University of Alberta

Management of Geohazards at Lihir Gold Mine
Papua New Guinea

by

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Abstract

Lihir Gold Mine in Papua New Guinea is one of the largest gold mines in the world situated in a seismically sensitive zone. The gold deposit is located in an extinct volcano in close proximity to the sea shore and presents a series of geohazards. Some geohazards are uncommon and include: geothermal outbursts, cavities, water inrush and earthquake/ tsunami. After a major multi-batter (5 benches high) slope failure that occurred on the 1st of October 2009, a team of engineers, lead by the author investigated the incident and made series of recommendations. Arising out of these recommendations, a comprehensive Geohazard Management Plan was formulated by revisiting, revising and putting together all the individual geohazard management plans as a single document.

This thesis describes the outcomes of the investigation and presents an overview and systematic approach in formulation of the Geohazard Management Plan, apart from a summary of the gaps that were identified in the existing system, major contributions that were made as well as the expected improvements and constraints in managing these geohazards.

Acknowledgement

I am profoundly happy at the conclusion of my thesis and greatly appreciate the support and services extended by Mr. Noel Foley, Ex General Manger of Lihir Gold Limited who offered me the opportunity to lead his team of engineers in the investigation of the incident of slope failure that took place in October, 2009 as well as contribute to the formulation of a comprehensive 'Geohazard Management Plan' for the mine. I also greatly appreciate the assistance given by Mr. Peter Knight, the Geo-Tech Superintendent of Lihir Gold Limited in providing me with wide range of documents and material on the subject as well as offering his expertise on various geotechnical issues. I very much acknowledge the support and spirit with which my team members accommodated my views and ideas on various aspects of the investigation as well as the geohazards and their management.

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1 Introduction

Lihir Gold Mine of Lihir Gold Limited (LGL) in Papua New Guinea presents a series of geohazards like; slope failures (pit slopes, dumps, stockpiles), landslides, rockfalls, geothermal outbursts, cavities, water inrush and earthquake/tsunami. Some of these hazards are unique to this mine and were being managed through some standalone geohazard management plans for each geohazard. After occurrence of a major slope failure in October 2009, a team of engineers lead by the author investigated the incident and following the recommendations, also formulated a comprehensive Geohazard Management Plan which is now a framework of integrated geotechnical and geothermal databases, files, maps, spreadsheets and reports to manage geothermal and geotechnical risks within the mining operations. It is also a reflection and reinforcement of the company's policies and procedures, and provides an overview of the management plan for use by the geothermal and geotechnical staff to effectively and proactively manage various geohazards.

The investigation of the slope failure that occurred in October, 2009 at Lihir Gold Mine highlighted that while 'engineering controls' did respond to the deteriorating situation, the 'administrative controls' mostly failed, underpinning the critical role of 'human factor' in the management system. During the exercise of formulating the comprehensive Geohazard Management Plan, it was noted that individual Management Plans for some geohazards did not exist at all while those available were mostly inadequate in terms of standard operating procedures, manpower requirements and skills, training, communication, instrumentation strategy and management of change etc.

The comprehensive Geohazard Management Plan thus not only addressed these discrepancies but also integrated individual geohazard management plans for all geohazards to eliminate duplication and multiple owners. This plan also implemented a uniform approach and centralised monitoring and control for better management.

It is believed that effective implementation of this Geohazard Management Plan would surely enable the mine operator to manage these geohazards more efficiently and proactively. While sufficient resources and an adequate number of competent persons would be the key to its success, documentation controls are also needed to capture, store and retrieve data for decision making. As more information and data become available, this Geohazard Management Plan would need to be revisited and up-graded as and when necessary.

Two terms; 'Hazard' and 'Risk' find frequent mention in the thesis and for the reader to understand their context, these terms and associated processes have been defined below.

'Hazard' is a condition, situation, or behaviour that has the potential to cause harm, or influence the results of what is being done. 'Risk' is the likelihood or probability that a hazardous condition could turn into an event. Risk has three compounds; event, probability and impact. Thus risk is an event that has the likelihood of happening and resulting harm or impact. This may include injury to workforce, damage to equipment, property or environment.

'Hazard Identification' is the process of examining the mine area, machinery and the workforce to identify all the hazards which are "inherent in the operations". 'Risk Assessment and Evaluation' is defined as the process of assessing the risks associated with each of the hazards identified. The goal is to agree on control measures that can address the risk involved. 'Risk Control' is the process of implementing the most cost effective measures to control the risk (Bell, 1999).

1.1 Regional and Geological Setting

Lihir Gold Mine is located on Lihir Island in New Ireland Province of Papua New Guinea and has been actively mined since 1997. The island is located approximately 900 km North-East of Port Moresby, the National Capital and is part of the Tabar-Lihir-Tanga-Feni Island Chain as illustrated in Figure 1. Recent studies by Rutter et al. (2008), have suggested that the Lihir Group and other islands in the chain have developed in a back-arc setting associated with south to north convergence of the Solomon Sea Plate and the South Bismark plate. More recent volcanism in the region south of Lihir, most noticeably at Rabaul, represents true island arc style volcanism formed above the New Britain subduction zone.

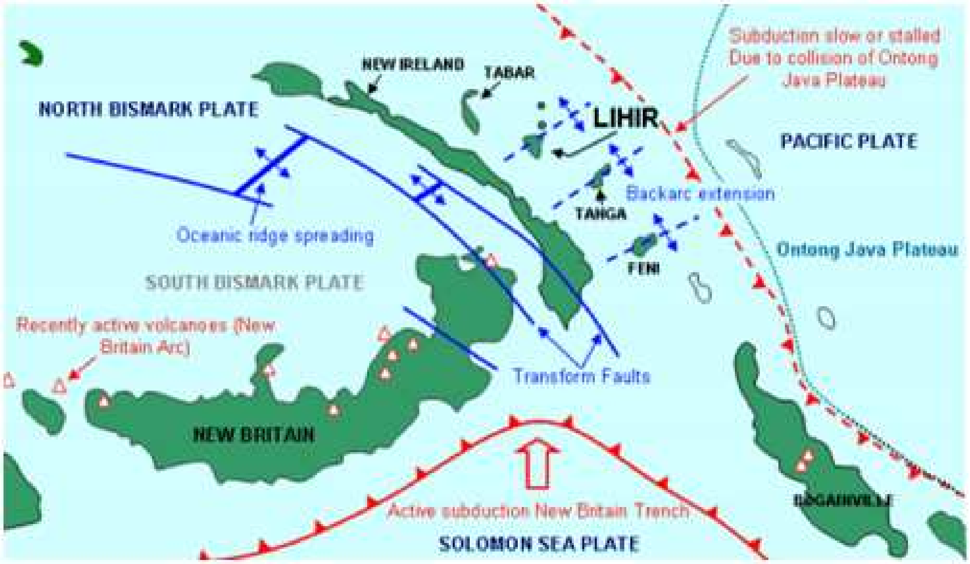


Figure 1: Location and tectonic setting of Lihir Island (Rutter et al., 2008)

The Lihir Group includes 5 major islands with the largest (Lihir or Niolam Island) being comprised of five volcanic edifices, the most recent of which is the Plio-pleistocene age Luise volcano that hosts the Ladolam Gold Deposit (Rutter et al. 2008). A major pre-historic eruption resulted in a sector collapse that left the north-east of the caldera open to the sea forming Luise Harbour, Figure 2. These are extinct volcanoes with no chance of erupting again (as opposed to dormant volcanoes, which still will erupt again at some point in the future). Epithermal sulphide hosted gold mineralization is associated with residual geothermal activity that post-dated the caldera collapse.

The local geology consists of a wide variety of volcaniclastic rock types including breccia, tuff, lahar and lava flows. However, classification of rock types for mining and geotechnical purposes is based on "ore type" which takes into account properties such as alteration, hardness, degree of brecciation and mineralogy. These ore types are heavily influenced by the weathering and geothermal regime.

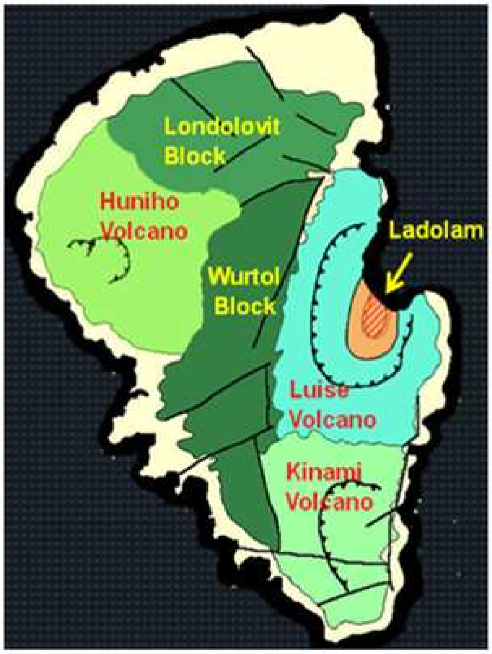


Figure 2: Location of the Ladolam gold deposit in the Luise volcanic crater (Rutter et al., 2008)

1.2 Geothermal Regime

The geothermal regime within the Luise caldera consists of two "reservoirs" based on depth, (Allis, 2003), which influence mining and the potential for power generation as illustrated in Figure 3. The deep reservoir is located approximately 600 m below the ground surface and is tapped by a number of large diameter wells for geothermal power generation. This is located above a monzonite intrusive which is thought to be the high temperature source of the geothermal system. The deep reservoir is separated from the overlying ore body and shallow reservoir by a low permeability cap provided by the anhydrite seal ore type. This rock type is named for its extensive anhydrite veining. Anhydrite is a reverse soluble mineral that is precipitated in the high temperature geothermal environment.

The shallow reservoir is contained within a permeable rock type known locally as the "boiling zone" which also contains the majority of the ore zone. The shallow reservoir directly impacts mining and needs to be depressurized and cooled as part of the mining process. Overlying this is the relatively impermeable argillic unit which has clay-like properties and has developed both from geothermal fluid alteration and as a result of weathering from surface derived meteoric water. This unit acts as a cap on top of the geothermal system which is only penetrated through zones of structural weakness that result in hot springs on the original surface and on mining benches.

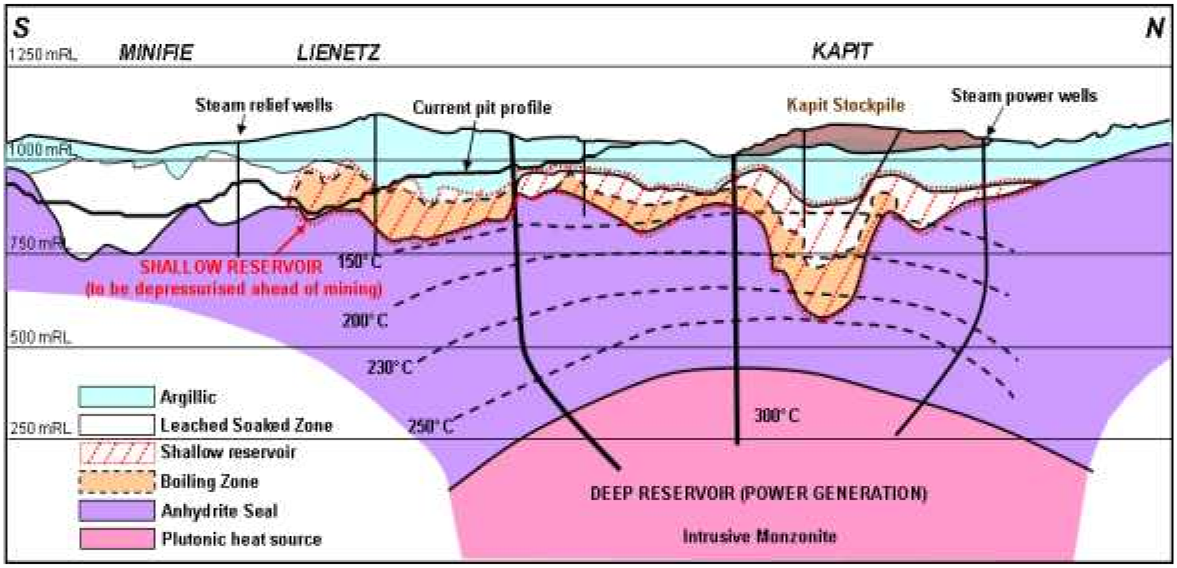


Figure 3: N-S section showing the geothermal conceptual model (Lihir Gold Ltd)

The boundary between the anhydrite seal, boiling zone and overlying argillic rock types varies considerably in depth in the mine area. In general, the anhydrite seal becomes closer to the surface from the south to north. As a result, temperatures in the mine increase from south to north. Also the primary heat upflow zone is centred beneath the Kapit pit. Heat is transmitted from the anhydrite seal to the shallow reservoir in a mostly convective manner, although there may be limited zones of convective heat transfer which are currently not well understood. Mine development as discussed at section 1.3 is affected by this, with temperatures (pre-mining) rising from approximately 120°C in Minifie, to 160°C in Lienetz and to 200°C in the as yet undeveloped Kapit deposit. Corresponding pressures of the geothermal system also increase from the south to a maximum of around 15 bar in Kapit which is currently only partially depressurized ahead of mining. These high ground water pressures are increasingly being understood to play a major role in the stability of the mine slopes.

1.3 Mine Development

1.3.1 Mining Background and History

Lihir Gold Mine is one of the world's largest producers of gold and Papua New Guinea's largest gold mine. Construction of the mine and processing facilities commenced in November 1995. Following commissioning of the ore processing plant in May 1997, more than eight million ounces of gold have been produced as on date. By global standards, the Lihir ore body is very large, with a recently published reserve and resource of 29 and 43 million ounces, respectively.

The existing operations at Lihir Island comprise an open pit mine producing about 13 million tonnes of ore and about 33 million tonnes of waste annually. Waste rock is disposed into Luise Harbour either by direct dumping from shore or from a fleet of bottom-dumping barges that discharge waste rock into water more than 100 m deep approximately 0.5 km from shore. The ore is processed using pressure oxidation and carbon-in-leach cyanidation producing about 850 thousand ounces of gold annually while the neutralised tailings are disposed to the deep ocean using a deep sea tailing placement system. Tailing is discharged from a pipeline that extends from the de-aeration tank through a directionally-drilled hole in the shoreline at Putput point to a discharge point beneath the euphotic (sunlight penetrating) zone at a depth of 115 m below the surface.

Mining is carried out by conventional open pit method employing O&K hydraulic shovels and CAT 785 trucks. Mining is conducted in a series of cutback phases. The deposit deepens to the North and at its deepest point, the pit will reach a depth of 300 metres below sea level. Due to the geometry of the deposit, a series of in-pit dumps infill the southern pit lobes as the active pit progresses to the north.

Construction is underway to upgrade the processing plant produce one million ounces of gold per annum by 2013.

1.3.2 Open Pit Development Sequence

The Lihir (or Ladolam) resource can roughly be divided into three deposits which, from south to north, are Minifie, Lienetz and Kapit. Development of Minifie is the most complete with ongoing mining in the Phase 12 area as shown in Figure 4. The majority of current mining activity is focused in the Lienetz pit with two active cutbacks (Phase 8 and Phase 11). Future mining will be undertaken in the Kapit area, which is currently located beneath the Kapit low grade (LG) ore stockpile. Due to the restricted land area within the caldera, the majority of waste material is dumped in the deeper part of Luise Harbour using barges. Low grade ore stockpiles have been developed inside the Minifie Pit and in the Kapit area. The latter stockpile will be relocated to an area further north (Kapit North) prior to the Kapit pit development.

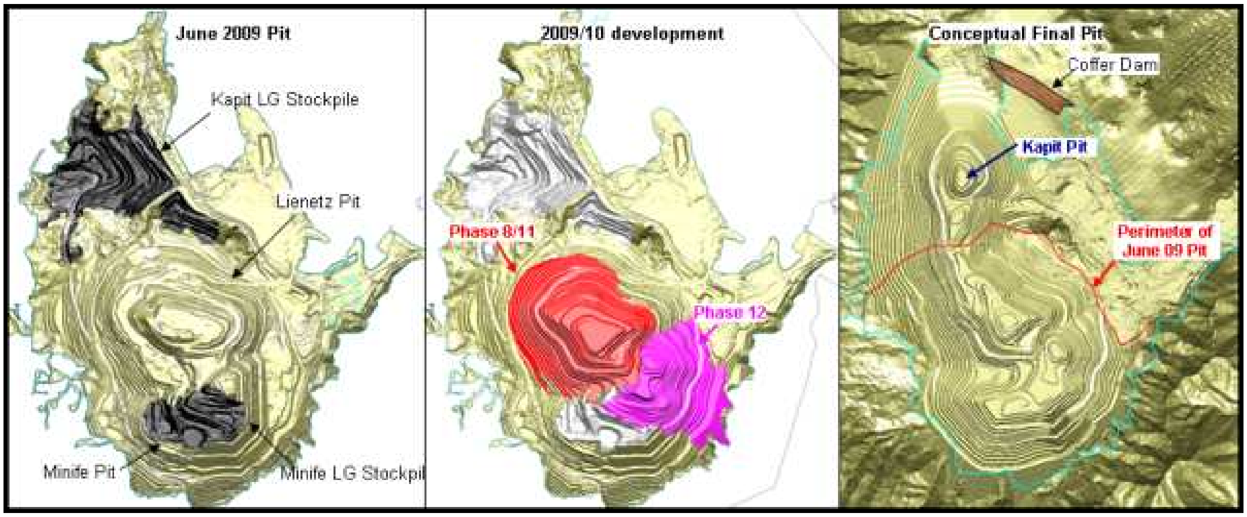


Figure 4: Plan views showing mine development (Lihir Gold Ltd)

1.3.3 Impact of Geothermal Regime on Mine Development

The geothermal regime has had a substantial impact on mining activity at Lihir with specific procedures being developed to minimize safety risks to personnel. The principal hazard is geothermal outbursts or eruptions caused by removal of overburden from high temperature and pressure zones by the mining activity. On a smaller scale, the presence of hot water and steam presents the risk of burn injuries, and possible concentrations of CO_2 and H_2S gas present a risk of asphyxiation.

