ANGLOGOLD ASHANTI
VAAL RIVER OPERATIONS

DOLOMITE RELATED RISK MANAGEMENT AT THREE TAILINGS PUMPSTATIONS AND ROUTES – VAAL RIVER OPERATIONS

REPORT NO : FWA 02/17/393

6 February 2017

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SOUTH AFRICA

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Index Page

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6 February 2017

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DOLOMITE RELATED RISK MANAGEMENT AT THREE TAILINGS PUMPSTATIONS AND ROUTES – VAAL RIVER OPERATIONS

1. INTRODUCTION

We refer to a request by Mr. John van Wyk for information we have available in the GIS data base on dolomite data and the likely sinkhole and subsidence hazard at the following three facilities:

- The Harties 1 and 2 Pumpstation.
- The South East TSF Pumpstation to Sulphur Pay Dam (SPD)
- East TSF to East Pumpstation

Herewith please find a report on our findings about ground conditions that prevail at these facilities and their susceptibility to dolomite related ground movements (sinkholes and subsidences).

Because the facilities are located on dolomite land, we believe it necessary to first provide a brief description of the mechanism of sinkhole and subsidence (doline) formation. The mechanism of sinkhole development and the geological terrain with which it is associated is described below, together with a summary of the scientific basis on which the likelihood of such ground movements is established and recorded by way of geotechnical investigation.

2. BACKGROUND ABOUT GROUND CONDITIONS ON DOLOMITE.

All three the above-mentioned facilities are located on Malmani Dolomite of the chert rich Monte Christo Formation, Chuniespoort Group, Transvaal Sequence. The typical profile on dolomite in the area is shown in Figures 1 to 3 overleaf. While the diagrams suggest that the bedrock may be deep, this is not necessarily the case in this instance. The principles applicable to the development of sinkholes and subsidences nonetheless remain valid.

A sinkhole is a feature that occurs suddenly and manifests itself as a hole in the ground while a subsidence (doline) is an enclosed depression which usually occurs gradually. It can be as a result of the consolidation, at depth, of low density dolomite residuum (dewatering situation) or the subsurface erosion of loose residuum into lower lying receptacles. The latter type of depression can occur in both a dewatering or non-dewatering situation, as explained in the next paragraphs.

The dolomite rock has weathered over geological time (i.e. millions of years) to form a karst topography of pinnacles and grikes (valleys in the dolomite bedrock) including solution chambers in the "solid" dolomite. In the Klerksdorp – Orkney – Stilfontein area the karst is overlain by dolomite residuum, which is usually covered by a thin mantle of windblown (aeolian) sand (1). The residuum is the weathering product of dolomite and consists of chert gravel and boulders as well as wad (MnO_2) in a matrix of "loose" sand and gravel (3, 4 and 7). The thickness of residuum and transported material over the tops of the underground karst landscape can vary from zero to tens of metres. In general terms the thicker the cover over dolomite rock the larger the sinkhole and subsidence features that can potentially develop.

The depth of the water table plays a major role in the development of instability on a dolomite site. The original water level (OWL) in Figure 1 is shown as relatively high. Water, wad and other debris would have filled most of the solution caverns. The only exception would have been an air filled cavity in the residuum (5) in the figure. It is assumed that the water table was lowered from A to B in geological time (i.e. millions of years). Should the area have remained largely undeveloped, it would be in equilibrium with the environment (rainfall, farming etc.) and few subsidences or sinkholes would have developed.

Considering the same typical profile with the water table again being lowered from A to B in geological time (Figure 2) and superimposing development on the dolomite, the following could/ is likely to happen:

