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MASTER

Innovation enchained

two case studies on the innovative behaviour of a firm in the South African civil construction sector

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Two case studies on the innovative behaviour of
a firm in the South African civil construction sector

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Date 1st August 2003

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Two case studies on the innovative behaviour of a firm in the South African civil construction sector

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Preface

Graduation for the Technology and Society course of the Eindhoven University of Technology entails conducting Master thesis research. This thesis, written for that purpose, is based on case study research executed in South Africa. The thesis contains a mixture of technological elements from the field of civil engineering, and society-related elements involved with innovation policy issues. The combination of these elements in one thesis allows a suitable end to a three-year's study of Technology and Society.

The case study research is part of a bigger scheme to provide information on innovative capability in South Africa. Research to expand the available knowledge on this topic is conducted in a combined effort of the Department of Engineering and Technology Management (ETM) of the University of Pretoria and the department of Technology Management (TM) of Eindhoven University of Technology. The South African Innovation Survey 2001 (SAIS 2001) forms a substantial part of the inter-university research effort.

The opportunity to do research abroad provided me with a chance to broaden my perspective and gain experience in an international setting. The unfamiliar context in which the research was conducted posed additional challenges and as a consequence added educational value. The help I received during my research was very much appreciated. I would like to thank the staff of the University of Pretoria for their hospitality and the supply of the necessary facilities, the supervisors of both universities; Dr. Gerrit Rooks, Mr. Philip Viljoen, and Prof. Dr. Tinus Pretorius, for their effort and guidance, and my fellow students Mark Nooij and Marcel van Gool for their friendship, and cooperation on the collectively developed research design. In addition I would like to acknowledge the contribution of the staff of AFRICON, ARQ, Franki Africa, Dura Piling and Rodio, especially Willem du Preez, Alan Parrock, Nico Visser, Alan Berry, George Byrne and Paul Segatto. Thanks also to Maya Denneman for repeatedly reviewing this thesis.

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1 Introduction

In 1994, with the ending of the "Apartheid" era, South Africa gained new political momentum. As a result of this transformation, South Africa entered the competitive international markets. The primary basis for global competitiveness and one of the key driving forces for economic growth is innovative capacity [1,2,3].[i] A country's innovative capacity is determined by the strength of its national system of innovation (NSI). The NSI is an interactive collection of institutions that supports innovative activities within a country [4,5]. The national system of innovation plays an important role in directing and supporting the processes of learning and innovation [4]. From the mid-nineties there has been a broad perception in South Africa that the country has a lacking NSI [6,28]. The government became aware that innovation should be a central issue for business and policy strategies.

In order to formulate strategies and policies to give guidance to and support innovation, a clear picture of the present innovative capability of the country is needed. The South African Innovation Survey 2001 (SAIS 2001) is part of the effort to expand knowledge on the economic and innovative performances of South Africa's firms. The survey provides valuable information on the innovative behaviour at a national or macro level, but it does not give an in-depth insight in innovation processes at micro or firm level [7]. To extend the scope of the SAIS 2001 from macro level, to innovation on a micro level, additional research into the innovative behaviour of individual South African firms was devised. The supplementary research to explore the innovative behaviour on micro level consists of case studies conducted in three different South African companies in various industrial sectors, i.e. base metals, renewable energy and civil construction.[ii] This report contains the findings of the case studies in the civil construction sector. Two case studies were conducted into innovative projects of a South African consultancy firm in civil engineering. The case study format was selected, because it is the proper research type for explorative study of contemporary events [8]. The aim is to get an in-depth insight into the innovative behaviour of the firm regarding these two projects.

Firms embark on innovation processes because innovation is the primary basis for firm's competitiveness and one of the key requirements of business success [1,9]. The downside of innovation is the uncertainty regarding the results of the innovation process and the problems that will be encountered during the process. Firms are unable to predict the output of innovation processes simply through analysing, and determination of the input [10,11]. The inability to predict the innovation process's results and problems is caused by the complexity of the process. The overall complexity of an innovation process is made up of the total of complexities involved with every step made, up until end product. During the innovation process the firm relies on its knowledge base[iii] to get ahead. The moment a firm lacks the knowledge to take the next step in an innovation process this constitutes a problem, with a certain amount of complexity. The firm needs to obtain additional knowledge in order to overcome the problem. Additional knowledge can either be developed internally through Research and Development (R&D), or acquired externally from the firm's environment.

External acquirement of knowledge has potential benefits; it can be less costly and risky than developing the knowledge internally and it can help to reduce the time needed to obtain the knowledge [18]. A negative effect of external acquirement of knowledge is the transaction

[i] This report is based on data collected in two case studies. The research protocol calls for more than one source to support every fact mentioned, which leads to a substantial number of references. To prevent a disorderly appearance of the report numbered references in the text will be used e.g. [1,p111].

[ii] The same research protocol was used in all case studies in order to produce comparable data, and enable cross case analyses of the studies in different sectors on a later date.

[iii] The knowledge base of a firm is built through its historical activities and consists of tacit and codified knowledge from three areas. Firstly there is the general scientific knowledge on principles underlying technology. Secondly there is knowledge specific for the industry or product-field. Lastly there is knowledge related to the firm itself [10].

costs[iv] involved with the reduction of the risk of opportunism [42]. What knowledge is developed internally and what knowledge should be obtained externally is usually a strategic consideration and depends on the firm's competencies and long term planning. What sources of external knowledge are used is determined by the transaction costs involved [18]. The decisions of the South African firm to develop knowledge internally or obtain it externally are a part of its innovative behaviour that will be studied in this research. This leads to first of the explorative research questions to be answered in the case studies:

- *What were the firm's motivations to develop knowledge internally or acquire it externally?*

Making sensible decisions on where the firm should acquire the necessary knowledge is one of the demands on management, engendered by an innovation process. The descriptive approach by Tidd et al [18] suggests that during an innovation process different phases induce specific demands on management. In the scanning phase the organisation scans the environment for possible innovation opportunities. In the succeeding selecting phase the firm is challenged to select the opportunity providing the best exploiting possibilities. Once an innovation opportunity is chosen, the firm needs to organise resources required to fulfil the objective. In the subsequent implementation phase the resources are integrated in order to complete the innovation process. An additional learning and re-innovation phase can be identified to maximise learning and to prevent a repetition of failures. The organisation procures learning by reflecting upon the past innovation process and store relevant experiences and knowledge. These phases and demand on management can be identified irrespective of the way a firm structures its process management. However, the chances of successful innovation depend on whether the firm is successful in meeting the demands of the various phases [18]. To explore the way the innovation processes were managed and the performance of management, the second research question reads:

- *How were the innovation processes managed and was that management effective?*

To be able to compare the firm's behaviour in a complex and less complex situation, two innovation processes were selected with divergent levels of complexity. Complex innovation processes are likely to engender more problems and uncertainty than less complex innovations [11]. The different levels of complexity may influence how the innovation process is managed and where required resources are obtained. For that reason the third research question is:

- *How did the level of complexity influence the firm's innovative behaviour?*

One of the factors known to influence innovative behaviour is the environment in which a company is situated. The "environmental" or "context" variables consist of the sector in which the innovation takes place, the effectiveness of a country's NSI and firm specific factors [12,18]. Chapter two of this report discusses a number of factors determining innovative behaviour that are common to the civil construction sector. The product of every project in civil construction is unique and can be seen as an innovation, however the Project Based Organisations (PBO) conducting this kind of projects deploy highly standardised procedures and construction methods. The innovative capability in the sector as a whole is modest, which can for a large part be explained by the way the industry is structured. From literature a number of factors hampering innovation specific for the sector are identified and explained. In the same chapter factors influencing innovation specific for South Africa's civil

[iv] Transaction costs involve: the costs from identifying and evaluating potential partners, costs of negotiating and writing an agreement (contract), costs involved with the monitoring of the compliance to the agreement, and costs associated with the settlement as a result of one of the parties breaking the agreement [42].

construction industry are portrayed. The local construction industry predominantly uses foreign technology as a result of South Africa's lacking ability to innovate, caused by a deficient NSI. The last of the context variables determining innovative behaviour is the organisation that performed the innovation process and its characteristics. AFRICON is the consultancy firm hosting the research. The firm's history, capabilities and organisational structure are discussed in the last part of chapter two. The impact of the contextual factors described in chapter two on the firm's innovative behaviour is another topic to be studied in the case studies. Consequently the fourth and final research question is:

- *How did contextual factors affect the innovative behaviour of the firm?*

The results of the case studies with regard to the four research questions are recorded in chapter three. Chapter three starts by comparing the levels of complexity of the two studied innovations. Subsequently the behaviour of firms involved with the innovation processes in their quest for resources is discussed. Several behavioural factors, specific for the South African civil construction sector are identified. The chapter ends with the derived conclusions on the compliance of the events observed in the case studies with the general theory on innovative behaviour and the sector specific factors from chapter two.

Although every project in civil construction is an innovation in a sense, the execution of an average project by a specialised PBO using a standard method can hardly be called innovative. For the purpose of the case studies it was therefore decided to look at projects that deviate from the standard. Projects were selected where innovative construction techniques were used. This research embraces Rogers's definition of innovation: '*an innovation is an idea, or object that is perceived as new by an individual or other unit of adoption.*" [13, p 11]. Hence, an innovative construction technique is any construction method that is perceived as new by the adopting organisation, in this case AFRICON. A further requirement for the two case study subjects was that they differ in their levels of complexity. In other words: one complex and one simpler innovation process. In February 2003 a meeting at the AFRICON head office in Pretoria was held to discuss projects that could be used as research subjects. Two projects recently completed by the geotechnical section were proposed for this purpose. In both projects a foundation method was used new to AFRICON. After an exploration of the available data on the projects, it was decided that they would suit the requirements for research. Although the notion of complexity for the case study research had not been worked out sufficiently at the time, the two projects were ranked on basis of their technological and organisational complexity.

The first project, containing the complex innovation, is the "founding of the Welgedacht Water Treatment Works". The innovative part in this project is the combination of stone columns[v] and a soil raft[vi] for the plants foundation. The innovation process is complex from a technological and from an organisational perspective (number of people and organisations involved). The unit of analysis is the innovation process that led to the implementation of stone columns and a soil raft for the foundation of the Welgedacht water treatment works.

The second project pertains to the stabilisation of a road's embankment by means of jet grouting[vii]. This project is less complex from an organisational perspective in the sense that AFRICON was the only party involved in the design of this project and there was only one contractor. The project was technologically also less complex, because the performance of the method was less hard to predict. The unit of analyses for this project was: the process that led to the innovative use of jet grouting techniques for the stabilisation of a road embankment.

Both cases were studied simultaneously; research and writing of the reports took from February to August 2003. During this time the companies involved in the projects were

[v] Stone column: foundation element formed insitu, consisting of compacted stone.

[vi] Soil raft: foundation system in which soil conditions are improved either by compacting insitu soil or replacing it with material with a higher stiffness.

[vii] Jet Grouting involves the ejection of cement under high pressure to partially replace soil in-situ. The cement mixes with the coarse particles and when it hardens a column is created.

visited several times. The first step in the research was the study of the project files for both projects at AFRICON. Special attention was given to technological details and the correspondence between parties involved in the projects. For the case study on the founding of the Welgedacht Water Treatment Works it was deemed necessary to expand the research to ARQ, a consultancy firm responsible for the early stage of the design. At ARQ a comparable study of project files was done. Selected documents from the files of both companies are included in the database. In the second phase of the research a literature study into the background and origin of the technology of the innovation was conducted. Related technologies and their characteristics were studied as well. After the review of project files and literature on the concerned technologies, information needed to complete the research was sought through meetings and interviews with the consultants and contractors involved in the projects.

The actual narrative descriptions of the "Welgedacht" and "N17"innovation processes are included in chapters four and five. Using the five phases of innovation processes proposed by Tidd et al [18] as a theme, the report portrays the events that took place, in a chronological manner. The discussion of the innovation processes starts with a description of the problems that were eventually solved with an innovative solution. After a discussion of the projects organisation, concerning the involved firms, the different phases of the innovation process are described. In the scanning phase the company searches its environment for possible solutions. The discussion of this phase includes an overview of the considered technologies and their properties. Subsequently, in the strategy phase, the firm decides what specific technologies will be used. The next phase is the resourcing phase. Uncertainty and complexity lead to a need for resources to complete the innovation process. The discussion of this phase focuses on where and how the required knowledge was acquired. The actual construction of the foundations using the innovative method is portrayed in the sections on the implementation phase. The report on the case studies ends with a description of the reflection phase, where the question whether the firms involved have learned from the processes is answered.

2 Innovation in South Africa's civil construction sector

In civil engineering every project's design is unique, furthermore, the products made (roads, bridges, etc) are not put to use in the same sector. Therefore, every design can be seen as a product innovation [14]. However, although the form of the product is always distinctive, the technology involved in the construction and the materials used vary little and remain unchanged for long periods of time. Slow incremental development is a characteristic of scale intensive sectors and their technological trajectory [18]. Research and Development (R&D) expenditures in the industry are low in comparison to other sectors [15]. It is fairly rare to find revolutionary new construction methods or processes. In this light, the construction industry is often referred to as lacking in innovative capability. The inability of firms in the sector to bear technological change has been the research subject of several studies. The way in which civil construction projects are structured is identified as a main cause for the relative absence of innovative behaviour in the sector [15,16,19]. This chapter begins with an elaboration on the characteristics of the civil construction sector and its consequences for innovation. South Africa's history and its still developing economy induce attributes distinguishing its local construction sector from that in other countries. These attributes will be described in the subsequent section. The last section contains a discussion of the characteristics influencing innovative behaviour particular to the research-hosting firm.

2.1 Innovation in chains

Contrary to mass production goods, the products of civil engineering are expensive and customised to fit the needs of an individual user. Experiments with, or prototypes of, construction designs are expensive if not impossible. The absence of pre-construction experiments induces an amount of uncertainty on design performance. The perceived risk is even higher when radical new technology is employed [18]. The uncertainty leads to a conservative design approach, because structural failure can lead to severe costs and possibly to loss of life. In the last decades computer models are used on an ever-larger scale to predict structural behaviour. To a certain extent the software helps overcome uncertainty, although a computer simulation remains a simplification of reality [17].

The actors usually involved in a construction project can be categorised in end-user, contractors, sub-contractors, advisors, specialised suppliers and government bodies [16,17]. The main sources of technology for construction projects are engineering departments, contractors experience and specialised suppliers of equipment and components [18]. End-users in general have little knowledge of the technology involved with construction and are usually represented by an advisor. The engineering department of the advisor often designs the construction and draws up a tender document containing predetermined technological specifications for the construction. The main contractor for the construction is then selected through a bidding procedure called tender. Contractors enter bids based on their estimation of construction costs for the desired construction. A disadvantage of the predetermined technological specifications in the tender document is the little room left for innovative changes to the design in a later stage, because the advisor typically evaluates a contractor by its tender bid and not on its qualitative attributes [19]. The inability of a contractor to sufficiently communicate innovative options to end-users forms an obstacle for implementation, limiting the opportunities for new technology to enter the market.

Because the contending contractors enter bids to construct the exact same end product, they have to be competitive in price. To be competitive, contractors are forced to use relatively low profit margins. Blackley and Shepard [15] mention lack of recourses as a result of low margins and a small average firm size as a cause for limited R&D spending in the construction sector. In addition, innovations inevitably involve risks, which companies will be reluctant to take when profit margins are low. The perceived risk involved with innovation is increased further by uncertainty about future demand-side developments. Demand in the construction industry is characterised by conjuncture-induced fluctuations. The combination of risks engendered by fluctuations in demand and the uncertainty of an innovation's effectiveness form a disincentive for large investments in innovative equipment or solutions by contractors [15].

A prominent task for the main contractor selected in the tender procedure is the organisation of the production through division of activities over specialised sub-contractors. Civil construction projects are produced in a joint effort by project-based organisations (PBO), which form a coalition for the duration of the project. A construction project normally contains several phases; feasibility studies, detailed design, tender, construction, commissioning and maintenance. Phases follow a common order during a process that can take many years. During the project the PBO's involved have to rely on companies with whom they may be in direct competition for other projects. This is a result of the high level of horizontal and vertical fragmentation in the sector.[viii] There are not many, if any, companies that have all the specialised skills, knowledge and equipment within their organisation to complete the whole cycle themselves. Although recently large companies have started to design and construct quite extensive projects, it is difficult to conceive of a project for which such a company would not require the skills of a single specialised subcontractor. Consequently, in the construction industry companies in general have no choice but to engage in knowledge networks. During the construction process there is a constant flow of information between the actors regarding the technological details of the project. As a result of the high level of fragmentation, construction projects in general involve complex networks of interlinked companies from different technological backgrounds. Such a knowledge network would seem to be an ideal situation for the diffusion of innovations. The high level of interdependency within the network however, makes that companies cannot innovate without others having to make adjustments to their related technologies [15]. Products from the construction industry are a result of different firms putting together a chain of components in a harmonised way. The different components making up the final product are highly standardised to make integration possible. If one of the companies in the chain decides to radically change its production method or output, chances are that it cannot be implemented without other firms changing their products too. The gain in its production efficiency achieved by one firm through innovation, may well lead to a decrease of efficiency for the chain as a whole. The firms in the chain will therefore actively resist innovative gumption from a single actor for the possible threat it poses to the chain's existing efficiency [19]. For this reason, contrary to what would be expected, a stable network in the construction sector with a high level of interlinking, trust and sharing of knowledge, effectively reduces the urge to innovate.

Apart from being highly standardised to fit the chains, the products of the construction industry have to satisfy very specific demands posed by the building standards and regulations. Governments draw up regulations for structures and check compliance to those regulations, to ensure structural integrity for safety considerations. The standardisation of components, resulting from the demands arising from the production chain and government regulations, represents a significant barrier to new, divergent technologies to enter the market [15]. Moreover standardisation has a negative effect on inter-organisational learning according to Håkansson et al. [20].

Organisational learning by PBO's is hampered as a result of their involvement in entirely independent projects. It is difficult to transfer knowledge from one project to the next, due to customisation to factors unique to that project, such as individual user needs or local geology. PBOs often consist of highly specialized departments, which are involved in independent projects in their particular field of expertise. The communication between those departments is often poor due to cultural differences, which makes organisation-wide learning difficult [17,21].

[viii] Horizontal fragmentation concerns the amount of work subcontracted to other firms, vertical fragmentation pertains different activities, and non-construction activities executed by construction firms like real estate finance [15].

2.2 Local factors affecting innovation

South Africa's construction sector plays a significant role in the country's economy. It generates a considerable percentage of the Gross Domestic Product (GDP). In 1991 the sector accounted for 4,9 percent of South Africa's formal employment, making it the third largest work provider [22]. South Africa has a developing economy in the literal sense of the word; its economy has lately picked up pace. While the Western world is entangled in serious recession, South Africa's annual growth rate amounts to 3 percent [23,24]. The domestic growth causes a mushrooming of construction projects, even though foreign investment is limited. Foreign investors associate South Africa's emerging market with instability and refrain from making serious investments. [23,25]. The popularity of the country with investors has lately decreased further due to controversial statements by President Mbeki on HIV&AIDS and his failure to condemn land invasions in Zimbabwe [26].

Notwithstanding the share the construction sector has in the countries economy and the recent increase in demand, the sector has its problems. The capacity of the sector has declined in terms of the number of companies and employment. The size of the sector has decreased with 20 percent in labour and 60 percent in capital since 1970 [22]. The industry itself is technologically well behind on foreign industries. This is partly a result of the isolated position South Africa was in before 1994. Due to this isolation, foreign competition on the internal market was low, and as a consequence, so was the need to innovate [27]. In the current situation, the civil construction sector is dependent on foreign countries for the bulk of its technology. This phenomenon applies for most of South Africa's industries and is common to developing economies. It is known as "technological colony" and is the result of a deficient National System of Innovation (NSI) [28]. In a technology colony the activities are mainly focused on the manufacturing of products, depending on other countries for the development of new technology. The main shortcoming of South Africa's NSI is the amount of R&D spending. Over the years the country slowly began to move towards a fully developed NSI. Buys proposes a course of five industrialisation stages a developing country follows to a complete NSI [28]:

- Stage I: Local distribution, marketing, sales and after sales services of foreign products and services;
- Stage II: Local production and manufacturing of foreign products and services;
- Stage III: Local improvement of foreign products and processes;
- Stage IV: Local development of new products and processes;
- Stage V: Local technology development.

Most industries in South Africa are currently in phase II, where they depend on foreign technology for their manufacturing processes [28]. In the civil construction sector building methods are very dependent on local conditions (climate, soil conditions, materials). Imported technology has to be adapted to local conditions, effectively placing the civil construction sector in stage III, where foreign products and processes are improved locally.

Besides being dependent on foreign technology the construction sector, as many sectors in South Africa has to cope with a shortage of skilled personnel and management [22,31]. Unemployment rates are high in South Africa (ca. 35%) and labour is cheap, but the available workforce is under-skilled and poorly educated [26,29]. A survey on technology management under South African managers identifies '...the *dearth of managerial and technological skill available from a poor educational system, and low commitment by the workforce*' as one of South Africa's largest challenges for innovation [30, p 15]. The shortage of skilled personnel is worsened by the rate at which qualified workers are leaving the country and the high prevalence of HIV/AIDS [32].

