A review of current practices of survey control in sinking shafts in Southern African operations

by E. Vascotto[1], S.M. Rupprecht[1], H.C. Grobler[1]

Affiliation:
[1]University of Johannesburg, Gauteng, South Africa

Correspondence to:
S.M. Rupprecht

Email:
rupprecht.steven@gmail.com

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ORCiD:
S.M. Rupprecht
https://orcid.org/0000-0003-2462-2819
H.C. Grobler
https://orcid.org/0000-0002-4729-5753

Abstract

Shaft sinking survey practices in Southern African mining operations have been refined over many decades to meet the stringent accuracy, safety, and productivity demands of deep vertical excavation. However, much of this specialised knowledge remains poorly documented, and the decline in new shaft sinking projects presents a risk that these proven practices may be lost to future generations of mine surveyors. This paper reviews and synthesises current survey control methodologies employed during shaft sinking operations, with particular emphasis on the establishment and maintenance of surface and underground control networks, shaft verticality control, and elevation transfer. Traditional techniques, such as plumb-wire plumbing systems, steady brackets, and calibrated steel shaft tapes, are discussed in detail, alongside quality control principles and common sources of error affecting coordinate transfer. The paper further examines the integration of modern technologies, including total station resections and LiDAR-based laser scanning, highlighting their benefits, limitations, and practical constraints in active shaft environments. By documenting both established and emerging practices, this review aims to preserve critical institutional knowledge, support consistent survey standards, and provide guidance for accurate spatial control throughout the shaft sinking lifecycle.

Keywords

shaft sinking, mine survey control, vertical alignment, LiDAR technology, geodetic networks

Introduction

Shaft sinking practices in Southern Africa are well established. Contractors and mining houses have refined the standards and procedures used in the spatial control of shaft sinking, construction, and infrastructure development over the past decades. These procedures are not always documented well, and as the number of sinking operations decline, there is a significant risk that this hard won knowledge may be lost to new generations. This paper summarises current shaft sinking survey practice, and although it does not claim to be a complete summary of the science, it reflects current practices and future developments.

Shaft sinking involves excavating vertical shafts in the earth's subsurface, typically for mining or construction purposes. Shaft sinking is a costly and time consuming operation. Time schedules and sinking progress are usually linked to contractor performance contracts and individual performance bonuses. The hazards in vertical shaft sinking are numerous and can be considered high-risk.

To ensure a streamlined sinking process, surveying the shaft regularly and accurately is essential. The aforementioned factors mean that a surveyor will be expected to perform work at specifically scheduled times with only a limited time to perform the work while at the same time requiring the highest levels of repeatable accuracy in the establishment and extension of survey control (Zagibalov et al., 2015) for sinking, construction and level establishment. Time lost due to work taking too long or having to be repeated can amount to significant financial losses.

Shaft sinking surveying typically involves establishing a control network on the surface, measuring the initial position and orientation of the shaft, and conducting regular surveys to monitor any changes in position or orientation. It also involves monitoring the stability of the ground around the shaft and measuring the size and shape of the excavation. It consists of establishing a control point at the surface, measuring the initial position and orientation of the shaft, and conducting regular surveys to monitor any changes in position or orientation. Another critical aspect of shaft surveying is measuring the excavation's size and shape, typically done using a scanner or laser profiler, which can generate a three-dimensional excavation model. The model can monitor the excavation's progress and ensure it is carried out according to the design specifications.

The functions performed and techniques employed in shaft surveying

Contractors and mining houses have refined the standards and procedures used in the spatial control of shaft sinking, construction and infrastructure development over the past decades. The following primary procedures are required during sinking operations. The techniques employed in shaft surveying include:

- *Geodetic control*. This technique establishes a precise measurement reference framework. It involves using global positioning systems (GPS), total stations, and other surveying instruments to establish control points with known coordinates. These control points are the foundation for all subsequent measurements and calculations in shaft surveying.
- *Control of verticality*. The principle of verticality is crucial in shaft surveying to ensure the shaft is accurately aligned along the vertical axis. It involves measuring the deviation from the plumb line at various shaft depths, typically using plumb bobs, electronic inclinometers, or laser-based instruments. Ensuring verticality can address issues such as shaft convergence or deviation.
- *Elevation control*. Precise levelling determines the relative heights or elevations of different points within the shaft. Precise levelling instruments and multiple observations, using automatic or digital levels and shaft tapes, measure the differences in height between reference points. This allows for the creation of accurate vertical profiles and cross-sections of the shaft. The elevation of all underground excavations is transferred from surface benchmarks using these methods.
- *The establishment of underground survey networks*. On each level using surveying techniques, including traversing and resections. Traversing involves measuring horizontal angles and distances between points within the shaft. Traversing enables the creation of accurate plans and maps of the shaft, including identifying key features such as shaft stations, equipment locations, and access points. This is essential to accurately position the development infrastructure to the orebody model to ensure compliance with the mine design.
- *Laser scanning*. Light detection and ranging (LiDAR) technology is increasingly used in shaft surveying to capture detailed three-dimensional (3D) data of the shaft interior. Laser scanners emit laser beams that measure the distance to various surfaces, creating a point cloud representation of the shaft. This data can be used for precise measurements, visualisation, and analysis, including detecting deformations or structural issues. Laser scanning produces point cloud data that can be used for excavation over- and underbreak, design compliance, and mapping geotechnical structures in the excavations.
- *Survey data*. Whether obtained through traditional surveying methods or laser scanning, need to be processed and analysed. This involves applying mathematical calculations, coordinate transformations, and specialised software to create accurate plans, profiles, and digital shaft models. Data analysis helps identify discrepancies, deviations, or potential safety hazards.
- *Quality control*. Principles are essential to ensuring the accuracy and reliability of the survey measurements. These include regular calibration and maintenance of survey instruments, adherence to standardised procedures, and cross-checking measurements to validate consistency.