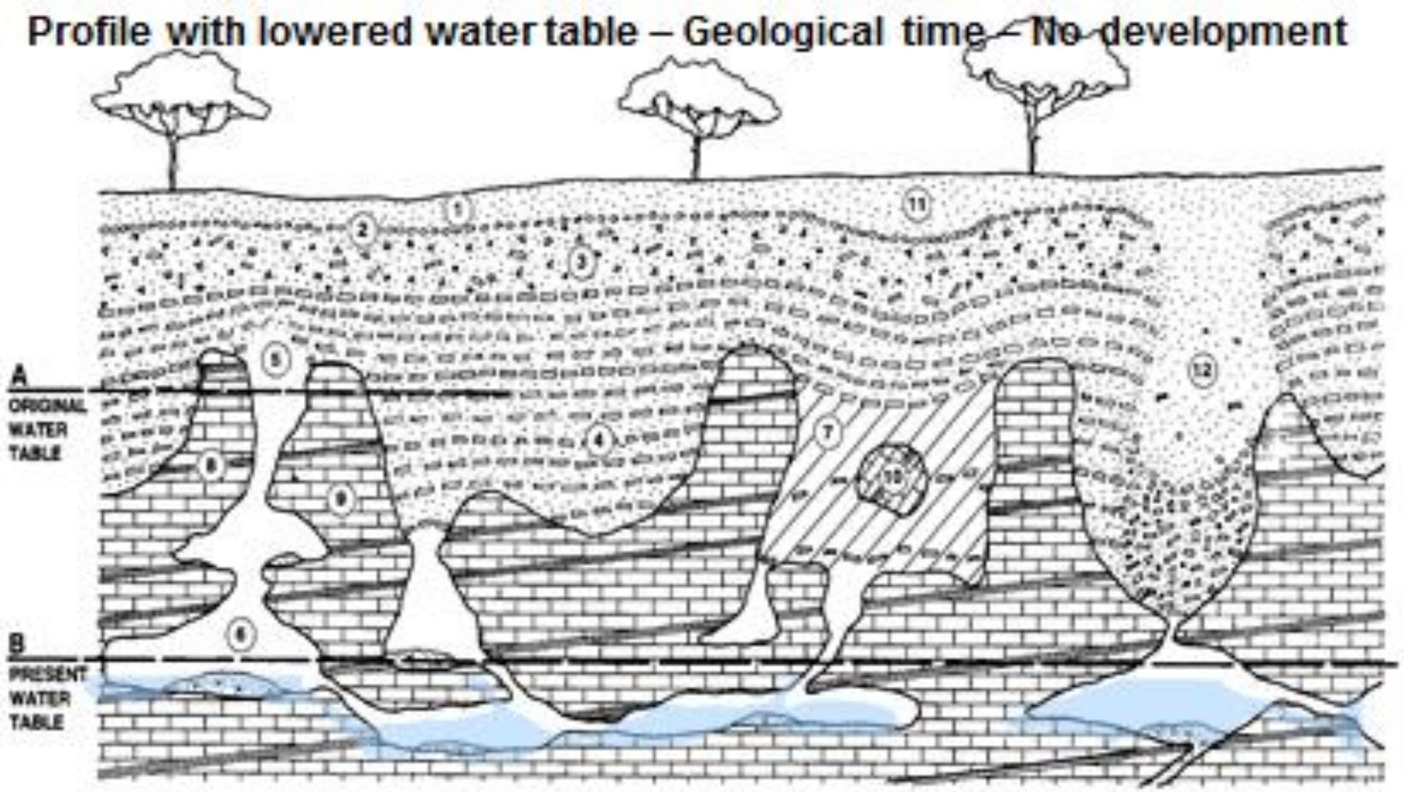
- A storm water pipe leaking could cause the soil arching over the previous cavity (5) to soften and collapse into lower lying caverns. Water flowing in an unlined road side drain or tailings conveyance facility would aggravate the situation. A sinkhole could form in the residuum.
- At the first house a leaking water supply pipeline could cause subsurface erosion of material into lower lying receptacles, leading to a surface subsidence (doline) at the corner of a house and causing it to crack.
- At a palaeo (old) subsidence (doline) (11) and palaeo sinkhole (12) the development has had no effect as there has been no concentrated ingress of water into the subsurface at this location.

With large scale pumping taking place in an area to facilitate mining or to serve agriculture the water table would be lowered from A to B in a short time (months to years). In such a case the area would become unstable as shown in Figure 3.