Emigration of skilled personnel poses a serious problem; it has been observed that 22% of management employees have emigrated [31]. Official government figures report that 13.085 highly skilled professionals left the country at the peak of their economical active ages, between 1996 and 2001. A resent study[ix] of the Counsel for Scientific and Industrial Research (CSIR) shows that the real number is three times higher than reported by the government [32]. Irrespective of what the exact figures are, South Africa's developing economy can ill afford this knowledge drain.

A political factor identified as one of the reasons for this knowledge drain is the policy of affirmative action that is taking place. This remedial policy is designed to ensure equal participation in economic activities for people from formally disadvantaged groups. It is intended to restore the balance between racial groups that was distorted through past discrimination practises. The need for such a policy in South Africa is clear, but some negative side effects can be identified. The South African government has set targets for the presence of Previously Disadvantaged Individuals (PDI) in boardrooms and management positions that need to be reached by the public and private sectors. This practice of quotas has been criticised, for it can result in quantity, not quality. Affirmative action created an unfavourable situation for part of the qualified workers. They have seen their career chances diminish and are leaving the country, leaving a knowledge gap behind. Critics say that for affirmative action to succeed far more effort should be put in improving South Africa's educational system [31].

An ominous factor with significant impact on training of personnel and long term planning is AIDS. About 20% of South Africa's population is infected with HIV [24]. 40% of all deaths in the age group 15-49 are AIDS-related, which has considerable consequences for the active workforce [30]. Productivity in some of South Africa's industries has already dropped due to AIDS-related illness.

Recent numbers specified for the civil construction sector as regards to the problems of AIDS and the exodus of qualified workers were not found. Nevertheless, since a shortage of skilled personnel and managers already existed in 1996 [22], it is not likely the situation has improved since then.

[ix] Report to be released in August 2003

2.3 Company hosting the research

AFRICON, a South African based international consultancy was found willing to host the case study research in the civil construction sector. The firm was approached because of its innovative activities in the field of civil engineering, which matches the technical background of the author. The company, founded in 1951 under the name Van Wijk & Louw, changed its name in 1994 after the political change in South Africa had taken place. Currently AFRICON employs 1200 people and is active in many countries mainly on the African continent.

AFRICON, like most companies involved in civil engineering, is a Project Based Organisation (PBO). It provides consultancy services in engineering, infrastructure-related development and management and its core business is to design solutions in a project-based fashion for multiple projects at the same time [33]. In civil construction projects the company will typically act as advisor, managing coordinator and/or designer. The intention to provide innovative solutions in each of these roles appears in their mission statement: '...to provide to all its clients excellent professional consulting services in engineering, infrastructure-related development, with an emphasis on innovation and value.' [34]

The first contact for the case study was established with an associate of the geotechnical section which is now part of AFRICON's transportation division. At the time of the studied innovative projects AFRICON consisted of nine divisions, three more than in the current situation. The geotechnical section was subsumed in the Civil, Geotechnical and Environmental division [35]. AFRICON has provided geotechnical services for over half a century. As a result, the geotechnical section has extensive experience with the design of foundation systems under local conditions. Its geotechnical knowledge base contains a broad understanding of the construction methods that can be applied in South Africa and in local soil conditions. Other results of its long track record are a well-established name, and ties with firms in the sector.

To efficiently function as a PBO, AFRICON's organisational form is aimed at dealing with multiple projects at the same time. The firm is structured as a so-called matrix organisation. The matrix model is a common form for the organisation of a multi-project company. It is a flexible form of organisation where employees are placed in sections together with colleagues with the same technological background. In the matrix model there are two kinds of

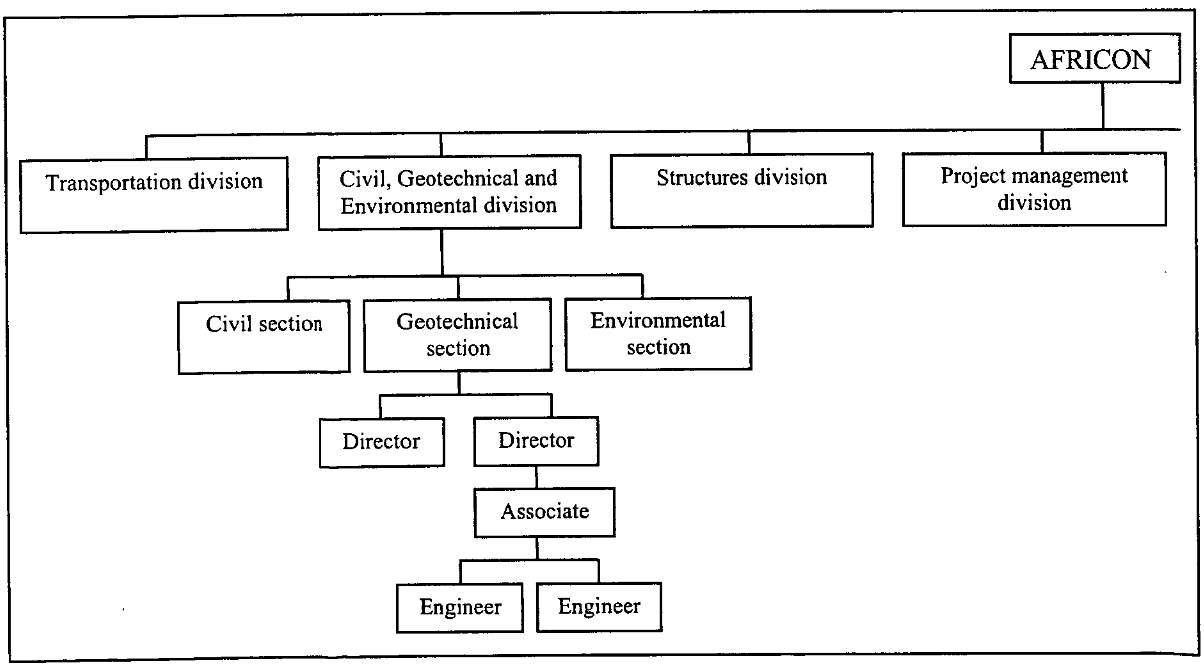


Figure 1:Organisational structure of AFRICON

managers. The first kind is the functional manager, who provides technical guidance to his subordinates. The second is the project manager who oversees and supervises projects. Project managers form a dedicated project team by selecting the necessary personnel from different technological sections. The advantage of this form of organisation is the flexibility it provides in forming temporary multi-disciplinary project teams, while allowing personnel to consult colleagues with the same area of expertise [36]. Figure 1 shows the organisational structure of AFRICON at the time of the projects. The director/project manager was in both cases approached by the client to do the project. After the director decided to accept the order he formed a project team, which had the same composition for both projects. The Associate is the functional manager from the matrix organisation model; he provided the technical supervision for the two engineers in the project team [35,88]. Since the projects did not require knowledge from more than one discipline, only engineers from the geotechnical division were selected. The project team consisting of four people and support staff (secretary, CAD[x] technician, Geotechnical technician) took care of the whole process for the two projects on AFRICON's behalf.

[x] Computer Aided Design

3 Case study results

In this third chapter the innovative behaviour observed in the case studies is analysed. The four explorative research questions are answered in this chapter. The analysis precedes the actual detailed accounts of the technological innovation processes, which are given in chapters four & five. Theory states that complexity is a property of the problems a firm has to overcome in order to complete an innovation process. A problem is an obstacle in an innovation process the firm cannot solve by using its available resources. The firm has to acquire extra resources to overcome the problem.[xi] It can either develop the resources internally or acquire them externally. The firm can obtain resources from its environment via the ties it has with organisations in its network. A firm may have various reasons to acquire additional resources externally or develop them internally. The behaviour of the South African innovating firm on its quest for additional resources is the main research topic for the case studies. The two innovative projects supplied by AFRICON were assumed to have dissimilar levels of complexity, based on a first description of the projects obtained at the start of the case study research. The innovation processes were selected to be able to compare the firm's behaviour in complex and standard innovation processes. To assess differences in behaviour, it first needs to be established that the processes indeed did have dissimilar complexity levels. For this reason, chapter three starts with a comparison of the levels of complexity of the two innovation processes. The comparison is made on basis of the number and properties of the observed problems in each innovation process. Next a description will follow on how the innovation process was managed and how the acquirement of additional resources was carried out by AFRICON. Based on this information a model of the innovation processes is drawn up. The last section, before the conclusions, describes observed local and sector factors influencing knowledge transfer and the aspects determining the use of technology specific for the sector in South Africa.

3.1 Rating complexity

At the start of the research it was assumed that the founding of the Welgedacht facility was more complex than the stabilisation of the N17 embankment. Here, in retrospect, an attempt will be made to objectively compare one project's complexity with the other. This will be done on the basis of the problems that were identified in the case studies on the "Welgedacht" and "N17" projects. An overview of the sources and nature of these problems is given in appendices I & II. The tables in the appendices further describe the types of complexity of the problems, the considerations of the firms on where to acquire additional resources and where, and in which form, the resources were acquired. The case studies depict the process from the first decision to pursue a certain goal, to its completion. During both the "Welgedacht" [xii] and the "N17"[xiii] project the initiative to get to that goal shifted between parties. The different

[xi] The most distinctive example to support the notion that complexity leads to a need for additional resources to come from the case studies is the use of Finite Element Analyses (FEA) software in the Welgedacht project. The FEA software was used to predict the settlement of the foundation. The design required a higher than standard level of certainty regarding the amount of settlement. In order to make a high quality prediction of settlement a large number of interacting variables, i.e. soil parameters and the foundation's stiffness, had to be taken into account. Instead of applying standard hand calculations, it was decided to use tacit knowledge in the form of FEA software to more efficiently predict the result of the many interacting parameters.

[xii] The process that led to the innovative foundation of the Welgedacht water treatment facility, started with the East Rand Water Care Company (ERWAT) picking a site for the establishment of the plant. It had done some geotechnical investigation to assess the suitability of the site. ERWAT instigated a subsidiary called AquAfrica to coordinate the design and construction of the plant by selecting an international firm. AquAfrica failed its mission and was eliminated. A local consultancy firm named ARQ was hired to coordinate the entire design and to do the geotechnical design. The design was put to tender and the selected contractor Qhude BBE hired ARICON to improve the design.

[xiii] Its administrator, the National Road Agency (NRA), first noticed the subsidence of the N17 road embankment. The settlement was measured over a period of time to assess the extent of subsidence. AFRICON was hired to find out what caused the failure of the embankment and to come up with a solution, which was then put to tender.

parties involved during the innovation processes all gathered knowledge to overcome the problems they were faced with while they had the initiative. The final designs are a product of this accumulation of knowledge. It is therefore unjust to describe the process within one firm only when one studies the innovative solutions. Because the use of innovative foundation methods came about with the accumulated knowledge from the different phases, appendices I & II are not restricted to AFRICON's knowledge queries only. A total of 27 situations were observed in the two case studies, where extra resources were needed in order to reach the goals of the innovation processes. In the innovation process for the foundation of the Welgedacht water treatment facility 17 problems were identified and 10 in the innovation process for the stabilisation of the N17's embankment. Knowledge was in all 27 observed cases the required additional resource.

The total complexity of a project can be seen as the sum of the complexity of all sub-problems. The complexity recognised in the case study may only be a small part of the total complexity faced by the firms during the projects. The level of complexity may also differ per problem; it is by no means certain that every problem has the same level of complexity. The method used to study both innovation processes was however identical, and therefore problems had an equal likelihood of being discovered. Furthermore, a large part of the problems encountered had a similar source and nature. From this perspective the "Welgedacht" innovation process with 17 observed problems appears to have a higher level of total complexity than the "N17" process with 10. This means that the assumption of the "Welgedacht" project being more complex was correct for the total complexity.

The total level complexity observed in the case study research cannot be used when assessing the influence of complexity on a firm's behaviour. How complexity is perceived is subjective. In this research the subject experiencing complexity is the firm faced with a problem. Decisions on how to overcome a problem and where to acquire resources are made on the basis of complexity as perceived at that moment in time. Because AFRICON was in both cases not involved from the very start of the project, it was not concerned with all the observed problems of the innovation processes. The company did not have to overcome the complexity of the problems that were solved before it became involved. Those problems did not influence AFRICON's behaviour when acquiring resources. To rate the level of complexity that influenced AFRICON's management decisions, the phases in which other firms had the initiative, need to be discarded.

Complexity can originate from various sources and it is hard if not impossible to compare complexity levels of problems with a different source. Kim and Wilemon identified six sources of complexity; Technological, Market, development, marketing, organisational and intra-organisational complexity [37]. These sources are used to categorise the nature of each of the encountered problems, described in appendices I & II. To rate the difference in complexity levels AFRICON faced for the completion of the innovation processes, a comparison was made for each separate source. The comparison is based on the number of observed problems and the relative complexity of the problems.

Technological complexity- is the complexity involved with the understanding and integration of technologies [37]. During the Welgedacht project 9 problems involving technological complexity were established (see appendix I). The research identified 7 technologically complex problems in the N17 project (see appendix II). The nature of the technological problems can be divided into three categories i.e. soil conditions, details of foundation method and performance of the method.

Table 3-1: Number of problems per category of technological complexity

	Soil conditions	Construction method	Performance uncertainty
Welgedacht	3	1	5
N17	3	1	3

As can be seen from Table 3-1, the number of problems caused by uncertainty about soil conditions is equal for both projects. However, the way in which the soil conditions were investigated in the Welgedacht project was more extensive because of the size of the project and the number of soil parameters that needed to be established in order to make accurate prediction of settlement possible. The knowledge required on the principles of the construction methods was comparable for the two projects. In both cases basic information was gathered from literature and contractor's experience. There is a large difference between the projects in the uncertainty involved with the prediction of the performance of the foundation designs. The many interacting variables determining the settlement of the Welgedacht plant's foundation brought about a need to use advanced computer software, whereas the design of the grout columns for the stabilisation of the N17 embankment was done by establishing a practical spacing using standard calculations. Even after applying the software, AFRICON's first two design alternatives turned out to be technologically not feasible after they were proposed. Uncertainty impelled the quality control for the Welgedacht foundation to be more extensive than that of the grouted columns in the N17's embankment. The required level of certainty for the performance of the Welgedacht foundation was only achieved after the execution of a full-scale load test. Concluding, the technological complexity faced by AFRICON in the "Welgedacht" project was higher than in the "N17" project, because of the number of soil parameters that needed to be established and because of the complexity involved with the prediction of design performance.

Market complexity- Market complexity is caused by uncertainties in the company's environment [37]. AFRICON had to inquire with the only contractor they knew capable of jet grouting whether they had the equipment available for the N17 project. In the Welgedacht project AFRICON worked on an optimisation of a design applying a method of which it was sure the contractors involved could perform it. The market complexity of the N17 project was a bit higher, but the uncertainty was gone after an informal meeting with the concerned contractor 88,100].

Development complexities- Are complexities involved with the planning of the R&D process itself [37]. The research did not produce any data on this source of complexity, but it is not expected to be very different for both cases. AFRICON's project team considered both projects to be "standard" projects no extraordinary planning was involved in either of the projects.

Marketing complexity- Concerns complications in marketing a new product [37]. The marketing effort of AFRICON was limited in both cases. AFRICON was approached by Qhude BBE to improve the tender design for the "Welgedacht" foundation as a result of a personal relationship between staff members of the companies. The investigation and repair of the subsidence of the N17 embankment went to AFRICON because they had done the original design for the road. In other words, no major marketing efforts were involved and thus there was little or no complexity [88].

Organisational complexity- The number of functional groups and individuals needed to complete an innovation process determines the level of organisational complexity [37]. For both projects the same director assembled a project team that comprised of the same people. The organisational complexity was therefore virtually the same in both projects [88].

Intra-organisational complexity- comes about from difficulties in communication, relationships, sharing of profits and contributions when more organisations are involved with the same innovation process [37]. Here again, the Welgedacht project is much more complex. The stabilisation of the N17 embankment only involved three organisations with well-defined responsibilities. The first organisation is the client, which was concerned with the commissioning and financing of the works, the consultant was responsible for the design of the solution and finally the contractor who was responsible for the quality of the construction process. The foundation of the Welgedacht water treatment plant involved a client, the client's consultant, a main contractor, a contractor's consultant, and a joint venture between two specialised sub-contractors. The consultant, AFRICON was responsible for the design, but had to agree on settlement criteria with ARQ, the coordinating consultant for the client.

ARQ was responsible for the design parameters because they had produced the tender design. Qhude BBE, the main contractor hired sub contractors Franki and Dura for the construction of the foundation. The joint venture of the specialised sub-contractors guaranteed the integrity, settlement and capacity of the product and would have to bear the costs if more columns needed to be installed than expected [38]. The intra organisational complexity for the foundation of the Welgedacht works in terms of companies, people, agreements and contracts involved, was higher than that of the N17 project.

The results from the case studies clearly established the assumption made in advance that the innovation process involved in the foundation of the Welgedacht plant had the highest level of complexity. The higher level of complexity led to more uncertainty and a more substantial need for additional knowledge[xiv]. The next section will investigate how AFRICON responded to the demands on management posed by the innovation processes. The objective is to identify possible effects, of the dissimilarity in the complexity levels of the processes, on the behaviour of AFRICON when in need of additional resources.

[xiv] Complexity makes the outcome of an innovation process uncertain. The risk involved with complexity led to higher costs for the contracting side in the "Welgedacht" project. The lump sum offer done by the contracting side in the tender phase was based on the assumption that the tender design could be optimised and on an estimation of the amount of columns that would be used. The contracting side, which included AFRICON, accepted responsibility for the performance of an alternative design. Because soil conditions were worse than expected the design had to be revised and the number of columns increased. As a result, revenues from the project were less than expected [xiv].

3.2 Resourcing innovation and the demands on management

The record of the case studies in chapters four & five is structured according to the five phases of innovation processes with different demands for management proposed by Tidd et all [18]. The question to be answered here is how the firm managed the innovation processes and if there were differences in management for the complex Welgedacht" project and less complex "N17" project.

3.2.1 Innovation management

How a firm deals with the challenges for management in the different phases of an innovation process is determined by its strategy. AFRICON's organisational structure results in a decentralised management of innovation processes, with dedicated project teams acting relatively independent from the rest of the organisation. Projects are organised using standard procedures. Both innovation processes were carried out for AFRICON by the same project team. The project team was responsible for all the decisions taken by AFRICON concerning the two projects, including the decisions on where to acquire additional knowledge. As a result, the innovative behaviour that was observed in the case studies was foremost the behaviour of the project team. The case studies show that the management of the different phases was similar for the two projects; it can therefore be discussed here without making a distinction between the projects.

Scanning phase- in the scanning phase a company searches its environment for signals of innovative opportunities. The demand on management in this phase is predominantly to guarantee the identification of valuable opportunities [18]. In both innovation processes the project team detected a number of construction methods with potential to be used in the project. The options that were recognised were filtered for efficiency and effectiveness and the most promising were retained. The knowledge on that was gathered during this phase was mainly on general technical principles and the properties of various foundation systems methods.

Strategy (selection) phase -After the signals from the environment have been processed, the firm needs to decide to which innovation opportunity it will commit resources. One of the main considerations in this phase is the selection of an innovation that suits the long-term strategy of the firm and lies within its capabilities. Innovation involves risk, and this risk increases significantly if a firm does not have previous experience in the field of the innovation [18]. Consultancy firms like AFRICON try to supply their clients with the most cost-effective solution they can come up with for the situation at hand. In both studied cases this solution involved the use of a construction method new to AFRICON. The decision to use new technology was made after qualitative comparison with other technologies. Although the use of the new methods brought about some extra uncertainty, the risk could be managed by testing the performance of the techniques in the early phases of construction. Most of these tests would probably also have been necessary if more common techniques were used. The use of new construction methods is in alignment with the core capabilities of AFRICON, which is the design of effective solutions for technological problems in civil engineering. The additional knowledge required during this phase had a higher technological level than the information used in the scanning phase.

Resourcing phase- in the sequence of phases, the strategy phase is followed by an innovation phase where new and existing technology is integrated into a new system. The knowledge can be gathered within and outside the organisation. In this resourcing phase the first draft of the solution is drawn up [18]. In the Welgedacht and N17 projects there was no separate resourcing phase; the information needed to complete the design was gathered during earlier phases, in order to compare the new construction methods with other technologies. To be able to reach a sensible decision on what method to use, the performance of the different foundation options had to be established, requiring most of the knowledge used in the final design. Therefore, much of the resourcing took place in the scanning and strategy phases.

Additional knowledge that was still required after the Strategy phase was collected in the implementation phase.

Implementation phase- In this phase the ideas from the earlier phases are transformed into a product ready to be brought on the market [18]. For both studied innovation processes the implementation phase started with the preliminary design being approved for construction. During the early stages of construction, tests on the performance of the design as well as additional geotechnical investigation were done. The results of these tests necessitated a final adjustment of the designs.

*Learning and re-innovation-*Is about the improvements on products after they are put on the market to be used in future generations. Furthermore, firms can try to store the knowledge they gained from the innovation process, so it becomes part of their knowledge base [18]. AFRICON gained important knowledge and experience on the founding methods used in the "N17" and "Welgedacht" projects, which can be used for future practice. Also, through learning by doing, the confidence in the performance and predictability of that performance has increased, making future use of these methods in other projects more likely. The information and experience gained in this project is for the most part tacit and codified knowledge kept by the engineers involved. No procedure was used at AFRICON to facilitate organisational learning concerning the gained knowledge. An attempt was made to pass some of this knowledge on to individuals outside the project team and outside AFRICON (the reasons for this will be discussed in 3.3.2), by publishing papers on both projects [39,88].[xv]

3.2.2 Choosing the source of knowledge

Apart form the demands for management described in the last section, the innovation processes engendered a need for additional knowledge. This section will investigate how knowledge was acquired and if there were differences for the complex and less complex innovation process.