In a general sense, ground temperature increases towards the north. Minifie pit in the south is relatively cool with temperatures generally <80°C with a maximum of 120°C. Lienetz pit has temperatures generally <100°C with a maximum of 160°C. The Kapit pit to the north has temperatures >200°C. The life of mine plan pit development sequence starts in the south and progresses northwards with the hotter Kapit pit being mined last.

1.4 Geohazards Identified at Lihir Gold Mine

Location of the Lihir Gold Mine gives rise to some unique hazards not normally faced by mining operations, such as geothermal environment, cavities, earthquakes and tsunamis. Although in a volcanic region, the Luise volcano is classified as extinct and as such no longer presents a hazard yet the remnant heat does lead to the geothermal activity within the mining lease. The mine being located in close proximity to the sea as well as seismically sensitive zone poses additional threats from earthquakes and tsunamis.

The various geohazards identified for Lihir Gold Mine together with their potential consequences are summarised in Table 1.

Table 1: Geohazards and their potential consequences (Lihir Gold Ltd)

Geohazard	Description	Potential Consequences
Earthquake, Seismic Event	Earthquakes are transient earth motion (seismic) events caused by sudden failure of the earth's crust due to fault slip, volcanic activity or sudden stress change. A seismic event may have sufficient energy to trigger slope failure or rockburst that could result in rock being shaken or forcibly ejected from the rockmass surrounding the excavation.	Sudden and rapid movement of rock walls
Tsunami	An earthquake-triggered ocean-borne energy wave that is most destructive in shallow water.	Inrush of sea
Major Geothermal Outburst or Hydrothermal Eruption	Geothermal outbursts can occur when hydrothermal pressure exceeds the overburden lithostatic pressure, posing a risk of hydrothermal eruption or rock outburst. This may result in geothermal noxious gas, steam, hot water, mud and/or rock being forcibly ejected under pressure from the rockmass surrounding the excavation.	Burial of equipment and personnel LTI's, serious injuries or fatalities
Pit Wall or Inter-Ramp Scale Slope Failure	Shear failure of the very low to low strength rockmass forming the pit slopes through the interaction of through-going structural discontinuities (faults, shears, joints, etc) can result in the destabilisation and failure of slopes. Adverse structural orientation, weak strata, high clay content and water can also contribute to slope failure. Geothermal groundwater pressure is potentially a major contributing factor to failure, saturating strata, pressurising and lubricating the planes of weakness along which failure may occur. The potential for failure increases during or after prolonged periods of high rainfall or during a seismic event.	Damage or loss of mining machinery Temporary or permanent loss of access to mining area or mine infrastructure (eg pump stations, explosives manufacturing facility) Loss of ore Loss of reserves Environmental damage Local community impact
Landslide failure of caldera slopes overlying pit walls	As outlined above	
Landslide failure of access road cutting or embankment	As outlined above	

slopes		
Waste Dump/Ore Stockpile failure	Failure of waste dump/stockpile slopes during or after prolonged periods of high rainfall or during a seismic event. Failure at an active tip-head can occur due to poor drainage, poor dumping practice, low strength material forming preferential failure zones, combination of truck / dozer dynamic loading or approach too close to tip head.	Serious injuries or fatalities Reduced dumping location options for stockpiles or waste Damage or loss of mining machinery Environmental damage Local community impact
Bench-Scale Slope Failure	As outlined above for Pit Wall Failure	Serious injuries or fatalities Damage or loss of mining machinery Temporary loss of access to mining area Loss of ore
Rock Fall from Bench Face or Waste Dump Slope	The potential for an uncontrolled fall of loose rock of less than one bench height increases during or after prolonged periods of high rainfall or during a seismic event.	Serious injuries or fatalities Damage or loss of mining machinery
Sub-sea slope failure	Failure of sea floor slope due to excessive dumping of waste material from barges Failure can cause wave surges that can impact on nearby land based operations	Serious injuries or fatalities Damage or loss of mining machinery (near wharf) Environmental damage
Cavities	Small openings or voids, usually as a result of dissolution of anhydrite Equipment or people may fall into them May harbour concentrations of noxious gases (H2S and/or CO2	Serious injuries or fatalities Damage or loss of mining machinery Temporary loss of access to mining area
Inrush	Inundation of mine workings from the sea, groundwater or surface water	Serious injuries or fatalities Damage or loss of mining machinery Temporary loss of access to mining area Loss of ore

2 Investigation of Phase 12 Slope Failure

2.1 Introduction and Timeline

A multi-batter (5 benches high) slope failure occurred in PH12 south on October 1, 2009. Three pieces of mining equipment suffered serious damage as they were partially enveloped in the failure mass at the toe. Three workers narrowly escaped the failing area after noticing a large crack propagating whilst work on lining the PH12 diversion drain on the 1016 bench.

Although no injuries were suffered, there was a potential for multiple fatalities to occur. The LGL management constituted a technical team under the leadership of the author to investigate into the incident and make recommendations to better manage such recurrences and also develop a comprehensive Geohazard Management Plan for the mine.

At approximately 4:38 am on 01/10/09, a significant slope failure with a volume of between 246,000 bcm and 381,000 bcm occurred at the southern end of the Phase 12 mining area as illustrated in Figure 5. There was no injury to personnel but significant damage occurred to the plant, some of which was partially engulfed by the failure mass (light vehicle and shovel). Toe heave at the bottom of the failure resulted in a rollover of a parked haul truck. The failure incorporated part of the Phase 12 slope and a larger part of the adjacent older Minifie (Phase 4) slope. Initial observations indicate that the failure had a strong structural control which may have contributed to its rapidity of movement, which was in contrast to the slower moving failures experienced in recent years in the GW28, Phase 7 upper and Kapit 6 Slip areas.

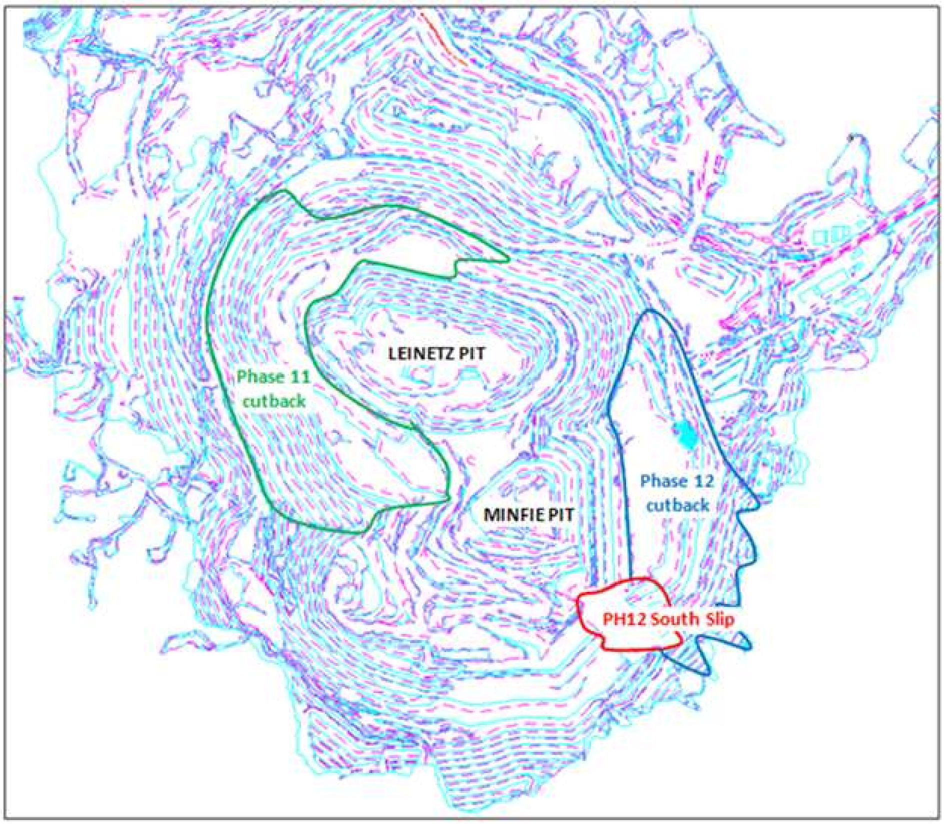


Figure 5: Location of Phase 12 South failure

The timeline in Table 2 incorporates timings recorded in witness statements taken from Mine Production Operators and Geotechnical and Mine Operations staff. Timing of rapid failure is based on Dispatch records of truck movements.

Table 2: Timeline of events in the PH12 south failure

Date & Time	**Witness**	**Event**	**Comments**
27/09/09 03:48	NA	ATS2 Scans PH12 monitoring area. No significant displacement detected	Including prisms 1025, 1026
27/09/09 06:30	C Karaut	Geotechnical Engineer (GE) inspects PH12 as part of daily inspection	No signs of instability noted
27/09/09 11:00	C Karaut	GE completes weekly 274 pit inspection report (all monitoring checked including PH12)	Passed to Senior Geotechnical Engineer (SGE) for review / signoff on 28/09/09
27/09/09 13:15	NA	PH12 Production blast 980519 fired	Southern most production blast on PH12 980 bench.
27/09/09	NA	Excavation of 980519 commences	22275 tonnes mined (dispatch)
27/09/09 19:20	NA	ATS2 scans PH12 monitoring area. Prisms 1025 and 1026 show up to	Does not exceed alarm threshold – not noted by Geotechnical

		9mm movement	
28/09/09	NA	Excavation of 980519 continues	42526 tonnes mined (dispatch)
28/09/09 06:30	C Karaut, T Johnson	GE and SGE inspect PH12 as part of morning pit inspection	1016 drainage berm is inspected. No signs of instability.
28/09/09 08:30	T Johnson	SGE inspects pit for JSO and drives full length of 1016 berm out to Minifie	No signs of instability noted
28/09/09 09:30	P Knight	Superintendent Geotechnical & Geothermal (SGG) drives the length of the 1016 berm while undertaking informal pit inspection	No signs of instability noted
29/09/09 06:30	Cletus Karaut	Geotechnical Engineer (GE) inspects PH12 as part of daily inspection	No signs of instability noted
29/09/09	NA	Excavation of 980519 continues	20250 tonnes mined (dispatch)
30/09/09	NA	Excavation of 980519 is completed	8505 tonnes mined, trim blast behind is free faced.
30/09/09 6:00	C Karaut, T Johnson, P Ruing, P Green	Geotech Ops are locked out of office when lock breaks. 2 x GE, SGE, and groundprobe radar operator visit Phase 12 to inspect area and plan radar move.	1016 berm is inspected (no instability noted). 980 berm is visited and free facing of trim 980528 is noted.
30/09/09 11:35	NA	Minifie rainfall email alarm received (15mm/15mins)	No rainfall noted as confirmed by daily rainfall report. SGE requests investigation from environmental on 2/10/09.
30/09/09 14:20	NA	Trim blast 980528 fired at toe of slope.	22545 tonnes mined prior to failure
30/09/09 14:30	Paulus Ruing	GE requests access to inspect blast. Denied due to residual gas around shot	Not inspected that day
30/09/09 15:00	T Johnson, C Karaut	During a review of monitoring data, SGE notes accelerated displacement from prisms 1025 and 1026. Contacts GE by trunk and requests GE inspect the area.	Monitoring review initiated by SGE on 28/09/09. PH12 monitoring area reviewed after Minifie SE Wall and Minifie South Wall areas.
30/09/09 17:00	T Johnson, C Karaut	After toolbox meeting SGE asks GE about PH12 inspection. GE indicates he has not yet inspected the area. SGE repeats request.	Geotech safety toolbox between 15:30 and 17:00
30/09/09 17:10	C Karaut	GE commences inspection starting with the 1016 drainage berm. No cracks or signs of instability are noted. Toe and crest either side of drain are inspected. GE then proceeds to 1028 bench where prisms are located. He notes a vertical structure in the face between 1016 and 1028 but no cracks. Once on 1028 GE notes a 5cm wide	Following his inspection GE concludes that significant failure is unlikely based on scale of cracking and experience with past slips in mine area. GE does not report findings further. From witness statement by GE Cletus Karaut.

		crack traversing the width of the berm near the 1026 prism and running up the batter toward the 1040 berm where it is lost in vegetation. GE then walks to prism 1025 but does not note further cracking. GE then returns to 1016 bench and inspects this area again. Still no cracking noted on this bench.	
30/09/09 22:47	None	ATS Autoslope alarms are triggered by prisms 1025 & 1026. This is not noted by Dispatch and hence is not reported further.	Review of ATS system log by Softrock at direction of SGE shows a positive confirmation that the primary audio visual alarm in dispatch was triggered. A test on 1/10/09 confirmed operational status of alarm. Secondary email alarms were disabled to dispatch and not sent (sent to Geotech). Night shift dispatcher reports no audio visual alarm was noted.
1/10/09 04:38	O Gami, L Diat	Supervisor, O Gami notes a crack on the 1016 drainage berm running across the road into the drain. He acts immediately to evacuate workers and excavator. The crack opens up shortly afterwards. After receiving call from Orim, excavator operator L Dait walks his machine to the supervisors location. The bench level drops behind him immediately afterward.	From witness statements by Orim Gami and Levi Diat. Timing from Dispatch records.
1/10/09 04:38	P Moab, J Kailegi	F crew supervisor Panual Moab in LV is caught up in rising ground at the toe of the slip. He abandons his vehicle and runs to safety. EX05 operator grounds his bucket and also evacuates safely. Truck 12 is tipped upside down by bulging ground at the toe of the slip. The operator (Jerry Kailegi) kicks out the windscreen and moves to safety	From witness statements by Panual Moab, Jerry Kailegi. Timing from Dispatch records.
1/10/09 05:20	P Knight, T Johnson	SGG is contacted by Peter Dodds and informed of the incident. SGG contacts SGE and both travel to site	
1/10/09 05:45	P Knight, T Johnson, C Karaut	SGG & SGE pick up GE and proceed to incident location.	

2.2 Monitoring Deployed in Failure Area

Monitoring in the vicinity of the slope failure and the adjacent Phase 12 slope at the time of the failure was restricted to ATS prisms and visual inspections, carried out daily. At the time of the incident, monitoring frequency of the Phase 12 South East Wall prism group ("PH12 SE Wall" in Quikslope) was once per scheduled list monitoring cycle (monitored from ATS 2). On this monitoring frequency, the prism group was picked up approximately every 8 to 9 hours. Other areas were monitored more frequently due to their perceived higher risk (e.g. GW28 slip area). Prism locations at the southern end of PH12 are illustrated in Figure 6. Prisms had been installed on 1028, 1040 and 1052 benches. The intention was to install additional prisms on the 1016 berm. However, this was delayed due to the storage of rip-rap material for the drain along the bench crest and subsequent delays to the completion of the drain (still under construction at the time of the failure). The bench on either side of the drain was not considered suitable for prism installation as it would be used for drain maintenance.

Visual inspections were normally carried out daily commencing at 6:30 am. These typically but not exclusively included an inspection of the PH12 mining area (usually a drive or walk on the 1016 drainage berm). From the 27th September 2009, the area was subject to daily inspections as listed in the timeline above.

Monitoring of the old Phase 4 Minifie slope was largely restricted to the west-north-west facing slope below Phase 12 cutback ("Minifie SE Wall" prism group). The majority of these prisms had been removed ahead of Phase 12 mining above. The slope to the south west of Phase 12 was not covered by prism monitoring due to the perceived low risk, the lack of recent mining in the area, high vegetation cover and difficult access. The area was also extensively vegetated making visual inspection difficult. Heavy vegetation also precluded radar monitoring.

Crack pins were installed across tension cracks associated with a minor structurally controlled batter scale failure located about 100 m north of the main failure (Figure 6). This area failed in July 09 when heavy rainfall overran the banks of the partially completed diversion drain and washed out the failed material. The crack pins were made obsolete after the area was washed out.