The extent of instability will depend on factors such as the size of the open caverns, the thickness and properties of cover material overlying the dolomite, the original level of the water table and the rate of pumping from the aquifer. In Figure 3 a sinkhole and subsidence has occurred as shown due to subsurface erosion caused by the lowering of the water table. The palaeo sinkhole at (12) has been reactivated due to the same reason. The palaeo subsidence at (11) has been reactivated due to an increase in the effective stress in the wad (7), caused by the lowering of the water table.

The situation at the Harties 1 and 2 Pumpstation area and along the tailings conveyance routes between SE TSF and the SPD as well as East TSF to the East Reclaim Pumpstation is that the water table has not been lowered by mining, but that the water level is probably already situated within the dolomite bedrock. Should dewatering occur in future, which is highly unlikely, mobilization of unconsolidated material can only take place along narrow slots present in the bedrock and with the sinkholes manifesting as features at surface. Water ingress from surface can likewise erode material down only into slots and smaller cavities below, resulting in sinkholes potentially manifesting at surface. This is, however, not the situation with ingress of water from leaking services or poor storm water control as described later.

The description above is intended to make the Contractors and the Plant Operators aware of the dangers of concentrated water ingress into the subsurface of a dolomite site. Such infiltration could lead to the formation of sinkholes or subsidence with possible loss of life and damage to plant and equipment.



<u>Figure 1</u>: TYPICAL SOIL PROFILE OVER DOLOMITE IN SOUTH AFRICA

NOTES: - Area in equilibrium with environment.
- Cavity in residuum and paleeo doline stable.