Complexity is a matter of perception and in the eyes of the project team's engineers neither the Welgedacht nor the N17 project was very complex. In fact the projects were perceived to be standard civil construction projects. The only factor that made these projects somewhat special is the use of construction methods that were new to AFRICON [88]. The core business of AFRICON as a PBO is to find solutions to unique problems. The construction method used is just one variable in an always distinctive construction design. Nevertheless, the newness of the construction methods did require the project team to acquire additional knowledge on both the method and its implications for design. These resource queries come on top of the need for knowledge involved in a standard project that does not involve new construction methods.

Table 3-2: Problems and knowledge queries per project

Project	Number of problems observed	Number of knowledge queries induced	Number of knowledge queries per problem	Number of times knowledge was acquired internally	Number of times knowledge was acquired externally
Welgedacht	9	17	1,9	7 (41%)	10 (59%)
N17	7	10	1,4	1 (10%)	9 (90%)

Table 3-2 is based on the information in appendices I & II and shows the number of problems that were identified for both projects and where the project team acquired the additional knowledge. The sample size is too small to make valid statistical significancy tests possible

[xv] Papers published: R.W. du Preez, A.D. Berry, K. Schwartz, A. Parrock, *Founding of the Welgedacht Waste Water Treatment Works by means of Stone columns and a soil raft,* SAICE Geotechnical Division: Seminar on Ground improvement Johannesburg, South Africa. 8&9 October 2001, (ED-DAT-0001)

T.E.B. Voster, R.W. du Preez, P. Segatto, *Stabilisation of a road embankment by means of Jet Grouting,* SAICE Geotechnical Division: Seminar on Ground improvement Johannesburg, South Africa. 8&9 October 2001, (ED-DAT-0002)

[40]. The strength of case study research lies not with statistical tests of hypotheses, but with descriptive explorative analysis. The table shows that the more complex innovation process induced a larger number of knowledge queries per problem (1,9) than the less complex innovation process (1,4). On average the project team used more sources of knowledge to solve a problem in the "Welgedacht" project, than in the "N17"project. Table 3-2 shows substantial differences between the projects as regards the origin of the knowledge. This effect can be explained by looking at situational factors; it is not a consequence of the difference in complexity levels between the projects.

The section on the rating of complexity showed that the additional knowledge required due to technological problems can be divided into three categories. Extra knowledge was required on the innovative foundation method, on soil-parameters, and the performance of the method under local conditions. Technical details on the foundation methods were gathered through informal meetings with contractors and from literature on the methods. The project team went outside of the firm to get this knowledge, because the transaction costs involved were low or non-existent. Firms in South Africa's civil construction sector tend to share technological information for reasons that will be discussed in section 3.3. Knowledge on local soil conditions was not readily available from any source and had to be developed. Had this information been accessible in other firms, the project team would probably have acquired it from these firms since development of such knowledge is expensive. The only way to develop this knowledge is by performing in-situ[xvi] geotechnical investigations. AFRICON did not have the equipment available to do all the required tests, consequently, specialised sub-contractors were hired. The decision to use external resources in this situation is typical of the fragmentised civil construction sector. The prediction of the performance of the foundation in local soil conditions is where the specialisation of AFRICON's project team comes in and that knowledge was therefore developed internally. By integration of the new knowledge on the method and soil conditions, with elements from AFRICON's knowledge base (e.g. calculation methods), new knowledge on the behaviour of the foundation system under local conditions was developed. This knowledge was then used in the design for the foundation. Completed designs were discussed with the different parties involved in the project, and when approved, implemented. The designs were changed on several occasions, because one of the firms that reviewed the design advised so. During the implementation, the performance of the design was monitored using own resources and resources supplied by a specialised contractor. On several occasions during the process a need for extra data as a result of new developments was perceived, which in turn led to a new resource acquirement. Abovementioned shows that the project team's decisions were not so much driven by complexity of the problems, but by the availability of resources in the network.

Considering the way knowledge was acquired and integrated, a pattern emerges. Figure 2 gives a graphical representation of the innovation process as was observed in both case studies. The representation is based on the observed management of the processes described in section 3.2.1 and the knowledge acquirement discussed in the past few paragraphs. This pattern was observed on three different occasions during the case study research. Apart from the foundation design for the Welgedacht plant and the N17 highway at AFRICON, the separate design phase for the foundation of the Welgedacht facility at ARQ was also studied. The case study shows that the innovation process and the acquirement of resources at ARQ took place in a very similar way. ARQ, like AFRICON, consulted local contractors and literature on the technology involved in its scanning phase and used a geotechnical investigation report drawn up by a firm in an earlier stage of the project. It developed new knowledge on the performance of the foundation method in local soil conditions by using a computer model. The design was approved by ERWAT and put to tender. It was never implemented as such, because the contractor decided to have AFRICON try and find a more cost-effective solution.

[xvi] In the original position.

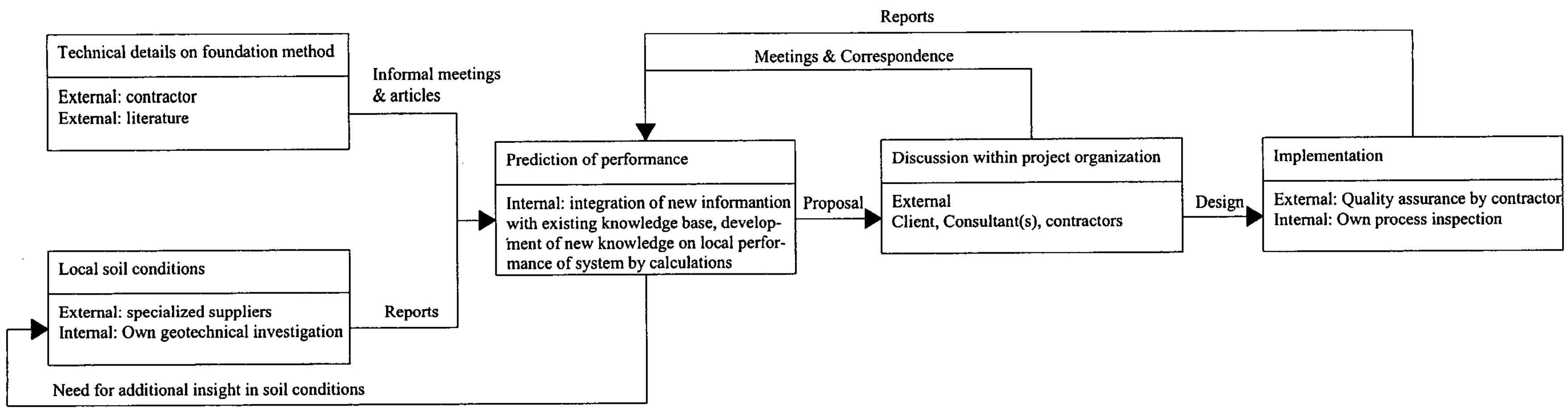


Figure 2: Graphical representation of the innovation processes

3.3 Diffusion of innovation in South Africa's civil construction sector

The previous section hinted on the ease with which the project team obtained technical information from other actors in the network. This seems to be one of the distinct characteristics for innovation in the South African civil construction sector. Information is shared between firms that are involved in the same project, or on the basis of contacts established during previous projects or even between total strangers. This behaviour constitutes a clear contrast with the situation in other sectors where technological knowledge of a firm is often a valued secret in these sectors. Knowledge is protected in order to avoid opportunistic behaviour of other firms, resulting in high transaction costs. Based on the interviews held with employees from various companies involved with the two studied projects, three explanations for the divergent behaviour in the civil construction sector are proposed. Besides the transfer of knowledge between actors, other context-specific factors influencing innovation were observed. The research identified consequences of South Africa's lacking NSI and poor local economical conditions. A factor positively affecting innovation to come out of the research is the use of tender contracts open to alternatives. The case study results showed many of the sector-specific characteristics described in chapter 2. Both projects required several specialised firms to work closely together. The products made are a result of the combined effort of these companies. During the research several factors surfaced that seem to be specific for South Africa's civil construction sector.

3.3.1 Personal ties and inter-firm dependencies

The first factor that seems to induce the intense flow of knowledge in the sector is the high quality and large number of ties between firms from all levels in the sector. Senior engineers from the firms involved in the studied projects have a dense network of contacts. Through previous projects they developed personal relationships with many actors in the sector, including people from firms that are typically involved as client, competitor or sub-contractor. Firms in civil construction generally take part in multiple projects at one time. The composition of the project organisation (i.e. the firms involved and the parts they play) often varies during different phases of a project and for different projects. Due to the horizontal and vertical fragmentation of the sector, firms often work together on one project while being each other's competitors for the acquisition of another.

Geotechnical works, like the foundation of the N17 and Welgedacht facility, are designed by specialised civil engineers. The South African Institution of Civil Engineering (SAICE) estimates that there are around 450 active professional geotechnical engineers in the country [41], which is a modest number considering the size of the country and its population. A large part of these engineers work for contractors and consultancy firms in the civil construction sector. The fact that firms work together in project organisations of different composition, and the relatively small population of professionals, results in engineers knowing their counterparts with most firms in the geographical area. Many relationships are based on a history of cooperation in numerous projects. During the projects the firms work to fulfil a common goal, sharing of information to improve the quality of the end product is a collective interest. Interviewed engineers stress the importance of "trust" in the sharing of knowledge in these relationships [54,65,88,100]. The importance of "trust" expressed by the engineers is in correspondence with literature, where "trust" has been recognised as a self-enforcing agreement to prevent opportunism in relationships [42].

Apart from knowledge sharing, stable relationships with a high level of trust are valuable assets in securing new orders. As was shown by this research, many a new project is secured through personal relationships between employees of different firms. Firms know they will depend on each other for and in future projects. Opportunistic behaviour such as leaking sensitive knowledge to competitors of the knowledge-providing firm can backfire, since it can by destroy valuable ties. This demonstrates the self-enforcing property of "trust".

3.3.2 *Technology as a marketing tool*

The trust in relationships between people cooperating on projects partly explains the large amount of knowledge transfer. The observed voluntary knowledge transfer is however not restricted to transmissions between acquaintances. Firms publish papers on the details of their latest technological advancements, which are presented on conferences. The reason for this is that a firm in civil construction does not sell a completed product, but it has to sell the idea that the firm is able to efficiently produce what the client requires [43]. The exposure firms get from sharing the new information with the sector is valued higher than the possible competitive advantage gained through secrecy. Contractors and consultants need to show exactly how advanced the technology they use is. So, instead of keeping secrets, they share it with as many clients as possible, taking for granted the leak of knowledge to competitors. That competitor can also turn out to be their next client, due to fragmentation of the sector. Interviews revealed that, the art is not to keep secret what the firm is good at, but to try and keep an edge on other companies in certain fields of expertise [54,88].

Ties between firms are important from a marketing perspective as well. In both the Welgedacht and the N17 project contractors through personal ties supplied the consultancy firms with information on the foundation methods before the projects were put to tender. They were not yet involved in the projects, but by providing the information they increased the chance of getting the order.

3.3.3 *Characteristics of transferred technology*

As mentioned in chapter two, technology in civil construction changes little over time. The jet grouting technology used in the N17 project is based on the dominant designs for such equipment developed in the 1970's. Although the contractor for the N17 project was the only party in South Africa with experience on the method, general knowledge on the principles of the method are widely available in textbooks and articles. As such, the entry barrier for other firms to start using the technology in South Africa, from a knowledge perspective, is low.

The construction method used by the contractors in the Welgedacht project was a combination of techniques. The use of stone columns as a foundation method started in Europe in the 1950's. The Dynamic Replacement technology used to compact the columns was developed in South Africa in the 1970's. Soil improvement by soil mattresses has been used all over the world for a long time. The combination of a soil mattress with stone columns is a logical iteration and was also used before. In other words, technology and experience were available, but here too there were only a few contractors in South Africa that possessed the necessary equipment. The knowledge transferred between the contractors and the consultants in both projects is information from experience. This knowledge however is not a prerequisite to use the method, nor did the contacted contractors represent the only possible sources for the information. The consultancy firms used the information provided by the contractors and gained from literature, combined it with knowledge on local soil conditions and developed new knowledge on the performance of the foundation system under local soil conditions. The prediction of the foundation's performance is done using proven theories from the science of soil mechanics. The understanding of these theories and their practical application are to a certain extent firm-specific, but the theory itself is pubic domain.

All the technology used in the designs was mature and available from more than one source. This is the last factor identified in the case study research easing the transfer of knowledge between firms. The innovation processes resulted in the application of proven technologies under unique local conditions. The knowledge that can be transferred to other projects concerns new experience with an old technique. The knowledge developed during the innovation process is for a large part specific to the unique characteristics of the project. These characteristics are the soil profile, the properties of the proposed structure and the boundary conditions. The knowledge cannot be used unaltered for future projects. The design itself is not transferable and protecting it by patenting is therefore not attractive.

The abovementioned shows that the knowledge needed to start a firm in civil construction can be obtained relatively easily. This does not to mean however that entry barriers for new firms to enter the market do not exist. Some can be identified, although those barriers are relatively low. Consultancy firms rely for a large part on their name and the tacit knowledge held by senior employees for the acquisition of new orders. The entry barrier for contractors in South Africa is mainly the high cost of the equipment.

3.3.4 Local innovation chains

The case studies established features that clearly indicate South Africa's status as a technology colony. The heavy equipment used in civil construction is not produced locally. The contractors involved in both projects were all established by foreign firms years ago. Although the firms are now independent, their equipment is for the most part imported via their former overseas parent companies. Most of the embodied technology is aged; in some cases the equipment used is over 50 years old. The norm in South African construction is to import written off equipment and refurbish it.

The purchasing power of local contractors is not large enough to be able to afford state of the art foreign equipment. This is caused by two factors, the first is economical, the second specific for the sector. The economical factor is the exchange rate of the South African currency, the Rand. The price level, and as a consequence, the income of South African contractors, is too low to purchase new equipment produced in Western countries. To make matters worse, competition in the sector as a whole is fierce, forcing contractors to work with small profit margins. While this impedes R&D expenditures in the sector in other countries, in South Africa it withholds contractors from updating their equipment. The negative effect of these factors applies for foreign firms as well. The low earnings that can be made in South Africa's civil construction industry, withhold foreign firms from entering the market and introducing new technologies [65,88,100].

Another reason why South African contractors do not invest in modern equipment is the availability of affordable labour in South Africa. As was discussed in the section 2.2, labour in South Africa is cheap compared to Western countries. The aspiration of Western firms to use as little labour as possible by investing in capital-intensive production methods is absent in South Africa. The government's support of the creation of low-skilled employment further amplifies this factor. The aim of the government's policy is to empower local communities, which is part of the affirmative action policy. The fact that modern equipment requires little, but skilled labour, is not per definition an advantage under South African conditions. Furthermore, the equipment requires high-tech spare parts when broken, and skilled mechanics to install it, both of which are difficult to obtain in Africa [65,86].

In contrast to contractors with their capital-intensive enterprises, a characteristic feature of consultancy firms is that they depend on human resources. Consultancies do not invest the bulk of their funds in expensive equipment and its upkeep. They are less hindered to use the latest technology in their field of expertise, which are for instance the latest scientific principles, the use of Computer Aided Design (CAD) and calculation software such as the FEA programs. The tacit knowledge in the form of FEA software used in the "Welgedacht" project is of foreign origin, but from a much more recent date than the foreign equipment used by the contractors. Nevertheless, for the solutions they devise, consultancies are just as limited by local conditions as the contractors. As was mentioned in the section on factors hampering innovation in the sector, no firm can produce innovative output without other firms having to change their production methods. In order for a design to be cost–effective it has to be suitable for construction, making use of local resources, which is the equipment of the contractors. For that reason, the consultancy firms in the Welgedacht and N17 projects checked with contractors to ensure the foundation system they proposed could be constructed with locally available resources.

3.3.5 Contracts enabling innovation

One of the factors hampering innovation in civil construction described in chapter two, is the use of locked tender contracts in the sector. These over-specified tender documents state exactly what has to be build and how, leaving little room for innovation from the contracting side. The tender document for the foundation of the Welgedacht facility, presented a clear contrast to the usual course of business in the sector. The tender document stated that the contracting side was allowed to come up with, and price, an alternative foundation design. Furthermore, all information and boundary conditions used for the design were included. The contractor seized this opportunity by hiring a consultant to attempt to produce a more cost-effective design. Interviews revealed that in South Africa most tender documents in the civil construction sector contain the option to price an alternative as well as the base case design. [65,88]. In this manner the constraints on innovation posed by traditional tender documents are lifted.

Interviews further revealed a regular occurrence of "design and construct" contracts in the South African civil construction sector. In the "design and construct" format the projected structure is designed and built by the same party, whereas in the more common situation a consultancy firm does the design and a contractor is selected for construction through a tender procedure. The design and construct format usually involves a "request for proposal" phase. The client invites parties to make proposals for the design and construction of a work. The design and construct format encourages innovative solutions.

3.4 Conclusions

The four explorative research questions in the introduction were answered in the case study results discussed in the passed sections. In this section conclusions will be drawn with respect to the answers and how they relate to the general theory on innovative behaviour from the introduction and the context specific theory in chapter two. Inferences are made on the extent to which the observed behaviour corresponds with the theory and on what additional characteristics of innovative behaviour surfaced in the research.

3.4.1 Tackling problems and complexity

The case study results show that the innovation process for the foundation of the Welgedacht water treatment facility was more complex than the process for the stabilisation of the N17 highway's embankment. The "Welgedacht" project engendered a larger number of problems and the average level of complexity of the problems was higher. As a consequence the uncertainty on design performance perceived by AFRICON's project team was higher, resulting in a substantially larger need for additional knowledge.

Results did not show that complexity influences the way in which the innovation processes were managed. In spite of their difference in complexity level, the demands on the management in the different innovation phases were met in a comparable manner for the two projects. This may well be a result of AFRICON's functioning as a PBO. AFRICON's organisational structure is designed to handle multiple projects at a time. The studied projects had an average size and were therefore managed and organised like any standard project. Looking at how the different phases in the innovation processes were managed, the absence of a separate resourcing phase catches the eye. The resources (knowledge) needed to fulfil the innovation processes were required and gathered in the scanning and strategy phases. The knowledge on the principles of the founding methods and soil composition was needed in these earlier phases, to enable a considered decision on what technology should be used. The research did not show any large deficiencies in the management of the processes and seems to be efficient. A shortcoming was identified in the learning and re-innovation phase however; no effort was made to facilitate organisational learning. The knowledge and experience gained in the innovation processes remained with the members of the project team. Difficulties with organisation-wide learning are common to PBO's as described earlier in chapter two.

No considerable differences were observed between AFRICON's behaviour when acquiring resources in the complex or less complex innovation process. The design of the Welgedacht foundation required more additional knowledge than the N17's foundation, but it was acquired in a similar fashion and from similar sources. Where the needed additional knowledge was acquired primarily depends on the availability of that knowledge, or the resources needed to develop that knowledge. If the required knowledge was held by one of the actors in the network, the project team obtained the knowledge from them, because transaction costs are low. Information from experience with the foundation methods was acquired from the contractors and literature. When the knowledge was not available in the network it had to be developed. Whether this knowledge is developed internally or externally is determined by the core capabilities of AFRICON as a consultancy firm (strategic considerations). The development of knowledge on design performance through calculation falls within AFRICON's core capabilities and was therefore done internally. AFRICON does not own specialised heavy equipment needed for most kinds of geotechnical investigation. In the fragmentised civil construction sector, heavy equipment is typically owned by contractors. The project team therefore hired specialised contractors to do most field tests needed for the development of knowledge on soil conditions. Abovementioned is partly in contradiction with the assumption of Tidd et all that: '*Strategic considerations suggest which technologies should be developed internally, and transaction costs influence how the remaining technologies should be acquired*' [18, p200]. In the civil construction industry the cost involved with experimenting and thus with knowledge development are high [17]. On the other hand transaction costs involved with knowledge transfer in the South African civil construction sector are low. As a consequence all relevant knowledge for the foundation design available externally, was gathered first. The core capabilities of AFRICON determined how the remaining knowledge would be obtained.

The fact that complexity did not significantly influence the management of the innovation process or the way in which knowledge was gathered is further supported by the report of the design process at ARQ. ARQ did an earlier design for the Welgedacht foundation. Due to their involvement with all aspects of the "Welgedacht" facility's design (they were the coordinating consultants) the project was perceived to be very complex [54]. Nevertheless the innovative behaviour with respect to management and gathering of resources was similar to that of AFRICON. ARQ's innovation process fits the graphical representation of the innovation process in Figure 2, modelled for the situation at AFRICON

3.4.2 Context and innovative behaviour

The firms involved in the studied cases share technological information on a large scale and transaction costs are low. Three reasons for the ease with which knowledge is transferred were identified. The first reason is the existing ties between firms originating from working together on projects. The professional community is small and engineers know their counterparts within other firms. Trust and interdependency between firms create an atmosphere favourable for knowledge transfer. A second reason for the ease with which knowledge is shared, is the marketing value. The exposure gained through communicating the knowledge possessed by the firm helps to establish its name. Firms in the civil construction sector do not sell a finished product, but the belief that they are able to produce what is demanded. The final reason to share knowledge is the age of the underlying principles. Mature technologies are transferred with lower transaction costs than new complex technologies [18] and although know-how may be firm-specific the required knowledge can be acquired through multiple sources. Moreover, the knowledge that is developed is highly specific for the project and its circumstances. As a result of this very local applicability, there are no large profits to be gained from protecting a design by secrecy or intellectual property law.