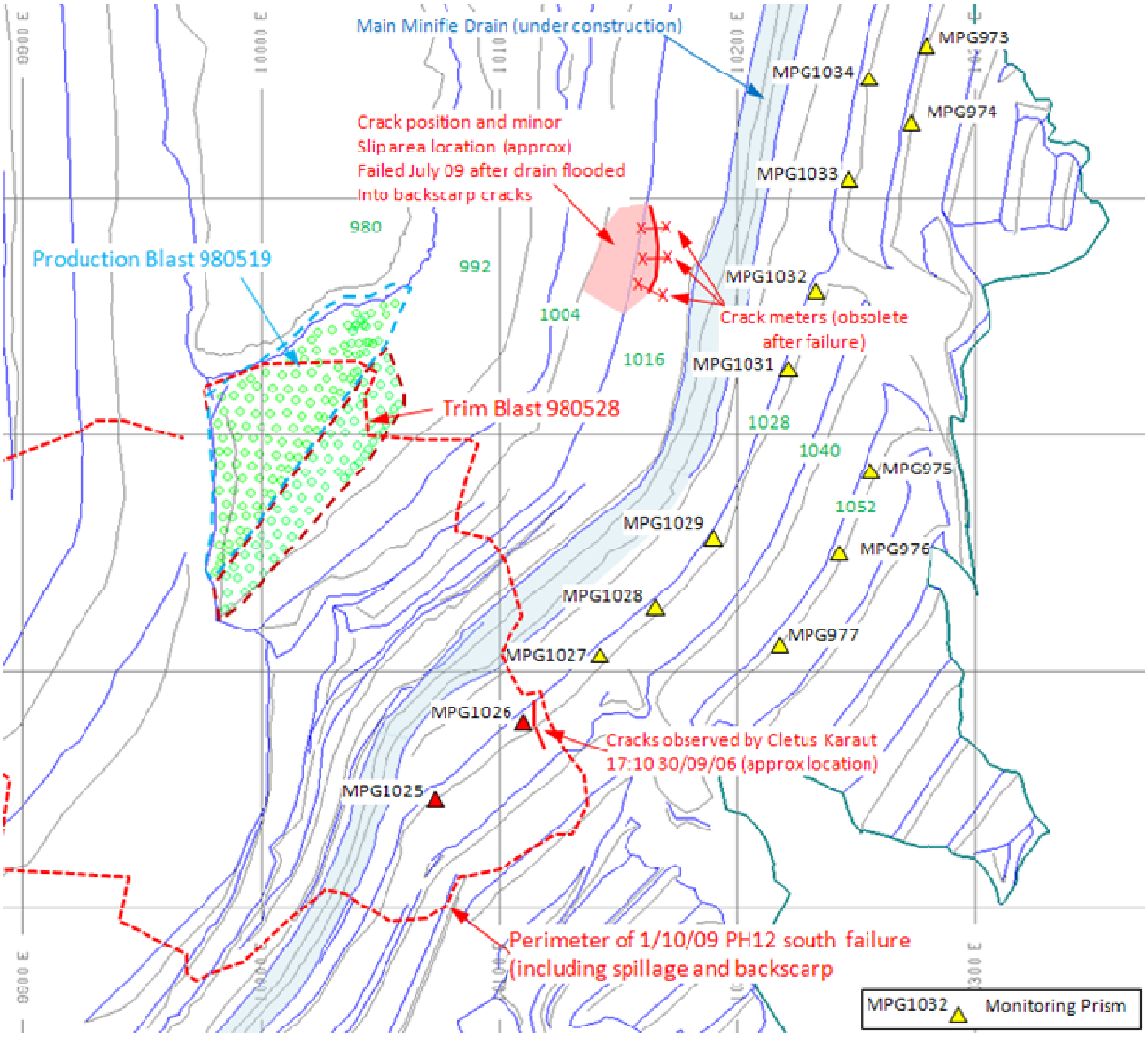


Figure 6: Southern end of PH12 prior to failure

2.2.1 Prism Monitoring Results

Prism monitoring results indicated that displacement of two prisms (1025 & 1026) at the southern end of Phase 12 started to report significant displacement from the pickup at 19:20 on 27/09/09. No displacement was recorded by the preceding pickup at 03:48 on 27/09/09. Displacement started after production blast 980519 located at the toe of the slope was fired at 13:15 on 27/09/09. Displacement continued at a rate of approximately 14 mm/day while 9805 19 was excavated until the 14:15 pickup on the 30/09/09. At 14:20 on 30/09/09 trim blast 9805 28 was fired. The next prism pick up at 22:47 on 30/09/09 recorded a substantial increase in displacement sufficient to trigger the ATS alarm the threshold for which was set at 90 mm/day. The displacement history as recorded by prism 1025 is illustrated in Figure 7.

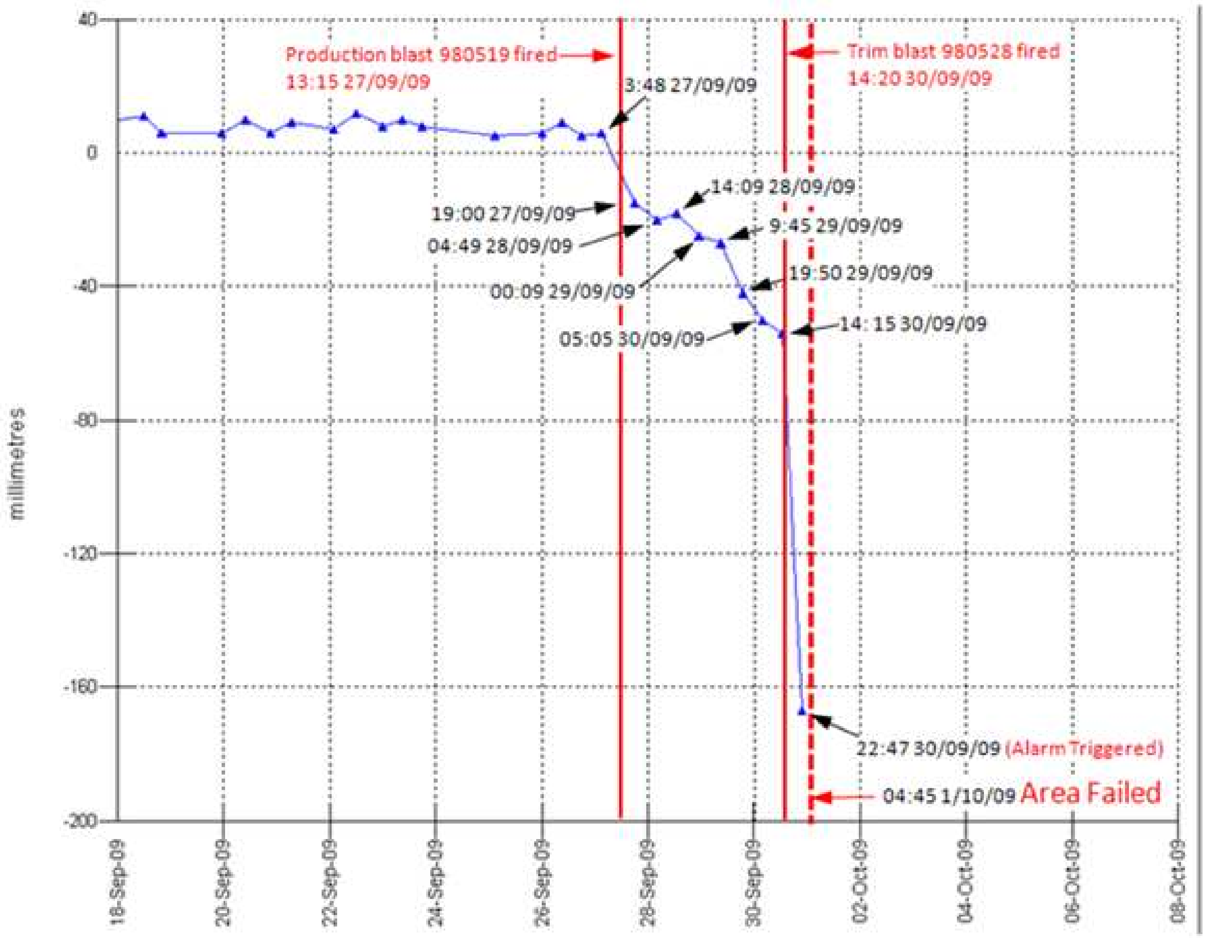


Figure 7: Prism monitoring results from MPG1025

No other prism in the PH12 area recorded any significant displacement and continued to record flat trends before and after the failure as illustrated in Figure 8. This included prism 1027 located closest to the failure boundary. It should be noted that there was no indication of displacement recorded prior to 27/09/09.

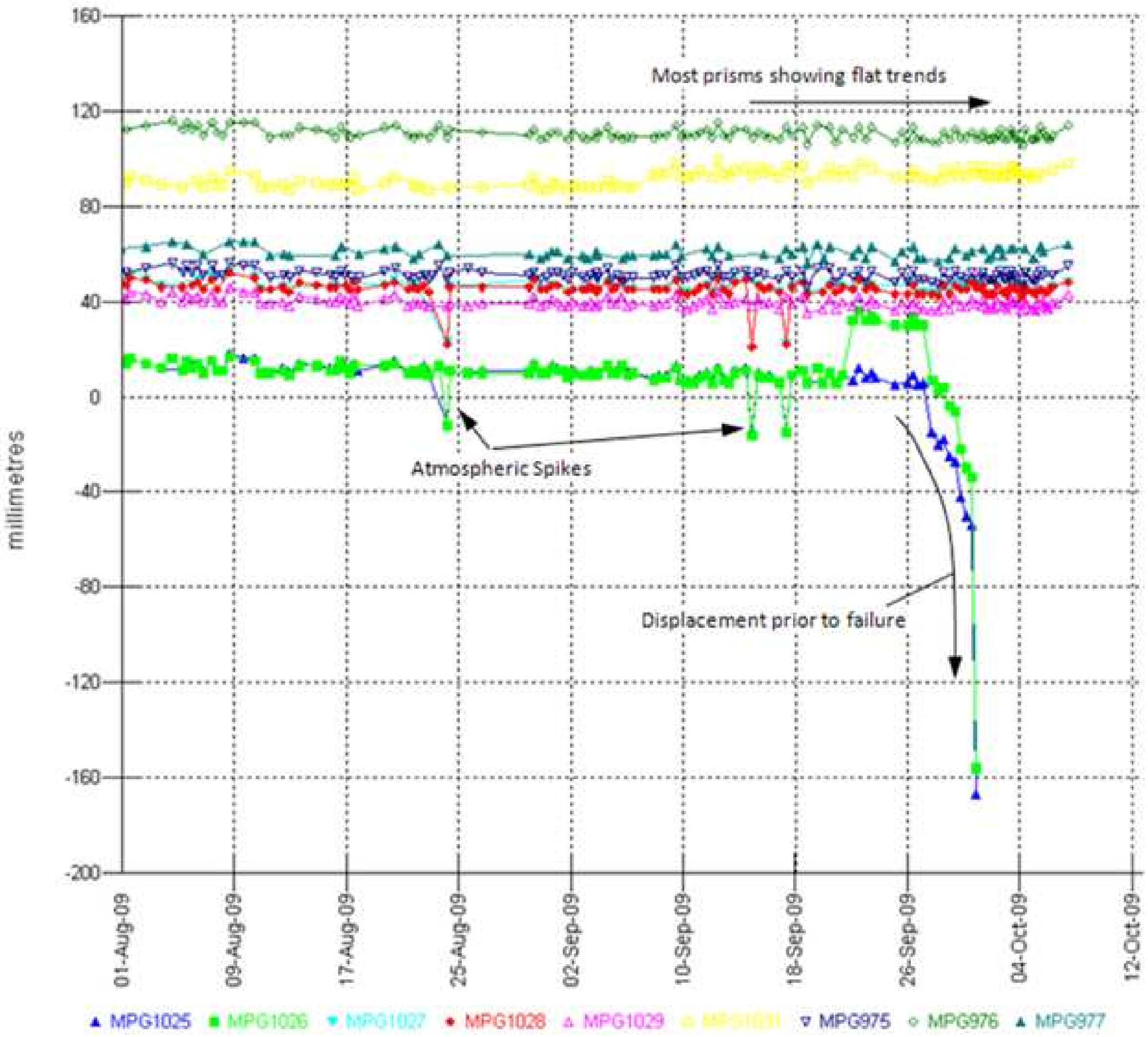


Figure 8: Prism monitoring results from southern end of Phase 12

2.2.2 Vibrating Wire Results

Vibrating wire piezometers (VWPs) were located south of the PH 12 failure, they were DDHL 885, 878 and 877. These instruments were installed at 1078, 1074 and 1029 mRL respectively as shown in Figure 9. Their monitoring was covered by a monthly schedule which was reviewed quarterly to ensure that the frequency of monitoring was adequate for the observed changes in groundwater heads. A review of this monitoring schedule was last conducted in August 2009.

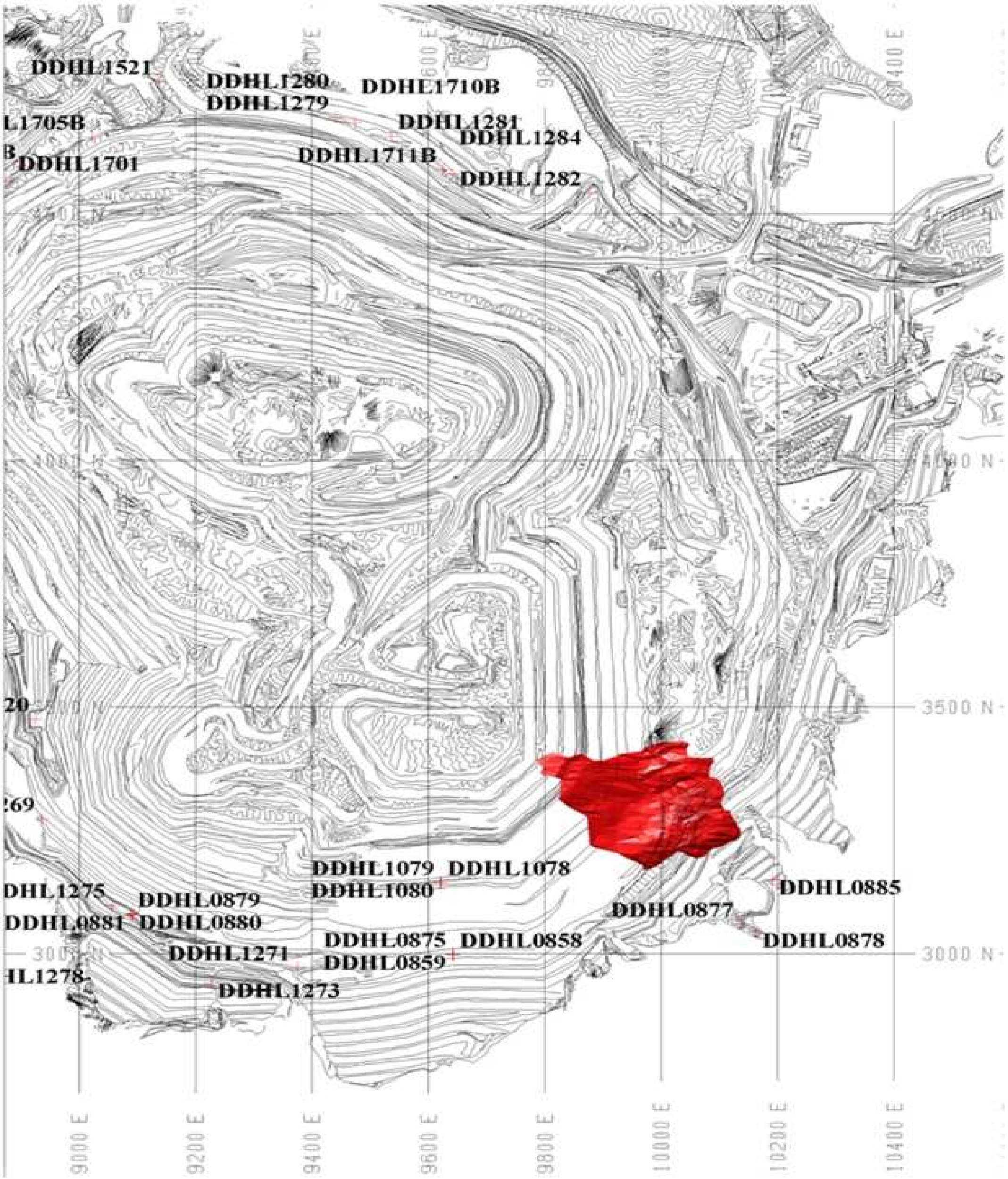


Figure 9: Locations of vibrating wire piezometers

Groundwater levels at VWP DDHL 885 indicated an increase of 1.52 m in the months leading up to the PH12 failure as shown in Figure 10. This equated to a very small increase in pressure, some 14 kPa and was the only VWP adjacent to the PH12 failure to indicate increase in groundwater levels. The other VWPs DDHL 878 and 877 either showed no change or a decreasing trend.

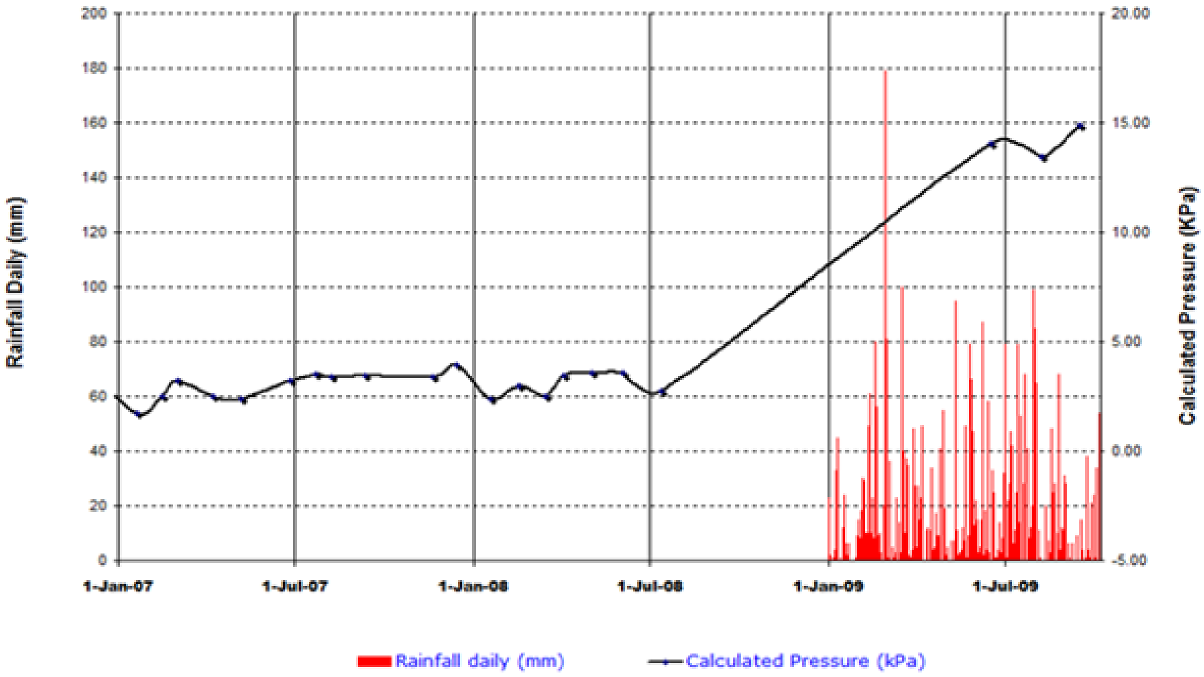


Figure 10: Ground water levels at VWP DDHL 885 (1078 mRL)

2.3 Description of Failure

2.3.1 Location and Geometry

The Phase 12 South failure occurred at the interface between the Phase 12 cutback and the older Minifie Phase 4 slope. The older slope was excavated prior to 2001 and remediated following a similar major failure in November 2001, with an associated subsequent cutback of the upper slopes performed in a number of stages during 2003 (Note: It was not clear if these remedial cutbacks removed all the 2001 failure mass).