Network establishment

Survey control must be brought in from the national survey system and continuously maintained, upgraded, and cross-validated. The survey control on site, generally through a global positioning satellite (GPS) network, will be brought into the shaft sinking area from trigonometrical beacons and GPS surveying. Where the network has been established by GPS, global navigation satellite systems (GNSS), the coordinate system employed, the projection, ellipsoid, scale factor, datum planes, and vectors must be saved in a calibration file. It must also refer to the beacons used or excluded. The calibration file and any changes made to the file must be documented and stored onsite and offsite, as well as a hard copy.

Prior to sinking, the geology and ground structure is determined through exploration boreholes. The shaft will be positioned so as to not sterilise the orebody or create unforeseen complications during the sinking process. The accuracy of boreholes should be confirmed through down-hole surveys (Bennett, Livingstone-Blevins, 2015) with suitably calibrated instrumentation. In most cases, modern shaft sinking will include shaft lining. The use of lining requires that all survey control in the shaft be of a high standard of accuracy. In most cases, the surveyor will be responsible for accurately measuring and reporting progress for the payment of contractors, measured from the controls established by the surveyor.

Minor errors in establishing control in the shaft can have significant consequences when survey networks are transferred underground on different levels. The error limit for mine orientations in South Africa is 2 minutes of arc (DMR, 2011). To meet this standard, several factors will influence the accuracy of the survey, and as a result, care must be taken in transferring coordinates through shaft plumbing methods. In some cases, too much attention was given to the transfer of coordinates onto a level while the plumbing procedure was not given adequate attention.

A network of site beacons should be established with mine beacons constructed of solid concrete pillars approximately 1.3 m tall. A permanently fixed, brass or stainless steel, UNC 5/8 – 11 or metric threaded adaptor, which will enable the threading of a survey instrument onto the beacon, is recommended. The location of beacons should, as far as possible, be determined in such a way that it will not be obstructed by construction at a later stage. It must be kept in mind that shaft sinking is a capital-intensive, long-term investment, and all structures and survey networks should be planned in such a manner as to provide a service for the life of the operation. The mine surveyor will be responsible for staking out the shaft positions and surface infrastructure. At this point, a gyro baseline check should be performed to verify the accuracy of the azimuth determined by GPS prior to sinking activities commencing. Bennett and Livingstone-Blevins (2015) noted the need to transform the mine survey coordinate system to a local engineering survey system due to construction requirements. In such cases, the engineering team must consider and verify scale factors and swing to ensure compliance and accuracy.

The accurate orthometric elevations of benchmarks must be confirmed by a closed levelling traverse, preferably with a precise level and adjusted by least squares, if required. This elevation will be transferred down the shaft and used as the reference line for all construction in the shaft, which will be transferred to the underground levels.

Surface network for the shaft collar reference line

A reference line is established across the shaft collar position. Some recommend LiDAR to ensure that this reference line is staked out parallel to the intended axis of the winding engine axis and a second line perpendicular to this line. Beacons must be placed and constructed so as to not be obstructed or damaged during the sinking process. These beacons will be used as the reference network for all construction in the area (Subbotin et al., 2003). It is prudent to ensure that external sightlines to reference beacons are visible to replace beacons that will inevitably be removed or damaged. It must be remembered that winder houses, headgear, and other shaft infrastructure will inevitably obstruct clear sight lines on the bank area. A line of beacons should ensure redundancy on either side of the shaft collar. It is recommended that a minimum of two, preferably three, beacons be spaced on each side of the line. Some sites prefer plinths or short pillars to prevent damage and ensure visibility. Each beacon must be distinctly marked and numbered. Figure 1 indicates the external survey network to establish shaft beacon reference lines.

Contract agreements typically predetermine the required accuracy level for all survey work and will be site-specific. The normal MHSA limits of error for a Class "A" survey will not be adequate for engineering construction in the shaft. The standard of accuracy of 2 mm for surface control networks and 3 mm for construction surveys, as quoted by Bennett and Livingstone-Blev (2015), appears to be an example of the industry norm. It is essential to realise that the accuracy of the survey equipment used on site will directly influence the achievable accuracy of the project and the achievable accuracy should be communicated to the project team.

Pre-sinking stage and collaring

Once the centre of the shaft is located and the corners are marked off, survey pegs should be installed that allow the centre to be located using wire strings crossing over it. It is essential to monitor any changes in the position and orientation of the shaft over time. This can be done by conducting regular surveys of the shaft using the same instrument used for the initial study. Sinking operations can commence at an approximate depth of 15 m – 20 m once the shaft collar is constructed and set in concrete. Once the shaft collar and sub-bank floor have been established, four survey pegs are installed on the sub-bank floor close to the shaft collar or on the shaft collar if there's no sub-bank.