Profile with lowered water table – Geological time - Development

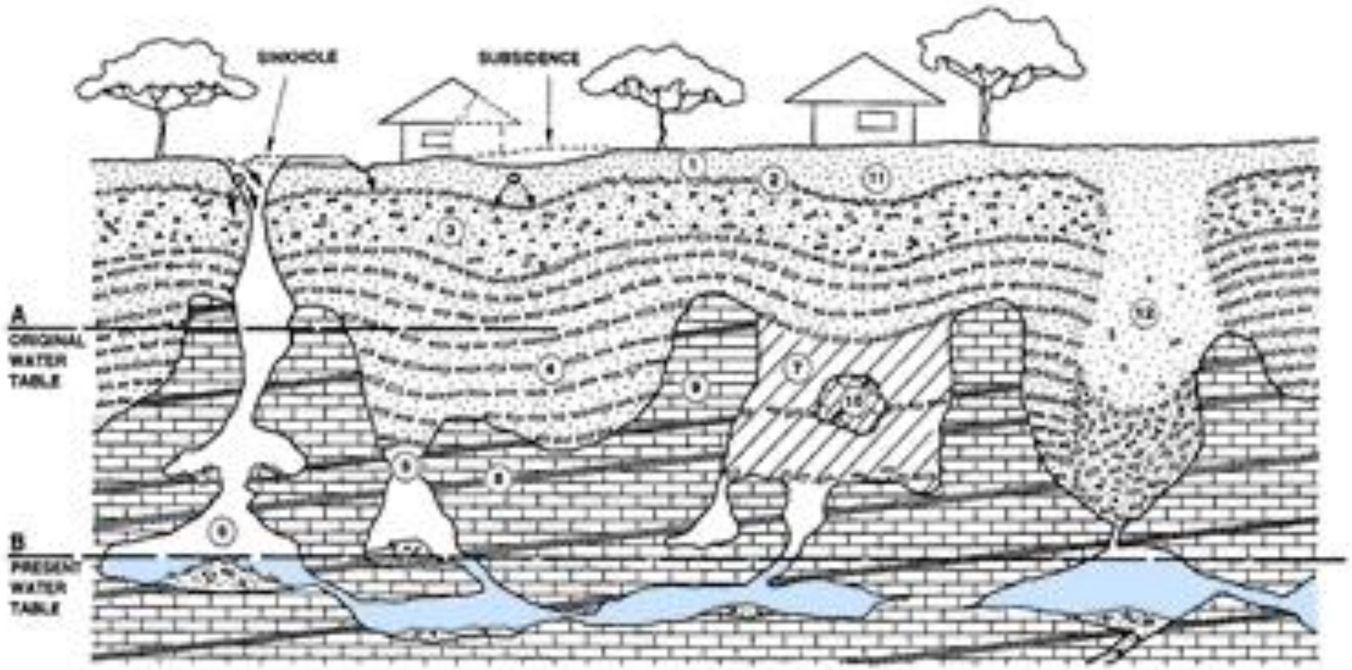


Figure 2: TYPICAL SOIL PROFILE OVER DOLOMITE IN SOUTH AFRICA

Notes:
- Water table lowered from A to B over geological time (i.e. millions of years).
- Area recently developed leading to piped water and water concentration on surface
- Concentrated water ingress into subsurface due to leaking services.
- Water ingress leads to sinkhole at road and subsidence below house.

Profile with lowered water table – Short time

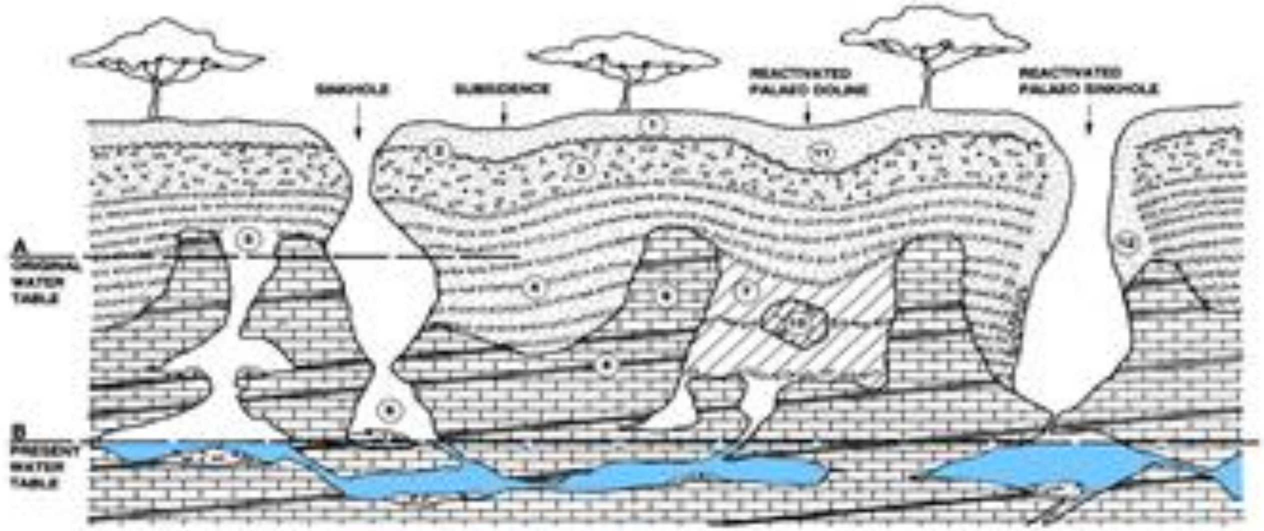


Figure 3: Typical soil profile over dolomite in South Africa

Notes: - Water table lowered from A to B over short time (months) due to mining operation.

- Lowering leads to sinkholes, subsidence and reactivated palaeo features

3. BACKGROUND ABOUT HAZARD CHARACTERISATION PROCEDURES AND FINDINGS

Geotechnical professionals have developed systems over time by means of which the likelihood and size of sinkholes and settlement in dolomite terrain can be predicted and communicated to other professionals involved on a project. This hazard characterisation is based on the properties of the ground profile that is present on the dolomite and which is basically assessed from studying the results of percussion boreholes drilled for the purpose, together with background information relating to the specific dolomite Formation on which the site is situated. This procedure has been formalised in a recently published SABS standard SANS 1936 Volumes 1 to 4 (2012).

