1. Introduction

1.1 Overview

The Gautrain rapid rail link is a South African project that links O.R.Tambo International Airport with Sandton, Johannesburg and Tshwane (Pretoria). Apart from the three anchor stations, there will initially be seven other stations. It has an overall length of 80km some 15km of which, together with three stations, are underground; see Figure 1 below. The project is the subject of a 20 year development/operation Concession contract.

Figure 1: Overall layout of the Gautrain Rapid Rail Link project – the 15 km underground portion runs between Park Station and the Malboro portal.
2. Background

2.1 The Gautrain Time Line

The history of Gautrain began some 13 years after plans for a heavy-rail mass transit system for Johannesburg [1] had been abandoned in the mid 1980s. A Pre-Feasibility Study for Gautrain was commissioned in 1998 and this led to a formal announcement of the project in 2000. A Technical Project team was then formed to act on behalf of Province and since then there has been ongoing progress in the planning, procurement and development of the project. The Feasibility study was completed in 2001, and two bidding groups were prequalified early in the following year. A Request for Proposals (Phase 1) was issued in June, and RFP (Phase 2) bids were received on 20th September 2003. The prices received were however above the budgetary limit. Province’s requirements were then reviewed and BAFO bids were called for. These were received on 26th January 2005, and the preferred bidder announced on 2nd July 2005. There then followed a lengthy period of negotiation which led to the signing of the Concession Agreement on 28th September 2006. However construction work could begin almost immediately as considerable progress had been made in developing the preliminary designs during in this period.

2.2 Geological setting

The engineering geology of Johannesburg and the surrounding area has been described by de Beer [2] and Brink [3]. The basement Halfway House granitic dome which lies to the north of the Johannesburg has influenced the present day structure of the later overlying sediments and metasediments. The southern portion of this structure is illustrated in Figure 2.

![Figure 2: Simplified North/South geological section through Johannesburg and environs – after Brink [3]](image)

Most of the Gautrain underground works were constructed in the Basement Granites in the northern suburbs of the Johannesburg. However the running tunnel immediately to the north of Park station was driven through the dipping shales and quartzites of the Hospital Hill Subgroup. Excavation for the entire underground works was carried out by drill and blast methods with one exception. The exception was the 3 km long EPB TBM heading that was driven in a southerly direction from Rosebank at shallow depth in decomposed granites.

3 PROCUREMENT

3.1 Form of Concession Contract

Province chose a PPP Concession form of Contract which was modelled on one used for a Light Rail System in Coventry (UK).
3.2 Risk of the ground conditions

The terms of the draft Concession Agreement as issued with the request for bids placed the risk of the ground conditions with the Concessionaire.

As noted above the bids received in September 2003 exceeded the budget. Province’s requirements were reviewed and a further BAFO round of bidding was entered into. This included the requirement that the Bidders submit two prices; one with the Concessionaire taking the full risk of the ground conditions (as previously) and a second one where the risk of the ground conditions was taken by Province. The recommendations on contractual practices published by the South African Committee on Tunnelling (SANCOT) [4] were to be the basis on which the second (lower) price was to be submitted. The discounts offered on this basis (for various options) averaged approximately 15%.

At the end of the day the Concession was awarded on the original basis, ie that the Concessionaire would take all the ground related risks.

3.3 SANCOT Recommendations on Contractual Practices

The South African Committee on Tunnelling (SANCOT) was formed in 1973 and was a founder member of the International Tunnelling Association (ITA) which came into being the following year. SANCOT’s Contractual Practices working group not only prepared their own recommendations on Contractual Practices between 1988 and 1990 but also contributed to the development of those published by the ITA’s working group in 1988.

The SANCOT recommendations reflect the intent and are consistent with those of the ITA but were more detailed and addressed various issues in the context of South African practice at the time. They were structured around the SA General Conditions of Contract (1990). The basic tenets of both the ITA and SANCOT recommendations have always been that the Owner takes the risks associated with the nature of the ground; and the Contractor takes the risks associated with his methods of working.