After the overburden has been removed, the barrel has been concreted and positioned, the shaft plumbing steady brackets and tape brackets are ready to be installed. The position of plumbing brackets must be verified, based on the shaft construction design and site requirements, and staked out very accurately. Plumb wires are used to transfer the survey network underground (Subbotin et al., 2003) and ensure the verticality of the shaft sinking process. Several synchronised electric plumb bob winches (Figure 1) are surveyed around the shaft perimeter. Freely hanging 30 kg to 40 kg plumb bobs used to reduce the amplitude of the swinging wires are suspended on 1.6 mm high tensile carbon steel wire, colloquially known as "piano wire". The number of winches depends on the shaft diameter and design. It is typically between four and seven but can be up to ten or more. The accurate positioning of these points is important as all measurements in the shaft are made to the plumb wires, and these wires are used to transfer the survey network underground (Grobler, 2022).

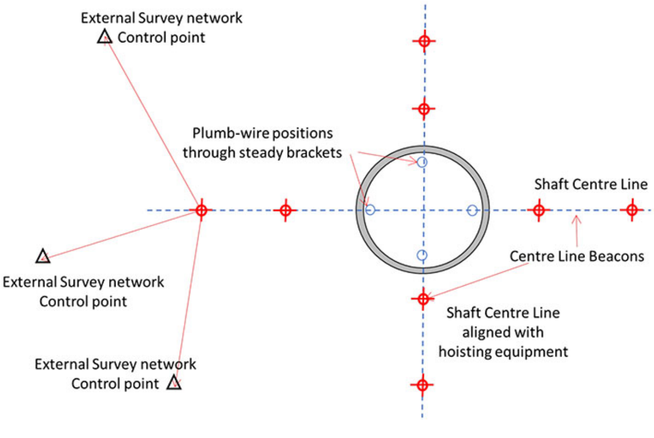

Figure 1—External network control to establish shaft beacon reference lines (Grobler, 2020)

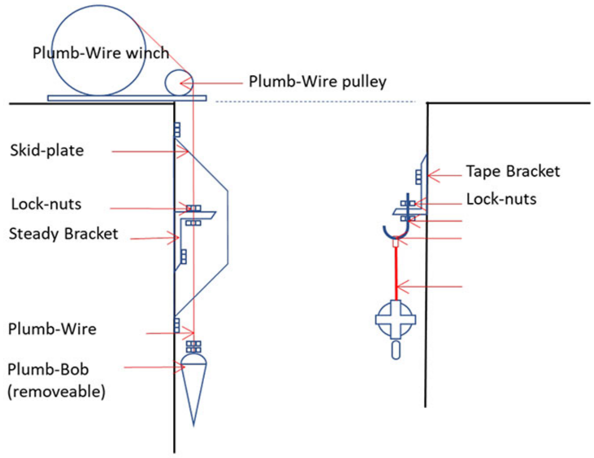

Figure 2—Cross-section of the shaft barrel and shaft plumbing surveying equipment (Grobler, 2020)

Plumb bob lines mark out the shaft outline to control the verticality of the shaft barrel during the sinking and all construction activities. Plumb wires are the only way the surface survey network is transferred into the underground workings. Plumb bob lines are hung at pre-prescribed points along the shaft's perimeter according to the shaft's engineering design. Shaft brackets are welded on the collar set frame, and tiny holes are drilled to allow the plumbing wires to pass through. To fix the positioning of the plumb bob lines, a mark on the required supports (obtained from the calculation of the joins) is drawn. At least three marks on the metal plates are scribed on the plumb lines' positions around the perimeter of the shaft. A small hole is drilled through the plate to accommodate the plumb line at the intersection of the drawn lines. Once all the holes have been drilled, the plumb lines are inserted through them and brought to the position where the first set of fixed supports will be installed.

The surveyor establishes the first set of steady brackets installed at collar level (on collar set), ready for sinking (reference point for sink). Plumb bob lines are installed on the perimeter of the shaft in predetermined locations and fastened by special clamps anchored to the shaft lining called "steady brackets" (Figure 2). These clamps are protected against objects that could knock against or fall on them by a heavy gauge steel bracket called a skid plate. The brackets are sometimes fastened onto the lining on the perimeter of the shaft using nut boxes cast in the lining or drilled in fixed anchors in unlined shafts.

When equipping the shaft, all permanent accessories such as guides, pipes, ventilation ducts, loading boxes, and accessories for the lifting equipment are aligned using plumb lines. Plumb bobs are used to maintain verticality and alignment of the shaft, pipework (concrete slick lines, services), and the position of the curb for the concrete lining. Steady brackets are installed at 100 m to 150 m intervals below the first set to ensure alignment from plumb bob (static) wires.

