Design and development of a decline shaft through poorly consolidated Kalahari deposits at Ghaghoo Diamond Mine.

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SYNOPSIS

The diamond pipe at Ghaghoo is overlain by approximately 70m of poorly consolidated Kalahari sequence deposits consisting of fine grained aeolian sand particles which are cemented weakly by a clay (smectite) binder. In places the sequence is more strongly cemented with calcite (calcrete) or silica (silcrete). The thickness and geotechnical characteristics of this sequence presented a challenge with regard to accessing the pipe.

An innovative decline shaft construction method using and Open Face Tunnelling Shield (OFTS) with installation of a segmental concrete lining for long term support was selected. While this method has been used extensively in international tunnelling projects, development usually has been close to horizontal. Little experience existed of development on an 8° (1 in 7.1) gradient.

Development of the box cut commenced during July 2011. An artificial portal was created, approximately 25m below surface, to minimise the cost and risk associated with box cut development.

Construction of the 6m diameter OFTS on site commenced in November 2011 and excavation of the decline commenced in December 2011. A total of 758, 600mm wide concrete rings were installed in the Kalahari deposits and weathered basalt before conventional development continued in basalt.

This paper briefly presents aspects of the design philosophy and method, construction and monitoring processes involved in excavating the box cut, constructing the portal and sinking the decline shaft.

1. INTRODUCTION

The ore body at Ghaghoo is covered by weakly cemented Kalahari deposits approximately 70m in thickness. Access to the ore body is via a decline shaft constructed at a gradient of 1 in 7.1 (8°) over a linear distance of approximately 500m through the Kalahari sediments and a further 70m through weathered basalt before reaching competent basalt.

The decline will continue to service successive mining phases over a potential mine life exceeding 40 years. A minimum cross sectional area of 20m² is required for ventilation of the early phases of mine development.

Due to the remote location of the mine and the difficulty in travelling over a distance of 180km on sand roads, key parameters to be considered in the access design included:-

- minimisation of initial capital expenditure;
- minimisation of mass of material and equipment to be transported to site; Maximum loads per vehicle were restricted to 10t.
- maximum use of on-site material; i.e. use of sand and waste rock for construction.
- minimisation of access risk to maintain safety and the planned development schedule;
- minimisation of development time.

This paper describes the geotechnical design and construction of the access development and includes: -

- box cut to provide access to the portal;
- the access portal;
- decline developed in Kalahari sequence sediments;
- decline developed through the transition zone;

2. THE KALAHARI SEQUENCE AT GHAGHOO

This sequence contains three geotechnical sub-domains:-

- **Upper domain** consisting of loose, unconsolidated aeolian sand. This domain was approximately 10m thick;

- **Mid-domain** consisting of weakly cemented fine grained aeolian sand with discrete lenses of silt and clay, gravel silcrete and calcrete. The silcrete/calcrete portion proved to form a significant, 20m thick portion of this domain in which the uniaxial strength of the silcrete was found to exceed 100MPa. The vertical thickness of this domain was approximately 55m;

- **Lower domain** consisting of oxidized and friable fine grained aeolian sand which was expected to be moist to wet. Although the cementing properties of the sand had been largely destroyed by water action, the material was relatively dry when encountered and was not prone to slumping as expected. The vertical thickness of this domain was a maximum of 5m.

A selection of site investigation boreholes is presented in Figure 1 to illustrate the variation in conditions across the site. A typical core sample is shown in Figure 2. Much of the sand sequence could not be recovered with conventional coring and a wash system was used to collect samples which were stored in plastic sleeves in core boxes.

Samples of sand from GEM08-01 were selected for laboratory testing. The average strength of sand, recorded from four tests, is 500kPa with a range from 300kPa to 680kPa. The strength of calcrete/silcrete that has been encountered in the sequence varies widely with a lower bound of 22MPa and an upper bound of 133MPa being recorded in three tests.

Based on the particle size distribution, sand was classified using the Unified Soil Classification System (USCS) and generally expected properties can be derived. The basic classification is illustrated in Table I. The average value of friction angle determined for Ghaghoo using this system is 34°.