The available information, including borehole data and geohydrological information gathered during an investigation, is reviewed and allows formulation of the hazard character of a given site. The predominant mobilising agencies that may lead to sinkhole and subsidence development on dolomite are major groundwater level fluctuations (>6m), ingress water causing subsurface erosion, ground vibrations and gravity. Use is made of a generalised list of evaluation factors to evaluate the risk of sinkhole and subsidence formation. These factors are:

- Degree of receptacle development in the profile;
- Presence of future mobilising agencies, particularly ingress water from leaking services;
- Potential sinkhole development space (depth to bedrock);
- Nature of the blanketing layer (erodibility and strength);
- Mobilisation potential of the blanketing layer;
- Bedrock morphology (pinnacle nature and presence of cavities in the bedrock).

The nature of the material covering the receptacles, be they above or in the bedrock, determines the susceptibility of the sub-surface material to erosion by ingress water. The presence of materials such as shale or intrusive, which can also act as aquitards, serve to reduce the mobilisation potential and enhance the stability.

In the case of dramatic groundwater level fluctuations the susceptibility of the soil material to mobilisation i.e. consolidation settlement (settlement/doline formation), or ravelling and arch failure (sinkhole formation) due to pore pressure changes in soils, is strongly influenced by the position of the original groundwater level in the subsurface profile.

The likelihood of sinkhole and subsidence formation is expressed in three broad categories, namely a low, medium and high Hazard Index. The following reference to incidences provides a perspective of the magnitude of problems encountered in each of the Hazard Index areas.

Hazard Characterisation	**Ground-Movement Events***
LOW	0 up to and including 0.1 events per hectare anticipated, but occurrence of events cannot be excluded.
MEDIUM	Greater than 0.1 and less than and equal to 1.0 events per hectare.
HIGH	Greater than 1.0 event anticipated per hectare.
* That have occurred per hectare in a 20 year period in the "type" areas (statistics based on inappropriate and poor service design and maintenance)	

For any particular study area on dolomite the ground conditions are characterised in terms of eight standard Inherent Hazard Classes. These classes denote the likelihood of a sinkhole or subsidence occurring, as well as its likely size (diameter). Generally speaking the larger the Inherent Hazard Class number, the greater the likelihood of a sinkhole or subsidence occurring and the larger its potential size, should it occur.

The meaning/definition of each Inherent Hazard Class is as follows:

Inherent Hazard Class	**Characterisation Of Area**
Class 1 Areas	Areas characterised as reflecting a **low** Inherent Hazard of sinkhole and subsidence formation (**all sizes**).

Class 2 Areas	Areas characterised as reflecting a **medium** Inherent Hazard of **small-size** sinkhole and subsidence formation.
Class 3 Areas	Areas characterised as reflecting a **medium** Inherent Hazard of **medium-size** sinkhole and subsidence formation.
Class 4 Areas	Areas characterised as reflecting a **medium** Inherent Hazard of **large-size** sinkhole and subsidence formation.
Class 5 Areas	Areas characterised as reflecting a **high** Inherent Hazard of **small-size** sinkhole and subsidence formation.
Class 6 Areas	Areas characterised as reflecting a **high** Inherent hazard of **medium-size** sinkhole and subsidence formation.
Class 7 Areas	Areas characterised as reflecting a **high** Inherent Hazard of **large-size** sinkhole and subsidence formation.
Class 8 Areas	Areas characterised as reflecting a **high** Inherent Hazard of **very large-size** sinkhole and subsidence formation.

The definitions above are summaries of the Inherent Hazard Class table presented in SANS 1936-2. Convention is that the Inherent Hazard is defined in terms of ingress water and groundwater level drawdown and reflected by two Inherent Hazard Class designations, separated by a double forward slash, i.e.-

Inherent Hazard Class (Ingress water) // Inherent Hazard Class (groundwater level drawdown).

As an example, a designation of 1//8 indicates that the zone displays a low Inherent Hazard with respect to water ingress but a high Inherent Hazard with respect to groundwater level drawdown. Further combinations may be appropriate. As an example, a designation of Inherent Hazard Class 1//1/4/8 indicates that the zone displays a low Inherent Hazard with respect to water ingress but a low to high Inherent Hazard with respect to groundwater level drawdown. This definition may, for example, be necessary in cases where groundwater was not encountered or the original groundwater level is not known and dolomite bedrock could not be confirmed.