Steady brackets (plumbing brackets)

Steady brackets are used to fix the plumb-wires' position and, if extended regularly, can account for airflow, vibration, spiral deformation, and convergence effects. A steady bracket is a bracket designed to allow the plumb wire to maintain its position and, at the same time, allow the wire and plumb bobs to be raised and lowered without losing their position. The steady bracket has a hole of around 30 mm diameter in the centre and a wire positioning bracket and lock nut to fix the position of the plumb wire (Figure 3). The locknut allows the plumb wire to pass through the nut for raising and lowering purposes without moving in the x or y plane. Steady brackets are planned for and installed in pre-calculated positions in the shaft lining. A numbering sequence for the steady brackets and plumb wires is determined by the site requirements. It is expected to number the steady brackets in a clockwise direction from the first bracket closets to the north (N) orientation. Steady brackets are extended based on site-specific requirements, but should be extended regularly to reduce excessive swing before being fixed again.

In some instances, a cylinder of a slightly larger diameter than the shaft plumb bob is bolted a short distance below the steady bracket, and the plumb bob is inserted in the cylinder filled with oil to dampen the effect (JCI, 1990).

The bracket consists of a hole with a second slotted section that can be slipped over the wire. Once the position of the wire has been determined by measuring the swing, the position is bolted, and the bracket is welded or brazed into position. This allows the wire to move through the bracket without being affected by swinging and cannot be moved (Kirby, 1952).

Brackets restrict the plumb bob movement around the suspension point as the wires tend to oscillate in turbulence from airflow, gravity, blasting, and the movement of shaft conveyances. Catch baskets are placed underneath plumb bobs in case they come loose, and shaft ventilation is ideally switched off during the outset, as this affects the movement of the wires.

Adjustment bolts, nuts, and spring washers are placed on the plumb line bracket before the plumb lines are attached and left to hang free by the fixed brackets. Steady brackets are fastened to the lining using the designed fixtures inserted onto the concrete lining, then moved horizontally until the plumb lines hang in the centre of the fixed brackets and are tightened.

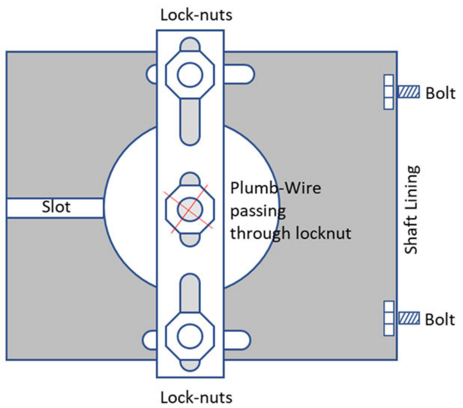

Figure 3—Idealised plan view of a steady bracket for shaft plumbing (Grobler, 2020

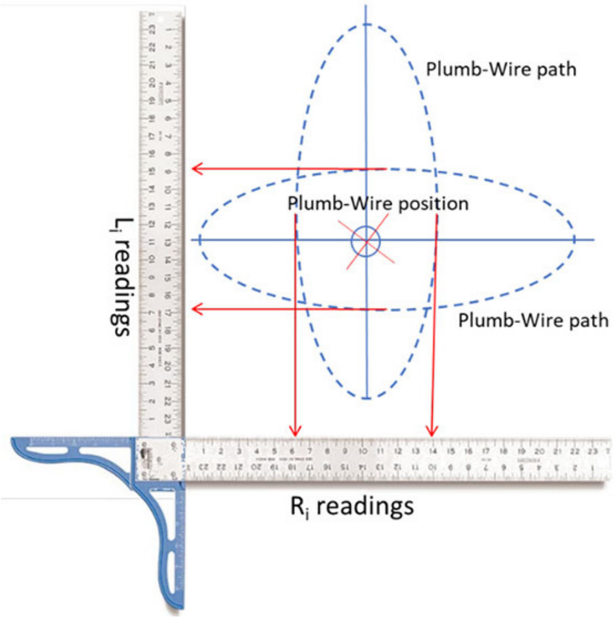

Figure 4—Measuring the swing amplitude to determine the final wire position (Grobler, 2022)

To facilitate accurate measurements, steady brackets can be provided with fixed measuring 'stubs' from which the oscillation of the plumb wire can be accurately and repeatedly measured. Steady brackets at most operations seem to be extended once for every two tape bracket extensions. The length of the shaft tapes will determine the maximum extension lengths and should be extended for a reasonable period before the maximum length of the tapes (normally 100 m) is reached.

Measurements of the plumb wire swing are made, and the readings are averaged to determine the wire's final position. This process is repeated for every plumb wire at that level.

Two methods exist:

- A straight mathematical average of the swing readings on the scale (Equation 1) or;

$$finalposition = \frac{\sum Swing\ Left + \sum Swing\ Right}{2} \qquad [1]$$

- A Shuler-mean of the readings

The cross-measurements must agree with the calculated 'join distance' between the wires, as determined from the coordinates of the original shaft design, and the final wire positions on the surface. If the measurements do not agree, the process must be repeated until the measurements agree to within 2 mm, 0.05% of the distance (IMSSA, 2001) or whatever site standard is required. The defective plumb line is identified by examining the differences (greater or lesser than needed). For example, if all the distances between the lines from 1 to 8 are correct, but the distances of the number 9 line do not match, the line needs to be inspected and adjusted. Wires must be checked for fouling and abnormalities by measuring the interwire distances before making any observations. Once clarified, the plumb bob line is released from the adjusting nuts on the steady bracket, allowed to oscillate freely, and re-adjusted. The measurements between all the lines are retaken and recorded. The interwire distances are measured and recorded (Figure 5) and should agree with the join distance between the wires.