The principles of the SANCOT recommendations have been successfully applied to most, if not all, of the civil underground works contracts in southern Africa which have been let since they were published. However all of these projects have all been let on a conventional Engineer Design – Contractor Build – Engineer Supervision basis.

4. Preliminary Geotechnical Investigations undertaken by Province

Prior to the signing of the Concession Agreement, there were two preferred bidders. Rather than the bidding consortia conducting their own investigations, an independent geotechnical consultant carried out the preliminary geotechnical investigation for this project. The main motivation for this was that there would be no duplication of work or effort. In addition there were the following advantages:

- The information gathered reduced the risk faced by the preferred bidders, which would otherwise have been built into the contract price,
- The information gathered would form a common basis for the bids, and
- There was only one team of personnel in the field.

The preliminary investigation was initiated in order to put together a set of documentation for the bidders that would give a basic appreciation of the anticipated ground conditions prior to carrying out tender designs (thereby reducing the amount of risk due to unforeseen ground conditions). The consultant’s brief during the detailed investigation was to collect, collate and present all relevant data to the bidding consortia. All evaluation, design and decisions with regard to construction technique were to be undertaken by the bidding consortia.
The main objective of the preliminary geotechnical investigation was to determine whether the tunnels along the proposed route were technically feasible, and to provide a basis for the bidders to price their bids. Some of the aims of the preliminary investigation for the underground works were to:

- investigate the final vertical and horizontal alignment,
- to confirm the bedrock profile along sections of the route where the tunnel is relatively shallow (in order to try and minimise expensive soft ground tunnelling costs), and
- to confirm the boundaries and extent of the various geological facets along the route.

In addition, sufficient information was to be gathered in order to assist the bidders to address certain critical issues and to determine:

- suitable locations for ventilation shafts and underground cross-links,
- the final location and geometry of portals and underground stations,
- the anticipated excavation methods and sequencing,
- the temporary and permanent support requirements, and
- whether there would be any influence on adjacent buildings due to the excavation process.

Before commencement of the fieldwork for the preliminary investigation, an extensive desktop study was carried out so that an initial assessment could be made with regards to the anticipated geology along the tunnel portions of the proposed rail link route.

Since very little information was available at depth, a field investigation was initiated in order to “flesh out” the results from the desk study. Seventy-nine boreholes were drilled during the preliminary investigation, which amounted to 4022m of drilling. Standard Penetration (SPT) and Lugeon tests were conducted during the drilling of the boreholes and laboratory tests were carried out on samples obtained from the borehole cores. Soil testing consisted of gradings, Atterberg limits, triaxial or shear box testing, consolidometer and permeability determination. Rock testing consisted of unconfined compressive strength, point load index, tensile strength, triaxial testing, Young’s modulus and Poisson’s ratio, XRD and petrographic analysis, and various tests to determine abrasiveness and boreability.

Wireline logging was carried out in selected boreholes. This logging gave a continuous visual record of the borehole as well as quantitative indications of borehole geometry, material density, seismic velocities, temperature, unconfined compressive strength and elastic / bulk / shear moduli. Dip and dip direction measurements were taken of joint and fractures from which polar plots were generated and fracture frequencies determined.

Piezometers were installed in the majority of the boreholes for purposes of measuring groundwater levels. In general, the measured water tables are very shallow, i.e. of the order of 10m below natural ground level, except in isolated areas of deeply weathered granites.

Information was gathered on previous seismic events along the proposed route, and predictions made with regard to possible future intensities, accelerations and maximum credible events.

A geohydrological investigation was carried out along the corridor of the proposed route in order to identify water-bearing features, provide estimates of water inflows into excavations, establish permeability of the rock mass, determine piezometric surfaces, etc. Data from approximately 2000 boreholes was collected along the route corridor.

