The Gautrain project requires a range of surveying experience stretching from shaft work, tunnelling, earthworks, stations, roads, precast, viaducts and cantilever bridges. It is rare for a project to require such multi-disciplinary surveying and for the various surveyors to work together as a team.

The Gautrain Rapid Rail Link Project is a new 80 km railway system linking Johannesburg, Pretoria and Johannesburg International Airport (JIA). The R25-billion project was designed with the intention of alleviating traffic congestion in the busy road corridor between Pretoria and Johannesburg. It is expected to provide the backbone to an integrated public transport system, with taxis, buses and Metrorail playing a central role.

The requirement that Gautrain’s travel time on the 57 km section between Johannesburg and Pretoria be below 38 minutes, requires the train to travel at maximum speeds of up to 160 km/h. The feasibility study indicates that the demand for such a rail service could exceed 70 000 passengers daily. The system will also provide access to the country’s existing rail network, via links with Johannesburg Park Station and the Pretoria Ring Rail System.

The main Gautrain stations are to be located in the Johannesburg CBD, Rosebank, Sandton, Midrand, Centurion, Pretoria CBD, Hatfield, Kempton Park and OR Tambo International Airport, with an extensive feeder and distributor system linking a wide range of other areas to the system. Parking garages (for park-and-ride) have been planned at most of the stations.

The route length for the core system will be slightly longer than 80 km and this does not include the track lengths in the maintenance depot. Most of the track will be double line with bi-directional signalling, but this may be phased in with some sections of single line, particularly where there are tunnels or viaducts.

The project has been implemented as a Public Private Partnership and includes financing, design-build, operation and maintenance. Gautrain will be transferred back to the Gauteng Provincial Government at the end of the concession period, which consists of a 5-year construction period followed by a 15-year operating period.

Contractors
Bombela Concession Company is the contractor for the Gautrain Rapid Rail Link Project. The consortium is made up of a partnership between Bombardier Transportation, Bouygues Travaux Publics, Murray & Roberts, and the Strategic Partners Group.

Planning process
As part of the planning process, Bombela started with some geological investigative work, which included geological drilling and logging, the conducting of survey work, the erection of survey beacons and the undertaking of environmental studies. Survey beacons were placed on ground level to act as physical pointers for the final drafting of the train’s path.

A team of surveyors and Bombela specialists visited the targeted work areas along the Gautrain alignment to inform the residents of the surveys and to request permission to access their properties to conduct the surveys.

The enabling works got underway in mid-May 2006 with the scope of the work including the upgrading of roads, demolition of identified buildings, the installation of site offices and pre-design surveys. Some of this initial work included the surveying of the positions of the various utility services that were positioned in areas where they would impact on the construction of the Gautrain.

Utilities
During the planning process government and managers of utilities such as Eskom, Telkom, Rand Water,
SURVEYING technical

Fig. 2: A view of viaduct 3 which is awaiting final adjustment.

Egoli Gas and cell phone providers agreed to work together on the movement of utilities to make way for the Gautrain. It was standard practice on the project to relocate all services prior to construction works to ensure continued uninterrupted services during construction activities.

Many utility services had to be moved to make way for the Gautrain but only where necessary due to the costs involved. For instance, an electricity pylon in section DPS is sitting right on the edge of a cut but instead of moving it unnecessarily, its foundations were reinforced with concrete and it will remain in position alongside the track.

Surface surveying

Surface surveying of the Gautrain project involves 21 surveyors whose responsibilities cover construction surveying, earthworks and substructure controls. Any construction activity performed on the Gautrain project needs to be coordinated by the survey department, and all surveying work is conducted according to the design specifications provided by the Committee of Land Transport Officials (COLTO).

The Gautrain project has been divided into sections with a chief surveyor allocated to each section as follows: DP4 Aidan Lynch, DPS Antonie Kruger, DP6 Norman Lincoln and DP7 Piet Meyer. Robert Agnew is the segmental survey manager responsible for the construction of the viaducts while Glen Gover is the precast senior surveyor responsible for preparing the segments for the viaducts. (See Fig. 1)

The original ground survey was conducted via aerial photogrammetry to provide an original ground terrain model for design purposes. The terrain model was re-measured prior to construction using RTK GPS and conventional total station to define the construction payline. Survey control network beacons were established using static GPS. The project projection is a Traverse Mercator system with the coordinate system being unique to South Africa (based on LO) with the central meridian of long 29 and the datum being Hartebeeshoek 94. The whole of the project falls within the 1 degree band either side of long 29.