Standard taping procedures, such as checking for sag, must be followed meticulously. If a specific error on one of the plumb wires

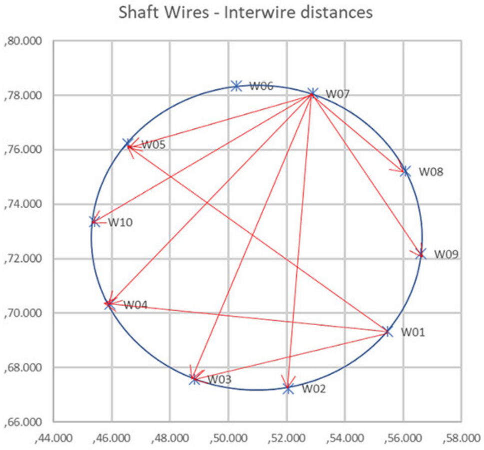

Figure 5—Shaft wires – interwire distances

is noted, the wire must be inspected for damage, re-swung and the measurements repeated. Only once all the wires have been verified will the brackets be fastened with lock nuts into the final position, and finally, a skid plate will be installed over the bracket.

The curb ring form is checked for alignment to the vertical wires and checked for level. Care must be taken to ensure no movement occurs during the concrete pour, as the sudden addition of concrete may cause the ring to shift out of alignment. The surveyor will check the alignment of the curb ring when a lift is poured. These operations are time-sensitive, and the surveyor will be on call-out for this operation. The surveyor checks that the plumb wires do not foul and that the tape brackets are correct and undamaged. The surveyor must allow for any sagging that may occur during the concrete's pouring.

Free station method of fixing wire positions

A setup near the shaft centre using the software application, using all the shaft wires for orientation, is made with a total station mounted on a bracket specifically designed for this purpose. The set-up position is determined from observations and reflectorless measurements of the free-swinging wires in the shaft to determine the calculated position of the instrument using a resection. Several combinations of resection observations are made to determine the reliability of each wire in the survey. The onboard free station or resection software can identify any wires that do not meet the level of accuracy. If a wire is identified as causing an error in the resection position, this wire is considered unreliable and removed from the resection observations. Once the instrument's position has been determined to the required accuracy, the final wire positions for the steady brackets are staked out (Shaft Sinkers, nd). Wire positions are staked out from the shaft coordinates and bolted and welded into a steady bracket to fix the position of each wire. A final check of the position of each wire is made and compared to the staked-out values. Any deviations are corrected, and the final wire positions are surveyed. This method of positioning shaft wires is deemed far more accurate than conventional observations of shaft wire 'swing' to determine the shaft wire position.

Tape brackets

Once the shaft collar and sub bank floor have been established, the first tape brackets can be installed. The plumb wires provide horizontal coordinate transfer into the shaft; as long as the lines remain plumb and unaffected by external influences, the position of the plumb wires on the surface should translate to the same spatial position at the shaft bottom. The transfer of the 'z', vertical control provides the elevation component of the survey. This is facilitated through the installation of tape brackets. Tape brackets are installed below the collar of the shaft before sinking commences. The position of the tape brackets is determined by the shaft design and layout, but will typically be equal in number and close to the steady brackets. Each tape bracket is observed and levelled using levelling techniques and checked by a total station survey. A tape bracket is a bracket with an adjustable threaded screw that can be locked in position with a locking nut. The tape bracket provides a zero position attachment point for a shaft tape. Specialised, calibrated, and zeroed steel tapes are hooked onto the tape brackets, and everything installed on a required elevation is measured from the recordings.

The tape bracket closest to true North is numbered 1 for orientation purposes, and all other tape brackets are numbered clockwise. Usually, the tape brackets are positioned at the same elevation as the steady brackets but not too close to each other because the tape may get entangled with the plumb wires.

The tape bracket is usually installed in the shaft lining nut boxes. The elevation of the tape brackets will be referenced to the national survey grid and transferred from a benchmark. The elevation of the tape brackets will be referenced to a height above mean seal level (AMSL); site construction may refer to a depth below collar (BC). A minimum of three tape brackets is recommended (IMSSA, 2001), and distances between the tapes should not exceed 0.01% of the length of the tape. Current survey tolerances for steady brackets appear to be in the region of ±2.5 mm, based on at least three independent tapes.

The level is set up, and at least two points with known elevation are observed to calculate a mean collimation elevation. The first tape brackets are levelled in by observing a suspended shaft tape at the surface collimation and at a shaft bracket close to the first tape bracket position. The elevation of the tape brackets can be calculated and verified from multiple observations.