Zones delineated on a site may be combinations of the above. In some instances, the Inherent Hazard Classes are indicated with the primary zone description given first, followed by a suffix in brackets. The primary Inherent Hazard Class describes the predominant characterisation of the zone and the suffix describes the characterisation of *anticipated* pockets or small sub-areas within the zone:

As an example, a designation of Inherent Hazard Class 8(4) indicates that the zone predominantly displays a high Inherent Hazard for up to very large-size sinkhole and subsidence formation with anticipated pockets or small sub-areas of Class 4 i.e. displaying a medium hazard for up to large-size sinkhole and subsidence formation.

Development design and the level of mitigation measures to be implemented is determined by the primary Inherent Hazard Class:

As an example, in a zone designated as Inherent Risk Class 4(1)//1, the Inherent Risk Class 4 will be the determining Hazard Class. If however the secondary Hazard Class represent high likelihood of a sinkhole developing, further attention need be given to the potential impact it may have on the proposed development.

4. SINKHOLE OCCURRENCES AND HAZARD ASSESSMENT FOR THE HARTIES 1 AND 2 PUMPSTATION, SOUTH EAST TSF PUMPSTATION TO SPD AND EAST TSF TO EAST PUMPSTATION FACILITIES.

A map showing proposed Trenches and Pipelines, included in Appendix 1, show the locations of the abovementioned three facilities in relation to the positions of existing sinkholes as well as the positions of boreholes for which inherent hazard assessments have been prepared as part of Subtask 2 of the Hazard Study at Vaal River Operations. Each of these are discussed separately below.

1) HARTIES 1 and 2 PUMPSTATION.

Boreholes drilled and trenches excavated in this location in the past show Inherent Hazard Class 5 conditions, i.e. although it reflects dolomite bedrock generally within 3 meters from ground surface, there is a high likelihood for sinkholes to develop upon water ingress. This is because of the presence of slot structures within the dolomite bedrock that harbour conditions susceptible for the mobilization of the residual soil (vertical erosion) upon ingress of water. Refer FWA report No 10/13/353.

The area east of these Harties TSF's has previously been used for the storage of storm and excess return water decanted from the TSF and was known as the "paddy fields". This has triggered a large number of sinkholes in locations as shown on the area map. In addition some of the sinkholes have been infilled with tailings and are thus not shown. Continued ponding of storm water will result in more sinkholes. In addition any leaking tailings conveyance will trigger sinkholes on this particular Formation on the dolomite.

2) SOUTH EAST TSF PUMPSTATION TO SPD.

The four boreholes drilled by Knight Piesold Consulting (Pty) Ltd for the future pumpstation on the south eastern corner of the SE TSF show Inherent Hazard Class 5 (3 boreholes) and Inherent Hazard Class 3 (1 borehole) conditions.

Sinkholes occurred in the SPD when the TSF was originally commissioned. In addition seven sinkholes exist towards the north of the SE TSF. These were triggered in the past when water accumulated in old borrow areas.

Because the conveyance route from SE TSF towards SPD and the facilities at SPD are located along the strike direction of the dolomite, conditions are similar to those that exist elsewhere on the Monte Christo Formation. The likelihood of sinkholes to develop upon water ponding and leaking from pipes and lined or unlined trenches is high.

We assume that a detailed geotechnical report was prepared by Knight Piesold on the findings of their investigation at the SE TSF Pumpstation as it will be an important guide for the Contractor to build the facility and for him to be made aware of the mitigation measures necessary during construction and operation to prevent the formation of sinkholes.

3) EAST TSF RECLAIM PUMPSTATION

Boreholes drilled during the site investigation for the pumpstation for the reclaim works to the south east of the EAST TSF also indicate Inherent Hazard Class 3 and 5 conditions. Refer FWA report No 02/15/361.

No sinkholes have as yet been recorded in this area but, similar to the two facilities described above, conditions for the development of up to a large sinkhole are highly favourable. Ingress from ponding of water and leakage from pipes, ponds and trenches are highly likely to trigger such events.