Both seismic and airborne electromagnetic surveys were also carried out. The seismic surveys were utilised to determine bedrock depth at critical locations such as portals and underground stations. During the airborne survey, a continuous record of magnetic and electromagnetic readings was obtained along the whole route. The results from the magnetic readings assisted in determining the location of contacts between differing rock types, identifying features such as dykes and sills, and determining the width, depth and dip of these features. The interpretation of the electromagnetic data also assisted in the interpretation of overburden thickness along the route.
The preliminary geotechnical investigation indicated that the tunnels between Johannesburg CBD and Marlboro were technically feasible and provided the bidders with a basis on which to price their bids.

5. Complementary ground investigation for the tunnels carried out by the civil contractor

Following a study of the existing (intrusive and none intrusive) investigation data a detailed geological model was defined by the contractor during the tender and preliminary study phase of the project using the records from the several phases of ground investigations along the tunnel route. Areas of uncertainty in the geological interpretation or where gaps in investigation data due to for example lack of access were defined as targets for additional investigation works following award of the concession contract.

Design development also resulted in the need for additional ground investigation to obtain data for the design process. The Detailed Design complementary ground investigation was undertaken to address a number of general and specific aspects arising from the Preliminary Design, namely:

- Determination of ground conditions along the tunnel alignment where density of boreholes from previous ground investigations was considered low in relation to geological setting,
- Determination of engineering rockhead elevation at station boxes and approach tunnels where it varies along the length of construction,
- Determination of ground conditions for detailed design of station car park foundations,
- Determination of ground conditions at shaft locations and havens, the positioning and design of which had not formed part of the Preliminary Design scope,
- Specific investigation of potential lineaments and existing structures,
- Provision of additional confirmation of weathering profile in areas of suspected significant weathering at tunnel elevation,
- The absence of ground/groundwater chemistry information from previous investigations,
- The lack of accurate groundwater level information from previous ground investigations, and
- Monitoring of installations during construction for groundwater profile.

The ground investigation comprised cored boreholes and open hole percussion drilling with in situ and laboratory testing.

The complementary ground investigation was a major undertaking. As usually happens in design and build contracts the data from the ground investigation (GI) was required urgently and design commenced at the same time as the GI commenced.

Lack of resources was a major issue with the local drilling industry being unused to working on such a large fast tracked project. Following a tender process three subcontracts were awarded for the investigation works over the 80km of route. Two of the contracts were awarded to a group of companies drawing on combined resources. The third was issued to a specialist drilling company and was limited to working on the challenging dolomite section of the project.

Standardisation of the geological logging of samples and core was foreseen early on to be a project issue to be addressed. International contractors and design consultants worked on the project and it was important that a common understanding the ground investigation information was achieved.

Prior to commencing the complementary investigation a project standard logging manual prepared defining descriptors to be used and reporting formats to be adopted. This document took as its basis the local South African standard but sections were enhanced based upon logging standard manuals from the Hong Kong "Geo Guides".

Additional specific in situ testing was carried out. This included pressuremeter testing in soils to establish lateral earth pressure parameters for design of the deep station excavations; full scale pumping tests to define the pumping requirements for dewatering one emergency shafts during construction and
acoustic televiewer surveys to obtain orientated discontinuity information in the rock mass specifically for cavern and shaft design which was unavailable from testing made during the early stages of the project.

A careful assessment of the data obtained from the televiewer data identified that the interpretation of the testing carried out at the earlier stages was incorrect and adjustments were made to the geological model to incorporate this new understanding of the structural geology.

As a result of the appraisal of the initial findings of the complementary investigation, additional exploratory holes were instructed, and these included:

- Park station area where particular issues relating to the Station, the construction shaft and the cavern design and construction,
- Emergency Shaft E2 where the shaft location was moved some 200m from the original position determined at preliminary design stage,
- TBM alignment in order to ensure that the possible "pinnacles" of very strong granite were avoided,
- Sandton North Shaft to assess the rock cover to the tunnels emerging from the shaft in a northerly direction,
- Mushroom Farm Park Construction Shaft, and
- Marlboro Portal.

A total of 172 (5692m) additional investigation holes were sunk along the tunnel section of the project to complement the existing data. This additional drilling was split between the tunnels/shafts and the three stations.