When the shaft lining reaches the position for the next set of tape brackets, the surveyor notifies the shaft foreman to install nut boxes for tape brackets in the ring 45 m below the previous set, which is the distance between any two sets of tape brackets when 60 m steel tapes are used. Typically, the daily advances of the shaft bottom and that of the lining are plotted on a longitudinal section of the shaft in the shaft foreman's office, on which are also shown the planned positions of all the tape brackets, enabling the shaft foreman to plan when the next set shall be installed. The exact

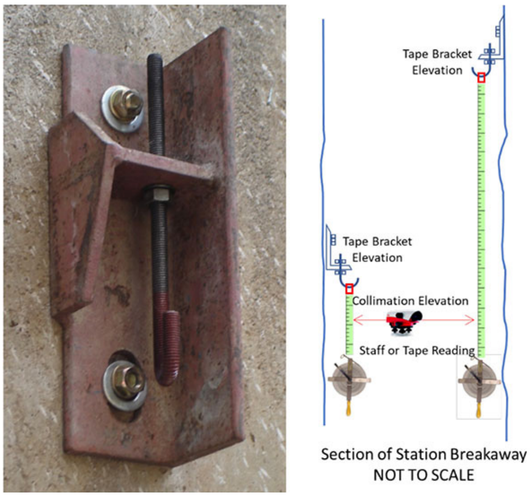

Figure 6—An example of a basic tape bracket and transfer of elevation from previous tape brackets

sequence time for the installation of the next set must be carefully planned. On a 6 m lift, the next curb ring will be set at 51 m. Once the barrel is brought down from the 45 m lift, the nut boxes for the tape brackets are exposed, and the new set can be installed. Missing this sequence will prevent the next curb ring of being set up, as only one more setting can be done from the previous tape bracket, because the curb ring falls at the 57 m mark. This demonstrates how important it is for the new set to be readily installed to set the elevation of the next curb ring.

After the stage is locked, the new tape brackets are bolted to the lining (Figure 6), and the tape hooks are inserted into the brackets. The hooks are roughly adjusted to the required elevation using the tapes hanging from the previous set, and the locking nuts are hand tightened. The surveyor then bolts the bracket for the dumpy level or laser plate onto the lining at a suitable height to read the tapes from the previous set and obtain a mean collimation elevation to adjust the new set to the correct elevation (Figure 6).

The extension of tape brackets is site-specific, best practice recommends installation when a distance of half the length of the shaft tapes used, is reached. A special bracket for a level is sometimes provided on the sinking stage in place of a conventional tripod.

All the tapes from the previous set must be read and recorded to ensure no hooks have been damaged and to eliminate any possible errors. When the required measurement to adjust the new hooks has been calculated, a shaft tape is hung at each new bracket, and the hook is adjusted up or down by turning the lock nuts until it is on the correct elevation.

Selection of shaft tapes and the extension of elevation down the shaft

It is interesting to note that, with all the technological developments in the field of surveying, the primary control in a deep vertical shaft remains the steel tape. Shaft tapes should be of high-quality steel and will be checked and certified for temperature and tension accuracy. If steel tapes are used in shaft construction, each tape must be supplied with a calibration and standardisation certificate. Each tape will have a standard coefficient of expansion at a specific temperature and a standard tension. Care must be taken so that the tapes are not stretched by weights exceeding their capacity, twisted or bent, or damaged during deployment in the shaft.

Shaft tapes are checked regularly for calibration accuracy against the master tape and surface baseline that the mine surveyor maintains with the necessary tension (weights) applied to each tape, which should not exceed 1.5 mm. The results of each tape comparison are recorded and used to install the following set of tape brackets. Unlike normal surveying tapes, the zero position of the shaft tape is the internal diameter of the ring of the tape. This means that when the tape is suspended from the hook, the zero position is on the inside of the hook of the tape bracket.

Tape tensioning weights (IMSSA, 2001) or bobs are sometimes used to correct for the stretch component of the tape by weighing the tape to conform to the standard pull of the tape (typically around 70 N) (Equation 2). Bannister and Baker (1989) discuss the elongation of steel tapes.

$$Extension\ over\ length\ = \frac{gx}{AE}\left[\frac{m}{2}(2l - x) + M - \frac{T_s}{g}\right] \qquad [2]$$

Where:

T_s	Standardised tension
G	Gravitational acceleration
X	Length of suspended weights
A	Cross sectional area of tape
E	Modulus of elasticity
M	Attached mass
M	Mass of tape per unit
L	Length of tape

As steel tapes are used in this vertical environment, the tension applied to the tape becomes part of the adjustment that needs to be considered by the surveyor. Steel tapes in the shaft sinking environment can introduce errors if not carefully standardised (Ritson, 1989).

Some studies have been done by Fourie (1951) and Gibbs (1952) on the required amount of weight to be added to the tape to measure correctly in a vertical shaft to prevent the 'creep' of distances caused by tape tension. Hooke's law provides a formula to calculate the correction for pull on a tape; in the case of a vertical shaft, this pull will be compounded by the weight of the tape and tape case (Equation 3).

$$Correction = \frac{(F_m - F_s) * L}{AE} \qquad [3]$$

where:

F_m	Measured pull
F_s	Standard pull
L	Measured length
A	Cross sectional area of the tape
E	Modulus

Fourie (1951) developed a formula correction for tension that includes the weight of the tape below the measuring point plus the weight of the tape case plus half the weight of the tape above the point (Equation 4):

$$w_s = w_{std} - (w_b + w_{bz} + \frac{1}{2}\, w_{az}) \qquad [4]$$

where:

w_s	Weight to be suspended
w_{std}	Standard weight of tape
w_b	Weight of tape box
w_{bz}	Weight of the tape below the point measured
w_{az}	Weight of the tape above the point measured

From Fourie's (1951) work, the weight added to the tapes varies between 2.1 kg for 7.6 m to 2.6 kg for 76 m measured. In most modern applications, shaft surveyors assume the weight of the tape is sufficient for its suspension. An additional check uses multiple tapes and tape brackets extended simultaneously during construction.