The surveying equipment used on the Gautrain project comprises mainly of Topcon 9000 robotic total stations. Topcon Hyper Pro RTK GPS systems are used for bulk topographic surveys and earthworks set-out. These receivers are GPS and GLONASS capable. The GLONASS constellation’s availability reached a maximum of two to three satellites due to the southerly latitude of the project and the preset elevation mask of 15 degrees to avoid very low satellites.

Trimble S6 one-man stations were selected as the instrument for the earthworks survey teams. This configuration puts the surveyor at the prism. It was found that the Trimble Controller Software was best suited for this application. It increased productivity of the survey teams and reduced survey blunders. Topcon’s electronic level (DL-101) was selected as the precise level and the ATG4 workhorse as the production level.

Due to the size of the project, managers and decision makers require accurate and timely results from the surveyors to plan and forecast activities to deliver milestones on time. Keeping this in mind, it was decided not to standardise the project on a single software solution, but to give the survey teams the tools they are familiar and productive with. The software solutions used are Terra Model, Model Maker, Civil Designer and Surpak. This eliminated the immediate need for intensive training and increased the reliability of the results from the survey teams.

One of the more sophisticated technicalities on the project was analysing and designing the noise mitigation. This involved compiling a 3D digital model of the design merged into the original ground model delivering a digital terrain model of the completed project. Other features added for consideration in the simulation were tall buildings, bodies of water and any other large structure that would influence the propagation of sound. The model was then handed over to the acoustic engineers who ran a simulation on the model to determine where the noise barriers would be required along the Gautrain line. This is the first time this has been done so extensively in South Africa.

As-built surveys are conducted on a monthly cycle for the whole Gautrain project. (An exception is the viaducts, where as-built surveys are only performed once the viaducts have undergone their final adjustment and are aligned and in position, see Fig. 2.) The as-built surveys are also used to control and verify the earth works performed. One specialised person per site has been made responsible for monitoring the quantities and reporting these.

Earthworks

The Bombela Civils Joint Venture is expected to excavate more than two million cubic metres of material as part of the earthworks and tunneling activities on the project. This volume
will be used as fill material in other areas along the alignment but there will still be some excess material which will be spoilt and shaped at designated spoil sites.

The Concor CSU joint venture is responsible for the bulk of the earthworks on DP5. They are using the Trimble RTK GPS (R8) system to setout the earthworks. Scribante is the main earthworks subcontractor on DP4.

Surveying on the earthworks starts by placing the toe pegs for the alignment. This represents the intersection point of the design side slope (batter slope) and the natural ground line. The earthworks plant moves in and removes the organic topsoil between the pegs and stockpiles this material where it can be recovered to replace on the batter slopes. Once the topsoil is removed, the cut or fill process is started. The height of the fill or depth of the cut is monitored by production until it reaches the design elevation.

The next step is placing the layer works on the earth works. This usually consists of four or five layers (200 mm thick) of various grading of gravel or crushed stone. Each of these activities starts with the survey team placing survey control for production to build the product to design requirements and is well defined in the COLTO specification.

The primary control network is audited every six months while the secondary network is re-measured every three months.

Surveyors on the project worked with precise level traverse from the national benchmarks using digital levels with a maximum tolerance of 2 mm per kilometre for a return run. The leveling is redone every three months to check any movement of the primary control beacons.

**Viaducts**

Construction for the Gautrain has involved the building of the first segmental viaducts in South Africa. Viaducts are distinctly designed, multi-spanned bridges for rail over roads, rivers or valleys. Altogether 10,5 km of viaducts will be constructed.
on the 80 km route of Gautrain. Construction of these viaducts has provided some interesting surveying challenges.

**Building of viaducts**

Construction starts with the assembly of the viaduct substructure. These are the piers (pillars) that the whole viaduct rests on. They are founded either on a mass concrete base or piles (reinforced concrete shafts). The type of foundation is determined by the geological investigation to determine the type of underground formation. Extensive geological investigations were conducted prior to foundation design. The piers are poured in lifts of 3 m. Before every pour a pre-concrete check needs to be performed on the shutter (concrete mould). This check comprises a series of observations that provide on the spot results (see Fig. 3).