USCS Class	Description	Angle of Friction (ϕ°)	Range (+/-)	No of samples in class
SW	Well graded sand. Little or no fines	38	5	0
SP	Poorly graded sand. Little or no fines	36	6	18
SM	Silty sands. Small percentage of fines	34	3	
SC	Clayey sand. Small percentage of fines	32	4	1

Table I: The Unified Soil Classification System applied to Kalahari sand.

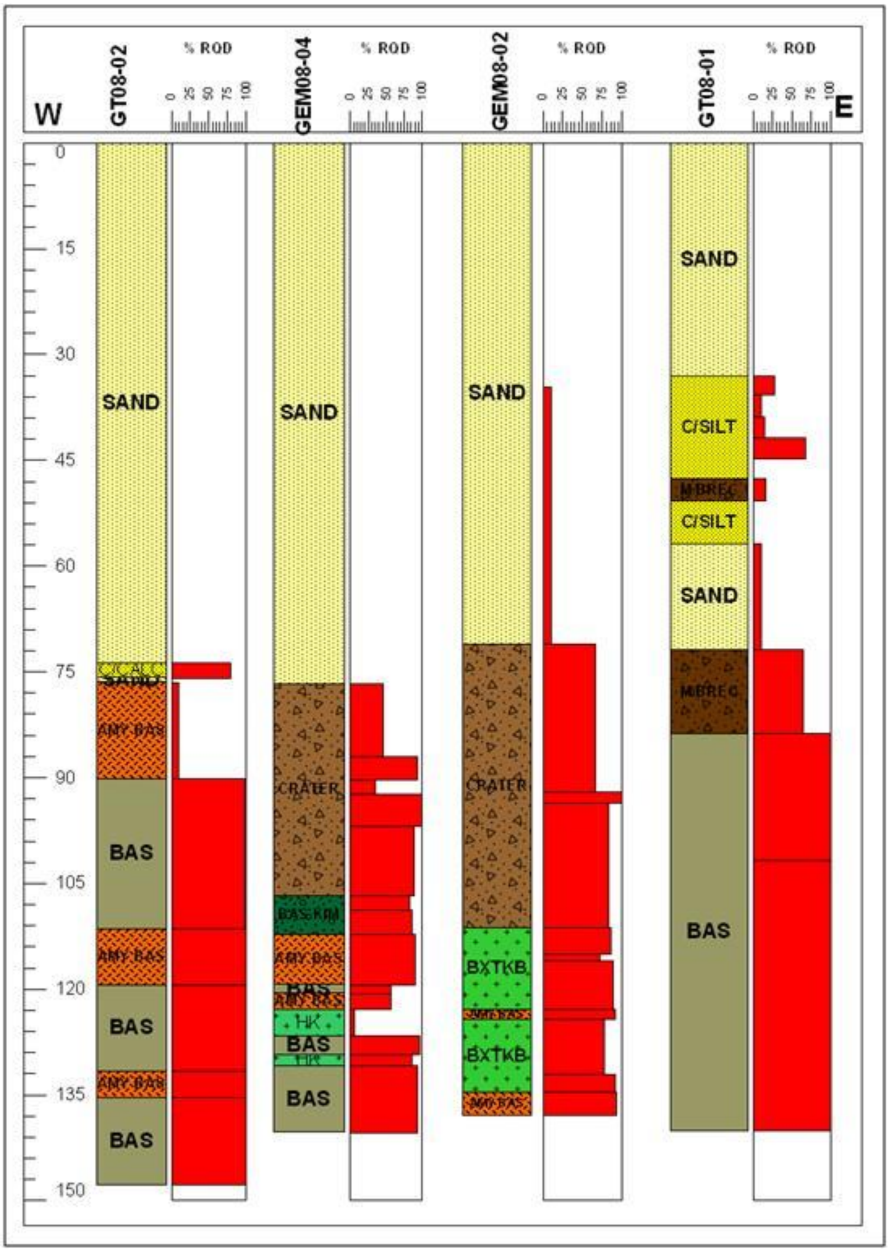

Figure 1: Lithology encountered in site investigation boreholes within the decline space.