The failure appeared to have been triggered by the excavation of the Phase 12, 980 bench material (at approximately 1000 mRL). Significant ploughing and possible heave of the toe, of the slope, indicated a potential structural plane may have been allowed to daylight by the firing of the 980-519 production shot (triggering first signs of prism movement) and/or in the adjacent 980-528 trim shot (triggering marked acceleration of movement as shown in Figure 7).

The failure moved in a North Westerly direction normal to the Phase 12 wall (approximate azimuth ~335°-340°) and may have had a component of spread due to freedom of movement down its southern flank into the old Minifie pit. This contributed to spillage down the older Minifie pit slope. Some component of this spillage in the south may have been fill material placed on top of an earlier ramp through this area, to build up and form the drainage berm. Evidence for this was noted in the exposed end of the drain at the southern boundary of the failure.

Approximately 5 berms were involved in the failure (1072RL~1000RL), a height of approximately 72 m from the 1052 berm down to the 980 bench. This included the major Phase 12 diversion drain (~5.0 m wide 1016 drainage berm). Post-failure the estimated failed length along the drainage berm was approximately 150 m, Figure 11.

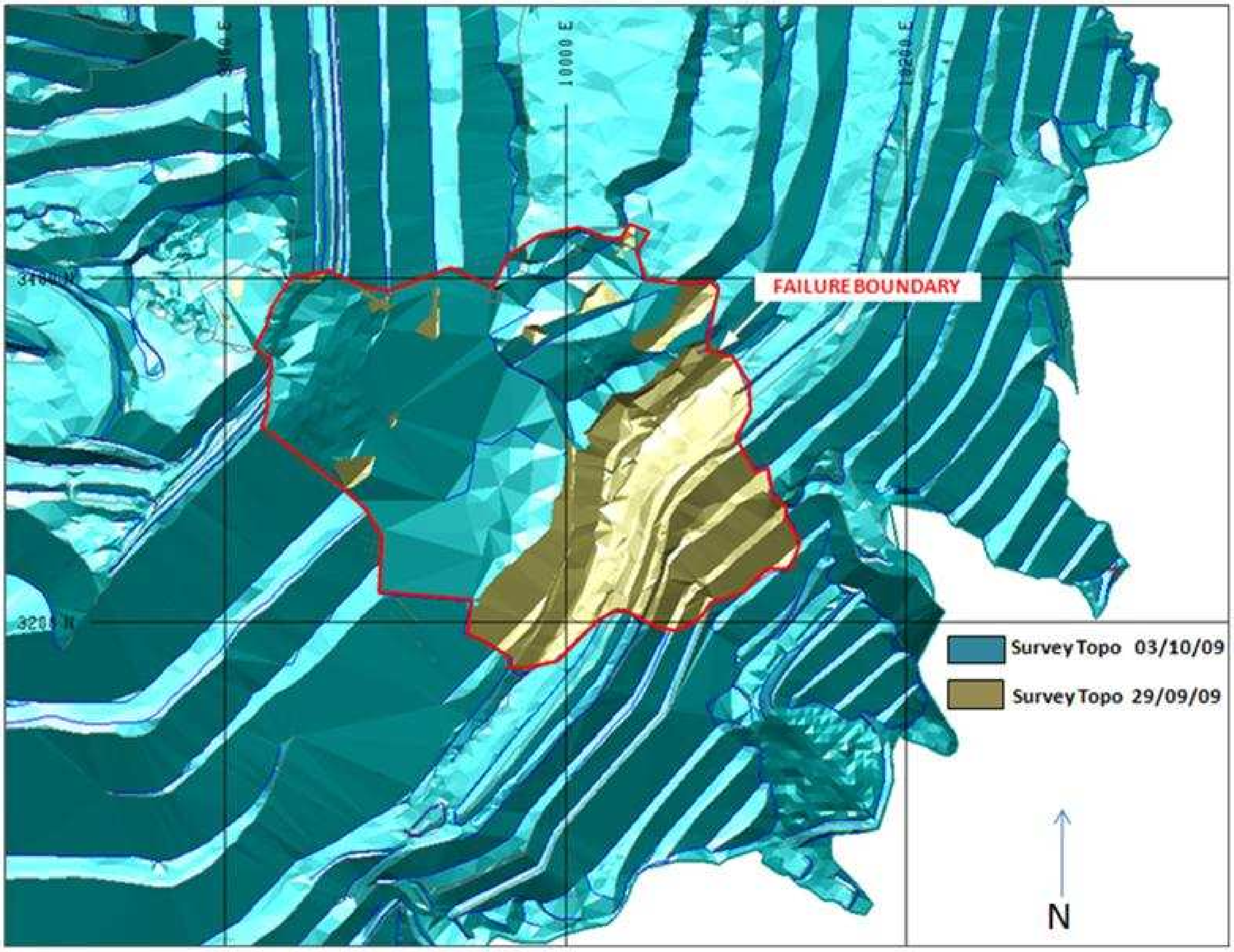


Figure 11: Plan of failure area

Volume of failure was estimated at between 246 Kbcm and 381 Kbcm, Figure 12. This range was based on failure models with postulated basal planes at 13° and 10° dip towards azimuth 340°.

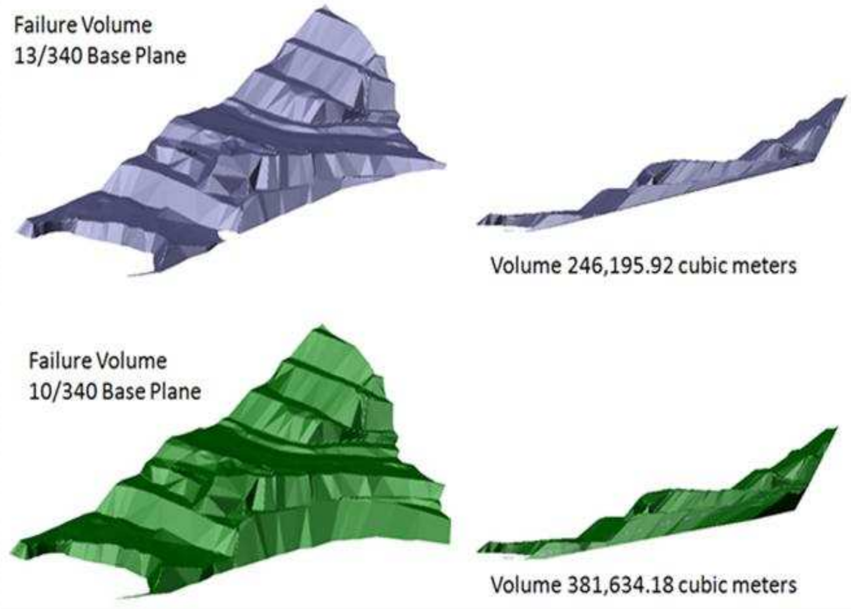


Figure 12: Failure volume

The following section describes the structural geology and structural model set up. It may be noted that the 2001 failure discussed earlier was also modelled with a 13° sliding plane.

2.3.2 Structural Geology

The location of the failure was to the East of the Minifie deposit, the dominant geology in this area was a combination of upper weathered oxides, colluvium and, moving down in elevation, into agglomeritic argillic altered breccia materials.

Major structures were evident in the batter faces but joint sets and structures tended to be truncated against each other with limited continuity evident during face inspections and mapping. The central portion of the failed mass was blocky in nature and evidence for a major joint set was noted. This set was oriented with a strike normal to the failure direction, with spacing approximately 5 m and continuity of >20 m across the failure. The dip was unable to be determined due to failure disturbance but was assumed to be sub-vertical.

Location of mapped structures relative to the failure outline are shown in Figure 13, which also shows the recorded major structures and interpreted wireframes (blue) of structures derived from photogrammetry by PSM Consultants. The failure boundary was surveyed using reflectorless instruments and shows the extent of failure plus the associated spillage into the old Minifie pit below.

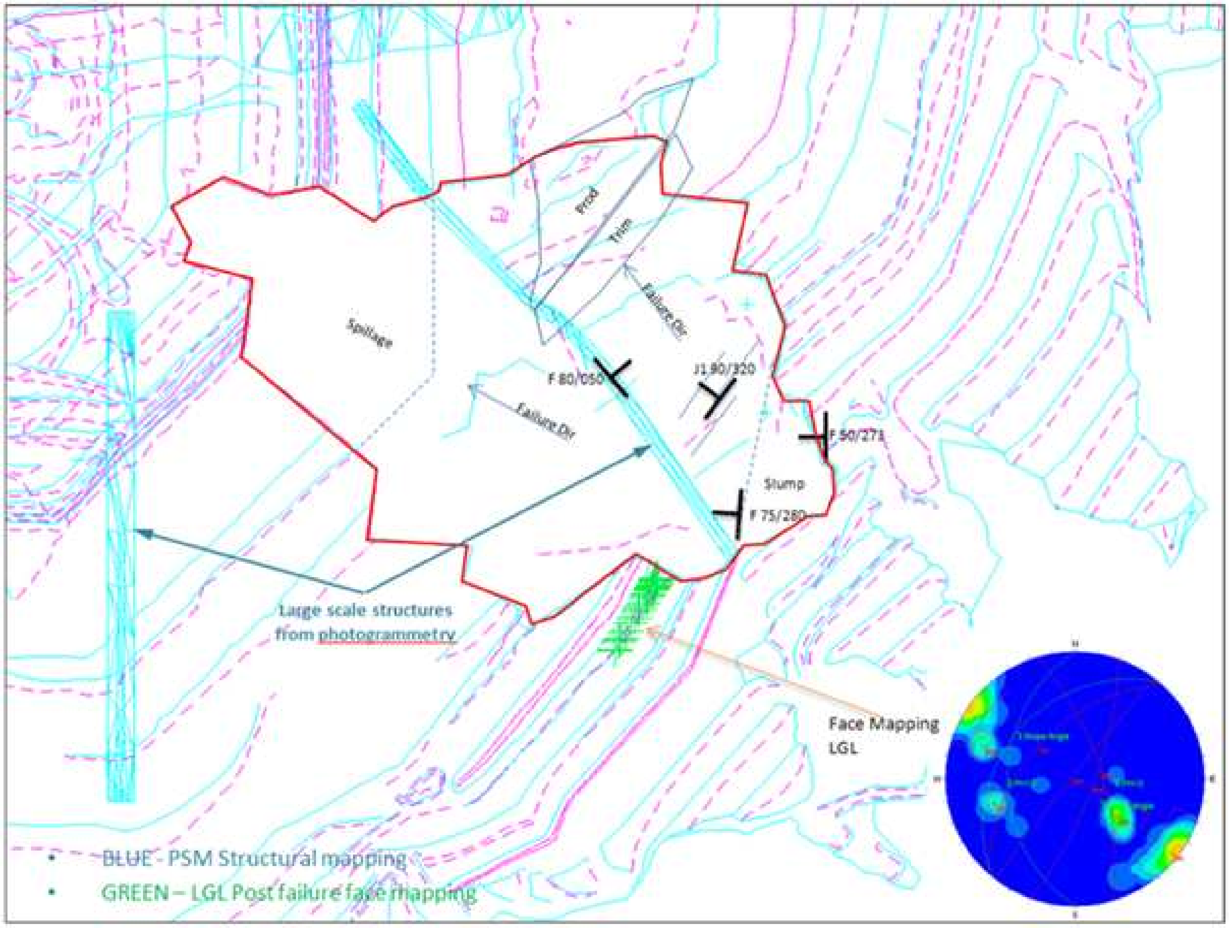


Figure 13: Structural geology

An additional mapping exercise was conducted to the south of the failure to identify any likely structures forming rock fabric controls on failure.

A relatively planar structure bounding the southern limit of the failure was located (40°/340°). This was noted to be grey in colour and coated with (alteration) clay. The failure back-scarp revealed a number of steep (60°) curvy planar (along strike) structures with signs of recent movement.

No flat dipping structures (i.e. <40°) were mapped. A low angle structure in the order of 10°-13° has been postulated allowing the failure to daylight on the 980 bench (thus explaining the response of the failure to the trigger mechanism of mining at the toe as discussed previously). Some evidence for these low angle structures can be seen in Figure 15 although they have not been directly observed within the failure area itself. Figure 14 is a photograph looking East at the Minifie East wall immediately below the 980 bench (failure toe). As may be noted, the structures evidently tend to roll steeper to the North.

Figure 14: Minifie East wall - low angle structures below failure

2.4 Failure Mode and Contributing Factors

Mapping in and around the failure revealed a number of major bounding structures and relatively continuous joint sets. These and the relatively fast failure rate lend weight to the supposition that the failure was structurally controlled. The mode of failure was complex but was largely structurally controlled with minor rock mass deformation through soil and colluvium at the top of the backscarp. The upper part of the failure gave a wedge-like appearance with sliding on steeply to moderately dipping surfaces with dip direction azimuths to the North-West and West. However, as neither of these structures undercut the slope, a shallow planar sliding plane must be present below the failure mass. This was interpreted to dip at between 10° to 13° toward an azimuth of 340°.

Observed joints varied in orientation both in dip and strike, especially in the failure back-scarp area. Generally, most structures dip in a North-West direction. The interpreted three dimensional failure model illustrated in Figure 15 was produced based on structural mapping and observation.

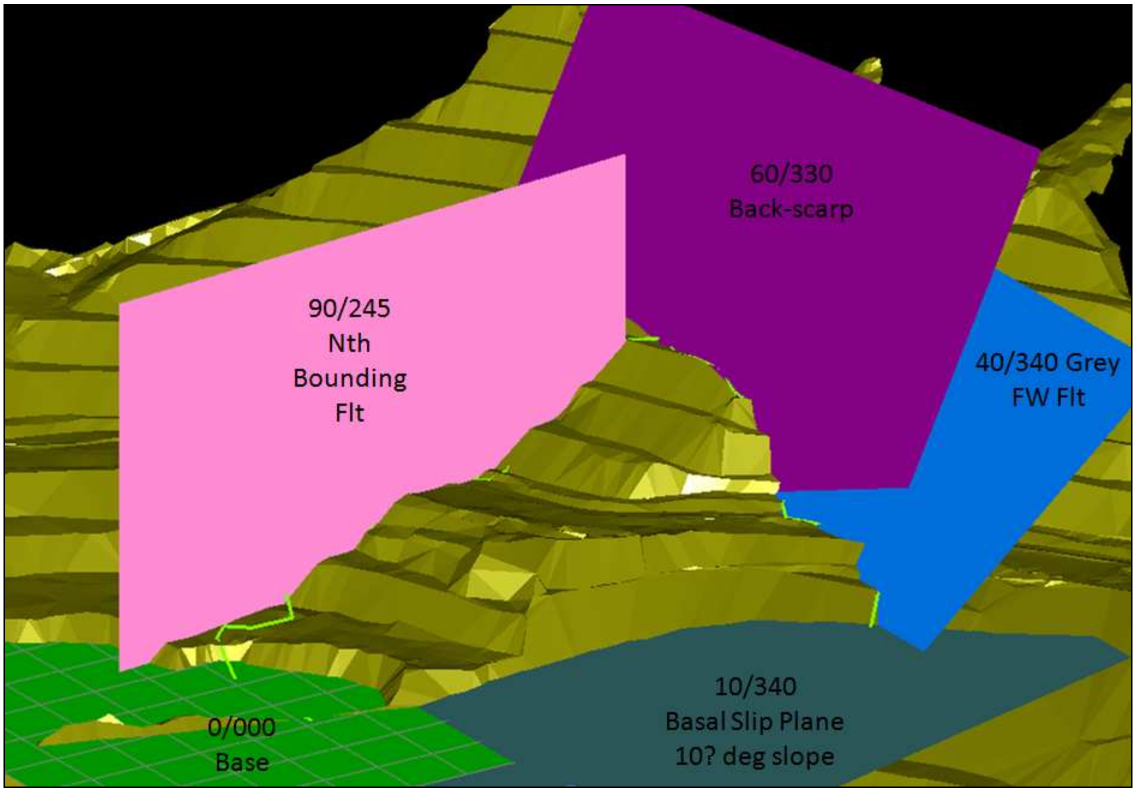


Figure 15: Structural geology interpretation

A northern bounding structure (90°/245°) was used to constrain the failure model. Observations in this area did not come up with a definitive structural control along this side and due to the blocky nature of the failure mass and the variable dip and strike of observed joint planes along this area, a component of shearing through rock mass was likely to have occurred, Figure 16.

Figure 16: Northern failure margin

A steeply dipping back scarp structure was modelled. Portions of this surface developed along fault planes although some circular failure components through colluvium were also possible. An average orientation was used (60°/330°), Figure 17.

Figure 17: Failure back scarp

The southern bounding structure (40°/340°) was based on mapped orientations of a joint plane below the end of the failed drain. This structure was interpreted to extend into Minifie where a similar structure existed known as the Minifie footwall fault, Figure 18. This structure was observed to be planar in nature and coated in clay.