As mentioned in the context specific theory in chapter two, on first glance highly integrated networks of firms, common to the civil construction sector, would seem to engender the perfect situation for the diffusion of innovation. In spite of positive influences, the high level of interdependency of firms also dramatically decreases the chances for innovation. As a result of South Africa's incomplete NSI and low financial resources in the sector, contractors depend on outdated foreign equipment, limiting the whole sector to the capabilities and efficiency of this equipment for solutions. The characteristics of available human resources are another factor keeping contractors from purchasing modern equipment. Labour in South Africa is cheap, but the skill level of the workers is low. As a consequence modern foreign equipment requiring few, but skilled operators and high tech spare parts to maintain, is undesirable in South Africa. This factor is further enhanced by the current policy of the South African government to empower PDI's by supporting the creation of jobs requiring low skills. The exclusive use of foreign equipment places the civil construction sector in phase one of the model for backwards integration of a NSI proposed by Buijs [28]. This is contrary to the phase three position expected in chapter two. In phase three, foreign technology is produced and improved locally, but interviews learn that this is not the case for heavy construction equipment.

A breach with conventional procedures in the civil construction sector observed in the research is the use of dissent contract forms. Tender documents are used that encourage the proposition of alternatives. The research found that in South Africa it is not uncommon for contractors to price an alternative when competing in a tender phase. Allowing contractors to improve on a base case design stimulates innovation. Another contract form encouraging innovation frequently used in South Africa is the design and construct format. On average contractors in South Africa are confronted with more flexible contracts than literature suggest is the norm for the sector in other countries. Interviewed contractors indicate to make frequent use of the option to implement innovative cost-efficient alternatives [65, 100].

3.4.3 Prospects for innovation in the South African civil construction sector

The South African civil construction sector currently faces some major problems hampering innovation. Although the shortage of skilled personnel did not noticeably influence the innovation processes studied in this research, interviewed engineers did express concern about skilled people leaving the country and the high prevalence of HIV. The sector has little control over the effects of HIV, but the HIV epidemic can have serious consequences for firms if not enough people are trained to fill the positions of skilled employees that have developed AIDS.

Another problem, which was extensively discussed in this report, is the use of inefficient, outdated, foreign technology. This situation is not likely to improve soon, because lately, supported by the empowerment policies, new contracting firms owned by PDI's are entering the market. In general these firms are low on resources and as a result they too will rely on old equipment. The competition in the sector will further increase due to the new entrants and as a result the financial resources situation in the sector will probably get worse. If nothing is done, it is to be expected that the construction sector will remain dependant on aged foreign technology for a considerable amount of time. Consequently innovation opportunities in the sector will be enchained by the limitations and inefficiency, of this, in other countries obsolete equipment for years to come.

When looking at the situation in South Africa, apart from the problems, opportunities can be discovered as well. South Africa's economy is growing, positively influencing demand in the conjuncture sensitive civil construction sector. Moreover, South African civil construction firms are increasingly performing on works elsewhere in Africa. These two growth factors provide the South African sector with an opportunity to expand in a healthy manner. The expansion of the market may result in a better financial situation for contractors. The growth will induce a larger demand for equipment. In the current situation heavy equipment used in the sector is not produced locally. A possible solution for the problem that could be investigated is the local development of equipment adapted to the African situation, instead of buying more written off machines overseas. In the design of the equipment local factors should be taken into account. The focus in the design should be on affordability, modern efficiency and maintainability using resources and skills found in Africa. The equipment could help to improve the efficiency of production in the civil construction sector. The equipment would be produced with local labour costs and resources, resulting in affordable products, job creation and added value. Other countries in Africa could be found interested in construction equipment designed for African and not European or American conditions. Technology for Africa may well be the opportunity to break the sector's chains.

4 Founding the Welgedacht Water treatment facility

In 1999 the East Rand Water Care Company (ERWAT) instigated a new subsidiary called Aquafrica. The task of AquAfrica was to manage the design and construction of a new wastewater treatment works in the Springs area in the Gauteng province. Situated south of the N12 highway in an environmentally sensitive area it is to satisfy anticipated future demand in the region. The works is to replace several obsolete installations and provide extra capacity [44]. The locus of ERWAT's activities lies in the Eastern Gauteng province. The company was established in 1992 and provides treatment for the wastewater of industry and 3,5 million people through 20 wastewater care works. It is a so-called "Section 21" firm, which denotes that it is a non-profit organisation. It is owned by the government but acts as an independent body [81]. The company strives to implement the policies of empowering historically disadvantaged groups [44].

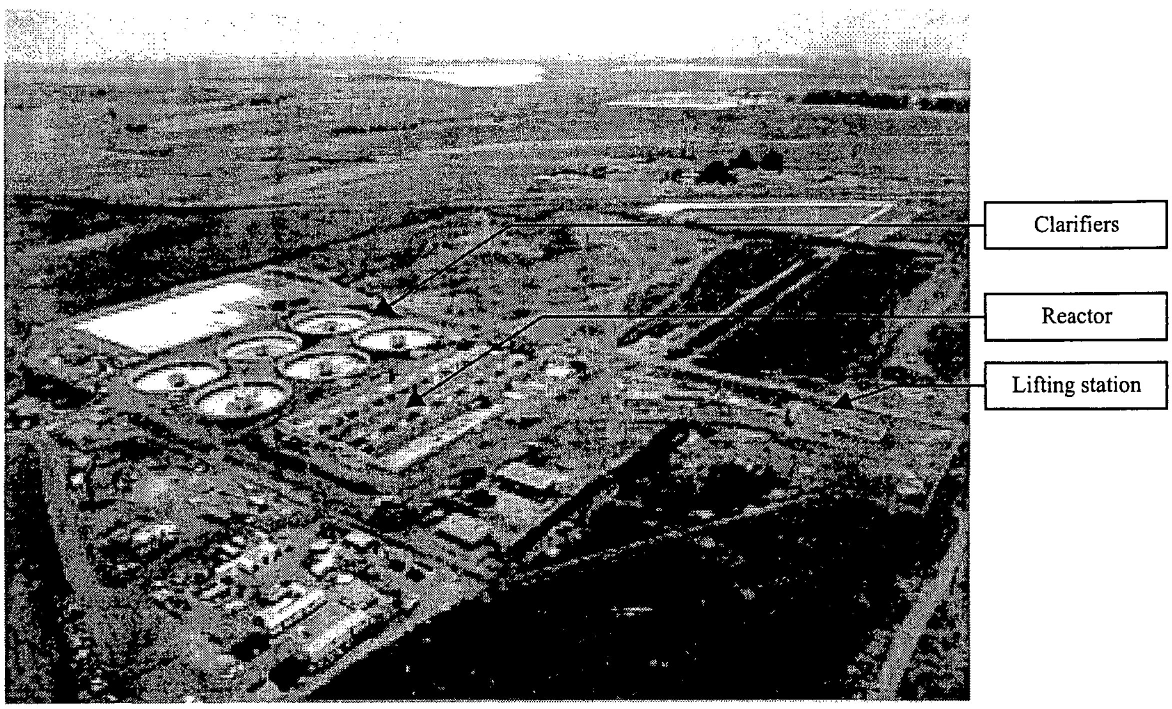


Figure 3: Welgedacht water care works during construction. Picture: ARQ Specialist engineers [45]

The Welgedacht water treatment facility is designed to process an average dry weather flow of 35 Ml/day. Wastewater is lifted with screws from the drainpipes and free flows through an activated sludge reactor and six clarifiers, of which three are chemical followed by chlorine disinfection and sulphonation. The effluent gravitates into the Blesbok Spruit only a few kilometres upstream of the Marievale Bird Sanctuary, which is part of an international wetland site. For that reason the effluent has to comply with high standards [53]. The sludge produced during the cleaning process is entirely biological and used by local farmers to fertilise their lands.

The unit of analysis for the research is the design process for the foundation of the plant's reactors and clarifiers (see Figure 3). The design led to the innovative combination of a soil raft and stone columns. The research covers the foundation's entire design and construction process which is not confined to AFRICON but also includes an earlier design iteration at a consultancy company called ARQ and the construction of the foundation.

This case study report contains: a problem description defining the soil conditions on the Welgedacht site, the project's organisation during its different stages and the design of the foundation in its two successive phases followed by the construction.

4.1 Soil conditions and its implications for design

In 1997 ERWAT picked the location for the new Welgedacht water treatment facility. To assess the suitability of the local soil conditions a geotechnical investigation was ordered. This first pre-design evaluation [46] of the foundation conditions was done by Jones & Wagner consulting civil engineers. It revealed compressible soil layers approximately ten meters thick above the dolomite bedrock [47]. The compressibility of the soil layers posed a challenge for foundation design.

The founding of structures on dolomite in South Africa has led to damage on numerous occasions and in some cases even to the loss of life. In particular the formation of sinkholes due to dewatering of goldmines, causes dangerous situations on a scale unprecedented anywhere in the world. On 12 December 1962 a crushing plant of the West Driefontein mine disappeared within a few minutes into a sinkhole that was 30 metres deep, taking 29 employees with it. This and several smaller incidents caused developers in South Africa to have considerable reservations when it comes to building on dolomite [48]. Dolomite rock formations cover about 3% of the total area of South Africa. However, most of the province of Gauteng lies on a dolomite group. Gauteng, South Africa's smallest province is also its economic heart. It is responsible for 38% of the country's Gross Domestic Product (GDP). Johannesburg, the countries largest city, and Pretoria, its capital, are situated in Gauteng and thus largely founded on dolomite. In fact it is the discovery of the world's richest gold-bearing dolomite reef by George Harrison in March 1886 and the resulting gold rush that brought about the birth of Johannesburg [49].

Dolomite ($3CaCO_3 .2MgCO_3$) is soluble; rock formations were shaped when the sea deposited it. When it comes in contact with groundwater, which is slightly carbonic acid (H_2CO_3) it will go into solution again as Calcium bicarbonate and Magnesium bicarbonate:

$$3CaCO_3 .2MgCO_3 + 5H_2CO_3 = 3Ca(HCO_3)_2 + 2Mg(HCO_3)_2$$

Groundwater flowing through cracks in the Dolomite, which is otherwise highly impermeable, widens these cracks. As a result of the ever widening gaps the top layer of the Dolomite bedrock is transformed into a typical structure with round pinnacles sticking out of the bedrock between dolomite residuum (Figure 4). Static groundwater levels can lead to the formation of horizontal cavities below the phreatic surface level. When the water table is lowered, for instance for mining purposes, these cavities can rapidly fill with loose soils from overhead layers [50]. This phenomenon is known as a sinkhole. Sinkholes can cause sudden collapses as in the case of the mine described earlier. Sinkholes caused all dolomite related cases of foundation failure resulting in loss of life in South Africa [48]. However, the mechanism of sinkhole creation will not be elaborated on further here, as it was no threat at the Welgedacht wastewater treatment works site, as a result of the shallow phreatic surface level[xvii] [46].

Where weathering of dolomite has taken place, a residual of insoluble materials remains. This residuum is made up of chert[xviii] in the form of gravel or boulders, iron, clay and a highly compressible substance known as wad. Wad consists of manganese and iron oxides; the amount of wad formed during weathering is dependent on the level of their presence in the dolomite rock [50,51].

The soil profile on dolomite at the Welgedacht site was typical residual dolomite profile in the Gauteng area [48]. Figure 4 shows an interpretation of the soil profile on basis of information from the geotechnical report by Jones & Wagner [46]. Jones & Wagner conclude in their report that the founding conditions of the hillwash[xix] are poor due to its high collapse

[xvii] Phreatic water: underground water in the pores of the granulate
[xviii] Chert: "a hard, dark, opaque rock composed of silica (chalcedony) with an amorphous or microscopically fine-grained texture" [51,p243].
[xix] Hillwash: soil layer made up of material flushed from hills by water

potential. The chert gravel possesses a reasonable founding capacity for light structures, but it is too irregularly shaped to support larger loads. Its load-bearing capacity could be improved by controlling the settlement of the wad layer. Wad is unsuitable for foundation because of its soft and compressible character. The Dolomite bedrock forms a proper foundation base, but it is at considerable depth [46].

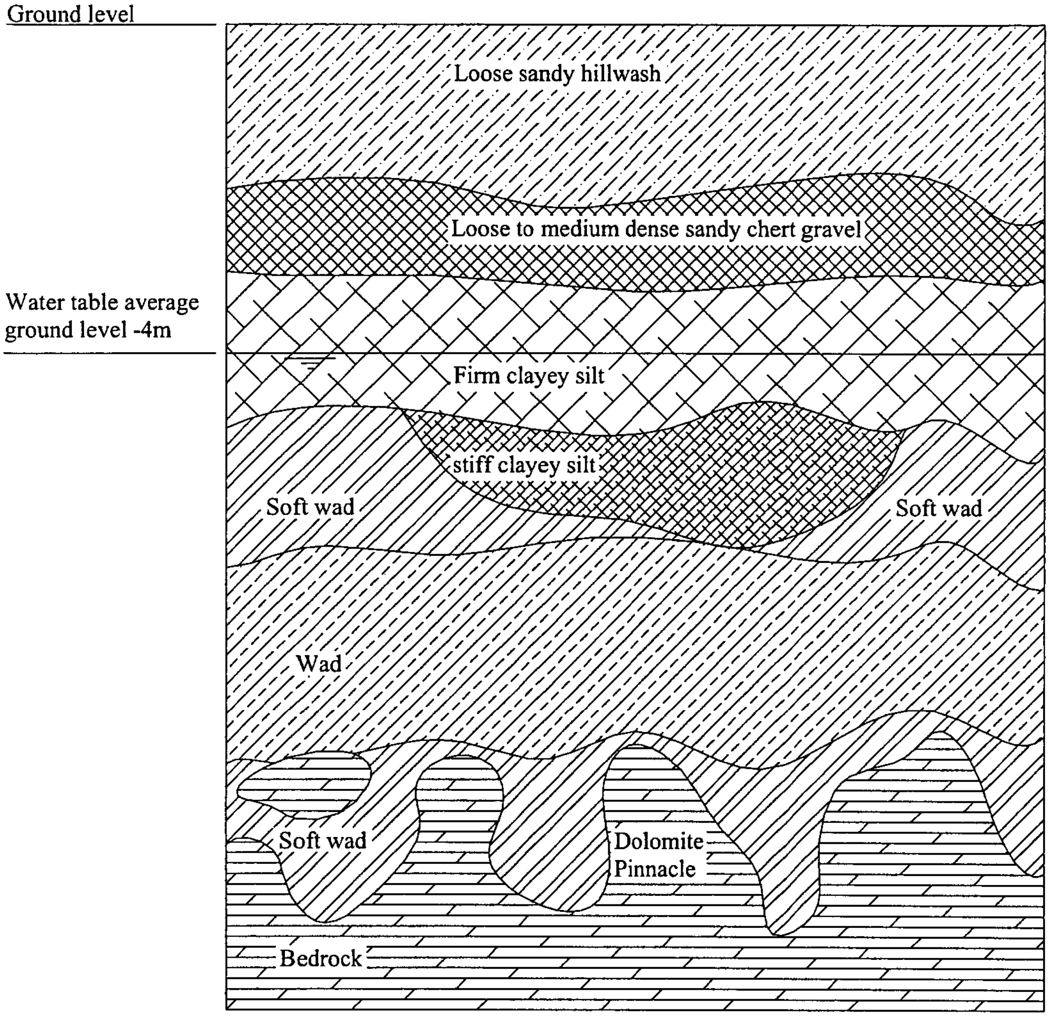


Figure 4: Representation of soil profile at Welgedacht site

The foundation design of the water treatment plant had to address two problems:
- Total settlement due to the compressibility of the layers above the bedrock.
- Differential settlement due to irregularities in the load applied by the structure, in the composition of the soil layers and the presence of dolomite pinnacles.

4.2 Project organisation

As with most projects in the civil engineering sector, the construction of the Welgedacht water treatment plant was a joint effort involving a number of specialised PBOs. Over time different companies were involved. This section discusses the division of work between companies involved in the design and construction of the foundation. To provide insight into the context of the foundations realisation, a rough description of the organisation for the entire plant's construction will be given.

4.2.1 Proposal phase

In this first phase The East Rand Water care company (ERWAT) instigated a subsidiary called AquAfrica to coordinate the erection of the Welgedacht water treatment works. The idea was to get an international firm to do the process engineering for the new facility. In this way ensuring a competitive design meeting the latest standards in wastewater water treatment [52]. The reason for this was that the effluent had to comply with new stringent standards of the Department of Water Affairs and Forestry [53]. Aquafrica invited three international companies from France, Belgium and Spain to propose designs for the wastewater treatment processes and give quotations for the realisation of those proposals [54]. For the civil engineering parts a request for proposal was also issued, concerning the design of foundation, pavement and sewage pipes. For this design any civil consultancy company could compete. The procedure led to ARQ being selected to act as civil coordinating consultant [54]. Pretoria based, ARQ - Specialist Engineers was established in 1993. This relatively small consultancy company specialises in the engineering of dams, bridges and geotechnics [55]. ARQ was selected for this project on the basis of costs and technical expertise [54].

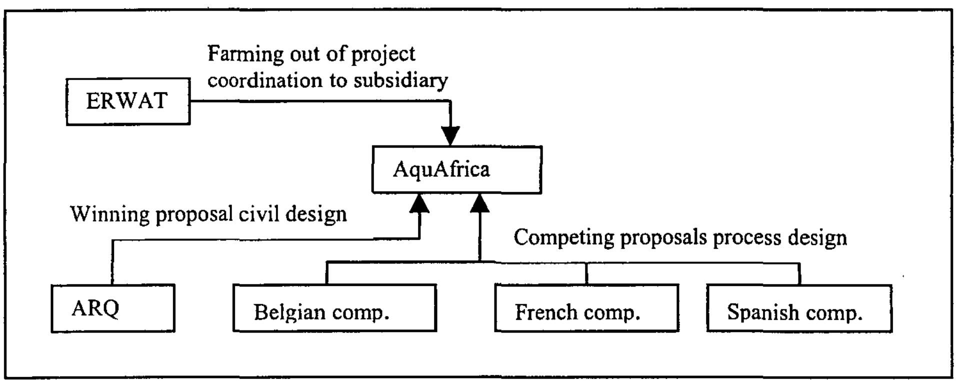


Figure 5: Organisation proposal phase

AquAfrica accepted entries by the three European firms for the process side of the water treatment facility. The proposals were not far apart in terms of construction costs. Based on these figures AquAfrica presented a proposal for the construction of the wastewater treatment plant to the board of directors of ERWAT. The construction costs were estimated at 166 million Rand. This turned out to be more than twice the amount expected by the board. Obviously the board rejected the proposal, decided to terminate the services of AquAfrica and to find local partners for the design and construction of the wastewater treatment process as well [52].

4.2.2 Local design

After the failure to find a suitable international company to design and construct the wastewater and the termination of Aquafrica, ERWAT assigned ARQ to be their coordinating consultant for the whole project [52]. As a result an organisation form common for projects in the civil construction sector took shape, with the client hiring a specialised intermediary to act on her behalf [19]. ARQ coordinated the multidisciplinary design of the wastewater treatment plant. The process involved independent local companies providing mechanical, electrical, process, environmental and structural consultancy. The engineers of these firms met on a regular basis to harmonise the different parts of the water work's design. Apart from the coordinating task ARQ was responsible for the geotechnical, hydraulic, dams and road pavement designs. It is in this phase that the combination of stone columns and soil mattress was introduced in the geotechnical design [54]. In this phase the responsibility for the performance of the design lay with ARQ. This design phase resulted in a tender document for the construction of the water treatment works [56]. The competing quotations that where send in on this tender amounted to 80 million Rand. ERWAT decided to award the appointment to an affirmative action joint venture called Qhude BBE.

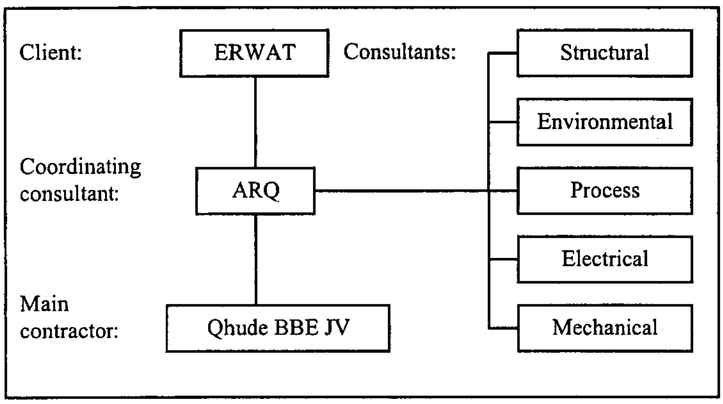


Figure 6: Project organisation after tender.

The name Qhude BBE stands for the joint venture of Qhude consortium (Pty), Burchell construction cc, Barrows–Frames Civils (Pty) and Engkon construction. It was selected by the client ERWAT in their effort to mobilise historically disadvantaged communities and individuals through empowerment. The involved firms are owned by PDIs[xx], the strategy of ERWAT fits the country-wide policy to encourage black ownership and investment [25,57]. None of the companies in the Joint Venture had experience with very large projects. This 80 million Rand deal made them the main contractor for the construction of the wastewater treatment facility [58].