Figure 2: Borehole GT08-01 showing the Kalahari sequence, transitional and competent basalt

3. RAINFALL

Based on monthly rainfall figures over the period 1959 to 1987, the annual rainfall is, on average, slightly more than 400mm. The highest rainfall is experienced from November to February with rain also in October, March and April. Occasional storm rainfall events can exceed 70mm within a 24 hour period. In summary, there is a probability of 9.4% that rainfall exceeding 100mm will fall in any month. The probability is 23% that falls exceeding 100mm will occur between November and February. There is a probability of 94.4% that rainfall during the period June to October will be less than 50mm in any month.

This information was used in determining surface water handling facilities that need to be incorporated into the design and to determine risk to construction due to flooding.

4. DECLINE SYSTEM DESIGN

The decline system at Ghaghoo was defined in terms of four critical risk areas. These were: -

- box cut to provide access to the portal;
- the access portal;
- decline developed in Kalahari sequence sediments;
- decline developed through the transition zone;

Anticipated risks and mitigation measures are summarised in Table II: -

Project design area	**Anticipated major risks**	**Mitigation measures**
Box cut access to the portal	Collapse of sidewalls over-running the access portal Flooding of excavations due to storm rainfall.	Slopes are designed at a conservative angle to ensure life-of-mine stability (safety factor > 1.5). A bund is constructed around the box cut to restrict inflow. Sump and pumping capacity provide water – handling infrastructure.
The access portal	Collapse of portal slope. Collapse of face during launching of the shield	Additional surface support is provided. Ground reinforcement and consolidation is applied. Standard Operational Procedure implemented.
The decline developed in Kalahari sequence sands.	Collapse of the face during excavation. Collapse of developed sections of the tunnel.	Support is offered by the shield. Standard Operational Procedure implemented. Lining designed to sustain loads

		equivalent to at least 80m of cover.
The decline developed through the transition zone.	Flooding due to groundwater influx. Face collapse in weak material.	Cover drilling to identify ground water accumulations. Ground consolidation where necessary.

Table II: Anticipated risks and their mitigation measures.

5. BOX CUT DESIGN

A base case design, which assumed that the box cut was excavated to a depth sufficient to create a portal in competent basalt (approximately 80m), provided, initial figures for comparison with alternative options. A number of different options were analysed. These were:

- Base case: 30° slope with maximum depth 80m;
- Option 2: 28° slope with maximum depth 80m;
- Option 3: 30° slope with maximum depth 20m;
- Option 4: 30° slope with maximum depth 25m
- Option 5: 30° slope with maximum depth 30m;
- Option 6: 30° slope with maximum depth 35m;
- Option 7: 60° slope reinforced with soil nails and cladding with maximum depth 25m;
- Option 8: 12m vertical, stepped faces supported by contiguous piles with maximum depth 25m.

The excavation volumes and representative surface areas for each option were calculated and a trade-off study based on technical and economic criteria carried out. Although Option 3 appeared to be preferable, to reduce the risk associated with creating a portal at very shallow depth in material consisting primarily of aeolian sand, it was decided to implement Option 4 with the further modification that the slope angle was reduced to 25°.

The design assumptions for this option to satisfy the requirements of the preliminary mining phase then became:-

- Stable slope angle is 25°;
- Although no support of sidewalls was envisaged to enhance stability, during construction it was decided to apply shotcrete to the lower portions of the slopes to prevent erosion and choking of the drains and sump with sand;
- Rain fall onto the catchment footprint can be controlled by drainage into a sump and bund walls to prevent ingress from an extensive outlying area;
- Ramp angle is 8°;
- The ramp width is 12m;

- Depth to the tunnel invert at the portal is 25m.

The general configuration of the box cut is shown in Figure 3 and a panorama showing graded slopes in Figure 4: -