In general terms therefore the dolomite hazard class assigned to the area on which the facilities are located is IHC 3, 5 (7)//5. Prior knowledge suggest that alluvium/colluvium/ residuum should generally be thin and with bedrock near surface, but some boreholes suggest that significantly deep slot structures are present (those assigned IHC 7 on the plan in Appendix 1). These slots are able to generate up to large sinkholes. The water table at intermediate depth is expected deeper than rock-head level and dewatering, in the unlikely event that it happens, is likely to have limited effect.

From the above it is apparent that the facilities are located on dolomite land with a high hazard for generating small, intermediate and large sinkholes upon ingress of water. It is therefore imperative that these facilities be designed so as to be watertight and that it be operated and maintained with this requirement in mind.

5. DESIGN AND CONSTRUCTION OF INFRASTRUCTURE

South African National Standard SANS 1936 -3 (2012) addresses the need for the prudent design and construction of infrastructure on dolomite land. Because more than 96% of all sinkholes that have occurred to date are man induced and in particular relate to ingress water from leaking water bearing infrastructure or poor management of storm water, there is clear need for detail attention about these issues in the design, construction and maintenance of facilities and the tailings conveyance systems in this area.

SANS 1936-3 (2012) details the requirements and precautionary measures on dolomite sites for wet engineering services and storm water and contains a wealth of relevant information. The Department of Public Works document entitled PW_344 Dolomite Manual-September 2010 and which is available on the internet in PDF format at www.publicworks.gov.za is a source of design detail that may be implemented, as appropriate.

We regard the implementation of appropriate design and construction measures on dolomite land as an imperative. Recent experience suggest that large sinkholes often cost more than R1m each to repair, an unnecessary expense that can be ill afforded.

The golden rule when occupying dolomite land is to prevent water from gaining access to the ground profile where it can erode unconsolidated cover material into cavities lower down, thus triggering the sinkhole or subsidence at ground surface. With this in mind no ponding of water must be allowed to occur at surface, whether from storm water or process water. Containment and conveyance facilities must be lined and any leakage/spillage from dams, pipes and trenches must be addressed forthwith. In this regard it is necessary that a dolomite risk management system be developed for each of the facilities and that a Dolomite Risk Manager be appointed. This individual should be tasked to take care about water care matters and have access to the Plant/Mine Manager so as to ensure that identified shortcomings be addressed.

6. INFRASTRUCTURE MONITORING

Experience has shown that even though the best intent may be followed when infrastructure is designed and constructed on dolomite, there invariably develop issues that may in the long term prove detrimental. These include the normal wear and tear of materials because of the harsh and abrasive conditions that exist in the mining environment. Monitoring and maintenance are critical actions required to prevent triggering of sinkholes and subsidence that occur because of deteriorating infrastructure and incomplete measures that were implemented in the first instance.

The generic monitoring activities that are considered appropriate discussed below. These should be undertaken in a formalised fashion and in accordance with a set program at each of the different elements that make up the three facilities above; some activities should be undertaken daily while others may only be necessary at much lower frequency:

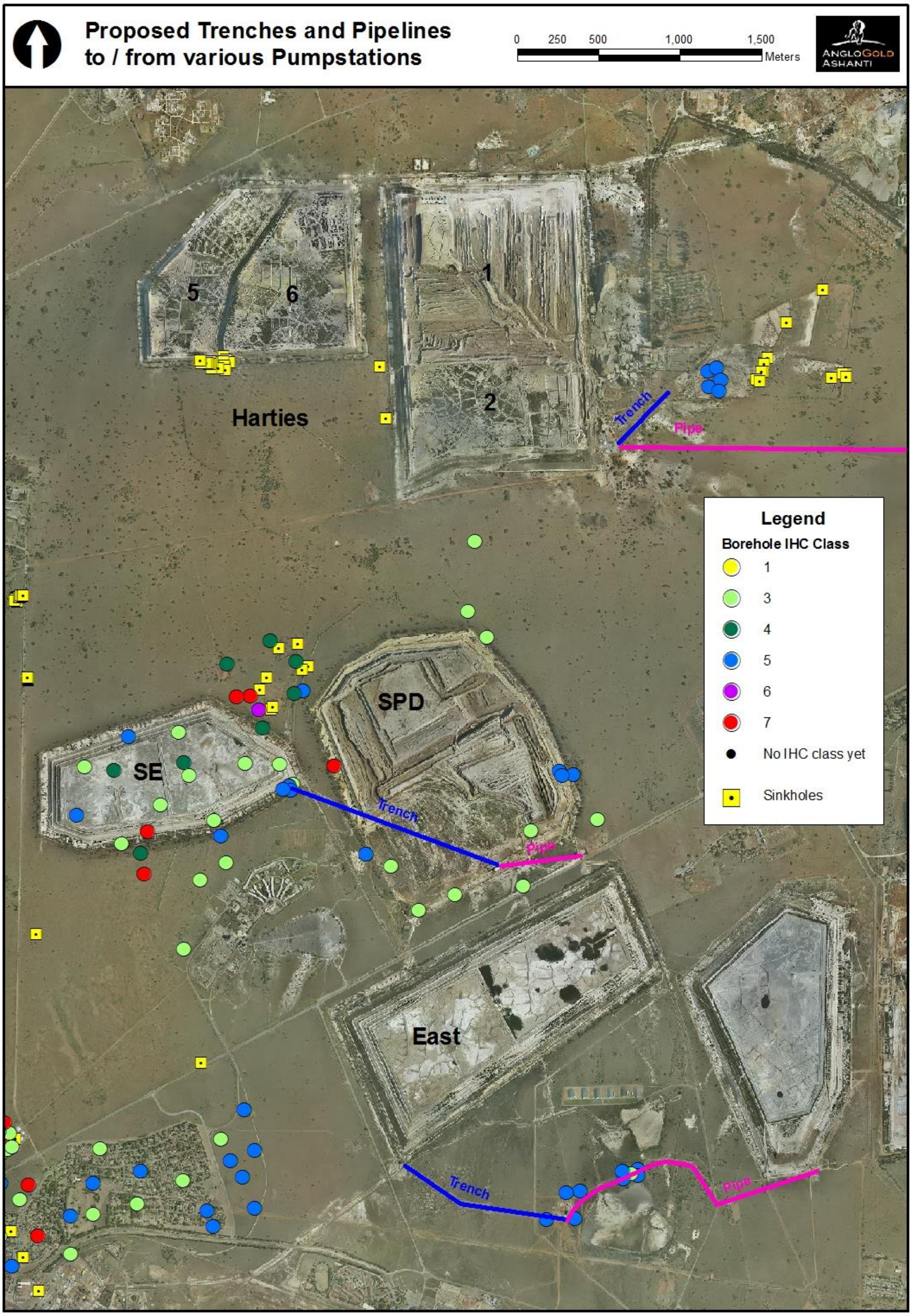
- Visual inspections of the ground surface, structures and above ground infrastructure as well as dry services, sleeves, ducts, manholes and facility chambers for standing water and possible water ingress.
  - Examine buildings for cracks
  - Visual checks for dripping taps, pressure valves, broken pipes
  - Check for damp and moss grown areas. Establish reason.
  - Check for areas that are overly wet and establish cause.
  - Check for blockages.
  - Check for ground cracks.
- Visual inspection of the storm water system.
  - Check for blockages and debris.
  - Check for flows in and out of manholes.
  - Search for cracks in lined and unlined channels.
- Checking and, where necessary, testing water and fluid bearing infrastructure for leaks. This applies to both above ground and underground facilities.
  - Isolate various sections of the system to check flow meters.
  - Pressure tests or camera inspections to locate leaks.
- Monitoring of structures and ground levels.
  - If movement is suspected, establish grid of precise levelling beacons and measure trend.

We trust the above is satisfactory and we remain available should further clarification or assistance with development of a formalised Dolomite Risk Management System be required.

F. Wagener Pr Eng
For Fritz Wagener & Associates

I Venter Pr Sci

APPENDIX 1
GIS DATABASE INFORMATION AVAILABLE IN THE AREA.



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