A significant amount of laboratory testing had been carried out during the preliminary stages of the project. Additional testing was limited and targeted zones where specific design parameters were required in both soils and rock material. To ensure a maximum reuse of good rock material excavated from the tunnels additional testing was carried out on rock samples from sections of the tunnel anticipated to be in good quality rock which could be reused as high grade fills.

A full suite of chemical testing was carried out on ground water samples taken at selected locations across the tunnel alignment. This provided data for design in terms of durability and also base-lined the water quality data to enable later confirmation that the project construction had not detrimentally affected the quality of the water adjacent to the tunnels.

In accordance with best practice the ground investigation data was used to develop geological models. Great effort was put into this interpretation by the contractor as previous international experience had clearly demonstrated the usefulness of the production teams being provided with such a model. This enhances their understanding of the ground and enables the team to make advanced preparations for all anticipated ground conditions in a knowledgeable manner.

Figure 3 shows one such model developed by the Contractors geological team. The model is for the particularly challenging southern section of the tunnel where excavation was through the Witwatersrand meta-sedimentary deposits. It is important to note that this model was kept “alive”. As additional information became available, be it additional drilling data or a better understanding of the ground as excavation progresses then the model was updated and provided to all of the concerned production, design and method teams. This procedure also is consistent with the requirements of the Code of Practice published by the International Tunnelling Insurance Group (which has been endorsed by the ITA).
In addition to understanding the geological model in advance of the tunnelling work from surface exploration drilling, it is important to also continue the investigation during tunnel advance. Probe drilling ahead of the tunnel is invariably a requirement of the project specifications and is carried out primarily to identify zones of potential high water inflow. If this probing is followed by a geologist and drilling parameters obtained form the drilling jumbos (which is possible with no additional effort in modern drilling rigs), a very good prediction of the likely ground conditions to be encountered over the length of the probe can be made (Figure 4).

![Figure 3: Geological model developed for the tunnel between Park Station and Killarney](image)

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![Figure 4: Interpretation of drilling parameters obtained from drilling jumbos probing in advance of the excavation face](image)

**Figure 4:** Interpretation of drilling parameters obtained from drilling jumbos probing in advance of the excavation face
While this may take a little extra effort on behalf of the production teams making the probe holes (usually on the Sunday maintenance shift), the benefit in terms of understanding the ground conditions over the following week of production can be enormous.

5. Conclusions

The extensive exploratory work carried out for Gautrain has ensured the successful construction of the underground works with the minimum of geological surprises. It is a classic example of how GI needs to be recognised as an ongoing process consisting of a series of campaigns which are developed to progressively eliminate or minimise areas of geological doubt.

There can be a lot of discussion on how much exploratory drilling should be done for a tunnelling project. Some have advocated that a certain percentage of the anticipated project cost should be budgeted for this purpose. This approach is hardly scientific as the extent and nature of the investigations must depend on the geology of the project area.

On the other hand, Cruise in a light hearted but thought provoking paper [8], has suggested a simple way of quantifying the amount of drilling required. It is based on considering just two factors - the depth and length of the tunnel; and then assuming that the spacing of the exploratory boreholes equals the depth of the tunnel. On this basis one then ends up with having an aggregate drill hole length equal to the length of the tunnel.

He justifies this hypothesis by pointing out that tunnels at shallow depth generally encounter weathered and variable ground whereas tunnels at much greater depth are usually driven through less changeable ground conditions. Thus with tunnels at considerable depth only a few long holes are needed, but where tunnels are driven at shallow depth, a much larger number of holes at close intervals are required.

On the other hand it seems that in most cases the total length drilled is somewhat less than the length of the tunnel. In the case of Gautrain the aggregate length of exploratory drilling for the 15 km of the underground route was just under 10 km.

Cruise’s rule of thumb must be recognised for what it is – arbitrarily empirical. On the other hand by applying it at the start of a project it will provide the investigation team with some kind of a yard stick against which they can review the extent of the GI proposed for their particular project.

References