Du Toitskloof — The main tunnel contract

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Synopsis
The construction methods employed and the specialized equipment used on the project are described. Details of the design aspects and the construction of the soft ground section to the second tunnel are provided. An alternative technique was used: ‘multiple face’ excavation supported by vacuum drainage of the ground water table.

Introduction
The Joint Venture (JV) of Concor-Hochtief was awarded Contract NVK 101023 of the National Transport Commission in September 1984. The Joint Venture was a 50:50 enterprise between Concor Construction (Pty) Ltd of South Africa and Hochtief AG of West Germany. The worldwide tunnelling expertise of Hochtief was effectively combined with Concor’s long-standing knowledge and experience of the South African conditions. The contract included 3,9 km of hard rock excavation, concrete lining and finishing works up to completion for public use. The original contract related to one tunnel tube, the South Tunnel. A typical cross-section is shown in Fig 1.

The soft-ground section of the south tunnel (see Fig 2) and a parallel pilot tunnel in the centre line of the north tunnel had already been executed under previous contracts.

Tunnel works — original contract
General aspects
The geological mapping of the pilot tunnel drive showed two distinct rock types and two major and numerous minor fault zones. This governed the first major decision of the JV in respect of the excavation method. The tender was based on splitting the excavation into a top heading (approximately 60 m²) and a bench excavation (approximately 30 m²).

Full face excavation was ruled out, mainly because:
1. The size of the tunnel (approximately 12 m x 9 m) would have required exceptionally sound and homogeneous rock for stability and safety, specifically of the tunnel face.
2. Large size tunnels in mixed rock conditions require the employment of a large variety of different excavation equipment as well as temporary and primary support systems.

The next step was selection of the optimal equipment combination, bearing in mind the geometry of the top heading section and the required high productivity. After an extensive study and on the basis of our own experience on other projects, the following equipment combination was chosen:
1. Tamrock HS 205 B jumbos with 500 series hydraulic drifters.
2. Broyt X41 EL loader (3,5 m³ shovel).

All equipment had to be imported from Europe, as no comparable plant was available on the South African market.

Hard rock excavation — south tunnel
The top heading was naturally the determining operation, as all following activities were dependent on its performance. The tunnel was attacked from two fronts, the west portal and the east portal. Each face was equipped with two Tamrock jumbos, one Broyt, five Kirunas and one 950/966 type wheel loader. A schematic layout of the excavation and mucking phases is shown in Fig 3.

The basic drilling and blasting pattern (see Fig 4) for the hard rock section was burntout with two large-size centre holes and ‘smooth blasting’ of the circumference. Two types of explosives were used: Dynagel for the cut holes and Amongoaginite (primed with Dynagel) for all other holes. The charges for the contour holes were prepared within omega-clips with Cordtex. High resistance No. 3 detonators were used for all blasting operations in the tunnel.

The existing pilot tunnel, running parallel some 36 m from the tunnel centreline, was incorporated into the overall tunnel operation. The major supply lines for electrical power, compressed air, water as well as exhaust-ventilation were routed through the pilot tunnel.

At intervals of approximately 330 m cross-connections (for pedestrian and vehicular use) were driven, through which the supply lines to the main tunnel were routed.

Diversion of the supply lines into the pilot tunnel facilitated the simultaneous, but geographically staggered, blasting operations along the tunnel. Excavating the topheading, the bench, the DWA water pipeline, side-drains and slipping ahead of the shutter became parallel activities because the supply lines were out of the way in the pilot tunnel.

Ventilation
To provide adequate ventilation, three major aspects were considered:

Diesel exhaust fumes: The minimization of air pollution and the drop in visibility from diesel exhausts was one of the factors in favour of choosing Kiruna trucks. They have a very favourable relation between payload (35 tons) and horsepower (250 HP) and their exhaust-cleaning devices are of a high standard.