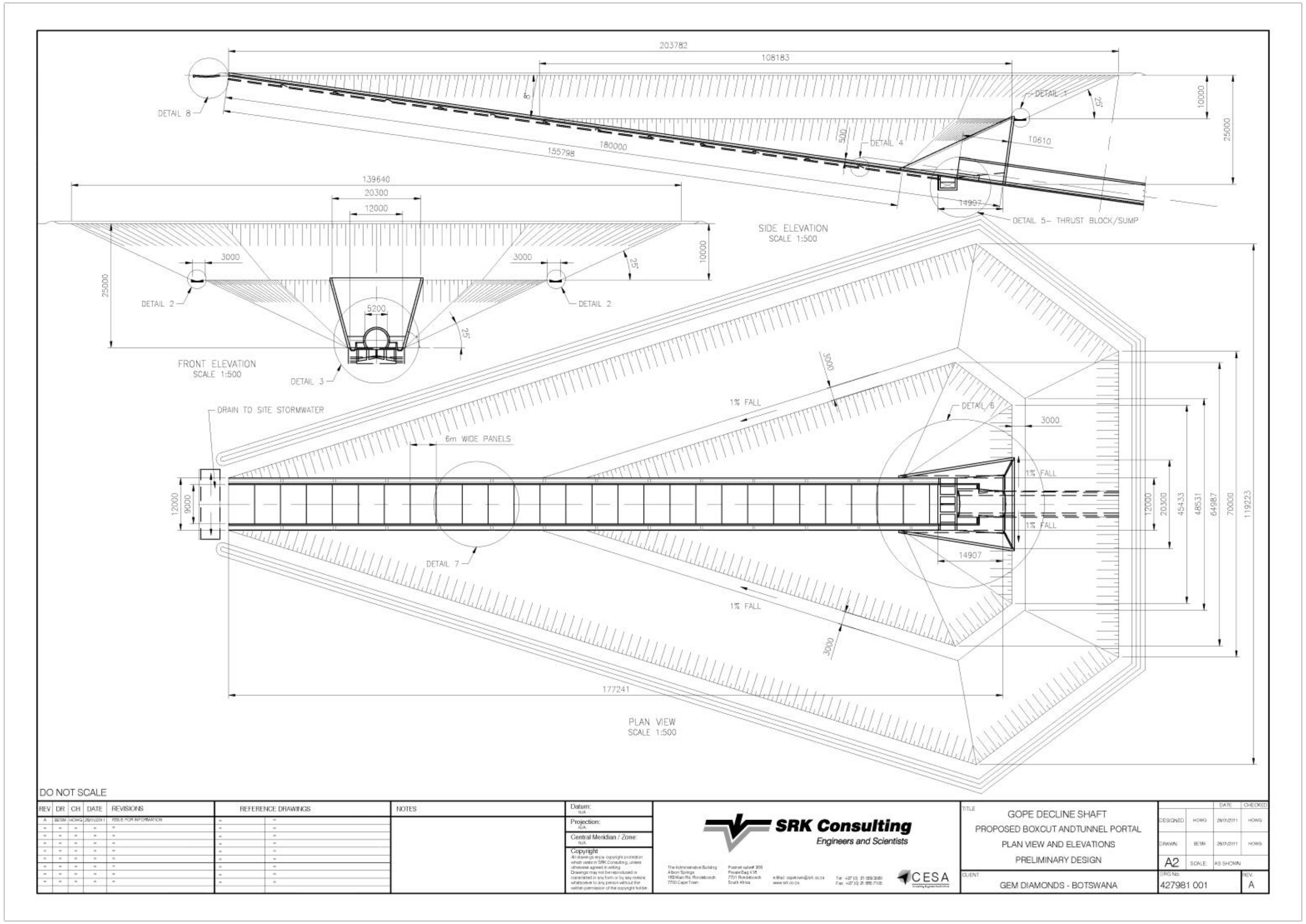

Figure 3: General configuration of the 25m Box Cut.

Figure 4: Panorama of the completed box cut showing graded slopes, December 2011.

6. PORTAL DESIGN

The purpose of the portal construction is to provide a secure face into which the decline can be developed. The design for portal construction included:-

- additional support of ramp sidewalls within 25m of the portal face with a nominal 50mm thickness of shotcrete;
- additional excavation of the portal face to create a sub-vertical face for the decline entry;
- additional support of the portal face using fully grouted soil nails in conjunction with 300mm of mesh reinforced shotcrete;
- support of the area peripheral to the decline access using 25mm diameter, 12m long spiling bars.

Additional excavation required to establish the portal face was carried out in lifts approximately 1.5m in height to facilitate installation of soil nail support and concurrent shotcrete application.

The general layout of the portal face together with recommended support is presented in Figure 5 while Figure 6 shows construction in progress.