4.2.3 Alternative geotechnical designs

The tender document contained an unusual feature; design criteria and the design itself were enclosed, for every aspect of the facility, enabling the contractor to come up with improvements on design, or even an entirely different design. This constitutes a breach with normal tender documents with fixed technological specifications and of which the only design data included comes in the form of drawings [54]. As discussed in the section on the construction sector and innovation, such locked contracts leave little room for innovative solutions in the form of alternatives.

The focus of the report will now shift from the organisation of the whole Welgedacht Water Care Works to the organisation of the geotechnical design. Since that is the unit of analyses for the case study. The events in the other design fields will not be elaborated on any further.

[xx] Previously Disadvantaged Individuals

During the tender phase Qhude BBE contacted AFRICON and requested them to try and come up with a more cost efficient solution for the foundation of the facility than the one proposed by ARQ [88]. AFRICON accepted the assignment thus causing the responsibility for the design performance to shift from ARQ to the contracting side. The construction of the foundation would require specialised technology. Franki Africa and Dura Piling acting in a joint venture were hired by Qhude BBE to be the subcontractor for the foundation works [52]. Franki and Dura are relatively large local geotechnical contractors. Franki Africa used to be part of the Franki concern in Belgium, but has been operating independently for 10 years now, although ties with Belgian Franki still exist [65]. A Dutch company instigated Dura Piling in South Africa in 1953. Currently a French firm holds the majority of shares in Dura piling [59].

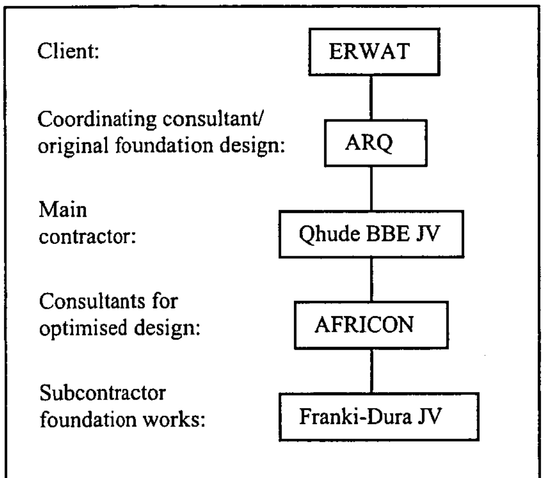


Figure 7: organisation geotechnical design

4.3 The ARQ design

The design of the foundation was done in conjunction with that of the structural system of the reactors and clarifiers. Three factors guided the design; the first was the minimisation of leakage risk. The new wastewater treatment plant was to be constructed in an environmentally sensitive area. It is situated directly adjacent to the headwater of an international wetland site. The design of the plant had to minimise the risk of leakage of polluted water from the facility into this environment [54]. The second factor guiding the design was cost-effectiveness. In every structural design one important consideration has to be made, that is, the balance between risk and costs. Every design has a probability of failing; it is the magnitude of this probability that determines the construction costs. Thus for the foundation of the wastewater works an optimisation had to be found between functionality and costs [54]. The expertise of the local contractors was the last factor guiding the design. It is not likely that a foundation design requiring imported equipment and knowledge is cost effective, therefore the design had to be realisable with local resources [54]. These factors and the soil profile in combination with the type of structure that had to be constructed led the designers to consider several foundation options [54, 56].

4.3.1 Scanning phase

The foundation design begun with the interpretation of the soil investigation report by Jones & Wagner [46]. It was estimated that reactors and clarifiers would impose a surcharge load of approximately 40 kN/m^2 [47]. The poor soil conditions in combination with the surcharge induced by the structures called for a specialised foundation design. This section will describe the scanning phase of the innovation process. As proposed by Tidd et al [18] companies search within their organisation and externally for possible opportunities. The stimulus in this case was not so much an opportunity to innovate but more a solution to the problem of how to design the foundation most efficiently given the factors that guided the design. Various foundation methods were deliberated upon; four were selected for further analyses using Finite Element Analysis (FEA) software. This eventually led to the choice of method used for the tender design.

Pile foundation: This foundation method is frequently used on dolomite [56]. Piles can either be pre-cast or cast in-situ. Piles are driven through soft soil layers to the bedrock or soil layers with a better load-bearing capacity. Especially on rock, piles form hard discrete supports. The utilisation of piles as a foundation system would have required a lot of them or rather thick floor slabs to be used for the structures. The load per pile increases with the increase of the area per pile. A large area per pile would necessitate thick concrete floor slabs to prevent them from punching through. Furthermore, to prevent leakage, the differential settlement between the support point and the area between piles would have to be limited by using thick floor slabs, which lead to increasing construction costs [88]. The uneven surface of the bedrock would probably have led to the choice for in-situ formed piles, because of their flexible length. This would have required drilling a hole for every single pile used. The use of a large number of piles to decrease area and load per pile would therefore also lead to high construction costs. The option of a pile foundation was rejected because of the high costs of such a system in comparison to other systems.

Surcharge fill: An effective way of reducing the settlement after construction is by forcing the wad layers to settle before construction begins. Pre-loading the area with a surcharge fill can do this. The surcharge fill is placed on the foundation (e.g. mattress) and the compressible layers are allowed to settle. After settlement the surcharge fill is removed and construction can begin free of additional settlement. This method is costly in both time and resources. It was decided that Surcharge fills were not feasible as means of foundation, because of time constraints [56].

Stone columns: This technique is frequently used for shallow foundations or in seismic areas where liquefaction is a threat. It comprises of partially replacing the soil with dump rock columns. The stone columns transfer the load of the structure to the bedrock, thus preventing loading of the compressible soil. In Europe where the technique has been used since the 1950s as well as in North America, the soil is replaced by working a vibrator into the soil. The vibrator is lowered in a pre-augured borehole or the soil is displaced by water pressure from a nozzle on the vibrator. When the required depth is reached the vibrator is raised a bit, allowing the stones to fall into position. The vibrator then compacts the stone and surrounding soil and is raised some more, this process continues until the column is complete [60, 61, 62, 63, 64]. The method used in South Africa differs from the dominant system in other parts of the world. Here another method of stone column creation, called Dynamic Replacement (DR), is becoming popular. The French company Menard developed this technique in South Africa some thirty years ago [65]. The original method involved dropping a heavy weight (pounder) onto the soil from considerable height. The crater created in this way is filled with dump rock, which is driven into the soil and compacted by dropping the pounder again [66, 67]. This process is continued until the column is complete. A variation on this technique requires holes to be drilled with an auger, and filled in steps with dump rock. After each step the stones are compacted by means of dropping the pounder [68, 69].

Like the pile foundation, the finished stone columns are of a ridged nature. Therefore they would also require thick floor slabs to be installed to reduce differential settlement of the structures [54, 88]. Unlike the pile foundation, there is no risk of the stone columns puncturing trough the concrete floor slabs, because they are less rigid and have a larger diameter [88]. Stone columns are usually cheaper than pile foundations less than 10 meters long, which was the case for the "Welgedacht" foundation [63]. The option of a stone column foundation was further explored and worked out to assess whether it could constitute an effective solution.

Soil mattress: Another method frequently used for founding on dolomite is the application of a compacted chert raft [56]. This method also known as soil improvement is applied for various soil conditions and consists of replacing the top layers of soil with a mattress of more stable soil types. The function of the mattress is tri-fold; it reduces the total and differential settlement in the top layers, the surcharge load is spread under an angle of approximately 45° and reduced to an acceptable level when it is transferred to the layers underneath the mattress, on dolomite the risks of small sinkhole and doline formation is reduced [48]. The efficiency of soil rafts depends on the depth of the pinnacles and bedrock. When pinnacles are present close to the surface they can absorb most of the loading from the raft and transfer it to the bedrock. This transfer is a result of the formation of a compression arch between the pinnacles (see Figure 8).

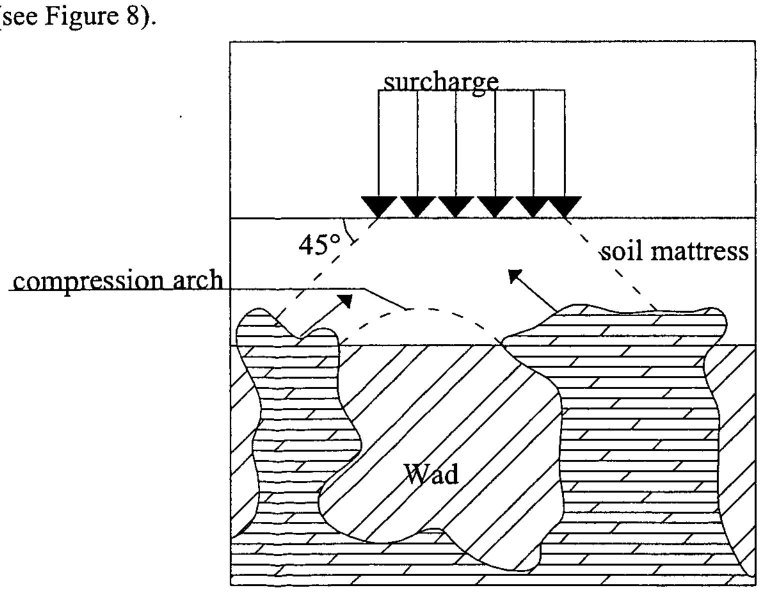


Figure 8: Soil raft on dolomite pinnacles

For that reason a soil mattress on dolomite is most effective when it is on or just above the pinnacles. The pressure arch reduces the load on the wad between the pinnacles, and with that the settlement [48].

The construction of a soil raft begins with the excavation of soil to the design depth of the raft. Depending on the quality of the excavated material it may be used in the raft. Material is placed in the pit in layers of 200mm thick layers and compacted [48]. At the Welgedacht site the chert excavated from the upper layers could be used to construct the mattress. However, because of decrease in volume after compaction, extra soil would have to be imported [46]. Application of a soil raft would allow thin floor slabs to be used because it provides an evenly support for the structure and therefore rather reduces differential settlement [54, 88]. The alternative of founding the Welgedacht water treatment works on a soil raft was studied further with finite element analyses, to see if it could satisfy the boundary conditions.

Soil mattress with geo-synthetics: A variation on the soil mattress foundation that was considered is the combination of the mattress with a geogrid at the bottom of the fill. Geo-synthetics are durable materials that are able to resist high strains used in geo-technology for the reinforcement of soil, or create impermeable or permeable boundaries between different soil layers. The idea was that this layer of geo-synthetics would help to the fill to act as a more homogeneous body to reduce differential settlement. This option was also taken to a higher step and analysed.

Combination of stone columns and soil mattress: The combination of stone columns with a soil mattress was taken in consideration as well, after consulting with local contractors who had installed this foundation system before [54]. This specific combination method probably evolved from construction soil mattresses over dolomite pinnacles and the understanding of the load distribution via compression arches. The same effect can be effectuated by constructing a soil mattress over stone columns, which are based on deeper bedrock.

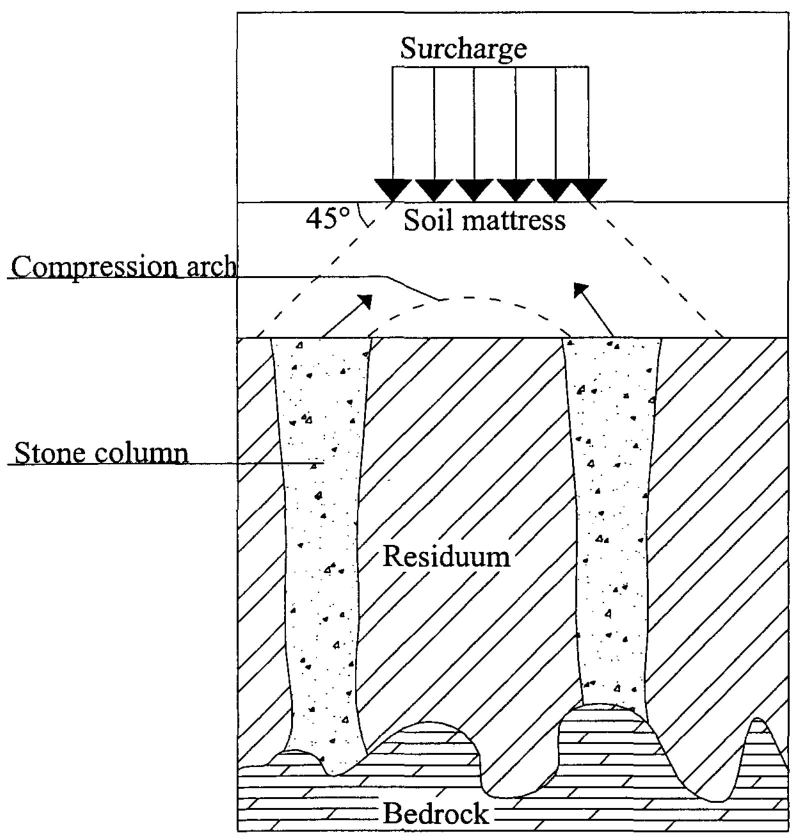


Figure 9: Principle of soil raft on stone column foundation

The method combines the stiffness of the stone column foundation with the load distribution of the soil raft (See Figure 9). The mattress provides a smooth support for the structure through which the load is transferred to the columns and finally the bedrock. The dumprock columns resist total settlement as a result of their stiffness and the soil mattress minimises differential settlement by forming a stable support for the whole area covered by the structure.

4.3.2 Selection phase

The second phase in an innovation process according to Tidd et al [18] is the selection of the technology to be used. ARQ set out to select the best option from the mentioned alternatives by exploring their performance and checking whether they satisfied design criteria. As was established in informal meetings between ARQ and local contractors, all of the technologies from the scanning phase were feasible with local resources, thus satisfying one of the design guiding criteria [54]. A second factor guiding the design was minimising the risk to the environment posed by wastewater leakage. The risk of leakage is determined by the structural integrity of the wastewater processing structures (e.g. reactors clarifiers, pipes). The concrete floor slabs of the reactors and clarifiers cover a large area. The slabs are divided into cells to prevent the concrete from cracking and leaking due to shrinkage. A membrane was used between the cells to provide a waterproof connection. To prevent the connections from leaking, differential settlements between cells had to be limited [88]. The relative settlement between different elements of the facility had to be restricted to guarantee the system of free flow of water through the facility and to prevent leaking due to damage of connections between different parts [70]. The demand for risk reduction can thus be translated into a demand for limitation of differential and total settlement. The determination of the boundary conditions for settlement was an iterative process. An optimisation had to be found between the performance of the structure on top and the deflection of the system below. A cheaper construction above ground places higher requirements on the performance of the foundation [54]. As mentioned before, it is an optimisation between costs and functionality. Initially, the maximum for total settlement was set on 5mm, but that would lead to an excessively expensive foundation, so the maximum was set at 10 mm. Eventually it was decided that 18,5 mm of total settlement and 5 mm differential settlement over 12 meters provided the most cost effective combination between structure and foundation [56].

The performance of the four foundation methods selected for further exploration was analysed using Finite Element (FE) software. A variety of idealised 2-dimensional representations of the soil profile were drawn up on the basis of data from the geotechnical evaluation report. From these various representations one comprehensive vertical profile of the subsoil was distilled [56] (see Figure 10) The phreatic surface was assumed to lie on 2,5m– ground level, forming the border between the dry upper chert and the buoyant lower chert. This profile was used to assess the performance of the different foundation methods.

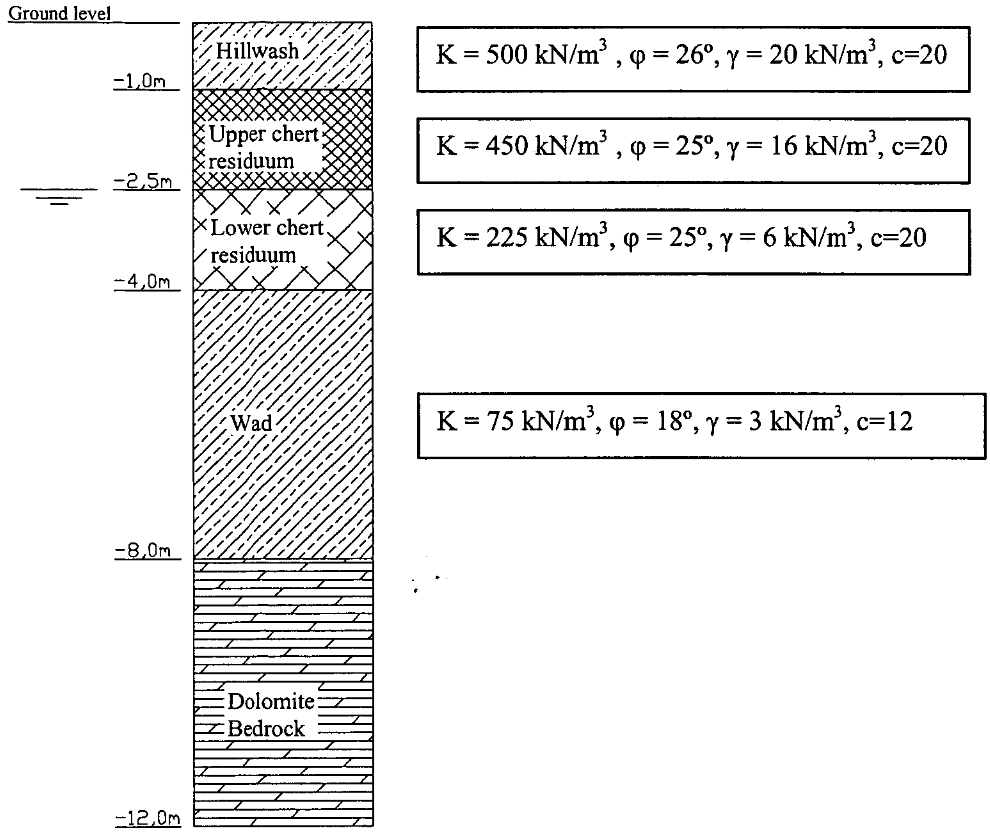


Figure 10: Interpreted soil profile ARQ[xxi]

For the properties of each layer hyperbolic stress and strain parameters were assigned, as proposed to be used in finite element analyses by Duncan et al [71]. The values used for these parameters were appointed on the basis material descriptions from the geotechnical report and from experience [56]. Figure 10 contains the values of the most expressive parameters assumed for the soil layers. The idealised soil profile was used to assess the performance of the various foundation techniques through six different analyses. The load engendered by the reactor and clarifier structures was assumed to reach a maximum of 40 kN/m^2 and was applied in the computer model by placing a linear elastic layer of soil 2,0m thick with a specific gravity of 20 kN/m2 on ground level.

- In the first analysis the behaviour of the soil was explored when the surcharge would be placed without any alteration of the soil conditions.
- The second analysis investigated the effectiveness of replacing the hillwash and upper chert layer by a compacted chert mattress. This was done by increasing the K modulus number of these layers to 300 kN/m^3 and slightly increasing their density.
- Analysis three saw the implementation of a geo-synthetics layer at the base of the mattress, all else remained equal to the second analysis.
- In analysis four the performance of dumprock columns was studied. The columns were modelled as being very stiff with a K modulus of 1300. The compaction of the material surrounding the columns as a result of lateral expansion of the columns was modelled by increasing the K modulus of these materials by a factor 1,5.
- Analyses five and six explored the effectiveness of combining the stone columns with a 2,0m thick compacted chert mattress on top. The hyperbolic stress/strain parameters for the columns and surrounding material were kept equal to analysis four.

[xxi] K:modulus number, φ Friction angle, γ: Specific gravity, c: Cohesion [71]

The results for the first analysis without implementation of any foundation system, revealed a settlement at ground level of 32 mm. Analysis two recorded a slight reduction of settlement to 28mm. Excavating the hillwash and upper chert layers to be replaced with a 2,0 m thick soil mattress proved to be ineffective. The total settlement was still unacceptably large, due to compression of the lower chert and wad layers that were not replaced. The effects of geo-synthetics included in the model for the third analysis were negligible. The stresses in the model were mainly vertical as a result of the even loading on ground level and the idealised composition of the soil layers. Geo-synthetics absorb only stresses in the plane of the textile. Since the geo-synthetic was applied horizontally and no differential settlements occurred due to the idealised composition of the model and load, there were no significant horizontal stresses. The analysis for the stone columns showed a significant reduction of settlement. Analysis four, with only the columns installed, resulted in a settlement of 18mm. The stone columns in combination with the soil mattress (analyses 5&6) resulted in a 16 mm settlement. Since the stone column alternatives revealed such encouraging results more analyses were done with columns at 5 and 7-meter intervals [56]. It was decided to recommend the combined solution of stone columns and compacted chert mattress in the tender document for the following reasons:

- Replacing the soil layers above the phreatic surface level would not sufficiently limit total settlement, because of the compressible nature of the soil layers below groundwater level. The construction of a thicker soil mattress was not considered a financially feasible option [56].
- The installation of merely stone columns as foundation for the reactor and clarifiers would sufficiently inhibit total settlement. The foundation would, however, provide an uneven support for the concrete floor slabs. The risk of leakage due to differential settlement would require thick floor slabs to be used, which would increase construction costs considerably [88].
- Combining the even support provided by the soil raft with the strong base offered by the stone columns, effectively decreases total and differential settlement [56].
- An additional advantage of the combination over the stone columns being applied separately is the impermeability of the compacted chert layer. If the structure were to start leaking at a point in time the wastewater would not penetrate the soil mattress easily [54].
- Furthermore the combination is a highly reliable system. The mattress evenly divides the load applied on top over many elements. If one column fails, its load is spread over others and the system remains intact. This in contrast to the foundation consisting of columns only. If one were to fail, the whole system collapses [54].