Blasting fumes: A rapid dispersion of the blasting fumes — and their toxic components — was achieved through a ventilation system that consisted of forced overlap face-ventilation and exhaust ventilation for the rear areas. The miners could remain, after the blast, in areas where no or very few blasting fumes affected them. A number of additional

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'Open' fans were installed in the cross-connections, withdrawing the blasting fumes from the rear areas. The above provided 5.44 m³/min per kilowatt of diesel-powered equipment.

Fresh air supply to the miners: In addition to the above, a further 1.5 m³/min and man was provided in the tunnel at any given time.

The total ventilation capacity installed was:
- Forced ventilation 2 000 m³/min.
- Exhaust ventilation 2 500 m³.
- 4 x 500 m³/min from fans at cross-connections.

Regular tests were carried out with a Draeger gas detector model 21/31 to detect any possible toxic concentrations of gases such as CO, CO₂, and nitrogen oxides. Fig 5 shows a schematic layout of the ventilation arrangements.

Temporary and primary support

The main support elements were spray concrete, wire mesh of different sizes, rockbolts and steel ribs. The standard support consisted of a relatively thin layer of spray concrete using accelerators for early strength. Where jointed rock occurred, tensioned resin rockbolts of 3 m to 4 m length were used and, where required, wire-mesh and spray

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Fig 1: Standard tunnel cross-sections

**Key**
1. Disturbed ground and fill
2. Quartzitic sandstone rock fill
3. Granitic Talus
4. In situ decomposed granite
5. Weathered granite
6. Fresh granite

Fig 2: Soft-ground tunnel (south) — longitudinal section

Fig 3: Schematic representation of excavation and muck removal phases

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Concrete was applied. The central fault zone as well as the Du Toitskloof fault zone were supported by steel ribs at distances of 800 mm to 1 000 mm. In addition, the Du Toitskloof fault zone was supported by an invert arch because the area showed rock movement.

**Concrete lining**

Fig 4 shows a schematic lay-out of the concrete lining method. The concrete was poured behind hydraulically operated and self-propelled steel shutter forms in a 'hit and miss' pattern of 8 m long sections. The concrete was placed with concrete pumps and compacted by poker vibrators and high frequency shutter vibrators. The steel shutter worked extremely well, the credit for this going to the designers (SMS of West Germany) and the manufacturers (Concor of South Africa).

The design concrete strength was 30 MPa. More critical was the required stripping strength of 15 MPa, because it dictated the cycle time, which was of paramount importance for the overall programme. Numerous test series with different aggregate compositions, cement contents
and additives were carried out. The best results in quality (early and final strength with an initial three hour retarding effect) and workability was achieved using Conplast 337 from Fosroc.

Following the concrete operation, contact grouting in the crown was carried out to ensure that all voids were filled and full contact between concrete and rock was achieved. In areas where groundwater was seeping through the rock prior to concrete lining, waterproofing had to be installed (2 mm hyperlastic — executed by Aquatan); this was required on approximately 35 000 m² of tunnel surface out of a total of 85 000 m².

Survey in the tunnel
The method of surveying line and level of the tunnel operations and the equipment as well as the skill of the survey team were of critical importance — not only for the 'final product', but also for the progress of the works. To guarantee a 'permanent' survey, laser stations were installed for the top-heading, bench excavation, subdrain, DWA pipe trench, etc, with the respective 'offset' tables in accordance with the stake value for the work crew.

For the initial setting out and the installation (and control) of the laser stations, as well as for the control profile, which was carried out at 2 m intervals following the excavation as closely as possible, the following equipment was used:

- Computer tachymeter Zeiss Elta 2 with programme 12 and MEM 800 Ref 200 (electronic field-book).
- HP 85 B computer for field-book processing.
- Epson FX-80 DIN A4 Printer.
- HP 7475A DIN A3 Plotter.