Firstly, the horizontal position was checked by comparing the design position of the pier corners to observed positions in the field. None of the corners were allowed further than 20 mm from theoretical position. Secondly, the elevation of the shutter was compared and had a tolerance of 5 mm from design elevation. The third and final check was verticality. The shutter was tested for verticality on two of the four sides. Verticality needed to be less than 10 mm per 3 m lift. Only once all these parameters of the shutter are confirmed, can production proceed with the concrete pour.

Once a pier is securely in place, construction of the viaduct span can start. Segments make up a span and these are put on piers. The average length per span is 50 m with each segment being 2,5 m in length (see Fig. 4).

The segments that are the precast building blocks of a span are lifted onto a bridge crane – girders know as Hakuna and Matada – that rests on two piers that will eventually hold the span. The segments are glued together with an epoxy. Once the whole span is glued and aligned, it is prestressed. During prestressing, steel cables, running through the concrete sections in prestressing ducts, are put under tension and anchored at the ends. This method of reinforcement is ideal for the needs of a rapid rail link where viaducts need to accommodate two rail lines for trains travelling in both directions at a maximum speed of 180 km per hour.

**Surveying work on the viaducts**

Due to topography, each viaduct is built at a different elevation. Each span on a viaduct has its own particular projection scale factor (scale and sea level correction). The design length of a span is given at sea level and this has to be adjusted by the surveyor to achieve the correct ground length.

Measurements in the precast yard where the segments are made and stored have to be extremely accurate (see Fig. 5). The senior precast surveyor is responsible for monitoring the dimensions of the segments in the precast yard. To facilitate surveying work in the yard the survey beacons in the precast yard are 4 m in height to ensure that the entire casting bed can be seen when taking measurements (see Fig. 6).

A method called match casting is employed in the PCY (precast yard) to ensure a perfect fit between segments. The process is as follows:

Firstly the SOPs (segment on pier or the first and last segment in the span) are poured on the short bed. This is a shuttering system that encloses the segment from all sides and almost all the sides are adjustable. This assures the correct size and shape of the first and last segment of a span. Secondly the two SOPs are moved onto the long bed. They are placed in the exact position that would represent the span length on the viaduct. Thirdly, these segments are then used as the one end of the shutter for the next segment. The next segment will be poured up against the SOP – hence match cast.

Every segment has four geometric control points that are drilled into the green concrete, while the segment is still on the casting bed, at predetermined positions. After every pour, the positional relationship of a matchcast pair is measured and recorded. Multiple sets of observations are performed and a standard deviation of less than 0,5 mm must be achieved before a set is accepted. Once a span is completed on the long bed, the geometric relationship of all the segments in the span is known. This data is then used by the viaduct erection survey team to launch a span by replicating the geometric relationship between the segments recorded in the PCY.

Various variables are considered during the pouring of the segments and assembly of a span on the viaduct. The first being concrete shrinkage. Second is the projection scalefactor – on average on the project this is about 15 mm/100 m). A third factor of sufficient magnitude is the thickness of the epoxy (around 1 mm/joint = 19 mm per span). An additional factor that has to be taken into account during span launching is the temperature effect of 6 mm per 10°C for a 50 m span. Expansion was taken into account during the design phases and provision was made for 50 mm expansion joints between the spans.
Three survey processes are involved during the construction of the viaducts and monitoring of the work is done using conventional total stations and precise levels. Local system survey is used when erecting the spans (pier to pier) and the spans are then finally adjusted using project control beacons. Simple techniques are employed to minimise errors due to production pressures.

The segments have prestressing ducts and 12-strand steel cables are run through the length of the span for prestressing. After the prestressing process the span will experience up to 80 mm of hogging (deflection) in a 50 m span. Most of the deflection will subside once the viaduct is loaded with the ballast and the track. When setting the bearings and the parapets, the creep and shrinkage of the concrete and hogging of the spans needs to be monitored.

Once the span is completed, it is lowered onto temporary hydraulic jacks on the piers. These jacks are the means for final positional adjustment of the span. The temporary jacks are removed once final adjustment is completed and the span lowered onto the bearings on the pier.