Factors that affect the accuracy of shaft plumbing and the transfer of coordinates

The error (Equation 5) in the network established on an underground level will depend on (Chrzanowski, 1967; Schofield, 1984):

➤ The error in the surface control survey network.
➤ Errors transferred during the placement of the shaft plumbing wires e_s.
➤ Errors introduced by the verticality of the plumbing wires at each steady bracket e_p.
➤ Errors introduced in the transfer of the network from the wires to the level e_u.

$$e_{az} = \pm\left(e_s^2 + e_p^2 + e_u^2\right)^{\frac{1}{2}} \qquad [5]$$

Any errors introduced during the shaft plumbing operation will influence the accuracy of the coordinates transfer. The shaft plumbing operations, specifically how the verticality of the plumb-wires is affected is described by Chrzanowski (1967) and Schofield (1984) in terms of:

➤ Airflow in the shaft barrel.
➤ The pendulous motion of the wires.
➤ Spiral deflection of the plumb-wire.

Chrzanowski (1967) observed that the most common mistakes occur in the incorrect selection of shaft plumbing wire and insufficient plumb bob weights.

Other methods of plumbing

Optical and laser plumbing methods are possible but have, in practice, proved difficult in a working shaft environment due to:

- Bad visibility due to ventilation, dust and water vapour.
- Unpredictable refraction of sight lines.
- Shaft plumbing by optical means requires access to the shaft barrel, which increases the risk to the observer and the equipment.

Optical alignment in good visibility (Subbotin et al., 2003) can be achieved using a nadir plummet (Janisch, 1966) placed on a fixed structure or a moveable platform on a steel construction in the shaft. Testing this instrument in three deep-level Free State gold mines, Janisch found that alignment over distances of up to 610 m was possible in ideal conditions. However, under realistic conditions, the accuracy declined rapidly from 180 m. It was found that air turbulence assisted in reducing any potential effects of refraction on the measurements (Janisch, 1966). The instrument was not deemed to be practical in wet shafts. Optical plummets must be checked for accurate alignment by aligning the crosshairs with a mark and rotating the instrument 360 degrees. If the plummet is in adjustment, the crosshairs will still coincide with the mark. In the case of a laser plummet, the red dot should remain in the same position. If it appears that the laser dot rotates with the instrument in a circular movement that deviates more than 1 mm from the aligned position, than the instrument may be off-level or misaligned. Richardus (1984) describes the successful use of optical plummets in transferring bearings in a tunnelling project, claiming that points can be aligned to 0.1 mm to a fixed point.

Basson (1971) listed three significant constraints for using a laser in a vertical shaft and the resultant abandonment of this technique in a deep shaft:

- The increased diameter of the beam over the length of the shaft increased to a size unpractical for use (150 mm) and was poorly defined.
- Continuous movement of the beam caused by vibrations in the steelwork, which in turn was caused by the movement of compressed air and water columns.
- The foot screw adjustments on the laser were too coarse to allow for accurate alignment and adjustment (Basson, 1971).

Walter and Doogan (1971) also highlighted the following:

- A drop in voltage during use can result in a weaker beam.
- There is a deviation from direction and grade of 100 mm over a horizontal distance of 1.6 km.

Shaft deformation monitoring

In addition to monitoring the position and orientation of the shaft, it is also essential to monitor the stability of the ground around the shaft. This can be done by installing monitoring equipment such as inclinometers or extensometers in the ground around the shaft. These instruments measure the deformation of the ground over time, which can be used to detect any movement or instability. Verticality and levels are controlled from surveys in plumb bob lines suspended from a set of winches fixed to the shaft collar, whilst elevations are transferred from the benchmark on the surface down the shaft using shaft tapes suspended from surveys in tape brackets. Overbreak and underbreak are measured from the edge of the curb ring once aligned with tapes and plumb bob lines suspended from brackets above.

Janisch (1966) refers to using a nadir plummet to monitor geological deformation in a goldmine shaft to determine trends in horizontal displacement. These measurements are affected by refraction, temperature, and the length of sight.

The accuracy of the transfer of coordinates into a new station requires a very accurate survey that needs to be verified with gyro theodolite to ensure that the orientation of the reference baseline (bearing) is transferred accurately into the new level. It is imperative to install a gyro baseline that is as close to the shaft wires as possible.

Use of LiDAR in shaft sinking

Laser scanning or LiDAR technology is increasingly used in shaft surveying to capture detailed 3D data of the shaft interior. Laser scanners emit laser beams that measure the distance to various surfaces, creating a point cloud representation of the shaft. The objects' shape, position, and spatial locations are recorded by millions of points, each with latitude, longitude, and elevation (X, Y, and Z) coordinates. Van der Merwe and Anderson (2013) detail the use of laser scanning to determine over- and underbreak. Accurate positioning and levelling of the shuttering are necessary to minimise concrete wastage and provide a smooth concrete barrel with the least air resistance for ventilation and an accurate foundation for shaft construction and equipping.