With the help of the above, an image of the actual profile was produced in which all survey points were automatically projected perpendicular to the centre line of the tunnel. As the Elta 2 'establishes' its own position in the computer, very little interruption to the progress of the works occurred. In spite of its technical sophistication, the equipment is comparatively simple to handle.

Outside works
Precast concrete elements
The finishing works of the tunnel called for approximately 35 000 precast elements of different types and sizes, such as for ceiling elements, slits gutters, manholes, kerbs, wall cladding panels, etc. A fully equipped precast factory was established on site with lowercranes and its own batchplant. Special moulds were used and tailor-made transport and installation equipment and tools were developed. The operation was very successful from both the quality and production points of view.

Portal buildings
The JV was awarded the selected subcontract for the portal buildings after the award of the tunnel contract. This necessitated the expansion of the site team into the spheres of structural concrete and building works. Although the execution side was independent, the back-up resources were shared with the main contract and many activities were actually integrated. The portal construction overlapped physically and in time with the major tunnel activities and a delicate balance of priorities had to be maintained to ensure unimpeded progress for both.

Earthworks
One major cut and two major fills (in excess of 800 000 m³) had to be constructed on the western approaches to the tunnel. The spoil material from the western tunnel excavation was used in the fill, except for that portion which was crushed for aggregates. To maintain economic progress on the fill, additional material from the eastern excavation had to be imported over the mountain.

To reduce the resulting difficulties in cost and traffic, an alternative design for the fill was proposed and accepted. The total quantity of material required was substantially reduced through the incorporation of a 'reinforced earth' portion.

The second bore — north tunnel
Following negotiations with the client, the JV was awarded the excavation contract for the second bore, the North Tunnel. This consisted of approximately 150 m of soft-ground excavation at the western portal and approximately 3 900 m of hard rock excavation.

Hard rock excavation
The excavation of the north tunnel was done similarly to that of the south tunnel. There was, however, a significant difference in that the pilot tunnel (located inside the profile of the north tunnel) was not available to house the supply lines and ventilation systems. To avoid repeated relocation (and damage) of these supply lines, it was decided to complete the entire top-heading first and to follow with the bench after break-through.

For the ventilation of the eastern excavation a Kofmann AL 17-750 two-stage high-pressure fan was installed at the portal, delivering up to 50 m³/sec (3 000 m³/min) of fresh air via 1 300 mm diameter ventilix air ducts directly to the face. All cross-connections had to be closed to prevent pollution of the air in the south tunnel, which was in the concreting and finishing stage.

At the western excavation no direct access was available as the soft-ground section was still under construction. An additional access tunnel had to be driven from the south tunnel, approximately 220 m from the portal. This complicated the ventilation system, as no fans could be installed at the portal. A similar system to the one used in the south tunnel was adopted, but with the difference that the exhaust ventilation had to be installed over the whole length of the tunnel and routed through the pilot bore in the soft-ground section.

Transportation of the excavation material from the north tunnel had to go through the south tunnel and the western portal, which at times had a serious effect on the finishing progress of these activities.

Soft-ground excavation
At the western portal, both the south and north tunnels had to be driven through water-saturated completely decomposed granite, requiring special tunnelling methods. The soft-ground portion of the south tunnel had been done under a previous contract using ground-freezing methods.

Concor-Hochtief proposed a 'multiple face' excavation with vacuum groundwater lowering for the soft-ground section of the north tunnel (approximately 150 m long).

'Multiple face' means driving a number of small tunnels on the periphery of the cross-section, which, upon completion, form the outer shell of the full tunnel section. The final phase is then the excavation of the core and invert.

Continuous dewatering of the surrounding soil is a necessity. Normal 'gravity' dewatering does, however, not reduce the porewater pressure (which is of paramount importance) in soils with a permeability coefficient of K = 10 — 8 m/sec (as existed in this specific decomposed granite) to an acceptable level. Even dewatering by vacuum application is normally beyond such conditions. The decomposed granite was, however, not, as the geological investigation showed, an absolutely homogenous soil mass, but was interspersed with joints and fissures. These, once they were intercepted by the dewatering pipes, acted as additional feeds and extensions of the applied vacuum system.