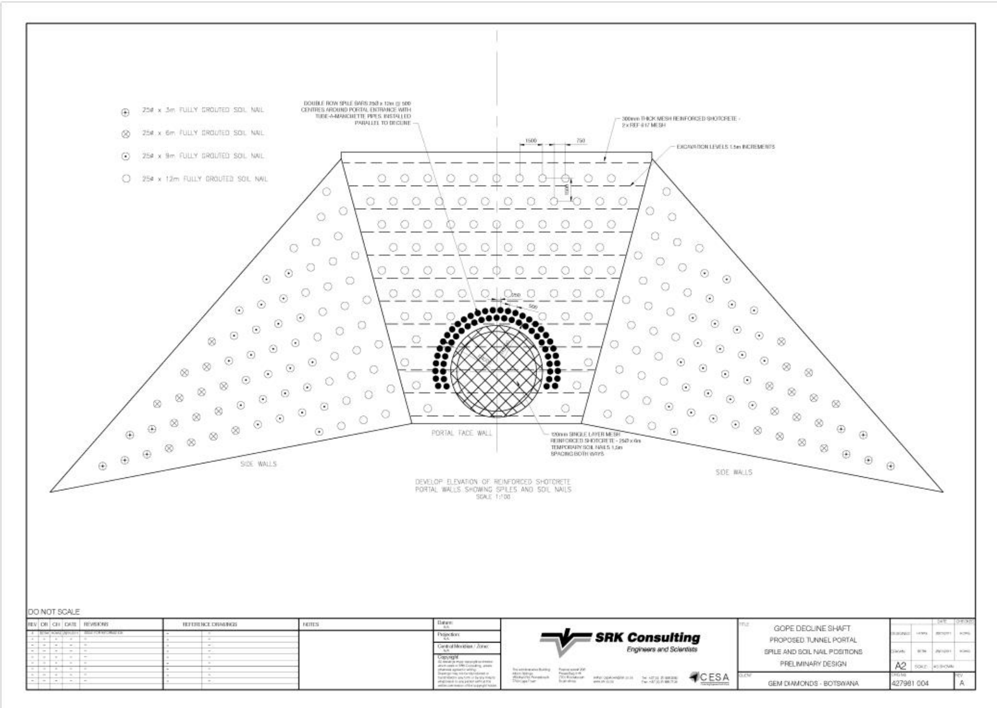

Figure 5: General support layout for the portal (front elevation).

Figure 6: Portal construction showing mesh installation prior to shotcrete placement.

7. DECLINE SHAFT DESIGN

A number of methods that have been used internationally to create tunnels in weak, poorly consolidated, ground were reviewed and a high level risk assessment was carried out on each of these methods with regard to their application to the decline at Ghaghoo. Key evaluation factors considered are safety, cost and schedule. The results of the evaluation are presented in Table III.

Using the scoring system to evaluate key parameters, the Open Face Shield (OFS) system was found to be preferable (manual shield). In this system, a narrow protective shield is advanced incrementally using hydraulic rams. The shield provides lateral support to surrounding ground while the face is exposed and advanced continuously. Excavation at the face uses mechanical or manual methods with waste material removed by conveyor. Once a certain amount of material has been excavated from the face, the shield is jacked forward using arrays of hydraulic rams acting against installed concrete segments to guide and maintain alignment. There is concurrent installation of a segmental concrete lining behind the OFS. This method provides for minimum risk with regard to safety, as personnel work at all times under cover of a steel shield.

Mining Method	Comment	Safety Issues	score	Cost Issues	score	Schedule Issues	score	total score
Conventional	Spiling with bolting and shotcrete	Falls of ground.	-3	Labour and time	-1	Slow advance rate	-3	-7
Pipe jack	High frictional resistance	Mechanised equipment	-1	Equipment and logistics	-3	Advance rate uncertain	-1	-5
TBM	Power and logistics	Mechanised equipment	-1	Equipment and logistics	-5	High advance rate.	-3	-9
Manual shield	Power and logistics	Face sloughing	1	Equipment and logistics	1	High advance rate.	1	3
Cut and cover	Additional earth moving cost at outset of project	Slopes	-1	Double handling of earth and tunnel construction	-5	Delay during construction	-5	-11
Open box cut	High volume of earth moving	Slopes	1	High volume	-3	Construction lead time	-3	-5

Table III: High level risk ranking of alternative decline development methods.