Figure 18: Southern failure bounding structure

Basal slip planes were modelled at 10° and 13°, dipping in a similar direction to the southern bounding footwall fault. The northern extent of this structure was assumed to daylight in the trim and production shots on the 980 bench. A structure dipping at 13° was found to be the steepest plane that met these requirements and also did not expose itself above the observed 40°/340° structure at the failed end of the drain.

No stability analysis was conducted. Both models were constrained by the back scarp plane (60°/330°). The variation in angle of the basal low angle structure affected the volume of the failure mass but not the potential cutback requirements. Due to relatively fast rate of failure, the steeper basal slip plane model was more likely and preferred for geotechnical stability analysis.

Two cross-sections of the failure are presented in Figures 20 and 21. Cross section locations are shown in Figure 19.

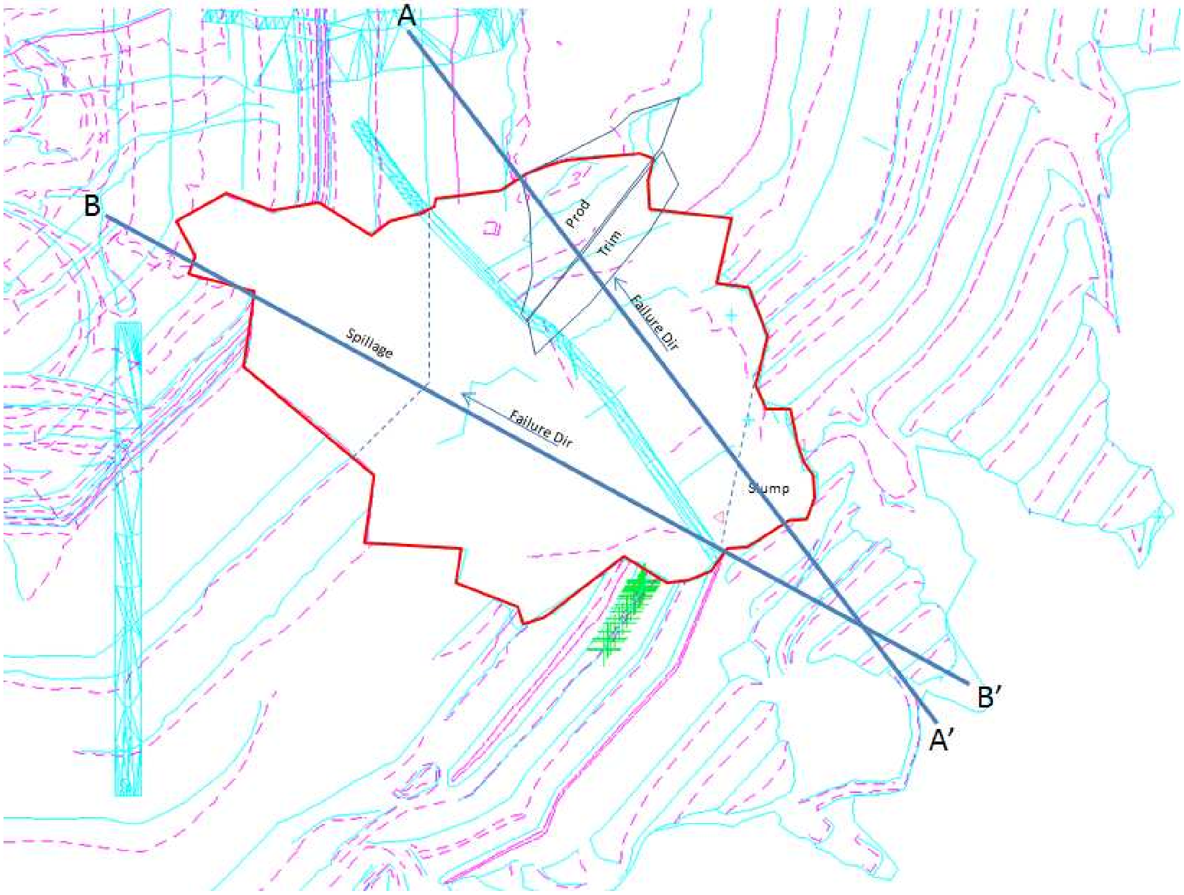


Figure 19: Cross section locations

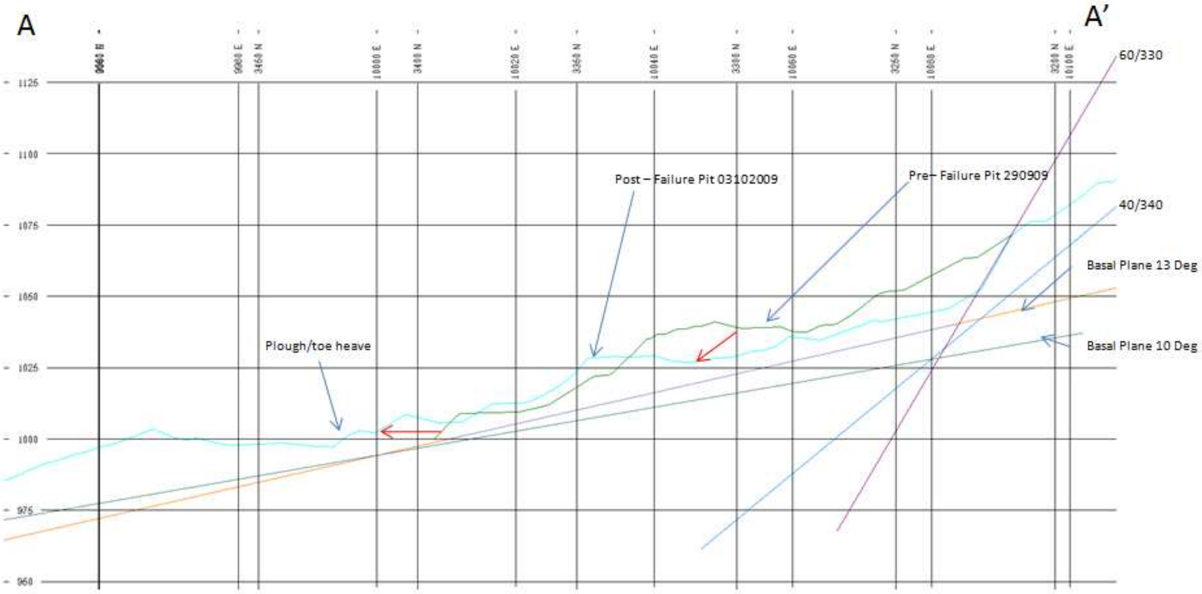


Figure 20: Cross section A-A’

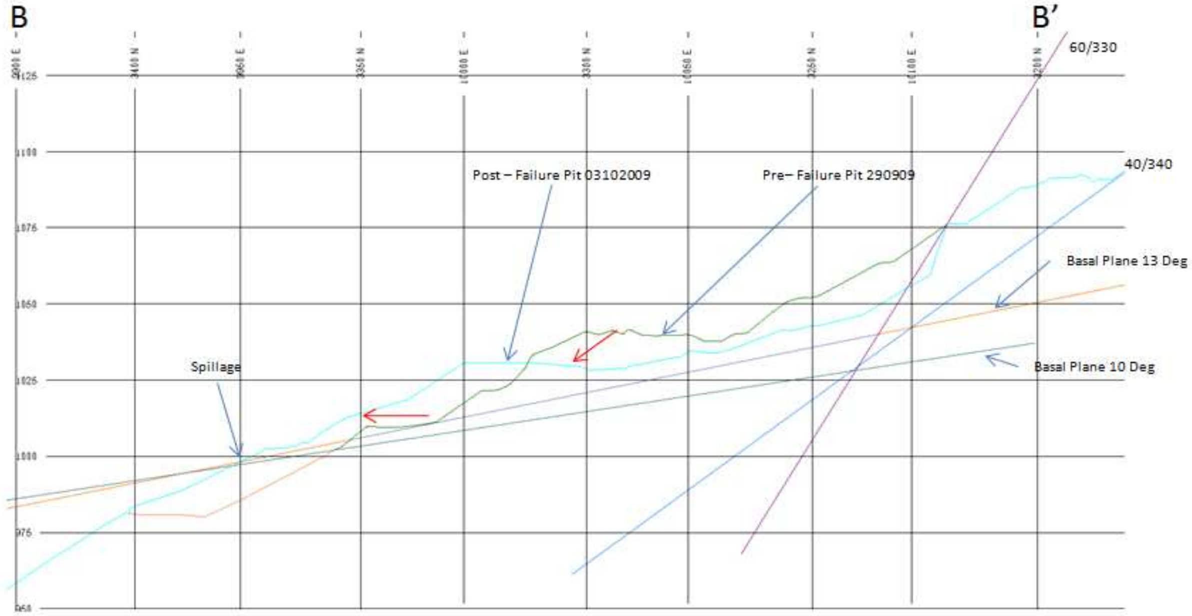


Figure 21: Cross section B-B’

As discussed above, the likely primary trigger to failure was blasting of the 980 shots during excavation of Phase 12. This allowed a low angle structure to daylight in the newly formed Phase 12 wall.

Although high rainfall was not a factor immediately prior to failure, it was likely that water pressure played a key role in the failure and may have contributed to the unusually high rate of failure.

The 1016 drainage berm was in the process of being lined, after re-alignment by the Phase 12 cutback, but had already been exposed to a number of months of rainfall, allowing water ingress into the back of the failure location. Historically, this drain ran around the front of Phase 12 cutback and had been pivoted back during Phase 12 cut.

Prior to Phase 12, to the Southern side of the failure, this old drain split into two and ran down an old ramp through the failure area as well as along the earlier Phase's drainage berm. This explained the fill observed in the failed drain to the south of the failure. This scenario pointed to a significant water influence on failure around this interface area.

During early excavation (late 2008) of the upper benches in Phase 12, the existing upper drain was cut out and the lower drain was again used to divert all water back down onto the 980 bench, Figure 22.

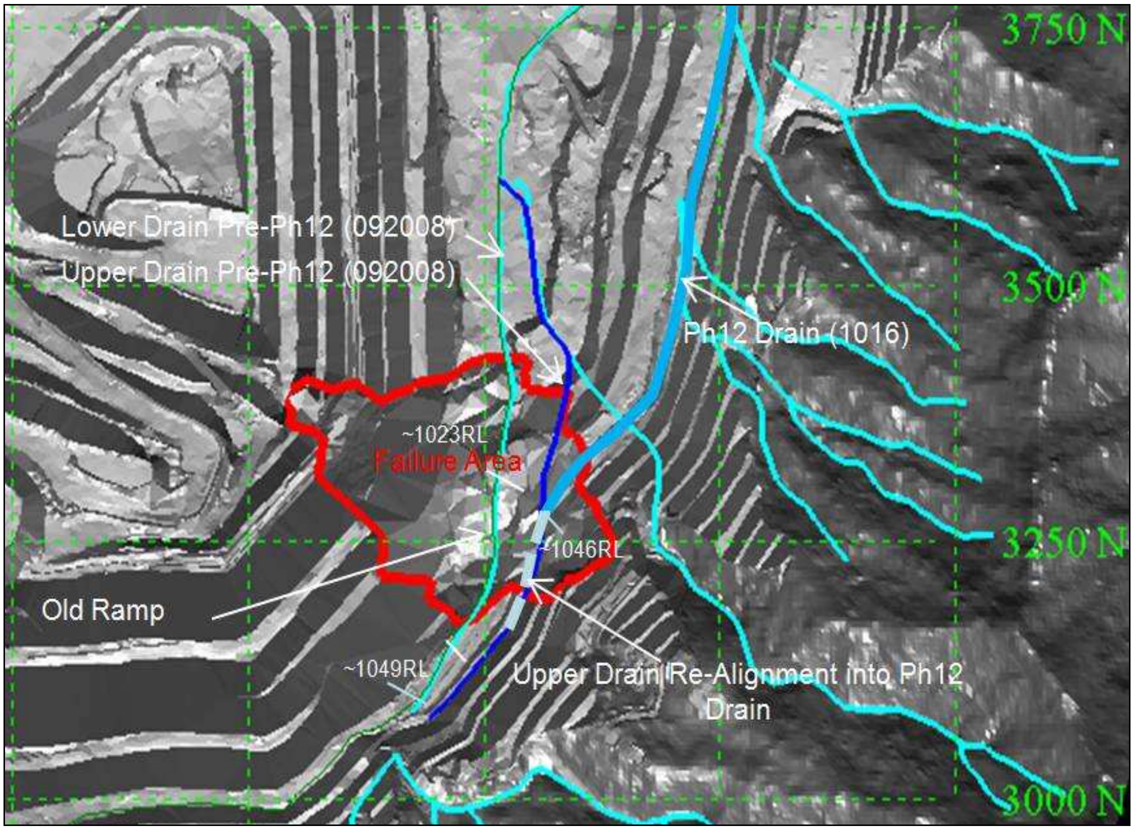


Figure 22: Old and new drain positions relative to the failure area

2.5 Summary of Findings, Recommendations and Actions

Geotechnical investigations revealed the failure to be structurally controlled but triggered by mining on the 980 bench. Accelerated prisms displacements were first recognised 3 days ahead of failure. The incident investigation further revealed the following failed defences.

- The relationship between mining at the toe and the initiation of cracking was not quickly established. This blinded thinking to the possibility of the potential for a large scale failure.
- The presence of a crack, picked up after inspecting the area (after recognising the accelerated displacement pattern), was not reported to the supervisor or Mine Production personnel. Consequently, they were not warned of the potential threat and mining operations proceeded during the night in the PH12 south area in the footprint of the eventual failure.
- Two prisms exceeded the alarm threshold, but the alarm system failed. Consequently operators were not evacuated from the threatened area.

The follow recommendations to prevent reoccurrence were made.

- Counselling of Geotechnical and Mine Dispatch personnel involved in this significant incident.
- Tie all elements of the existing geotechnical management system by creating an overarching Geohazard Management Plan (GMP) document.
- Ensure geotechnical investigations are sufficiently scoped to include hazards at the margins/periphery of individual cutbacks.
- Mine out the failure mass and reinstate the diversion drain; drain must be lined as soon as possible after construction.
- Increase prism density and reading frequency on PH12 and Minifie south slopes.
- Revise and improve prism alarm system in Dispatch for early warning.
- The communication system needs to be reliable.
- The alarm requires a manual shut off, or a minimum duration of 2 minutes.
- Continue rollout of geotechnical hazard awareness for all pit personnel.
- Ensure phase 12 development has adequate coverage of horizontal drains and piezometer monitoring.

3 Geohazard Management Plan

Apart from the aforesaid incident, the following geohazards were studied:

- Slope failures and rockfall
- Landslides (on natural slopes)
- Land based dumps and stockpiles
- Subsea slope failures (barge dumping)
- Geothermal outbursts
- Cavities (includes H_2S and CO_2 gas)
- Inrush – surface and groundwater and the sea
- Earthquakes and tsunami

The individual management plans were revisited, gaps identified and improved to form a comprehensive Geohazard Management Plan (GMP) which has since been adopted. The salient features and broader approach to formulate GMP are discussed in the following pages of this document, some in more detail than others for the reason that they are more prominent, elaborate and implemented on a day to day basis.

3.1 Slope Failures

The process flow for slope design is summarized in Figure 23.

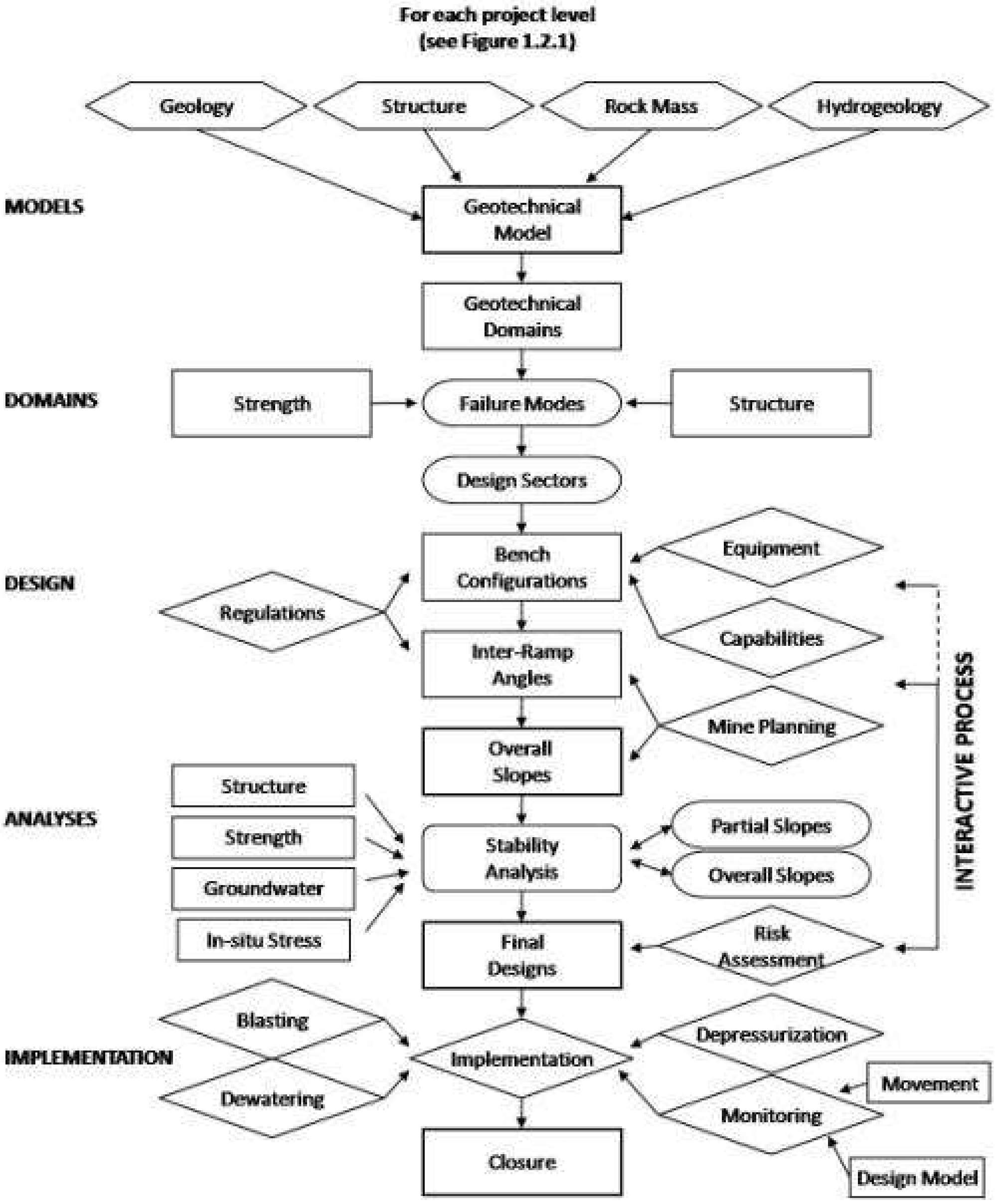


Figure 23: Slope design process (Guidelines for Open Pit Slope Design, 2009)

For Lihir, a modified process was developed to account for the unique conditions such as the geothermal activity and being in an earthquake zone, Figure 24.