The functionality of scanners differs between scanners, but generally, scanners have a 360° horizontal field of vision and 270° on the vertical axis. The accuracy of a LiDAR system primarily depends on the equipment's angular resolution (Gridnev et al., 2015) and the distance to the surveyed object.

The integrity of a laser scan is compromised with movement, thus, scanning from the stage or kibble is not viable, and a specially designed bracket fixed to lining mountings in the shaft lining must be made available for the laser scanner. In some cases, a laser scanner can be mounted on the conveyance (Gridnev et al., 2015) and scans can be made while the conveyance moves. Due to uncontrolled risks such as water, strong air currents can force water into the laser scanner and damage it beyond repair. Water droplets covering the laser emitter or receiving lens will compromise the accuracy of the point cloud. The shaft collar will cast a bright spot on vertical measurements with resultant losses of data in that axis.

In a case study on a platinum mine by Van der Merwe and Anderson (2013), areas of interest within a sinking shaft were surveyed, and the scans were positioned during post-processing. The survey team surveyed a network of targets with a total station to assist in the orientation of the laser scan. Combining the georeferenced targets with the targets identified in the point cloud made an accurate comparison of the target-to-target points against the total station possible. The 3D meshed model could then be compared with the computer-aided design (CAD) design of the shaft to identify over- and underbreak and deviation from the vertical. The authors compared the survey with traditional methods of elevating the set of six bunton plates cast into the concrete lining of the shaft using a dumpy level, which takes approximately one to two hours to complete, with limited information obtained. The trial scan took approximately 20 minutes, and the optimised time envisaged was seven minutes. During this time, vast amounts of data about the bunton plates and information regarding shaft alignment can be captured (Van der Merwe, Anderson, 2013). Gridnev et al. (2015) provide a case study on the practical application of LiDAR in shaft breakaway orientation and the transfer of coordinates and elevation into a new underground level.

In an ideal monitoring system, the system should be mounted to the hoist cage or skip (Figure 7), requiring neiter additional staff (automatic), nor disturb the regular shaft operation or require extra measuring time (Althaus et al., 2007).

Figure 7—Point cloud view of shaft infrastructure from LiDAR mounted under a conveyance (Althaus et al., 2007)

Summary

Shaft sinking remains one of the most technically demanding and high-risk activities in underground mining, requiring exceptionally accurate and reliable survey control to ensure safe construction, correct alignment, and long-term operational integrity. This paper reviewed current shaft sinking survey practices used in Southern African mining operations, focusing on the establishment, maintenance, and transfer of survey control from surface to depth.

The review highlighted the critical role of surface geodetic control networks, accurate shaft collar referencing, and the rigorous transfer of horizontal and vertical control through plumbing wires and calibrated steel shaft tapes. Detailed attention was given to the use of steady brackets and tape brackets, which form the backbone of traditional shaft surveying and remain the most reliable means of transferring coordinates and elevations through deep vertical shafts. The sources of error affecting shaft plumbing such as airflow, pendulous motion, spiral deformation, tape tension, and calibration were discussed, together with quality control procedures required to mitigate these risks.

In addition to conventional methods, the paper examined modern surveying technologies increasingly applied in shaft sinking, including total station resections and LiDAR-based laser scanning. These technologies provide significant advantages in terms of data density, speed, and improved monitoring of overbreak, underbreak, and structural deformation. However, their application is constrained by practical considerations such as movement, environmental conditions, equipment vulnerability, and the need for accurate reference control established by traditional methods.

By documenting both established and emerging practices, this paper provides a comprehensive overview of the current state of shaft sinking survey control, capturing critical operational knowledge that is often transferred informally within industry.

Conclusion

The accurate spatial control of shaft sinking operations is fundamental to the success, safety, and longevity of underground mining projects. Errors introduced during the establishment or transfer of survey control can propagate throughout a mine's life, leading to costly remedial work, unplanned breakthroughs, and compromised infrastructure. As demonstrated in this review, the importance of rigorous survey control during the sinking phase cannot be overstated.

Despite advances in surveying instrumentation and data processing, traditional methods based on plumb wires, steady brackets, and calibrated shaft tapes remain the most robust, cost-effective, and reliable means of transferring control through deep vertical shafts. These techniques, when properly applied and supported by strict quality control procedures, continue to achieve the high levels of accuracy required for shaft construction and equipping. Modern technologies such as total station resections and LiDAR scanning should be viewed as complementary tools that enhance verification, monitoring, and documentation, rather than as replacements for proven methods.

A key finding of this review is the risk associated with the loss of institutional knowledge as shaft sinking projects become less frequent. Much of the expertise required for accurate shaft surveying is experiential and site-specific, underscoring the need for thorough documentation, training, and standardisation. Capturing and formalising these practices are essential to ensure continuity of skills and maintain industry standards.

This paper contributes to preserving and consolidating shaft sinking survey knowledge and provides a reference for mine surveyors, engineers, and contractors involved in vertical shaft development. Future work will address the methodologies for transferring survey control from the shaft into newly established underground levels, further completing the documentation of this critical phase of mine development.

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