual foundation conditions from those predicted during the preceding site investigation phases. Such deviations from predicted conditions may enforce late stage design adjustments and changes.

In the case of dams with a safety risk, legislation (Water Act No 36 of 1998) further requires that the ‘as built’ founding conditions are recorded and presented in a report.

Even in the case of housing developments, such confirmation of the actual founding conditions is required for enrolment purposes with the NHBRC.

6.3 Monitoring

In addition to inspections and further testing, the consultant or designer may wish to instrument and monitor structures or parts thereof that could affect the design. The purpose of this monitoring is to confirm the assumptions made during investigation and design and ensure that the structure will perform as initially anticipated.

Instrumentation may be installed to record:

- settlement of foundations,
- lateral support movements,
- changes in groundwater levels,
- pore water pressures,
- stresses in the ground, etc.

The field instrumentation should ideally be undertaken during construction with monitoring readings taken at regular intervals. In some instances, e.g. where consolidation, heave or creep settlement is expected, it may be necessary to continue monitoring for an extended period after construction completion.

6.4 Active Design

An active design philosophy recognises the discrete nature of information obtained from geotechnical investigations and provides a design that is flexible enough to accommodate reasonable changes in the ground conditions from those initially anticipated.

The Observational Method of design proposed by Karl Terzaghi, and discussed in a well-known paper by Ralph B. Peck (1969), is one of the most widely used approaches to active design. The observational method is a continuous, managed, integrated, process of design, construction control, monitoring and review that enables defined modifications to be incorporated during or after construction, as appropriate. All these aspects have to be demonstrably robust. The objective is to achieve greater overall economy without compromising safety (Nicholson et al. 1999).

The observational method was introduced in an effort to reduce construction costs associated with designing structures based on the most unfavourable assumptions, i.e., geological conditions, soil engineering properties, etc. Instead, the base design is done on the most probable conditions rather than the most unfavourable. The gaps in the available information are then filled by observations, measurements (e.g. inclinometers and piezometers) and geotechnical site investigations. These observations aid in the assessment of the behaviour of the structure during construction, which can then be modified in accordance with the findings.

The method can be summarised as follows:

- Exploration sufficient to establish at least the general nature, pattern and properties of the deposits, but not necessarily in detail.
- Assessment of the most probable conditions and the most unfavourable conceivable deviations from these conditions.
- Establishment of the design based on a working hypothesis of behaviour anticipated under the most probable conditions.
- Selection of quantities to be observed as construction proceeds and calculation of their anticipated values on the basis of the working hypothesis.

- Calculation of values of the same quantities under the most unfavourable conditions compatible with the available data concerning the subsurface conditions.
- Selection, in advance, of a course of action or modification of design for every foreseeable significant deviation of the observational findings from those predicted on the basis of the working hypothesis.
- Measurement of quantities to be observed and evaluation of actual conditions during construction.
- Modification of design to meet actual conditions:
  - Where the monitoring results are better than the designer's prediction, consideration may be given to relaxing the design requirements.
  - Where the results are close to or slightly better than the range predicted by the designer, construction continues with caution.
  - Where monitoring results indicate that the behaviour of the structure is significantly worse than designed, construction is stopped and the foreseen contingency implemented.

The most serious risk in applying the observational method is the failure to select, in advance, an appropriate course of action for all foreseeable deviations of the real conditions from those assumed in the design. Therefore, the engineer must devise solutions to all problems that could arise under the least favourable conditions. If he cannot solve these hypothetical problems, even if the probability of their occurrence is very low, he must revert to a design based on the least favourable conditions

The correct implementation of the observational method can have significant time and cost benefits over the traditional methods of design. The experience gained from the use of this method will also lead to more efficient designs for future developments. Other potential benefits of the observational method are (Nicholson et al. 1999):

- Improved quality control
- Control of design uncertainties
- Flexibility of design

Examples of types of projects where the observational method is used vary from lateral support contracts, tunnelling, dam foundations etc. However, this approach to design is generally not recommended where the behaviour of the structure is brittle or the deterioration of the ground does not allow sufficient time to implement any alternatives. Typical examples of such instances include the deterioration of soils caused by ground water or brittle failure of structural members such as struts in multi-propped basement excavations (Patel et al. 2007).

6.5 Additional Investigations

Where possible, additional investigations and tests should be undertaken during construction. A number of the field and laboratory tests discussed in Chapter 4 could be repeated during construction. For instance, undisturbed samples may be obtained from excavation faces and sent for laboratory testing to confirm shear strength parameters used in the design of the lateral support system. The results obtained from these tests are invaluable to the successful completion of the project as they may alert the designer to potential changes that may have to be incorporated into the design.

In addition to undertaking tests during construction, the designer should endeavour to undertake tests on completed sections of the works to satisfy himself that the work has been undertaken in accordance with specifications. For example compaction control testing during earthworks. Continuous surface wave and plate load tests on completed terraces and foundation excavations provide a good indication of the stiffness of the soil strata and its suitability for the intended use. Other tests that can be carried out for various other developments and structures are:

- Pile load tests to confirm the load carrying capacity of piles
- Integrity testing of piles to qualitatively assess the uniformity of piles
- Lift off tests on ground anchors
- Permeability tests below dams etc.

6.6 Post-Construction

There are a number of developments that may necessitate long-term monitoring. This may be due to strict settlement and/or vibration criteria which are critical for the long-term performance of the structure. In these cases, the geotechnical consultant may install permanent instrumentation and take readings at the required intervals. Such an exercise can pick up any excessive settlement/vibrations and prevent the potential shutting down of a critical component of the structure.

Post-construction monitoring plays an important part in the assessment of structure performance where consolidation settlement, heave and creep effects extend beyond the time for construction.

Post-construction inspections could also identify operational conditions that may aggravate problem soil conditions, e.g. leaking services over dolomitic ground. These aspects should ideally be addressed in the final geotechnical investigation or design report.

6.7 References

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