The design recommended in the tender document was an optimisation of the situation described in the analyses. The design implied stone columns with a 1,5m diameter to be placed on a 5x5 m grid. The estimated load per column amounted to 1000 kN. The mattress of chert residuum capping the columns had a designed thickness of 1,5m [72]. The design was presented to, and approved by, ERWAT before it was put to tender.

4.3.3 Resourcing the innovation

The third phase in the management of an innovation proposed by Tidd et al [18] is the organisation of resources for the development of an innovative solution. Knowledge can either be created by R&D or through transfer from other organisations. The ARQ design presents a clear overlap between the selection and resource phase. The design had to be completed to a large extent before the selection of foundation method could take place. The knowledge needed for the design was for the most part gathered during the selection phase. The basis for the design came from the geotechnical evaluation by Jones & Wagener consulting civil engineers [46]. The evaluation report contained the information that enabled ARQ to form a profile of the soil composition and its properties. In the first explorative phases of the design much of the knowledge came from recent literature and contact with a local contractor. The literature[xxii] was on the most cost-effective grid to install stone columns by ram compaction. A representative of GeoFranki was consulted on the feasibility of the foundation method with locally available resources and knowledge [54,56]. GeoFranki had used the founding method with a soil mattress capping stone columns once before for the foundation of a storage building in Mauritius [66].

Although ARQ had applied the software used for the design before, it wasn't standard procedure to do so, because it is a time-consuming process. The usual course of business would be to make hand calculations to predict settlement. The foundation design for the water treatment works required a far higher than usual level of certainty on settlement predictions, which required a large number of interacting variables to be taken into account. Although the aim was still to keep the problem as simple as possible, the interaction between the different parameters results in very complex calculations. Complexity and required certainty made the use of software an efficient option in comparison to hand calculations [54]. As a result, the decision was made to use two Finite Element Analyses (FEA) programs for the design, i.e. AUTOMESH (1991) and SOILSTRUCT (1990). Both programs were developed in the U.S. The reference manuals[xxiii] on the software and the use of parameters used for the design were all developed at the Virginia Polytechnic institute and State University [72]. The use of the software resulted in more calculation made than would have been done when hand calculations were used and also increased the level of certainty for the design performance [54].

To further reduce uncertainty Jones & Wagener consulting civil engineers were asked to give their opinion on the design. Jones & Wagener performed the initial geotechnical investigation, but were not involved with the project any longer. The firm is in competition with ARQ. Nevertheless, the relationship between the firms is such that they give mutual advice. This kind of ties between firms seems to be common in the sector.

4.3.4 Implementation phase

Implementation is the last phase in the managing of an innovation [18]. It could be argued that the implementation from the side of ARQ was finished with the writing of the tender document and the construction would be the responsibility of the organisation selected to construct the foundation system. However, ARQ remained closely involved during the construction phase and had to evaluate the alternative design. Therefore, the implementation phase will be considered finished with the completion of the foundation construction

[xxii] The literature used:A. Oshima and N. Takada, *Relation between compacted area and ram momentum by heavy tamping.* Proceedings of the 14th international conference on Soil Mechanics and foundation Engineering, Hamburg 6-12 September 1997, Volume 3. pp 1641-1644

[xxiii] The manuals used:

G. Arranz and G. Flitz, *Automesh – IBM Reference Manual and IBM Tutorial Manual, Version 1,0.* Virginia Polytechnic Institute and State University, 1991

J.M. Duncan, P. Byrne, K.S. Wong and M. Phillip, *Strength, Stres-Strain and Bulk modulus Parameters for finite element analyses of stresses and movement in soil masses.* Virginia Polytechnic institute and State University, 1980

G. Flitz, G. Wayne Clough and J.M. Duncan, *Draft user's manual for program Soilstruct (Isotropic) Plane strain with Bem elements.* Virginia Polytechnic Institute and State University, 1990

4.4 Alternative designs AFRICON

The tender document stated specifically that the contracting party was free to optimise the design. The contractor that eventually won the contract; Qhude BBE contacted AFRICON during the tender phase to see if they could optimise the design done by ARQ. AFRICON consented and begun its own design phase [88]. Therefore in their tender proposal the contractors stated that they would take responsibility for the design of the dynamic compaction, including the number of stone columns, layout, diameter of the stone columns, design and thickness of the soil raft or an alternative solution when that would prove to be both technically and economically attractive [73]. Furthermore it was decided that AFRICON's professional fees would consist of 10% of the savings produced by selecting an alternative or optimised design [74].

4.4.1 Factors guiding design

The tender included the design done by ARQ and the performance requirements that would have to be met by an alternative design. These requirements would lead to discussion on a later stage, but at the start of their design AFRICON interpreted them as follows: a maximum of 18,5 mm total settlement, 15,1 mm total settlement at the stone column position and 9 mm differential settlement distributed over 12m [74]. These values represent the settlement performance of the design that was included in the tender document.

The primary reason for the contractor to hire AFRICON was find a more cost-effective solution. AFRICON had to come up with a design requiring less or cheaper materials or a cheaper construction method to be used, within the settlements that could be allowed [88]. One of the opportunities to cut back on construction cost was to use dumprock material that was available at a local mine [65].

4.4.2 Scanning phase

AFRICONs' scanning phase started with a review of the tender design and the soil conditions as described in the geotechnical evaluation report. AFRICON took notice of the design for a combination of stone columns and a soil raft, but decided to look for other solutions as well.

Pile foundation- Like ARQ did in its scanning phase, AFRICON looked at the implementation of a pile foundation. This idea was abandoned at an early stage for the same reasons as ARQ did, namely that it would not provide a cost-effective solution, due to the additional measures this would require for the structure [88].

Dynamic Compaction (DC)- of the soil was another possible solution considered by AFRICON. It would comprise of compacting the in-situ soil layers in three phases by dropping a 12-ton weight from 10 to 20m height. This method would compact the soil layers up to 8m deep and create a soil raft over this depth employing in-situ materials. If possible, applying this method would provide a fast and economical solution, because it would not be necessary to excavate and replace soils. The hillwash and chert layers are very suitable for dynamic compaction [74].

Soil mattress- AFRICON further considered the use of a thicker soil mattress to be applied than the one analysed during the ARQ design phase. It saw possibilities to design a 2 to 3 m thick soil mattress. It was thought that this would result in differential settlements within the specification limits and a somewhat larger total settlement, but that might be considered acceptable [47]. It was assumed that the settlement problems could be avoided by placing flexible joints between the different water treating structures.

4.4.3 Selection phase

The selection of the foundation method to be used would result in the "dynamic compaction" and the "thicker soil mattress" options to be worked out. The alternatives were proposed and eventually abandoned, because they were technologically not feasible. Subsequently the choice would be made to optimise the tender design, which produced the design that was finally implemented.

The alternatives

The engineers at AFRICON first looked at the alternative with a thicker soil mattress because they expected to be able to significantly gain on construction costs by eliminating the stone columns [47]. It was established that regardless of the foundation method a situation of "over consolidation" would exist in the deeper soil layers. The ARQ design suggested the in-situ soil to be excavated 3 to 4m below ground level and to be replaced with a 1,5m thick soil raft. This would mean 1,5 to 2,5m of soil is removed, which brings about a reduction of the load on the deeper soil layers equal to the weight of the removed soil (1,5m: ca 30 kN/m^2, 2,5m: ca 50 kN/m^2). The reduction of load causes a relaxation in those deeper layers, which than expand. In the end phase the surcharge caused by the reactor and clarifiers might even be less than the weight of the removed soil (40 kN/m^2) resulting in a situation of "over consolidation" [47]. In some cases a situation of over consolidation is used to construct without a foundation. The structure is built on soil layers that used to support a body of soil equal to the weight of the structure and equilibrium is reached.

The Welgedacht wastewater works needed foundation regardless of the degree of over consolidation. The settlement that occurs when the relaxed soil layers are loaded again had to be restrained. Moreover, because of the irregular composition of the soils, differential settlements still had to be limited [75]. On the other hand, the pre-loaded soil at the Welgedacht site would have an increased stiffness, this is why engineers at AFRICON saw a possibility to replace the stone columns by a thicker soil mattress. AFRICON distilled its own idealised soil profile from the geotechnical evaluation by Jones & Wagener (see Figure 11), to be modelled in FEA software [47].

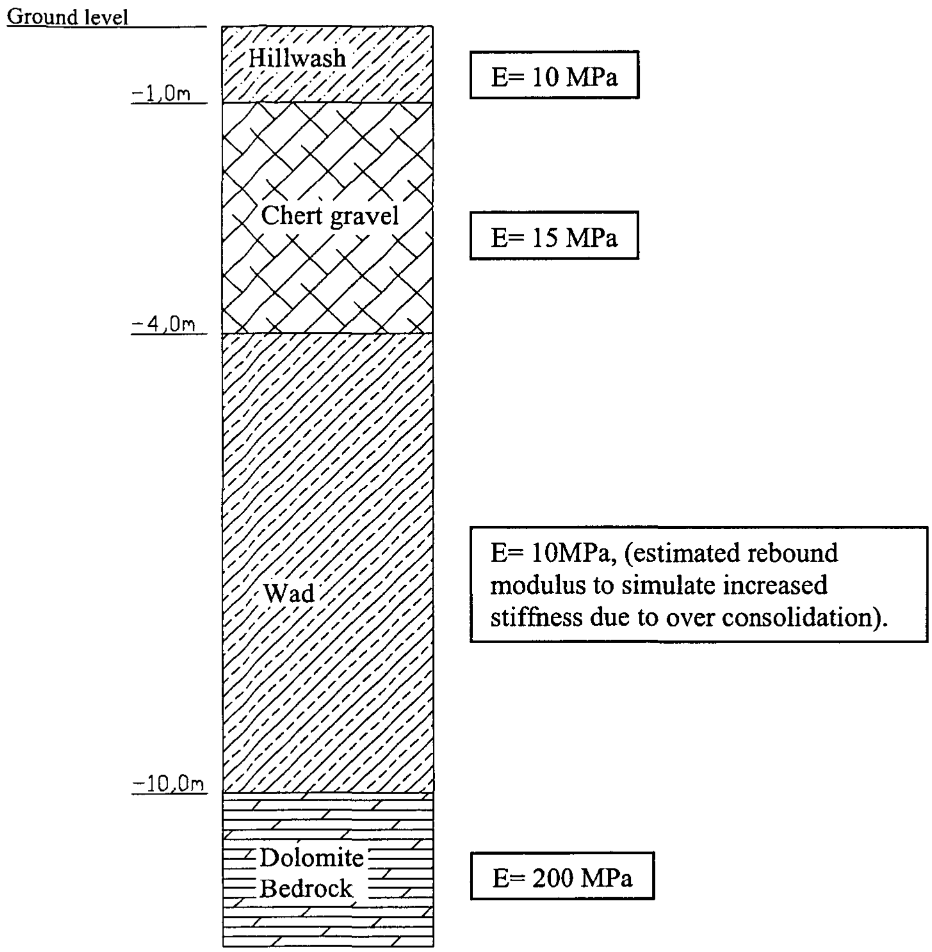


Figure 11: Interpreted soil profile AFRICON[xxiv]

Engineers at AFRICON used an FEA program called PLAXIS to evaluate the behaviour of the soil raft. The analysis was done for a 2,4m thick mattress with a stiffness of 40 MPa to be laid on a 3m depth. The simulation included the mattress to be placed in steps of 0,8m and compacted by means of an impact compactor. The modelled load imposed by the structures on top of the mattress was again 40 kN/m^2. The only design parameter that was uncertain was the rebound "overconsolidated" modulus of the Wad material. It was decided that the value for this modulus would have to be determined in an investigation prior to construction [47].

[xxiv] E= stiffness of material (MPa)

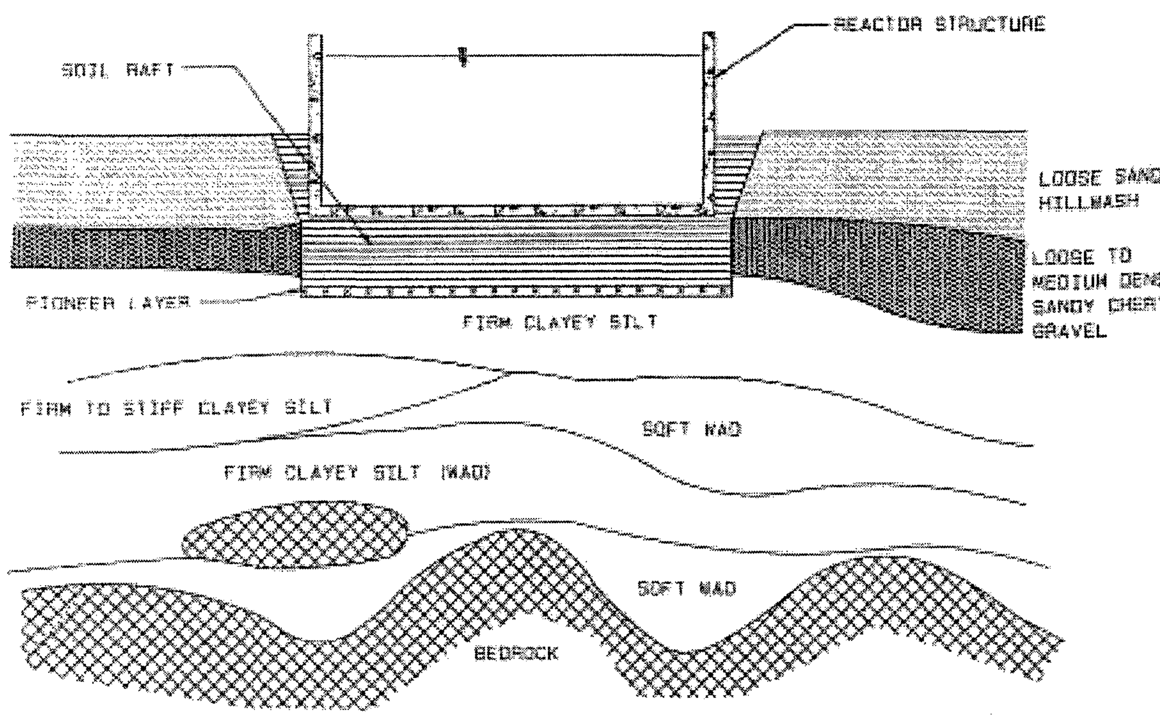


Figure 12: Soil mattress solution as proposed by AFRICON (source: AFRICON)

The results of the analysis showed a maximum total settlement of 22mm and a maximum differential settlement of 5mm over 8m. The total settlement was in excess of the maximum settlement of 18,5mm, however they considered this to be acceptable if the pipes of the water-retaining structures would have flexible joints. The plan was to allow the reactors and clarifiers to settle independently.

AFRICON decided to propose the thick soil mattress as an alternative for the stone column solution, together with the DC option. DC, if proven to be adequate, would be very economical compared to the other alternatives. The method would create an effect similar to the overconsolidation caused by excavation. It would pre-load the soil, thus increasing its load-bearing capabilities through increased stiffness. DC is hard to simulate and it was decided that the effectiveness would have to be explored in pre-construction field trials. Both the "DC" and the "thick mattress" foundation options were included in a first report on alternative solutions to be discussed with parties involved [74]. In a meeting held between staff members from ARFICON and ARQ (acting as the client's consultant) it was discovered that one important requirement was overlooked in the designs [76]. The design of the reactor and clarifiers placed the bottom of the structures on a depth of 3m. In the foundation designs the bottom of the structures were placed on shallower depths. With the floor slabs of the clarifiers and reactor 3 m below ground level a 2,4m thick mattress would mean the depth of the excavation would have to be 5,4m. A 5,4m excavation is considerably below the phreatic surface and would require extensive measures to keep the ground water from flooding the pit. Additionally, although differential settlement was sufficiently limited in the mattress design, the predicted total settlement (22mm) was in excess of the allowable [88]. When conferred with the contractor (Franki Dura JV) experienced in the construction of soil mattresses it was concluded that a mattress would never satisfy the tender criteria [65]. The total settlement could upset the system of free flow used in the wastewater treatment process [70]. For the abovementioned reasons the foundation alternative using a thick soil raft was no longer considered a viable option [47, 65,88]. The Dynamic Compaction alternative was also discussed with ARQ and Franki Dura JV and the conclusion was that the compacting of the in-situ soils by DC would not be enough to satisfy the settlement criteria [65].

Another source for discussion was the performance requirements placed on the alternative design. AFRICON had used the settlement predicted in the tender design as performance requirement for their design. The specifications ion the tender contract however required the total settlement not to be more than 9mm and the differential settlement to be less than 5mm over any 12m section. After a discussion that stretched over months it was decided that the contractors would take responsibility for the performance of the foundation. The criteria would be relaxed because the structures on top did not require such small settlements. The new criteria for the settlement in the end phase were set on a total settlement of less than 20mm and a differential of less than 10 mm over any 12m section [65, 77].

Optimisation of the base case

Following the dismissal of the thick mattress and ram compaction of the soil alternatives, attention shifted back to the foundation on stone columns capped with a soil mattress. It was decided to try to improve on the design supplied by ARQ, but to do this additional information was required [47].

An elaborate pre-construction geotechnical investigation was conducted consisting of: firstly a desk study of all available information and the tender design and secondly a geotechnical investigation of the soil conditions at the site to complement the research done by Jones and Wagener. The additional investigation involved the digging of 13, 5m deep test pits[xxv] to examine in-situ soil, 6 rotary core holes[xxvi] to investigate the composition of the soil at depths in excess of 5m and the laboratory testing of selected representative soil samples [47]. The investigations revealed a very incoherent composition of the soil and it was decided that to reach the required level of certainty more test would have to be done during the construction phase. The tests would have to confirm the soil profile and material properties that were going to be used in the FEA for the design. For the time being, the stiffness of the wad was lowered from 10 MPa to 7,5 MPa. The test showed that the depth of the bedrock ranged from 6 to 9m, with an average depth of 8m. Consequently, bedrock at 8m was adopted as the basis for design and not the 10m used earlier by AFRICON [78]. The stiffness of the stone columns in the analyses was set to 80 MPa based on the experience of Franki Africa with stone columns in earlier projects. 80 MPa was assumed to be on the conservative side because the stiffness was measured to be between 80-120 MPa during tests at other sites [65].

With the extra information gained from the conducted investigation, work begun on the optimised design and the formulation of a preliminary construction design. A new idealised interpretation of the soil profile was drawn up and used in the FEA program PLAXIS [47]. The design included mushroom-shaped stone columns 1,2m in diameter at the bottom and 1,8m in diameter close to the underside of the mattress. The 1,5m thickness of the mattress in the tender design was maintained. An analysis was done for the 5m spacing used in the tender design and additionally for 5,5 and 5,7m grid spacings [78].

[xxv] A test pit is a hole dug with an excavator or by hand in order to assess the composition of shallow soil layers [67].

[xxvi] Rotary core hole drilling: A drill bit on a rod is driven into the ground, during the drilling chips of soil and rock are flushed to the surface, where they are collected to be analysed [67].

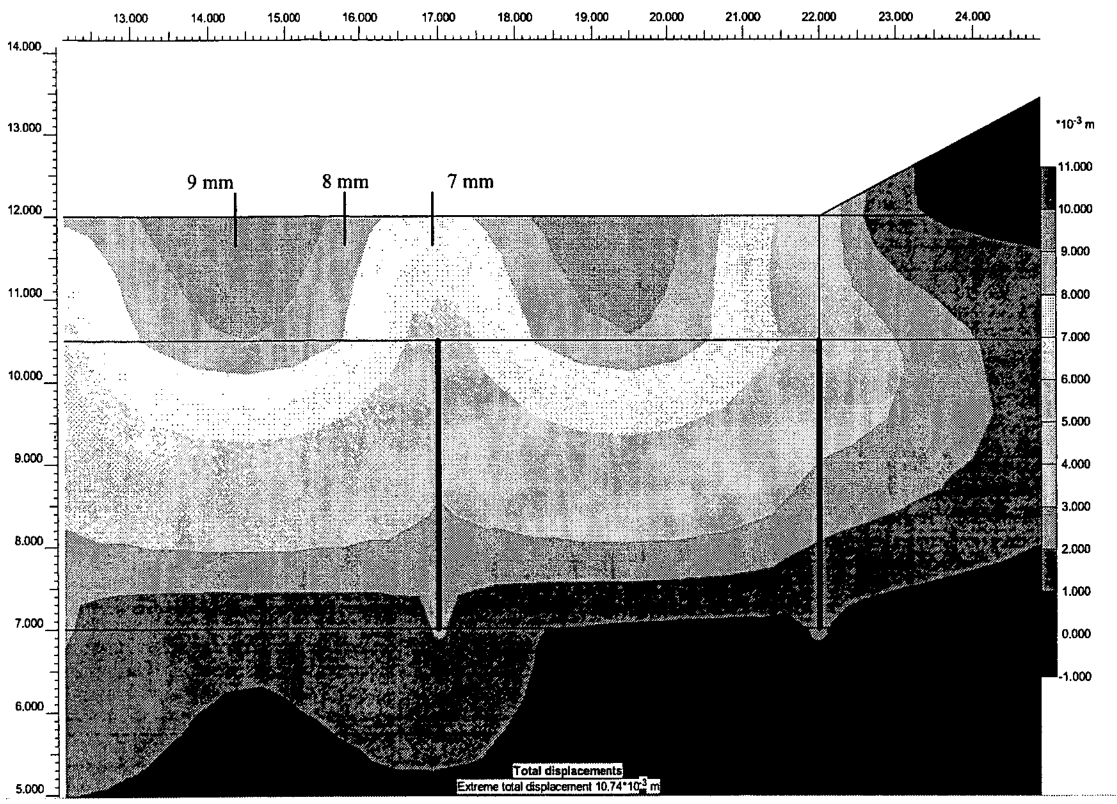


Figure 13: Print-out 5x5m stone column grid, source: AFRICON

Figure 13 shows the results of the analysis pertaining to stone columns on the 5x5 grid. The maximum total settlement in the field between two columns was 9mm, above a column 7 mm and thus the differential settlement over 2,5m amounted to 2mm. The results for columns on a 5,5m grid were 11mm total and 3mm differential settlement. For the 5,7m spacing the predicted total settlement was 12mm and for the differential settlement 3,5mm was found. Both total and differential settlements for all three spacings were well within the requirements for the design. AFRICON therefore recommended a 5,7m grid spacing to be used for the foundation [78]. If additional geo-technological investigation showed that in some areas of the site subsoil conditions were worse than expected, a reduction of the spacing would be applied [79].