**Monitoring**

Monitoring has been another big part of the job on the Gautrain with surveyors having to keep an eye on several factors:

- **Hogging** – steel cables are run through prestressing ducts in the segments and when the cable is tensioned there is up to 50 mm of hogging (deformation) in a 50 m span.
span. Due to continual concrete shrinkage, the hogging increases over time up to approximately 80 mm. When the ballast for the rail is added the hogging goes down 25 mm.

- **Dolomite** – structures erected in dolomite areas require extra attention due to the possible presence of cavities. The underground formations have to be tested and the results determine the foundation to be used. Heave monitoring is performed to determine the amount of movement around the pier foundations in dolomite areas. Sensors built into the final structure will monitor any subsequent movement of the concrete.

- **Pier sites** – each block weighs 10 tons and each pier site is loading 1000 blocks making it vital that the pier area be monitored for subsidence. First the pier area is preloaded with the blocks and then the area is unloaded. Following this the area is grouted with concrete and then monitored again for ground heave. The survey data obtained is included into the foundation design of the pier.

- **Newly built structures** – all new structures are monitored up until the project is complete. This is particularly important for those structures built in the dolomite areas. Monitoring of all newly built structures will continue on a regular basis as part of maintenance work.

### Independent certifier

Arup was appointed as independent certifier (IC) for the Gautrain project in October 2006, and will play a significant role on the project over the five-year period.

The company is responsible for certifying all the work that has been carried out on the Gautrain project. Its basic responsibilities, in terms of the IC agreement, include: certifying milestones, high level monitoring of construction and review of designs, certifying that operating commencement dates for phases one and two have been achieved, and issuing a certificate of final completion.

A key role for Arup is the certification of milestones. Payment to Bombela is based on more than 1000 milestones over the duration of the contract. Arup is responsible for going through the milestones that are put forward for approval and interrogating them by looking at the criteria for achievement in terms of the concession agreement and then deciding independently if the criteria have been met. If that is the case, the IC then approves the milestone.

### Surveying challenges

The surface surveying team have encountered several challenges while conducting the surface work for the Gautrain. The project is linear and long, and despite being divided into different construction sectors i.e. DP5 and DP6, it is vital that the survey controls for the various construction areas fit together. This makes scale factors important as well as sea level correction and the surveying team has to constantly bear this in mind. It is therefore vital that the whole team understand the geodesy limitations and the projection scale factors.

Another challenge on the project has been the constant design revisions. The design teams are working to tight time constraints and site conditions create scenarios that require design changes. Keeping track of design changes from revision to revision and the amount of work performed on each revision can be a daunting task. Before a new design can be implemented, a snapshot of the progress on the previous design has to be taken (complete progress survey) to be able to quantify the progress on the revision. This has a two-fold purpose – firstly to quantify what has been done according to the previous design and secondly, what is still outstanding according to the new design for planning and programming purposes.

A positive example of a design change is viaduct 2, over Modderfonteinspruit, near Midrand. Initially the structure was intended to be a viaduct, but design recalculations indicated that it was possible for it to be a conventional structure resulting in major time and cost savings.

The biggest surveying challenge on the project has been the need for a wide spectrum of skilled surveyors. It is not often that a project requires such a range of surveying experience stretching from shaft work, tunnelling, earthworks, stations, roads, precast, viaducts and cantilever bridges. It is rare for a project to require such multi-disciplinary surveying and for the various surveyors to work together as a team.

Another critical challenge has been the lack of experienced local surveyors available to work on the project. This is not a problem isolated to surveyors. To combat this problem, bursaries have been made available for students in engineering and related disciplines.

Several of the surveyors working on the project have recently qualified as surveyors and are gaining valuable experience on the project. In addition members of the construction chainmen have received training in basic surveying with four having recently passed their assistant surveyor exams. These four are now working as part of the leveling team responsible for constantly measuring up and down the length of the project (see Fig. 7). Members of the surface surveying team on the Gautrain report that it has been a very positive experience to share their surveying knowledge with these former chainmen.

### Acknowledgement

I would like to thank Antonie Kruger in particular for his assistance with the writing of this article as well as Robert Agnew, Glen Gover and Norman Lincoln.

Contact Antonie Kruger, Chief Surveyor-DPS, Bombela CJV, Tel 083 677 7928, antonie.kruger@bombelacjv.com