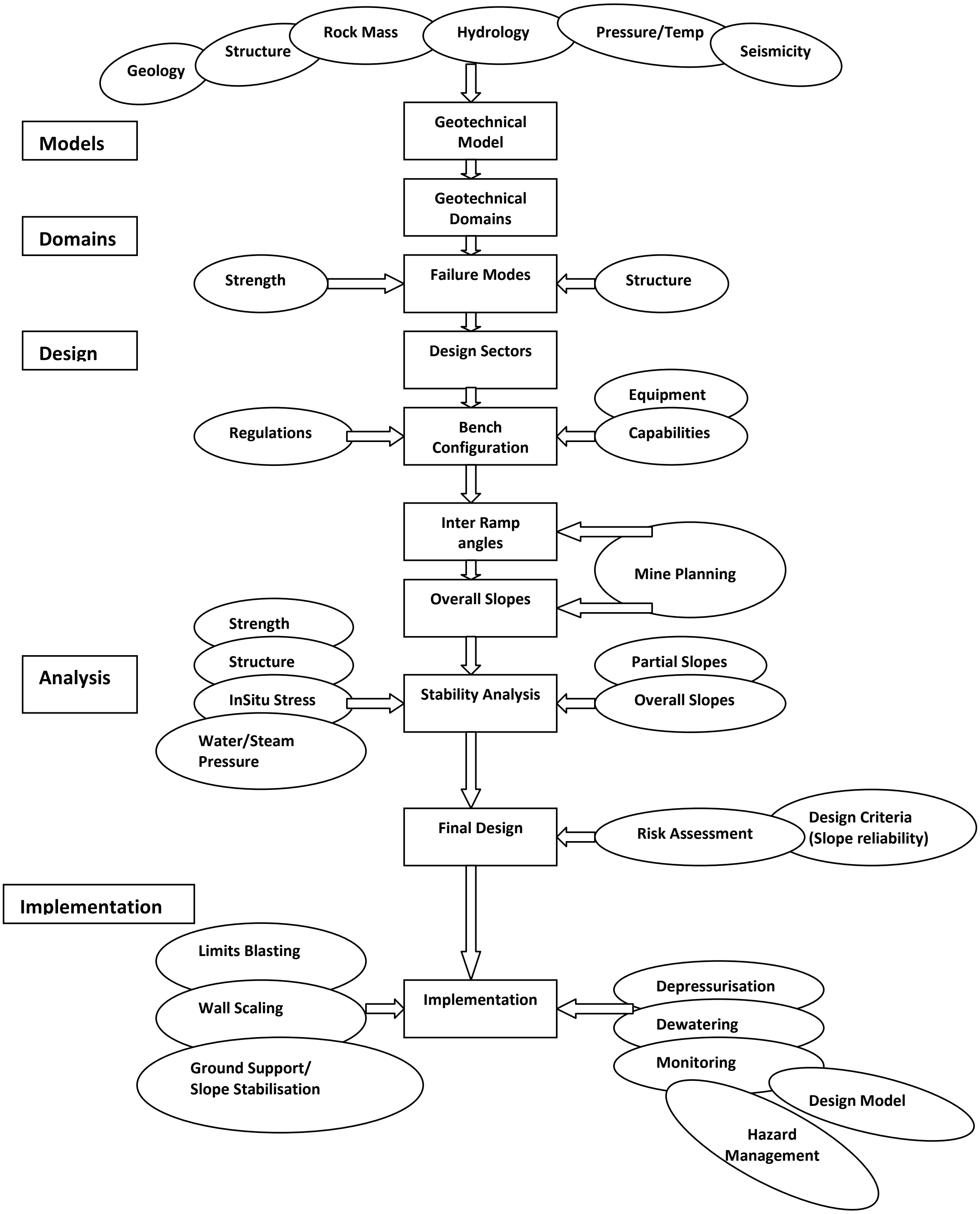


Figure 24: Slope design process for Lihir

Some elements of the process are expanded in the following sections.

3.1.1 Design Criteria

Where qualitative assessment is not appropriate or when stability modelling allows, a quantitative or probabilistic approach should be taken to determine risk tolerability. This approach would aim to put in place controls to reduce hazard to as low as reasonably practical (ALARP).

Requirement for detailed study goes up as risk impact increases. In general, geotechnical design parameters use a minimum factor of safety of 1.2 and probability of failure 10%. This may vary dependant on the risk tolerability, assessed in light of safety, economics and operation recoverability.

The design criteria adopted for slope designs at Lihir accounts for Seismicity as Lihir is located in the Pacific ring of fire, noted for its seismic activity as shown in Figure 25 & Figure 26 below. As such, specific design criteria have been developed for this hazard.

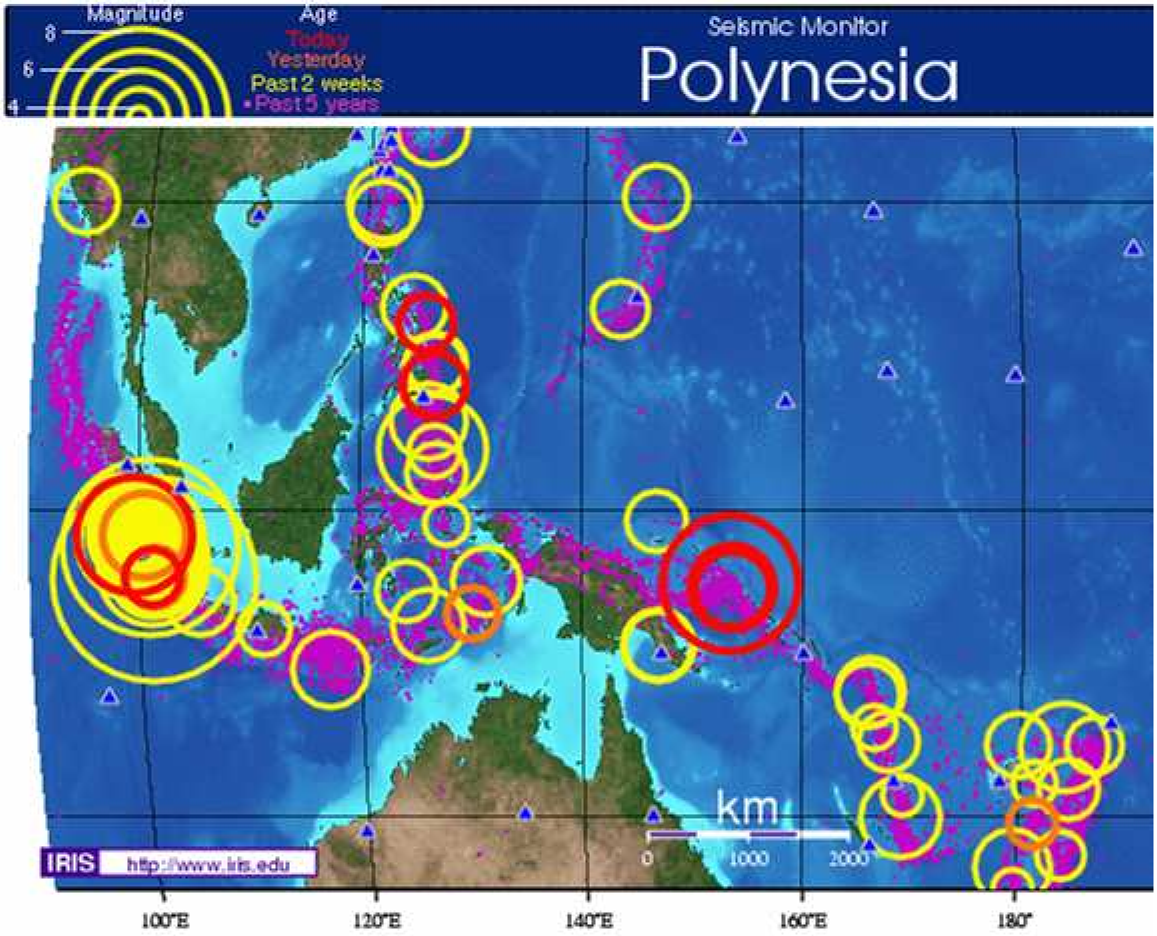


Figure 25: Seismicity around Lihir (DMPGM-PNG)

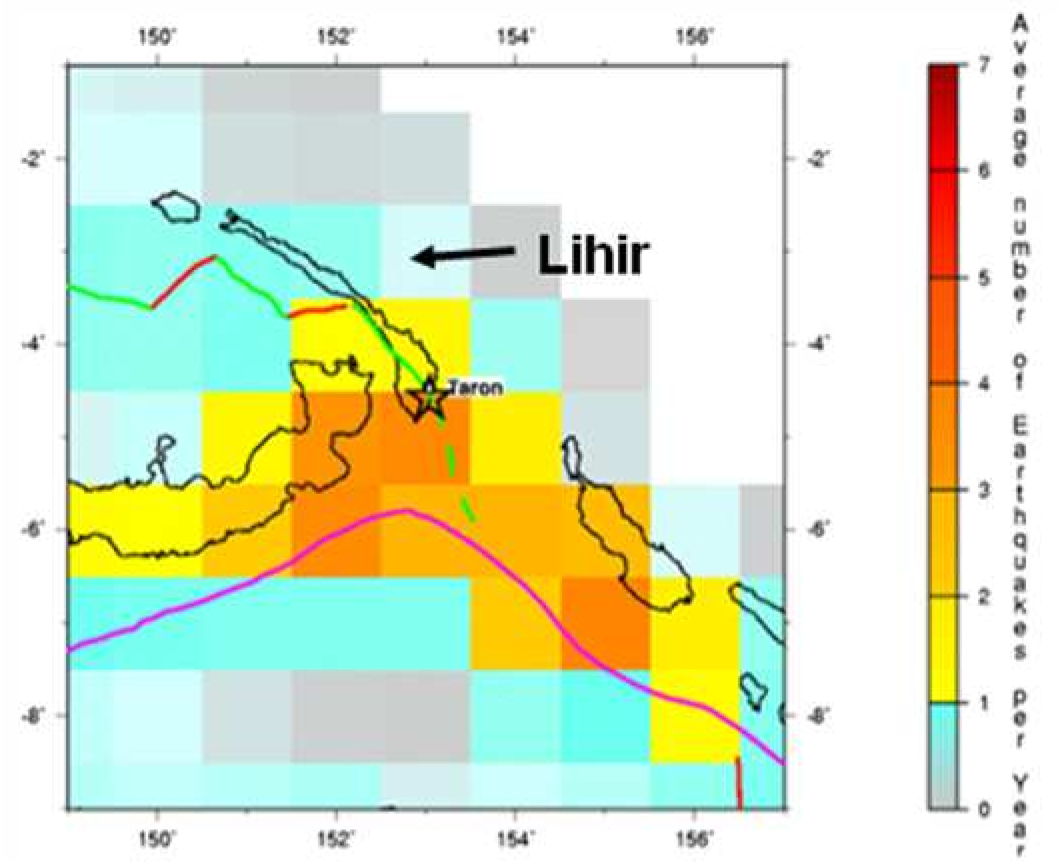


Figure 26: Seismicity around Lihir (DMPGM-PNG)

Pit slopes are designed to resist without yielding the degree of earthquake shaking estimated to have a 50% probability of being exceeded during the Lihir operation’s design life and to resist without causing major damage or injury, earthquake shaking estimated to have a 10% probability of being exceeded during the Lihir operation’s design life. These criteria are accepted internationally and the latter exceeds the requirements of the PNG Earthquake Loading Code for the estimated mine life of 30 years.

The maximum credible earthquake predicted from the foregoing studies is located an average distance of between 20 and 35 km from Lihir, with a magnitude of 7.5 and an estimated return period of between 1200 and 2000 years. In comparison, USGS database records referred to above for events from 1973 to present <35 km radius from site, show there were ten earthquakes with magnitudes from 4.0 to 4.8 and epicentral depths from 33 to 100 km. As an outcome of the 2000 seismic hazard study, seismic design criteria for Lihir operations stipulate structures, pit slopes and earth embankments are designed to resist without yielding, the degree of earthquake shaking estimated to have a 50% probability of being exceeded during the Lihir operation’s design life.

Additionally, in the case of structures, designed to resist without causing major damage or injury, earthquake shaking estimated to have a 10% probability of being exceeded during the Lihir operation's design life. A recent analysis by CSIRO of data recorded by Lihir's strong motion seismometer network has indicated that the seismic attenuation model used in earlier seismic hazard studies is still applicable until a larger database of events is established on site. These design criteria are accepted internationally and exceed the requirements of PNG Earthquake Loading Code for the estimated mine life.

3.1.2 Implementation

Implementation or slope control encompasses all activities involved in ensuring that slopes and any slope hazards are properly managed. These include:

- Controlled drilling and limits blasting to achieve the batter and berm design configuration but minimize slope damage,
- Wall scaling and cleaning to remove loose rocks,
- Slope depressurisation and dewatering to minimize the influence of water pressure on slope stability,
- Ground support or slope stabilization to minimize the risk of localised slope failure
- Performance monitoring - identification of slope hazards through inspections and monitoring of slope movements,
- Slope failure hazard management – assessing and implementing appropriate risk control measures.

The implementation process and the various aspects of slope control are discussed below:

3.1.2.1 Controlled Drilling and Blasting

Substantial damage to rock slopes can be caused through the use of inappropriate drilling and blasting practices. In addition to causing potential mining inefficiencies (increased waste, dilution of ore), there may also be increased requirements for ground support/control to manage safety and production requirements.

Although some blast damage is unavoidable, excessive blast damage can be minimized by the use of controlled drilling and blasting practices, particularly in the proximity of slopes. The design of the blast must be optimised for the specific combination of rock conditions to achieve the required degree of rock fragmentation while minimising damage to the rock remaining in the slope.

The Geotechnical Engineer is involved in blast design and provides the geotechnical information required by the Drill & Blast engineer to assist in the blast design.

The Drill & Blast Engineer undertakes regular monitoring of blasts. The Geotechnical Engineer liaise with the Drill & Blast Engineer to assist in improving blasting practices.

3.1.2.2 Digging Operations and Blast Master Plans

The daily dig plans are developed by mine engineering for both waste stripping and ore mining and contain the following information:

- Dimensions, orientations and shot volumes,
- Numbered mining sequence, and
- Scheduled date and time of shot.

The blast master plan (containing shot outline locations) is a controlled document (Mine Planning) and is developed by the drill & blast engineer for preparation of blast designs.

3.1.2.3 Drill and Blast Designs

The drill & blast engineer is responsible for the design of the drill and blast patterns according to site guidelines. The geotechnical engineer is to ensure that the site drill and blast guidelines have considered the potential damage that the blast may cause to the pit face and the geotechnical hazards that may be encountered during the mining step. A written record is kept of reviews and associated recommendations.

The following is considered:

- Blast design and potential slope damage,
- Local area blast historical performance,
- Location of slope hazards affecting the blast,
- Location of monitoring or spotters (if required), and
- Requirement for geotechnical post-blast inspection/clearance.

3.1.2.4 Wall Scaling

Specialised excavators are used to scale the final batters and remove all loose rocks. The excavator shall be capable of reaching to the crest of the batter. This may involve building a small pad from the batter trimmings. Where appropriate, a dozer cuts the crest line of the batter. Batter boards are installed to guide the excavator operator with the angle of batter face required to match the slope design.

3.1.2.5 Slope Depressurisation and Dewatering

The design of slopes in open pits generally assumes that a minimal hydraulic pressure head acts on potential failure surfaces. Depressurisation of the slopes through dewatering and drain hole installation is therefore critical to ensuring ongoing stability of slopes and managing slope safety and operating hazards. This issue is exacerbated at the Lihir Gold project as both liquid and steam water pressures act on the pit slopes. The geotechnical and geothermal team has a primary focus on advanced depressurisation of future mining areas. This reduces the pressures that may cause slope instability and can also assist in cooling the ground to allow mining.

A hydrogeology or geothermal consultant is normally engaged to carry out the groundwater modelling, independent from the site's geotechnical / hydrogeological team, with the in-house hydrogeologist developing water balance models and co-ordinating consultant activities, (White et al. 2004). The consultant's findings are then incorporated into the geotechnical modelling to ensure water pressure issues are addressed when formulating slope design parameters.

The team's groundwater responsibilities include:

- Reviewing the hydrogeology model, depressurisation and dewatering plans, and monitoring,
- Assisting with planning of drain hole and dewatering drilling programmes to ensure safe access to drilling positions and to fit in with mining sequence,
- Ensure the dewatering (depressurisation) programs minimise hydraulic pressure on potential failure surfaces, and
- Assist with supervision of drilling and installation of drain holes and dewatering wells etc, monitoring instrumentation, and regularly updating the groundwater database.