4.4.4 Implementation phase

When the order of phases in managing an innovation is applied strictly, the selection phase should be followed by a phase in which the necessary resources are gathered. Nevertheless, like Tidd et al mention in their description, there are countless variations possible on this basic theme [18]. As with the ARQ design there is an overlap between the selection and the resourcing phase. During the selection phase there was a need for knowledge, which was supplied through investigation and in the form of software. The implementation of the design required some alterations and additional investigation, therefore the reflection on the used resources is moved further back.

Construction design

At ARQ, acting as the client's consultant, there was some concern about the conservative 1,2m diameter of the columns and the large 5,7m spacing between columns in the AFRICON proposal. However, the pounder to be used for the construction was a square 1,4 x 1,4m weight. The rather large size of the pounder required the hole for the columns to be 2m in diameter, with a mushroom shaped top of circa. 2,4m. The columns formed would therefore be significantly larger than prescribed in the design and as a result the span between columns was also reduced. Moreover, additional analyses of the soil investigation results led the engineers at AFRICON to the decision to put the columns on a maximum 5,44m grid instead of the 5,7m designed. Some uncertainty on the actual soil conditions was still present and therefore more geotechnical investigations were planned for the construction phase. If these tests would show soil conditions to be worse than accounted for in the design, column spacing would be reduced even more [79].

The construction was started with the implementation of the newly specified grid of 5,44m spacings. The Dynamic Replacement method was used to create the stone columns, using a pre-augured hole. The first step (see figure 14) was to excavate the construction area to about 2m below ground level. Secondly a hole is drilled until bedrock is reached. The completed hole is partly filled with dumprock, which is then compacted by dropping the pounder. The procedure is repeated until the column is complete. Another 1,5m is excavated and a mattress of chert mixed with G6 quality material imported from a local mine is placed and compacted using Dynamic compaction [72].

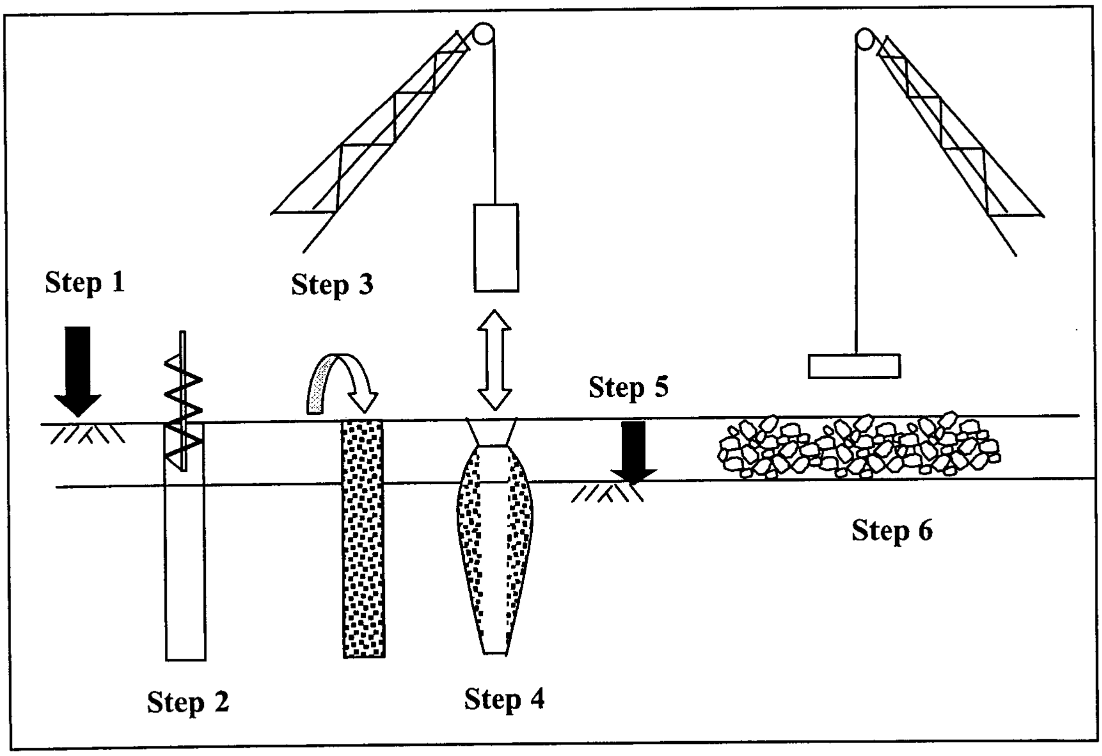


Figure 14: Construction process [72]

Design performance inspection

Simultaneously with the start of the construction of the stone columns, additional testing began on the soil conditions and column performance. The purpose of these tests was to assess the effectiveness of the columns and to further reduce uncertainty on soil conditions.

Consolidometer test- From the auger holes drilled for the installation of the columns undisturbed soil samples were taken. These samples were used to establish the pre-consolidation pressure in laboratory tests. The results showed that the soil stresses after the placement of the structures would be less than the pre-consolidation pressure [80]. In other words, the load from the structures on the soil layers would be less than the weight of the excavated soil layers.

Plate bearing tests[xxvii]- After the completion of the first columns, tests were conducted on the stiffness of the formed columns through vertical plate bearing tests. The results from these first tests were disappointing; many of the columns did not reach the 80 MPa used in the FEA that was previously assumed to be on the conservative side. Some columns only reached 40 MPa. [80] The results were a cause for concern and led to considerable debate between the experts involved as to what the cause was. A plausible explanation could be that the top of the columns had loosened during pounding [72]. To examine how the columns with this lower than expected stiffness would behave extra FEA was done. The FEA was done applying a value of 40 MPa for the column stiffness. Furthermore ARQ requested the surcharge to be increased from 40kN/m^2 to 80 kN/m^2, to nullify the effect of overconsolidation. The philosophy was that the foundation also had to suffice if the effect of overconsolidation would be less than expected [80,81]. This combination of halved column stiffness and doubled surcharge increased the total settlement slightly, but not so much that the requirements were not met. The differential settlement however decreased. The extra settlement of the columns reduced the difference between the settlements measured on top of the column and in the field between columns [72]. A total of 43 columns were tested during the construction; the lowest value to be recorded was 12MPa the highest 138 MPa with an average of 55 MPa. Plate load tests on the soil mattress revealed that the design value for the stiffness of the mattress of 40 MPa was reached [72].

Dynamic Probe Super Heavy [xxviii]- Extra cone penetration tests were conducted to evaluate the stiffness of the soil layers and to determine the depth of the bedrock across the site. Several soft spots in the soil composition and large fluctuations in the depth of the bedrock were detected [72].

Full-scale load test-In their first project combining stone columns and a soil mattress, Franki had used a full-scale load test to prove the performance of the method to their client [65]. It was decided to do the same for the Welgedacht design. A surcharge fill was constructed over a finished section with columns and mattress in place. The fill made up of soil with a density of 16 kN/m^3 was 2,8m high and effectively applying a load of 44,8 kN/m^2 on the foundation. The settlement was measured over a period of 35 days during which a final maximum total settlement of 18mm was recorded. The average settlement was 14,8 mm. The measured total settlement was therefore within specification [47]. These settlement measurements were done to prove the effectiveness of the technique. The contracting party had guaranteed the performance of the design and had to prove it met the settlement specifications.

Final design

When all the results from the various investigations were gathered, a final design was made calculating results for the foundation of the different structures separately. In this final design soil parameters were used specialised to local soil conditions under the different structures [47]. By means of cone penetration tests, two areas were identified at the location of the reactor, where the dolomite had weathered to a deeper level. Following additional FEA for this structure it was decided that in these areas extra stone columns had to be installed to reduce the risk of high differential settlements, due to the larger body of the compressible soil layers [47]. At the clarifiers the water table was shallower than elsewhere, therefore a 500mm thicker soil mattress was installed. Another concern was the 4m difference in foundation

[xxvii] Plate load test: the plate load test comprises a rigid plate placed on the surface to be tested. The load is provided by a hydraulic jack, ballast or an anchored beam is used as reaction force. The settlement at the applied load is measured, determining the stiffness of the tested material [67].

[xxviii] "In Southern Africa, considerable use is made of a local standard of the Dynamic Probe Super Heavy test" [67,p12]. A steel cone is driven into the ground using a mechanical hammer. The number of blows required is a 300mm is used to measure the friction induced by the soil.

depth between the centre and the wall of the clarifiers. Additional FEA proved these concerns to be unnecessary.

Quality control

Apart from the measurements stated above, the quality of the constructed foundation was assured by recording the blows applied to compact a column and the volume of the compacted stone per column. The number of blows applied is a measurement for the stiffness of the columns. The volume of stone used per column is a measure for the stiffness of surrounding soil layers, soft soil layers allow the column to expand and as a result more stone is used.

4.4.5 Resourcing innovation

In the search for alternatives and the optimisation of the tender design, more parties were involved than in the earlier stages of the design. The knowledge transfer in this stage occurred firstly through the tender document that contained all the design parameters used in the base case. AFRICON was provided with knowledge on soil parameters and the theoretical working of the method through Franki Africa, one of the contractors. This contractor had developed the knowledge on an earlier project in Mauritius where the same method was used. Furthermore, both Franki and the other specialised contractor involved with the foundation (Dura Piling) provided AFRICON with soil parameters from earlier projects in the same area [82]. Within AFRICON knowledge was available from earlier projects implementing either stone column or soil mattress foundation. Based on this experience they did not see any problems for the technical feasibility of the project. Some additional knowledge was gathered by AFRICON during study of literature on the subject and from searching the Internet [88].

The most important factors that led to a demand for knowledge was the uncertainty on the soil conditions and the settlement performance of stone columns and soil mattress. Although some knowledge on soil parameters and the performance of the founding method was available from experience in previous projects, the performance of the method under local conditions had to be investigated. Extensive geotechnical investigations showed a variety of soil compositions. The soil parameters established in the tests were to be used in calculations of the behaviour of the stone columns and soil mattress. Although this behaviour could in theory be predicted with hand calculations, the complexity of the interacting factors determining soil behaviour led to the use of computer software by AFRICON. The use of software makes it easier to adjust the different parameters, without having to redo the whole calculation. During the design soil parameters were adjusted to see how mistakes in parameter values would affect behaviour. The ease with which this kind of sensitivity analyses can be performed is an important advantage of using software [88]. The software used by AFRICON to do this was a FEA program PLAXIS, which is from Dutch origin and so is the manual used by AFRICON to operate it [xxix]. The uncertainty about the soil parameters and subsequent tests led to continuous design alterations. Even during construction, test results necessitated changes in the design. Despite all the geotechnical investigations and FEA analyses the uncertainty about the settlement was only really removed after the full load, full scale, in-situ settlement test proved the effectiveness of the system.

4.4.6 Reflection phase

Both AFRICON and ARQ indicate to have gained valuable knowledge from this project. The settlement predicted for the full-scale test with the FEA software was 20mm. The results showed a maximum settlement of 18mm. This fact gave both companies confidence that the design parameters used were very close to the actual soil properties. The result is that the involved engineers will be more confident when using the same method to predict settlements in the future [54,88].As to the combination of stone columns and soil raft, both firms indicate

[xxix] Vermeer PA,*Plaxis finite element code for soil and rock placity Version 7,* 1998

that they are more likely to use this technique in the future. The technique has proved to be effective and furthermore the firms have built a knowledge base, which can be used as point of departure for a future project [54,88].

5 Stabilising a road's embankment

Shortly after its completion in 1998, a small section of the N17 toll road's pavement showed signs of subsidence or imminent failure. The road's embankment next to Wemmer Pan in Johannesburg was settling over a section of 40m due to water ingress, and as a result the asphalt started to settle and crack [83]. The responsibility for the road's performance had recently been handed over from the government to a "section 21" company called the South African National Roads Agency (NRA). The Agency was established in 1998 with the goal to increase the efficiency and cost-effectiveness of road management in South Africa. Although the South African government is the sole owner, the NRA is an independent company functioning according to commercial principles. It is responsible for the upkeep and expansion of the road network in South Africa [84].

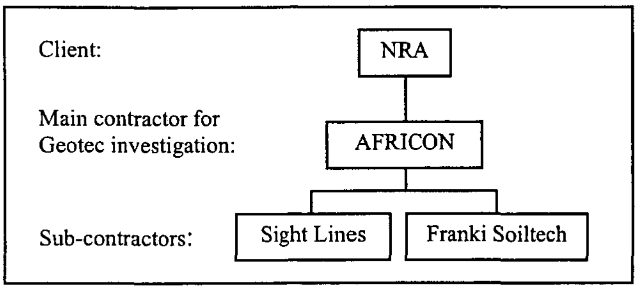
Figure 15: cracked asphalt and patched area, source: AFRICON

Initially, the NRA tried to recondition the highway by filling the gaps that caused subsidence with extra layers of asphalt on a regular basis, resulting in local patches of asphalt which were 300mm thick. After numerous costly repairs the NRA decided to get specialised advice. In February 2002 the NRA appointed AFRICON as consulting engineers for the investigation of subsidence of the N17 road embankment near Wemmer Pan [85]. AFRICON had done the original design for the road as well [86]. The research established that the subsidence of the subsoil and therefore the cracking of the asphalt, was caused by erosion of the subsoil due to water leaking from damaged storm-water drainage pipes and the softening of the subsoil as a result of accumulating moisture [87]. The investigation report contained recommendations on how to restore the road. After the completion of the geotechnical investigation, AFRICON was appointed to design a solution to correct the problem, with as little damage to the pavement and as little hindrance to traffic as possible [83,88]. The design phase that followed resulted in the innovative application of jet grouting to stabilise the road embankment. It was the first time for jet grouting to be applied as a foundation method in South Africa [89]. This report contains a case study into the process that led to the identification of the problem and its solution.

5.1 Project organisation

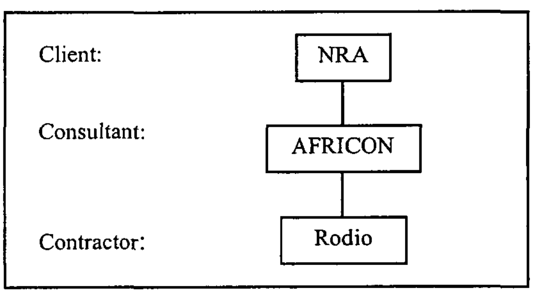
The restabilisation of the N17 project, like the Welgedacht project, contained phases involving different specialised PBO's, i.e. the geotechnical investigation and construction phase. The project's organisation is less complex than that of the Welgedacht project. There are fewer companies involved and their responsibilities are well defined.

5.1.1 Geotechnical investigation



The NRA appointed AFRICON to do a geotechnical analysis of the subsidence of the road embankment at Wemmer Pan. A specialised contractor named Franki Soiltech did the cone penetration and laboratory tests. Apart from the geotechnical investigation of soil conditions, the investigation necessitated the inspection of a damaged stormwater pipe. For the assessment of damage to the stormwaterpipe AFRICON hired a specialist in video investigation called Sight Lines [87].

5.1.2 Design and construction of the jet grouted foundation.



During the investigation of the subsidence, AFRICON considered to use jet grouting to stabilise the embankment. They knew of only one contractor in South Africa with the resources to do this [88]. This firm called Rodio entered the South African market in the 1940's. It was part of the international Rodio group that has its roots in Italy. Italy was the first country where jet grouting was applied on a large scale in the 1970's, after being developed in Japan. Rodio was actively involved in the development of the jet grouting technique in Italy and introduced the technique in South Africa in 1999 [100].

5.2 Identifying the problem

The NRA discovered the subsidence of the road's surface shortly after its completion and started to survey and record the settlement of the pavement over a period of 9 months. It was discovered that the largest part of the settlement took place during the rain season [87]. The maximum total settlement recorded over 9 months was 115mm [83]. Figure 16 shows the distribution of vertical settlement over the length of the influenced section. With this information AFRICON began conducting its research to the cause of the subsidence.

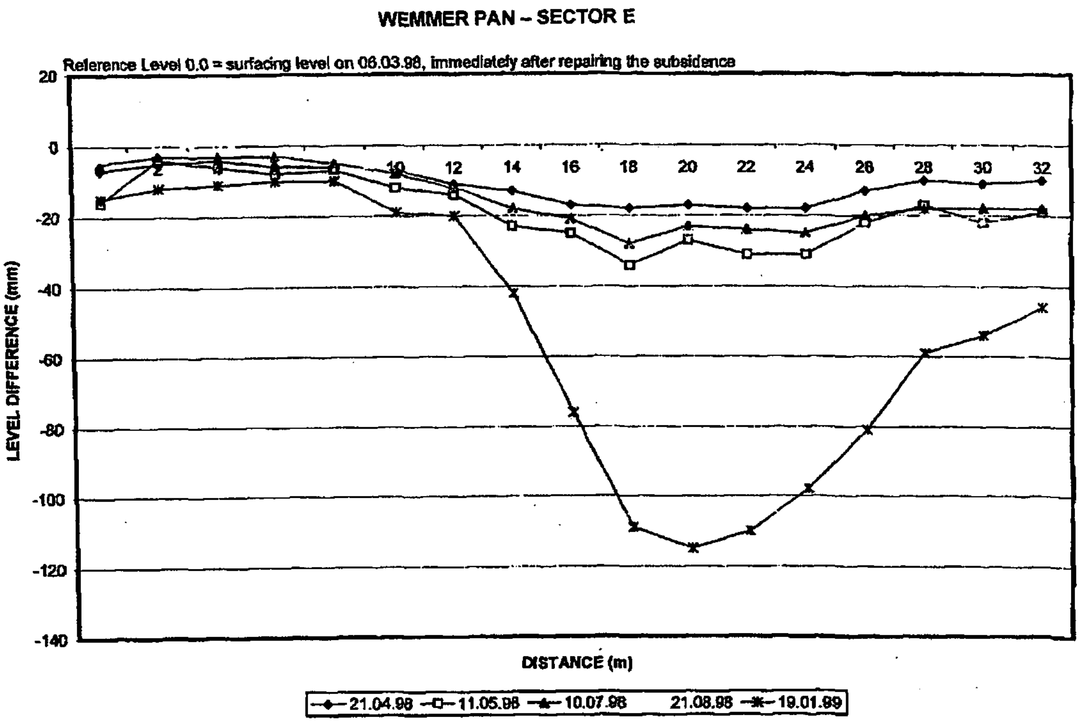


Figure 16: The subsidence profile as obtained from the NRA's Survey Record.

To ensure that any possible cause of the settlement would be identified, the geotechnical investigation was designed to assess all parameters determining slope stability. The investigation initially comprised three phases, but the results necessitated a fourth phase in which the integrity of the present storm water pipes was assessed [87, 90]. The first phase involved digging of four test pits to visually investigate the composition of the subsoil. The pits that were dug in the slope of the embankment showed the presence of various kinds of fills and gold mine tailing material[xxx]. Samples of the different soil types were taken for laboratory testing [87]. The second phase entailed 15 Dynamic Probe Super Heavy cone penetration tests. For these tests a cone is driven into the ground using mechanical blows. The resistance and therefore the bearing power of the soil are calculated by measuring the progress of the cone per blow. The test showed the presence of thick soft soil layers under the embankment. The thickness of the soft layers differed over the length of the influenced section corresponding with the distribution of the settlement, i.e. a large settlement at the location of a thick soft layer [87]. To assess the presence of groundwater in the embankment, two observation wells were installed in the holes left after the cone penetration tests. Moisture in the embankment could have caused softening of the soils. Although both wells and the test pits did not show any signs of moisture in the embankment, the presence of a wet spot in the

[xxx] The gold mine tailing material is soil dumped during mining.

embankment was established eventually. At a specific spot, the rod of the cone used for the penetration test was found to be wet at a depth of 2 to 6m below ground level. A local accumulation of water had been established by coincidence [87]. It was suspected that the source of the moist in the embankment was one of the two storm water pipes that run through the affected area. To investigate the integrity of these pipes, Sight Lines, a specialist in the field of video surveys, was hired. An electrical cart with a camera mounted on it was driven through the pipe. One of the storm water pipes showed damage at a connection and in the pipe itself, resulting in water flowing into the embankment and eroding it [87]. The conclusion of the geotechnical evaluation was that the cause of the subsidence lies in a combination of factors:

- Water leaking from the damaged storm water pipe was eroding the embankment by flushing fine material out.
- The subsoil's layers containing mining tailings were softening with the increase of moisture in those layers.