This 'partially open' system of the decomposed granite promised success by applying a high negative pressure. It was further known from investigations in the south tunnel that tapping of the main groundwater flow, which runs on the contact zone between solid (weathered) granite and decomposed granite, would result in a substantial drop in the existing water table.

These facts together with experience gained elsewhere on similar projects led to the final decision to employ the vacuum technique for the required dewatering of the soft-ground section.

Design: After an initial empirical design, based on a method of excavation using three small tunnels, one on each base and one in the crown of the full section and the pilot tunnel (see Fig 7), the stress distribution and consequential deformation of the soil and support system had to be established.

The 'finite element' method was chosen, since the complexity of the whole system of interacting parameters could not be defined by a 'simple method of calculation'. Material characteristics, geometry, loads, boundary conditions for the element-net as well as the support and load factors of the excavation phases had to be established.

A special computer program was developed to institute the specific two dimensional 'finite element system'. Furthermore, a decision had to
be made on whether three-dimensional calculations should be carried out. A full three-dimensional approach, considering the interactions during excavation, could only be justified if the elastoplastic action of the soil mass, specifically at the faces of the tunnels, could be defined sufficiently accurately. This is very difficult. To avoid such complications, a three-dimensional soil-bearing capacity 'model' had to be developed that simulates the 'practical' behaviour of the soil mass during excavation with sufficient accuracy.

For the subsoil, an eight-joint isoparametric quadrangle element with biquadratic displacement valuation was used. The shotcrete support was 'idealized' by a nine-joint (flexural) rigid support element with quadratic 'lagrange-interpretation' of the displacements.

After these basic considerations and parameters had been established, an initial computer run for the first empirical design was carried out. The result indicated clearly that the original proposal (three small tunnels) did not satisfy the safety requirements for the various phases.

The final design was the result of numerous computer runs with variations and interactions of methods and sequences of the excavation work as well as of the temporary and final support (Fig 8).

With close co-operation between the design departments of Hochtief in Essen and Electrowatt in Zurich, the final design was then established with five small tunnels.

Excavation sequence: In compliance with the design requirements, the following excavation sequence was applied:

1. Tunnels No. 1 (with the necessary enlargements for the drilling of drainage holes) were driven through the whole of the soft-ground section.
2. Tunnel No. 2 was driven independently through the whole length as well.
3. Tunnels No. 3 followed Tunnels No. 1 after their completion (including first stage wall concrete).
4. Section 4 followed the excavation of Tunnels No. 3 (including first stage wall concrete).
5. Sections No. 5, 6 and 7 followed Section No. 4 (including third stage wall concrete). The allowable maximum distance of this section to Section 4 was 15 m with the invert arch closed.

The temporary support of each of Tunnels No. 1 to 3 consisted of steel arches (IPB 140) at 800 mm to 1 000 mm spacing, 8 mm wire mesh and shotcrete. The final support of the tunnel consisted of 400 mm reinforced concrete (stages one to three) and shotcrete and was closed with a reinforced concrete invert arch.

Fig 9 illustrates the excavation sequence.

Arrangement of vacuum drains: As a first stage, 15 additional piezometers were installed from the surface just beyond the perimeter of the tunnel for monitoring purposes. Groundwater was intercepted at the contact zone of rock/soft-ground by a special drainage.

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**Fig 7:** Cross-section showing initial empirical design and sequence of excavation

**Fig 8:** Cross-section showing final design and sequence of excavation

**Fig 9:** Longitudinal section showing sequence of excavation

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The tunnel sections were protected by drain fans arranged along the tunnel sides. These fans were installed as the excavation progressed and were arranged according to the existing ground water level. Dewatering of the invert portion was dealt with separately.