Geothermal depressurisation / steam relief wells are drilled ahead of areas of active mining and regardless of material strength, all ground is pre-conditioned by blasting to minimise the possibility of geothermal outburst/hydrothermal eruption.

Sub-horizontal slope depressurisation drain holes are drilled to 150 m depth and spaced horizontally at 20 m intervals on each mining bench face in order to achieve semi-drained/ depressurised slope design requirements. The drainage hole drilling rig programme is part of the daily mine schedule.

3.1.3 Performance Monitoring

Monitoring the performance of slopes by visual inspection and instrumentation is an important aspect of slope management. Various monitoring instrumentation used at Lihir Gold Mine includes:

- Crack monitoring (crack meters),
- Auto-tracking survey of prisms linked to a SMS alarm system,
- Specialist geotechnical monitoring instrumentation – inclinometers, extensometers, and convergence meters,
- Groundwater monitoring – levels and/or piezometers,
- Real time monitoring of slopes using slope stability radar.

The selection of type and amount of monitoring is dependent on what data is required, how accurate this needs to be and the urgency of the response required, which depends on the consequences of the hazard.

Geotechnical monitoring in detail is not dealt with here. However, the type of monitoring equipment, quality (including installation) and quantity ensures that adequate information on the movement of slopes is available at any time to allow management of safety and production requirements.

3.1.3.1 Monitoring Strategies

Monitoring strategies currently being utilised at Lihir are summarised in the Table 3.

Table 3: Summary of monitoring for geohazards

Monitoring Subject	**Method**	**Summary Description**
Slope Displacement	ATS prism monitoring	Prisms are monitored from three stable survey pillars by motorised geodimeter with automated target recognition programmed to read each prism a set number of times daily. An alarm is triggered in Mine Dispatch if slope displacement exceeds a preset threshold value(90mm/day).
	Slope Stability Radar	Real time continuous scanning of the pit slope. An alarm is triggered in Mine Dispatch if slope displacement exceeds a preset threshold value (90mm/day).
	Condor DGPS system	A network of 12 real-time differential GPS stations is established around the pit and on the Kapit landslide and LGO stockpile feeding information to a central computer at 30 second intervals.
	Extensometer alarm	A simple wire extensometer linked to an audio-visual alarm that is activated when displacement exceeds a preset value.
	Crackmeters	Sets of two timber or steel pegs straddling a tension crack that can be used for comparative daily measurements of crack dilation.
	Drillhole inclinometer	Plastic casing installed in drill holes with special grooves for running tools that can detect casing deformation at zones where slope dislocation has occurred or is in progress.
	Visual inspections	An essential part of the role of the Geotechnical Section at Lihir – results are recorded on a daily inspection sheet that forms the basis for the weekly 274 inspection summary submitted to the Manager Mine Operations.
Geothermal Conditions and Groundwater	Vibrating wire pressure and temperature transducers	The transducers are drill hole installed at specific target depths to record piezometric pressure and ground temperature. Readings are taken daily manually or by data logger.

Some of the equipment used for monitoring is shown in Figure 27.

Figure 27: Slope stability radar and robotic theodolite

Monitoring slopes in an active geothermal environment presents many challenges, such as: steam obscuring the line of sight for survey prisms, and inclinometer holes being too hot to be read by the inclinometer probe, (Johnson, 2009). In addition to the above strategies, it is proposed (for 2010) to establish seismic monitoring based on the results of a successful trial conducted in 2005. It is anticipated the seismic monitoring will be a valuable management tool for refinement of stability modelling inputs.

3.1.3.2 Interim and Final Wall Inspections

Clean walls allow geological structures to be mapped and potential for future failures to be identified. The Geotechnical section inspects all scaled and cleaned walls and confirms that the excavated and cleaned faces comply with the design requirements and is within design tolerances.

Any slopes which are out of compliance with the design specifications are treated as slope hazards. The slope hazard management process is initiated and appropriate actions taken to either correct the non-compliance or to ensure that the slope remains within acceptable safety and operating risk limits.

3.1.4 Slope Failure Hazard Management

The slope failure hazard management process is shown in Figure 28.

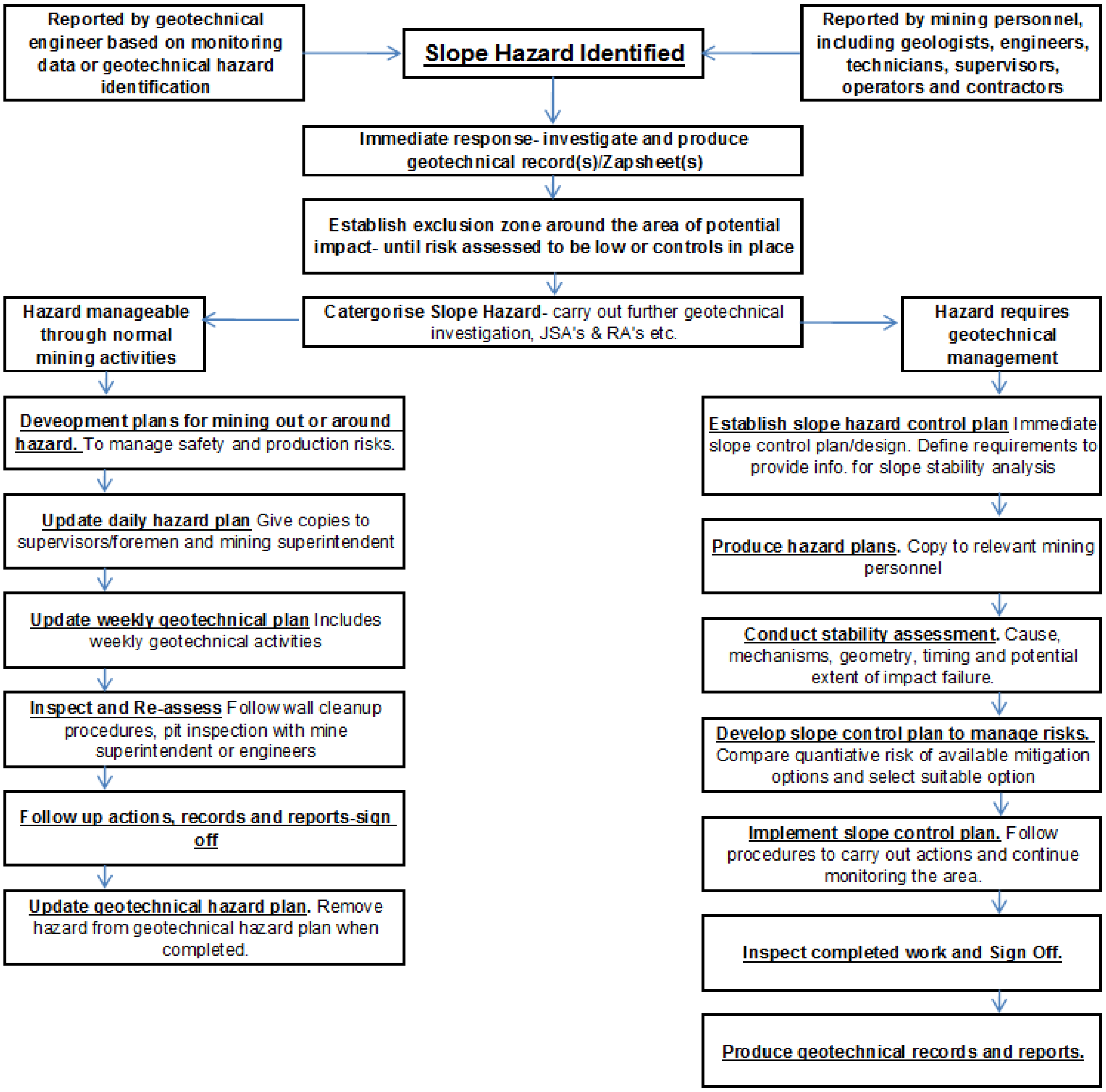


Figure 28: Slope hazard management

3.1.4.1.1 Weekly Geotechnical Plan

The geotechnical section reviews a draft of the weekly dig plan and annotates all local hazards for working areas in each weekly plan. The geotechnical hazards identified in each weekly plan are assessed and management actions agreed at the weekly operations planning meeting. The geotechnical section identifies suitable control measures and recommends actions. These actions are brought up, assigned and recorded in the daily production meeting and removed once complete.

3.1.4.1.2 Geotechnical Hazard / Monitoring Plan

The geotechnical engineer produces a pit plan showing current geotechnical hazards in the pit work areas. This Geotechnical Hazard Plan (GHP) is updated as required and updates brought up in the weekly planning meetings. Plans are displayed in operations crib rooms to aid in the communication of hazards. Plans are discussed in the morning production meetings.

The Plan includes recognised geotechnical hazards in the Lihir Mine Area, together with a simplified ranking of each hazard's threat to the operation.

The Geotechnical Hazard Plan is updated monthly in conjunction with the Monitoring Locations Plan also which shows preferential concentration of monitoring stations in areas of recognised instability.

3.1.4.1.3 Pit Slope Instability / Collapse / Rock Fall

An area of pit slope instability or potential failure is identified from observations including one or more of the following:

- Seismic activity,
- Geothermal outburst or increased steam activity,
- Visible development and opening of cracks or joints along the crests of slopes, on slope faces, berms, access ramps or pit floor, particularly post-blasting or after high rainfall events,
- Localised slumping, ravelling or rock fall,
- Observable or suspected changes in line or level of berms and/or slope faces,
- Acceleration of rate of slope displacement as detected from monitoring results, and
- Actual slope failure event.

When monitoring indicates excessive movement, or if any other signs of potentially hazardous movement are observed, or should there be failure or collapse of the slope, the Response Plan begins with the Pit Superintendent and G&G section being contacted immediately. Everyone working in the area is advised of the hazard immediately and if deemed necessary by the Pit Superintendent after consultation with the Geotechnical Superintendent, all personnel and equipment are evacuated to an area considered safe and/or access to the area cordoned-off and restricted.

The Pit Superintendent and nominated Geotechnical Person inspect the site from a safe location in order to assess the severity of the hazard, to what extent ground movement has occurred and the risk to operations.

A decision is made on whether the area is safe enough to re-enter. This is based upon current rates of ground deformation/slope displacement, most recent geothermal temperature/ pressure measurements and acceptable thresholds based on site experience, as well as the geohazard risk assessment/ management strategies outlined earlier. A geotechnical specialist may be required to provide a recommendation regarding re-entry to the area at the discretion of the Mine Manager.

Areas expected to be affected by possible excavation failure are to be barricaded by cones or signposts. Once monitoring and Standard Operating Procedures (SOP's) have been implemented, further operations controlled by those procedures may be conducted within the instability affected area. Essential operational controls during these episodes are:

- **Slip Area Cordons (SAC's)** are signposted and cordoned-off with black and yellow danger tape so as to restrict access and limit risk exposure to unstable active slip or rock fall areas. Radio notification to the Pit Co-ordinator is required upon entering and exiting those areas.
- **Slope displacement monitoring** using the installed remote ATS and GPS systems provides continuous coverage for most areas of the pit, particularly the identified hazard areas where monitoring is intensified. During periods of active instability, the ATS prism monitoring frequency can be increased and the alarm threshold adjusted accordingly. Increased frequency of geotechnical inspections during such periods is mandatory.

3.2 Landslides

The most significant example of natural slope instability recorded in the vicinity of the mine was the Kapit Landslide, Figure 29. Rapid failure of the Kapit Landslide occurred at about 3 am on Sunday 9 October 2005. The failed mass had a volume of about 15 million m^3 (up to about 650 m long, 700 m wide and up to 70 m deep). The landslide moved about 150 m on land and pushed the shoreline eastward by up to that amount causing a surge wave that impacted on the barge and boat harbours. The landslide moved at speeds estimated to be up to about 5 m/s or 18 km/hr.

There was a geothermal outburst at the time of the rapid failure with groundwater springs gushed from the back scarp following failure. The landslide resulted in two fatalities, one from the capsizing of a boat in the surge wave.

Figure 29: Kapit landslide, aerial view (Lihir Gold Ltd)

The movements of the Kapit Landslide prior to rapid failure probably involved reactivation of a pre-existing failure surface, most likely an old landslide (or landslides). The pre-existing failure surface was likely to have been, at least in part, in high plasticity clayey material within the intense argillically altered volcanogenic sediments. Evidence to support reactivation of an earlier failure surface (or surfaces) includes:

- The topography in the area prior to the recent movements (hollows and lobes, headland and the uneven sea floor contours).
- The relatively flat overall slope prior to recent movements (which indicated that the overall average shear strength of the failure surface was low and parts of the failure surface were probably at residual strength).
- The northern extent of the landslide (up to 300 m north of the stockpile).

Construction of the stockpile appears to have been a contributing factor. If the movements of the stockpile were part of a first time landslide, it would be expected that the northern boundary of the slide would be relatively close to the stockpile. Movements 300 m north of the stockpile suggest that there was probably a pre-existing landslide with a low shear strength surface.

Contributing factors were determined to be:

Stockpile Construction: The most likely contributing factor to the reactivation of landslide movements, first detected in May 2004, was construction of the stockpile. This had the effect of over steepening the overall slope and loading the head of the landslide, which increased the disturbing forces. The slowing in the rate of landslide movement following partial removal of the stockpile in late 2004 provides further evidence of the adverse effects of the stockpile on stability (and the beneficial effects of partial removal).

Rainfall: Above average rainfall appears to have contributed to the increases in the rates of landslide movement. There was above average rainfall in April and May 2005 and the three months prior to rapid failure were the wettest on record. Rainfall for September 2005 was the highest on record with 662 mm (double the monthly average of about 330 mm). The above average rainfall is likely to have caused a rise in ground water and, as the landslide moved, and tension cracks opened, more water would enter the unstable area (including water from the drain at the back of the slope that collects water from several catchments to the south of the landslide).

Earthquake: There was a Magnitude 7.7 earthquake 190 km south south-east of Lihir at a depth of 90 km on 9 September 2005. Rates of landslide movements increased after the earthquake and the earthquake may have contributed to the increase in rate prior to the rapid failure. Some landslide movement and loss of strength may have been caused by the ground shaking and it is also possible that the shaking may have partially disrupted sub-surface drainage.

Geothermal Activity: Ground conditions in the Kapit area are complicated by the geothermal activity along the Kapit Geothermal Trend. There was a geothermal outburst at the time of the landslide. The effects on slope stability of any changes in geothermal activity are difficult to quantify but they may have had an influence on stability.

3.3 Land-based Dumps and Stockpiles

Land-based dumps and stockpiles include ore stockpiles or waste dumps developed on land or into the sea. An example is the Kapit 6 Ramp Slip as illustrated in Figure 30, although the primary component of the failure was in the underlying weak volcanic rocks. Initially interpreted as gravitationally driven, circular rock mass failure, it had been suggested that the geothermal regime was also an influence. Back-analysed material strengths, even for a fully saturated slope, appeared to be unusually low considering the material type.

Figure 30: Cracking of Kapit 6 ramp haul road (Lihir Gold Ltd)

3.3.1 Harbour Base Waste Dump

On Thursday, the 8th October 2008, part of the Harbour Base 501 waste dump area failed into the sea. No one was injured and no equipment was damaged, Figure 31. Tension cracks had been observed approximately 20-30 m from the dump crest. When these cracks started dilating, the dump was closed prior to the subsequent failure 3 to 4 hours later.

Figure 31: Harbour Base 501 waste dump failure (Lihir Gold Ltd)

3.4 Subsea Slope Failures (Barge Dumping)

A subsea slope failure can occur if large quantities of barge dumped material accumulates on the sea floor slope and then fails catastrophically. The surface manifestation of such a slope failure is a wave surge. This can have adverse consequences on nearby operations such as ship loading at the wharf. Records show that even a relatively small wave surges can have a significant impact with damage being reported from waves 1 to 1.5 m in height. Wave surges with wave height <1 m are probably not reported due to the lack of adverse effects. Past events are tabulated in Table 4.