To solve the problems it was decided to propose repair of the damaged storm water pipe by lining it from the inside with a smaller diameter HDPE[xxxi] pipe. As to the soil condition now the cause of the subsidence had been identified, the next step was to find a suitable solution to construct a new foundation for the road [87].

[xxxi] High Density Poly-Ethylene

5.3 Selecting a solution

Apart from the geotechnical investigation, the NRA had requested AFRICON to include possible solutions for the subsidence of the N17. Engineers at AFRICON had to come up with a foundation method to include in the report that would effectively stop the settlement of the road and with that the necessity of costly repairs. The main design condition was minimised disruption of the functioning of the N17 during construction. This can be translated in a minimisation of damage to the road's pavement due to construction and a minimisation of construction time. A second requirement was of course cost minimisation. The latter is also largely dependant on the amount of damage to the pavement [88]. The project team considered several founding methods for the stabilisation of the road embankment

5.3.1 Scanning phase

In order to stabilise the road embankment, three foundation methods were considered. The three concerned methods do not involve soil replacement methods, because those would require the whole road structure to be demolished and would therefore cause too much hindrance for traffic on the N17. Of the three alternatives considered, two were taken to a next level to be studied in greater detail.

Dynamic Compaction (DC)- This method (described before in the Welgedacht study) pertains the compaction of in-situ soil by having a crane drop a large weight from considerable height onto the soil. It is a cheap method, but in this case it would require demolition of the road's surface. After the DC had taken place the embankment would have to be levelled and new pavement installed [87].

Pile foundation- Thought was given to creating a new foundation for this short section of the N17 on concrete piles. The piles would be placed on the more stable, deeper soil layers under the embankment. This would however require the creation of large holes in the roads surface for the piles to be installed. These holes would be on a relative short spacing. As a consequence the whole road's surface would have had to be resurfaced. In other words: both the DC and the pile option required resurfacing of the road, however, since the pile foundation is a lot more expensive than DC, it was no longer considered to be a viable option [88].

Jet grouting- During an earlier project in Botswana, AFRICON had applied a technique called jet grouting to create a weir made of grout columns [88] Traditional grout consists of a very liquid solution of cement in water. Grouting is the injection of this solution into the soil, where it replaces groundwater residing in the pores [91]. Once mixed with the soil, it solidifies, forming a solid body also known as "soilcrete". Grouting is used for an array of functions in geotechnical engineering. The most common applications are soil stabilisation, excavation support systems, structural underpinning, horizontal and vertical seepage barriers and cutoff walls for polluted soil [92, 93, 94].

The origin of the jet grouting technique lies in the oil drilling industry, where high-pressure technology was used to resolve blockings at large depths. It was first used for civil engineering purposes in Pakistan around 1950, by a firm called Cementation Co [95]. In the 1970's the competition of designs for the stabilisation of Pisa's tower sparked a simultaneous further development of the technique by two Japanese companies. The Nissan Freeze Company developed the Chemical Churning Pile (CCP) system and the Kajima Corporation came up with the Column Jet Grout (CJG) system. They represent the two dominant designs in jet grouting technology on which all current jet grouting systems are still based [96,97,98]. After its introduction in Italy jet grouting quickly evolved as a result of test programs aimed at the expansion of knowledge and the development of specialised equipment. With the gain of experience, it was used for an ever-increasing number of applications. From Italy jet grouting found its way to, and was used in, numerous other countries. However, many international companies involved in jet grouting still are Italian-based [95,96,97].

Jet grouting differs from other grouting techniques in the pressure that is used to inject the grout. With jet grouting the solution is injected under high pressures (ranging from 300-600bar) [99, 92], thus destroying the existing soil matrix. It can be used to form soilcrete bodies with large diameters (up to ca. 1,5m) in every soil type [91]. The injection method can be described as follows: By means of drilling, a steel rod is driven into the soil. When the desired depth is reached, grout is forced out of the drill chuck under pressure. The high cutting energy of the grout erodes the soil. The pressure nullifies the granular tension and enables the grout to mix with the soil. Meanwhile, the steel rod is gradually withdrawn and thus creates a soilcrete column over a predetermined length [92,99]. The engineers at AFRICON realised that they could create in-situ piles underneath the road with this technique. In contrast with the use of concrete piles, this technique would only require small holes to be made in the pavement, to accommodate the grout tube, which usually has a diameter of 50-75mm [67].

5.3.2 Selection phase

To reach a sensible decision, the pros and cons of jet grouting and Dynamic compaction with respect to the requirements were studied. The best option to come out of this comparison would be included in the report on the subsidence. If the NRA would approve of the proposed method a detailed design would be drawn up to be used in a tender phase.

Comparing technologies

When comparing the technical suitability of both methods based on literature and experience the following was concluded: The jet grouting technique can be applied successfully under the soil conditions at the N17 site. Apart from providing vertical support, the columns also prevent horisontal movement and help to retain the soil in the embankment. Furthermore, the amount of grout used automatically adjusts itself to the specific need of the soil. Softer layers and cavities would automatically absorb extra grout material forming a firm column [87]. Dynamic Compaction could also be applied successfully, but if the soil would be close to be saturated with moist at the time of DC, the method could prove to be ineffective. The pounding would cause pore pressures to build up, which would inhabit successful compaction. DC involves impact shocks, unlike jet grouting, which is vibrationless. The shock wave caused by the impacting weight could cause damage to nearby drainage systems [87]. The hindrance to traffic movement on the N17 would be far more severe when using DC than when applying jet grouting. DC would require the highway to be demolished over the whole breadth and the traffic deviated onto a temporary road, for the duration of the project. jet grouting could take place on one site of the carriageway at the time, leaving the other site open for traffic. Moreover, the use of jet grouting would only require small holes to be made in the road's surface allowing easy and speedy repair [87]. It was estimated that the construction time when using jet grouting would be half that of DC. The only real advantage of DC is that it is cheap when compared to jet grouting. The silty nature of the subsoil would require a relatively large amount of cement to be used for the jet grouting option [87]. The amount of cement used usually determines whether jet grouting is an economical solution [100]. The conclusion was that jet grouting represented the better option; the technique had a lower failure probability, and more important, the hindrance to traffic could be limited. For these reasons AFRICON proposed jet grouting to be used to stabilise the embankment in its report on the investigation of the subsidence. Although the jet grouting solution still had to be designed, it was estimated in the report that columns had to be installed to a 7m depth on a 2x2m grid [83].

Detailed design

The report on the geotechnical investigation of the subsidence of the N17 was presented to the NRA. Included was the proposal to use jet grouting for stabilisation and a description of the needed repairs to the storm water pipe. The NRA agreed that jet grouting would be the best solution for the problem and as a consequence AFRICON was asked to design the get grouting solution [88].

A jet grouting column in its essence is an in-situ cast pile, allowing the "standard" load-bearing capacity and settlement calculation method for in-situ cast piles to be used [88]. The length of the piles was designed to vary, corresponding with the thickness of the soft soil layers established in the investigation. The connections between the road section with the new stiff jet grouted foundation and the unaltered road on a soil embankment presented a risk of differential settlement. The unaltered road could settle more then the new stiff section, resulting in cracks in the asphalt. Employing shorter columns near the connection with the untreated road embankment, reduced this risk. The design called for columns with a length varying between 5 and 9m (7m on average) to be installed on grids 2,3 x 2,3m grid. The columns were to have a diameter of 600mm with a mushroomed 1200mm head to prevent them from punching through the pavement (see Figure 17 for design drawing) [87]. The spacing of the columns was worked out in collaboration with Rodio and primarily based on practical considerations [100]. This design would be put to tender, there was some uncertainty however about the diameter of the columns that could actually be created in this particular soil profile. The concern was that in the softer soil layers, very large diameter columns would be created resulting in excessive grout loss. It was decided to allow the contractor to create a small number of test columns next to the road at the start of construction. After the columns were formed, the soil around it would be excavated to inspect the results [83,88].

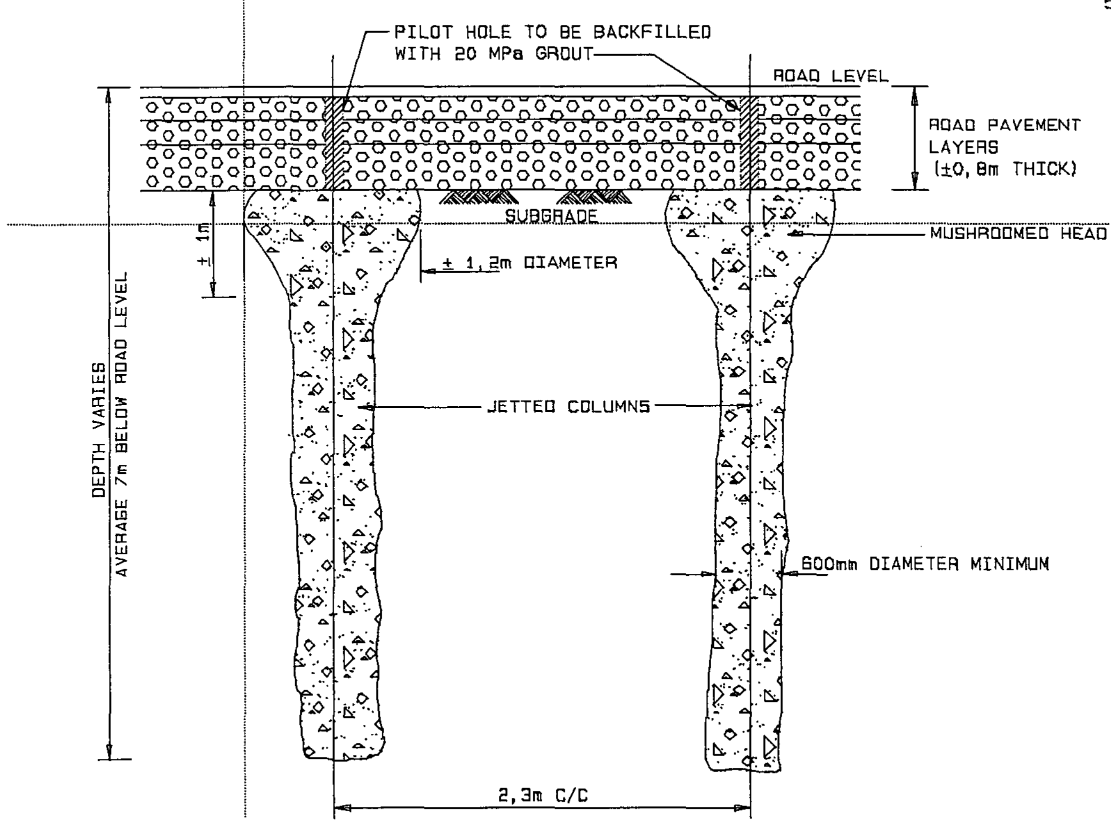


Figure 17: Design drawing of jet grouted columns, source: AFRICON

5.3.3 Implementation phase

The contract for the construction of the jet grouting design was put to tender. Contractors like Franki Africa and Dura Piling (also involved in Welgedacht project) bid on the design, however, they would have to import the equipment via their overseas connections. The only company that had the necessary equipment available in South Africa was Rodio. Rodio was the contractor that constructed the weir in Botswana designed by AFRICON. Since the other contractors had to bring in the jet grouting equipment from abroad, they were too expensive, and the contract was awarded to Rodio [88].

As was proposed during the tender, the construction started with the installation of three test columns next to the road to confirm the assumed grout absorption and needed jetting pressure. To further increase the degree of certainty on the effectiveness of the jet grout columns, auger holes were drilled next to three columns that were installed under the road. The columns were visually inspected to assess if they had the required diameter. The extent to which the required soil-grout mixing had taken place was also inspected. None of the test columns showed problems in their form or integrity and the construction continued according to plan [87]. During the construction of the columns the grout absorption was closely watched. The soft soil layers consisting of mining materials were highly erodible, leading to higher grout consumption. Possible locations with unusual thick soft layers would be detected in this way. The results of the monitoring of the grout intake showed some potential soft spots. It was decided to do additional cone penetration tests on these spots to assess the load bearing capability of the local soil profile. The design for some areas was altered based on the results of these tests. At some places more or longer columns needed to be installed to ensure sufficient load bearing capability and settlement reduction [87]. In all, 137 jet grout columns were created, after which the storm water pipe was repaired and the cracks and holes in the road's surface were sealed. That was the completion of the project [87].

5.3.4 Resourcing innovation

The resources necessary for this innovative solution were gathered during all of the different phases. The first knowledge input needed for the innovation process came from the geotechnical investigation, which AFRICON performed in cooperation with Franki Soiltech. In the scanning phase, knowledge from experience and geotechnical textbooks was used to identify technologies that would potentially be suitable for the situation. When the two most promising solutions had to be compared in the selection phase, a better understanding of the methods was needed. The advantages and disadvantages of dynamic compaction were well known to AFRICON from previous projects. Within AFRICON there was some knowledge available about jet grouting from a previous project in Botswana and the basic principles from textbooks. During this stage extra knowledge was gathered externally. The contractor involved in the Botswana project was approached to see if the equipment would be available. The contractor provided AFRICON with some tacit knowledge on the process of jet grouting as a foundation method and an article on the technical details of this process, which was used in the design.[xxxii] An Internet search produced a description of a similar project done in Paris, where jet grouting was used to restore the foundation of a railway line. The French consultants involved in the project, a company called Terrosol, were contacted and they provided AFRICON with an article on the determination of jet grouting parameters.[xxxiii] With the information gathered, a foundation was designed using jet grouted columns. The calculations for the bearing capability and settlement were done applying the "standard" calculation method for a piled foundation [88]. What remained uncertain to some extent was the shape the columns would take in the soil and the composition of soil layers across the site. Knowledge on these topics was acquired by the installation of six test columns and the monitoring of grout use. Excessive grout use on some locations was followed by an extra soil survey and an adjusted design [88].

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5.3.5 *Reflection phase*

Since the completion of the project no abnormal settlement has been reported at the site that saw the installation of jet grouted columns. It is therefore fair to assume that the operation was successful. The knowledge gained in this project has increased the probability of AFRICON proposing this method for foundation purposes in the future. AFRICON gained confidence in the performance of the grout columns and acquired insight in the formation of columns in soft soil layers.

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Actor/ phase	Problem causing need for resources.	Type of complexity	Considerations	Additional resources acquired by:	Internal/external, origin and form
ERWAT Early phase	Suitability of soil conditions at Welgedacht site for foundation for plant.	Technological	Soil investigation lies outside ERWAT corporate activities	Hire geotechnical consultant for soil investigation	External: Jones&Wagener Codified: report
AquAfrica Proposal phase	Need for a Hi-tech design meeting the latest standards in water treatment for a competitive price	Technological	The leaders in water treatment technology are based in Europe.	Invite 3 front line international firms to propose solutions for the treatment process	External: European firms Codified: written proposals
	Civil design of (foundation, pipes, pavement)	Technological	Find firm with adequate knowledge and that operates on favourable rate.	Open proposal phase for civil design.	External: ARQ Codified: written proposal
ARQ Tender design	Request for foundation proposal by AquAfica	Technological	What information on local soil conditions is available	Geotechnical investigation done in earlier phase.	External: Jones&Wagener Codified: Report
	Feasibility of foundation methods with local resources	Market	Existing ties with local contractors from previous projects.	Consult local contractor.	External: Franki Tacit: informal meeting
	How to most efficiently design stone column solution	Technological	Existing ties with local contractors from previous projects.	Consult local contractor	External: Franki Tacit: informal meeting
			What information on DC can be found in literature.	Literature research	External Codified: article
	Required certainty about performance of various founding methods.	Technological	Large quantity of interacting variables make hand calculations inefficient	Use of Finite Element Analyses (FEA) software	Internal: Automesh& soilstruct (US) Tacit: software
	Remaining uncertainty about the performance of the completed design.	Technological	Existing ties with colleague consultants, who also did geotechnical evaluation.	Have other consultancy firm evaluate design.	External: Jones&Wagener Tacit: meeting
AFRICON Alternative design	Qhude BBE requests alternatives for tender design	Technological	What information on local soil conditions and proposed foundation method are included in the tender document?	Acquirement of tender document	External: Jones&Wagener Codified: report External: ARQ Codified: Tender document
	Required certainty about performance of alternative founding methods	Technological	AFRICON has an edge in the use of FEA software	Use of FEA software	Internal: Plaxis Tacit: software
AFRICON Preliminary optimisa-tion design	Mechanics of combination of soil raft and stone columns	Technological	Sub-contractor Franki has experience with the combination method and stone column foundations.	Consulting Franki	External: Franki Tacit: meetings Codified: article
			Availability of information on stone column foundation on Internet and in literature?	Internet/literature research	External Codified
	More detailed information needed on soil conditions for optimised design.	Technological	Sub-contractor Franki has experience with soilconditions in the area	Consulting Franki	External: Franki Tacit: meetings
			The only way to find out more about soil conditions on the site is insitu testing. AFRICON doesn't have test equipment but involved contractors do.	Hire Burchell Construction to dig 13 test pits and have geologist AFRICON examine soil profile	Internal: geologist External: Burchell Con. Codified: report
				Have Burchell Construction drill 6 rotary core holes and geologist AFRICON examine soil profile	Internal: geologist External: Burchell Con. Codified: report

Actor	Problem causing need for resources.	Type of complexity	Considerations	Additional resources acquired by:	Internal/external, origin and form
AFRICON (continued)				Take soil samples from core holes for laboratory testing	Internal: laboratory Codified: report
	Required certainty about performance of optimised design	Technological	AFRICON has an edge in the use of FEA software	Use of FEA software	Internal: Plaxis Tacit: software
AFRICON Construc-tion design	Remaining uncertainty on soil conditions	Technological	AFRICON doesn't have equipment, but contractors on site do.	Have Franki Soiltech do cone penetration tests	External: Franki Codified: report
				Have Qhude drill 13 rotary cores and AFRICON geologist examine soil profile	External: Qhude Internal: geologist
				Take soil samples for laboratory testing	Internal: laboratory Codified: report
	Uncertainty about performance of stone column/ soil mattress foundation method	Technological	AFRICON doesn't have equipment, but contractors on site do.	Have Franki Dura JV do plate load tests on stone columns	External: Franki/Dura JV Codified: report
				Contractors construct full scale load test. External surveyer measures settlement.	External: contractors/ surveyer Codified: report
				Take soil samples of chert gravel for laboratory testing	Internal: laboratory Codified: report
AFRICON Final design	The results of various tests make specific designed foundation for reactors and clarifiers a necessity	Technological	AFRICON has an edge in the use of FEA software	Separate FEA analyses for reactors and clarifiers	Internal: Plaxis Tacit: software
	Quality assurance	Technological	Monitoring of construction and tests give extra certainty	Monitor: augur refusal depths, CPT refusal depths, core hole refusal depth, DC blows applied, volume of compacted stone/ column	Internal/external: AFRICON, contractors Codified: report.

Actor/ phase	Problem causing need for resources.	Type of complexity	Considerations	Additional resources acquired by:	Internal/external, origin and form
NRA	Need to establish the magnitude of the subsidence of a section in the N17 highway	Technological	Try to find out if the road is settling and at what rate	Monitoring of settlement	Internal: monitoring Codified: report
	Further settlement is established. Need to find out what causes it and how can it be solved	Technological	NRA doesn't have the required skill to do geotechnical investigation. AFRICON was involved with the original design.	Hire AFRICON to do geotechnical investigation and to come up with solution.	External: AFRICON Codified: report
AFRICON Geotechni-cal investi-gation	Need for knowledge on the soil profile under the subsided section.	Technological	Only way to find out soil conditions is to do insitu test. AFRICON doesn't have all the equipment, therefore some tests are sub-contracted	Dig test pits and assess soil profile	Internal: geologist Codified: report
				Hire Roelf Fourie to do Cone penetration test to test load bearing capability of soil	External: Roelf Fourie Codified: report
				Have Franki soil tech do laboratory tests for shear strength of soil	External: Franki soiltech Codified: Report
	Investigation results show very local wet sections. Need to establish if storm water pipes are leaking.	Technological	AFRICON doesn't have the needed equipment.	Hire specialist in video surveying to inspect pipes.	External: sight lines Codified: report & tape
AFRICON Preliminary design	Need for knowledge on whether or not the Jet Grouting equipment is available locally	Market	AFRICON knows only one contractor with the available equipment which is Rodio	Contact Rodio about availability	External: Rodio Tacit: informal meeting
	Need for more knowledge on the use of Jet Grouting as foundation method	Technological	Rodio has knowledge on how to use Jet Grouting as foundation method.	Contact Rodio on knowledge of method.	External: Rodio Tacit: informal meetings Codified: article
			Internet may contain information	Internet search, results in name of French company that used method before.	Externel: Terrosol (F) Codified: article
	Need to predict performance of columns	Technological	Jet grout columns are de facto insitu cast piles	Using standard calculations for insitu cast piles	Internal: calculation Codified
AFRICON Final design	Need to know how the columns would form in the soil	Technological	Allow contractor to form test columns to see if the method will work	Rodio constructs a total of 6 test columns	External: Rodio Tacit: site inspection Codified: report
	Need to reduce performance uncertainty	Technological	Contractor is qualified to check production.	Monitor grout intake	External: Rodio Codified: report
	Need to check the results of grout intake monitoring	Technological	Contractor has necessary equipment	Perform cone penetration test	External: Rodio Codified: Report