It is obvious that the final extent of such a dewatering system (numbers and lengths of drains to be installed) cannot be predetermined accurately as it varies with the in situ conditions. The system was flexible, however, and allowed the installation of more and longer drains, where required.

Figs 10, 11, 12 and 13 illustrate the above.

Drilling method: In view of the prevailing ground conditions, consisting of weathered or partially weathered rock, as well as completely decomposed granite, full casing of the drilling bore hole was essential.

A double power drilling system was therefore employed in which the inner and outer drill stems can be revolved independently from one another. Drilling in sound rock was executed by a ‘down-the-hole’ hammer.

Owing to limited space in the advancing partial tunnel sections, a specially designed short feeder was used, rigged onto an electric-powered crawler-type base rig.

Selection of vacuum filters: The high content of fines in the decomposed granite and the long period for which the system was required (one year) necessitated careful selection of the filter material. Consideration was also given to the fact that the drains were up to 30 m long and had to be installed on the incline.

Thick-walled PVC filter drains (39 mm diameter) with threaded joints and shop-coated epoxy resin filter material were selected. The filter material consisted of 20 mm thick quartz sand (0.7 mm to 1.2 mm) bonded with epoxy resin. These special drainage materials had to be imported as they were not locally available.

Fig 14 shows a typical drain.

Performance during construction: The first drains tapping the weathered zone yielded a considerable amount of water (in excess of 5 m³/h), which resulted in a drop of a few metres in the groundwater level. The side drainage fans were then drilled and installed at a spacing of approximately 15 m, working from the advancing No. 1 tunnels.

The vacuum dewatering stabilized the decomposed granite sufficiently to allow for excavation in dry conditions. The tunnel face remained stable and required only a relatively thin layer of shotcrete to guarantee safety during planned work stoppages, such as pay weekends.

Additional measures had to be taken for the safe passing of a former

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**Fig 10:** Arrangement of vacuum drains along tunnel side walls

**Fig 11:** Arrangement of vacuum drains in invert

**Fig 12:** Arrangement of vacuum drains

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cave-in area above the pilot tunnel. Here, a system of bore holes was drilled in advance and the disturbed section was stabilized by means of grouting. In the course of the progressing tunnel excavations, the groundwater table was thus lowered below the tunnel invert arch level.

A total of 3 500 m of special drains was installed, with drilling lengths of up to 35 m. The vacuum dewatering installations included seven high-capacity vacuum pumps equipped with control and warning devices, as well as an emergency power supply.

The full dewatering system, whilst in operation, drew approximately 11 000 m³ of water per month in the dry season, which increased to 12 000 m³ during the rainy season. This relatively low increase confirmed the low permeability of the decomposed granite.

The successful completion of the soft-ground excavation demonstrated that even under adverse soil conditions, the application of vacuum dewatering can be a safe, economical and technically acceptable alternative construction method.

Final comments

The construction of the Du Toitskloof Tunnel together with the additional work awarded during the contract period proved a challenging and stimulating experience. The interaction of expatriate personnel with the local teams was achieved in a short period. As in tunnel works elsewhere, the start of the project was marked by an initiation phase (learning curve). For a temporary organization composed of people of different nationalities, mentalities, company 'cultures' and experience, this was a crucial phase. The situation was further aggravated by the introduction of unaccustomed equipment and a different tunnelling 'philosophy'.

On completion of the works one can state that the formation of highly motivated and effective teams was achieved in a remarkably short period, albeit not entirely without pains. The production rates and quality of work compared well with international standards. The top heading, for example, was completed after 11 months with a maximum weekly advance of up to 90 m, in spite of the slow progress during the passing of the two fault zones.

As is so often the case in construction in South Africa, it will not be possible to use the hard-earned expertise and prowess of the teams on a subsequent contract and this expertise will be lost in time. The specialized equipment is also gone. These are the disadvantages of contracting in a small market. It is, however, encouraging to realize that international resources can and will again be joined with local industry whenever this may be necessary to tackle engineering challenges.