A two dimensional, plane strain numerical analysis was carried out to provide an indication of shear forces and bending moments that could be experienced within the concrete lining. Results of this analysis are presented in Figure 7 and Figure 8 for axial forces and bending moments respectively for a best estimate stress condition where the horizontal stress is 30% of the vertical stress.

Based on this analysis, a lining with a minimum thickness of 250mm and containing steel reinforcement at 114kg/m^3 with 50MPa concrete was recommended for overburden depths of up to 80m.

The OFS initially was constructed at the point of manufacture prior to disassembly and reconstruction on site to ensure that a minimum amount of engineering adjustment was required. Figure 9 shows construction in progress on site at the portal position.

Concrete segments were manufactured in Gaborone and transported to site. Figure 10 shows pre-fabricated segments in storage on site.

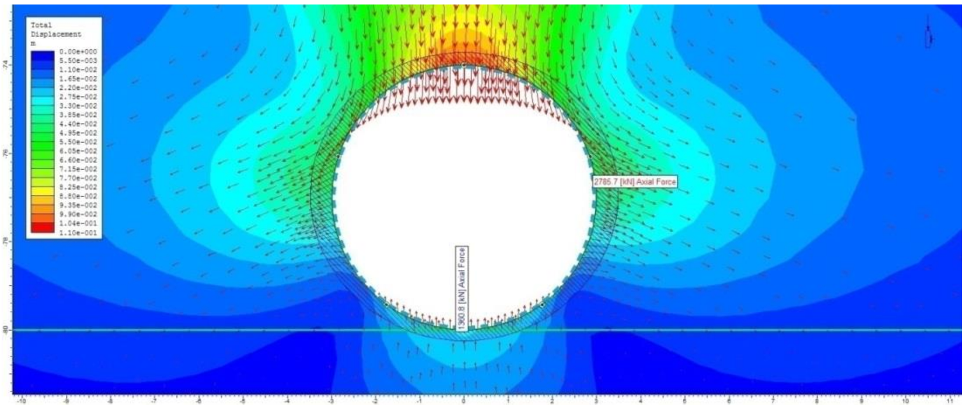

Figure 7: Segmental Lining: Axial Force and Displacement: $\sigma_x = 0.3\sigma_y$

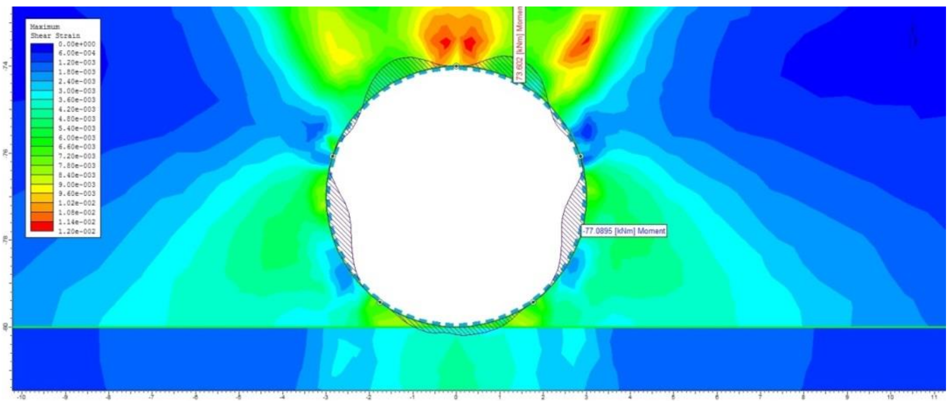

Figure 8: Segmental Lining: Bending Moment and Max Shear Strain: $\sigma_x = 0.3\sigma_y$

Figure 9: On-site assembly of the OFTS

Figure 10: Storage of concrete segments after transportation to site in preparation for underground assembly

8. PERFORMANCE OF THE DESIGN

Regular visual inspections of the decline shaft and associated infrastructure were made during construction. No significant displacements or deterioration were observed during construction nor since the concrete lined section of the decline through the Kalahari sequence has been completed.

In addition, regular survey measurement of monitoring points installed on the portal face, within the decline shaft and on surface from the crest of the portal to a point close to the transition zone has been undertaken.

In no cases have significant displacements or deterioration been observed. A general view of the decline shaft shortly prior to completion is presented in Figure 11.

Figure 11: General view of the segmental concrete lining in the decline shaft.

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