Table 4: Past subsea slope failure events (Lihir Gold Ltd)

Date	Wave Height (m)	Displaced Vol (m3)	Impact	Displaced material depth (m)
29/08/2009	1.5	6.6×10^6	Swamping of containers in the rebuild yard and a broken mooring on an excavator pontoon	100 – 450
13/10/2004	1-1.5	$5\text{-}7 \times 10^6$	Not recorded	190 – 400
08/08/2002	2.3	17×10^6	Not recorded	125 – 350

The process flow for sub-sea slope failure management is shown in Figure 32 below:

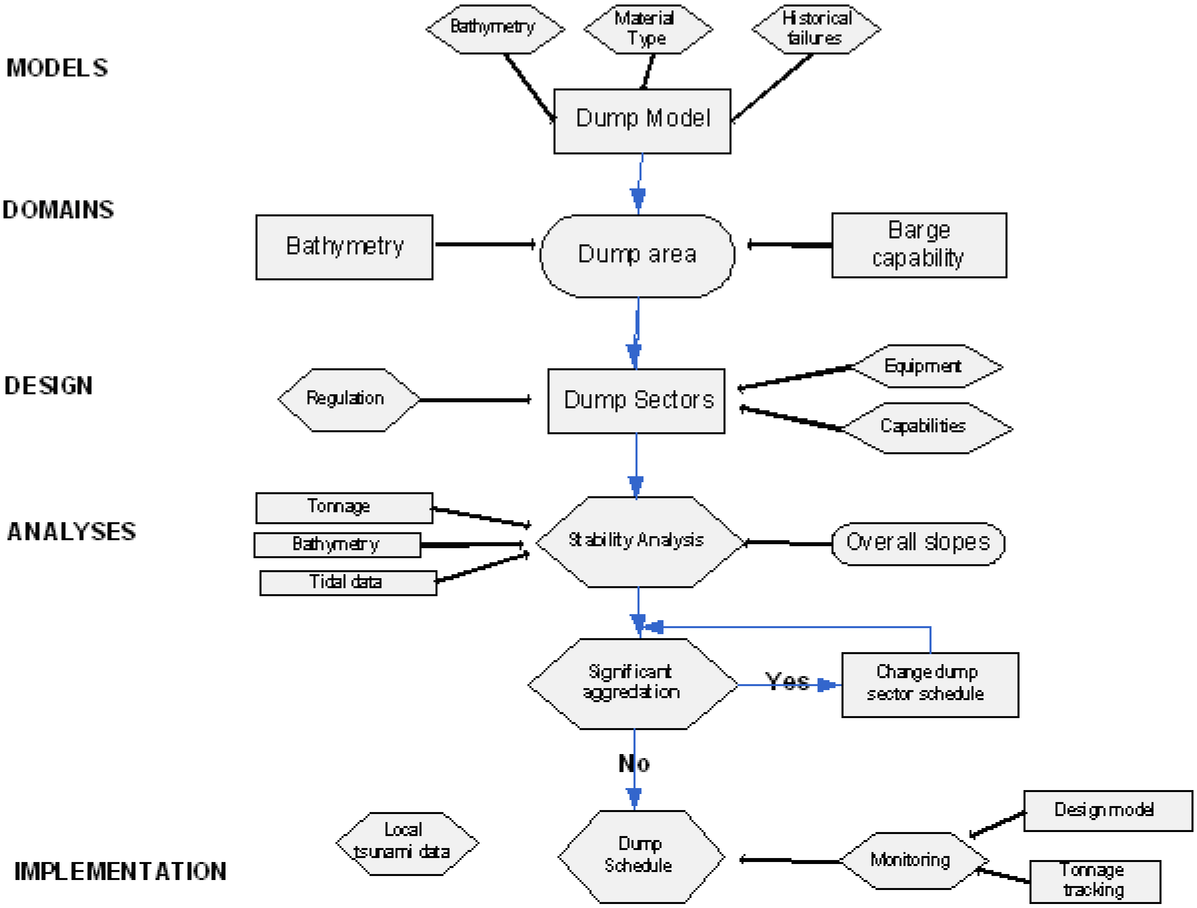


Figure 32: Process flow for sub-sea slope failure management

3.4.1 Design

Barge dumping strategy is designed to encourage dumped material to continuously rill down the subsea slope. In this way, it will prevent large scale localised build-ups of material on shallow, flat seafloor that could catastrophically fail. It is considered that spreading the dumped material over a large area reduces the incidence and potential size of dump failures and hence the resultant tsunami. In order to enforce this, a grid system within a pre-defined polygon is to be used on a cyclic basis to ensure even distribution of dumped material. The dump grid is illustrated in Figure 33.

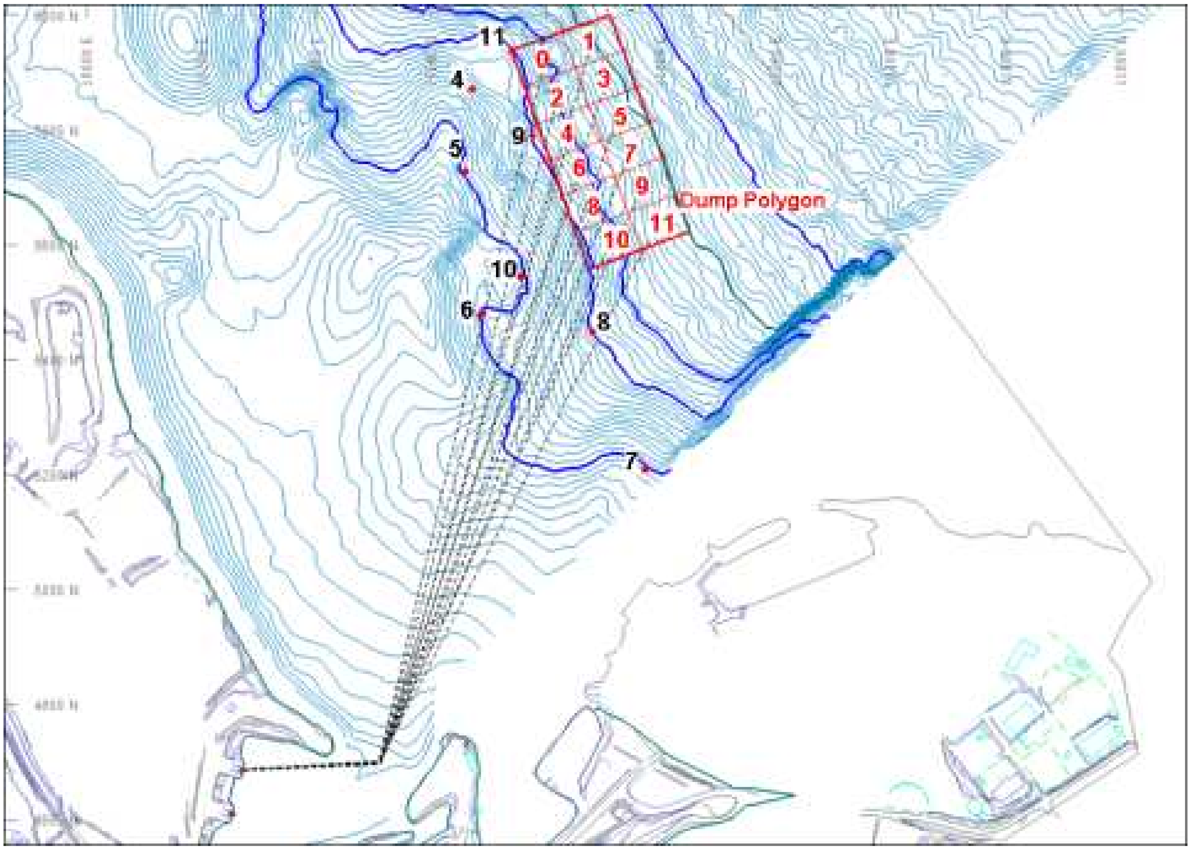


Figure 33: Grid dump system (Lihir Gold Ltd)

The criteria for selection of this area are listed below:

- The seafloor depth within the polygon varies between approximately 150 m and 250 m below sea level. Although deeper dumping would be desirable the selected range is a compromise between barge travel distance and tsunami source water depth.
- The grid is located above the steepest part of the seafloor slope to encourage constant rilling of material in small volumes. This will hopefully prevent build-up sufficient to cause large scale failures.
- The southern termination of the polygon is designed to avoid an area of shallower slope in a marine valley area.

3.4.2 Implementation

Implementation of the current dump grid requires the cooperation of the Dispatch and Marine Sections of the Mining Department. Detailed instructions on barge manoeuvre are detailed in SOP 2430-011 Waste Dumping.

- One dump location is selected for each fortnight period. Analysis of recent dump tonnages sent to dump 9 indicated that it would be sufficient to ensure the $1x10^6$ tonne limit is not exceeded (average days to dump $1x10^6$ tonnes to dump 9 is 16.5 days).
- Barge scheduling and destination is set by the Wharf Controller using the Modular system.
- Each dump is utilised for a limited period a fortnightly period only. This gives a 5.5 month capacity for the dump area, well within the quarterly bathymetric review period. After a dump box is filled, the next dump box shall not be the adjacent one.
- Dumps are located within a box defined in the modular system that is equivalent to the grid box. Once a barge intersects the box dumping can commence. Precise positioning of the barge within the dump area is not required. Modular is so set up that the barge operator can only see the active dumps and the required track to reach them on their GOIC screen.
- Dispatch provides reconciliation information to Geotechnical and Marine on a weekly basis. This includes dump location and material source.
- Each dump site is “rested” once 1 $x10^6$ tonnes have been dumped at that site.
- Bathymetry assessment is carried out prior to re-opening rested dump locations.
- Dump grid is re-assessed following a quarterly bathymetry survey and risk assessment.

3.4.3 Monitoring

Tonnes to each sector are tracked daily and triggers change of dump sector. Bathymetry is reviewed quarterly.

Standard Operating Procedures (SOP) have been developed and the ultimate aim of this SOP is to gain an understanding of the level of risk of dump generated tsunamis. Although the absolute risk cannot be known, a relative risk is assessed based on previous history. The risk assessment is based on the volume of accumulated material shown by the bathymetry survey, its location and depth, and the potential size of a tsunami, were it to fail. The latter estimation is based on historical records of actual tsunamis. This is very limited, hence the importance of documenting future events.

Due to the paucity of tsunami size versus failure volume reconciliation data, it is reasonable to be conservative when defining a size of potential failure mass that could lead to a significant tsunami. In the SOP, this is set at 2-3 $x10^6$, one half of the volume reported for the 1.5 m tsunami described above.

This conservative number also reflects the potential for a failing pile of accumulated material at the top of the slope to trigger a shallow-seated failure of material further down the slope.

Material sent to the barge wharf and subsequently tipped at the marine dump sites is generally reported in tonnes by Dispatch. Conversion to m^3 is required to reconcile dumped volume with volumes of accumulated material reported by the bathymetry. A number of 1 $x10^6$ tonnes has been set as the maximum amount that can be dumped at each grid location. This equates to approximately 660,000 m^3. Four adjacent dumps with this amount of material would have an overall accumulation of material similar to the 2-3 $x10^6$ m^3 value discussed above.

In addition to the discussion above, the following general guidelines are used to assess risk of dump failure,

- **High Risk** – Dumps with large recent and localised accumulations of material with steep seaward faces. In the order of 2-3 $x10^6$ m^3.
- **High Risk** – large volume accumulations of material on the lower slope below the dump sites. In the order of $5x10^6$ m^3
- **Medium Risk** – Dumps retaining past significant accumulations of material but with no or minor accumulation of material during the monitoring epoch.
- **Medium Risk** - Dumps with localised accumulations of material <2-3 $x10^6$ m^3 but with additional accumulations of material on the lower slope below.
- **Low Risk** – Dump areas with negative accumulations of material determined during the monitoring epoch (i.e. already failed). Other areas of seafloor with no or negative accumulations of material.

3.5 Cavities (including CO_2 and H_2S)

Cavities have been recorded throughout the development of the mine, with the majority occurring in the Lienitz pit, Figure 34 & Figure 35. Cavities range in size from 2-10 cm to 3-5 m.

Figure 34: Cavities observed in the Lienetz Pit (Lihir Gold Ltd)

Figure 35: Cavities observed in the Lienetz Pit (Lihir Gold Ltd)

Cavities primarily present a hazard to people working on foot, particularly walking on blasted muckpile. However, larger cavities can pose a threat to mining equipment. Cavities may also provide a repository for noxious gases (CO_2 and H_2S) to concentrate, or where excess steam pressure could build up and then lead to an outburst. There have been no known cases of excessive gas build up documented at Lihir.

All relevant geological/geotechnical information is collated that may indicate the presence of cavities or voids. Cavities generally occur along faults or at intersections of different lithologies, typically the Boiling Zone and Argillic ore types. They are believed to be formed by the dissolution of anhydrite Figure 36.

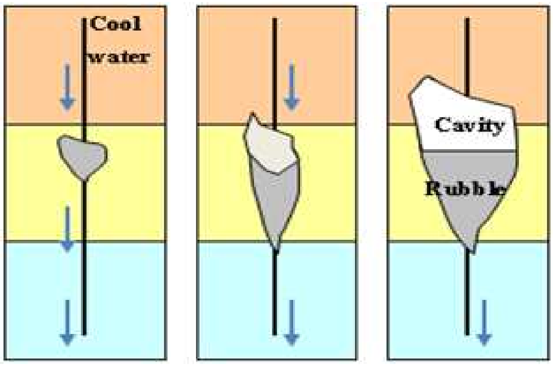


Figure 36: Model for cavity formation (Lihir Gold Ltd)

The Aquire drill hole database was used to generate Minesight models of high core loss and zero RQD. These helped define discrete zones or “cavity sectors” where the potential to encounter cavities is increased, Figure 37.

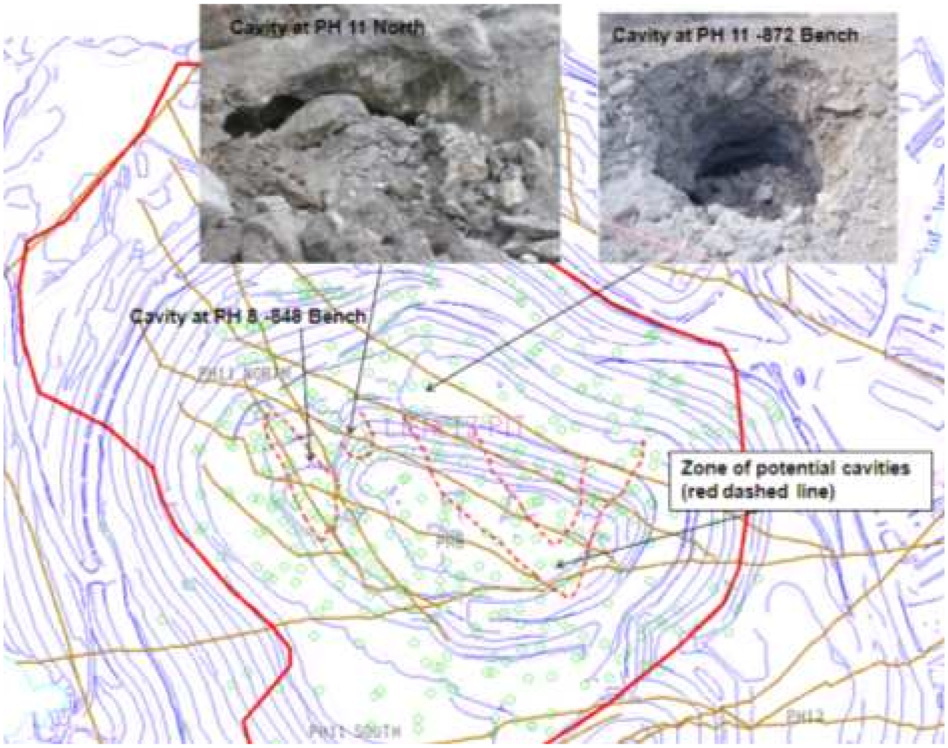


Figure 37: Zone with higher potential for cavities

Some elements of the management process are described in the following sections.

The process flow for cavity management is shown in Figure 38.

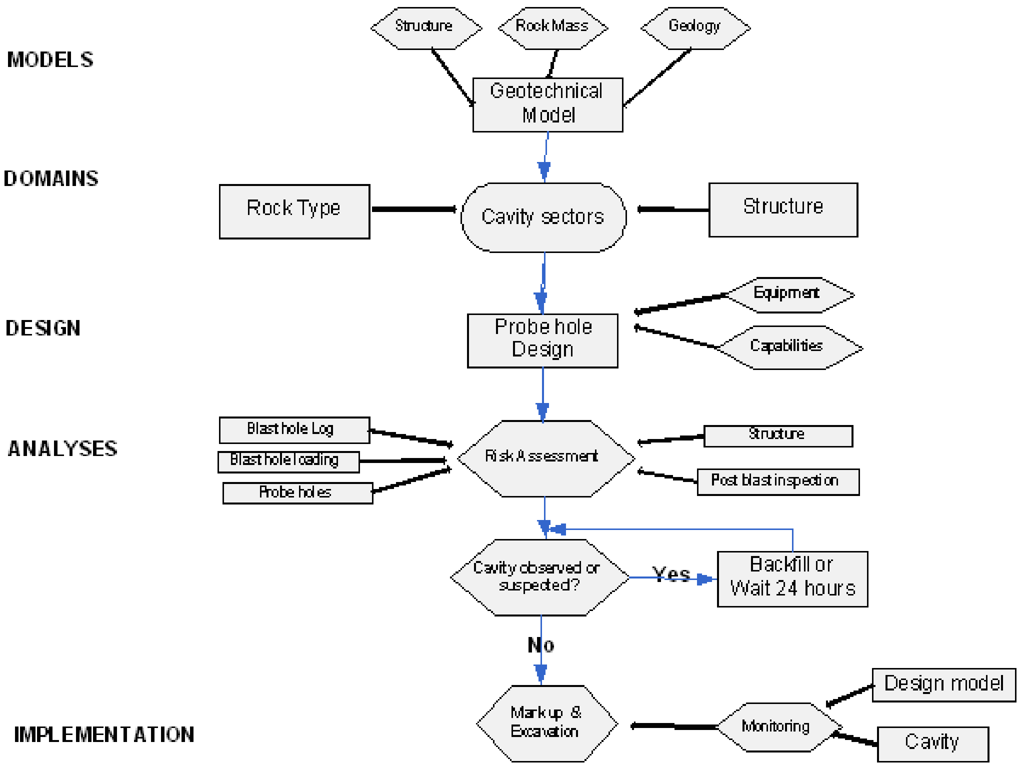


Figure 38: Process flow for cavity management

3.5.1 Design

Procedures are in place to record the potential occurrence of a cavity or void from blast hole or probe hole drilling information.

The density of 24 m deep probe hole drilling is increased for areas within the zone of potential cavities to try and pro actively detect the presence of cavities.

The blast hole driller records information on potential cavities, i.e. rods dropping, on the blast hole drill sheet. The explosive supplier, Dyno records the amount of explosive pumped into each blast hole and notes those holes that require any amount > 50 kg above the design charge weight. This information indicates the potential for a cavity and is passed on to the Mine Geothermal team.

Mine Geothermal Scientists assess the available data for each blast within the "potential cavity zone" and do a risk assessment. This assessment includes a post blast inspection (from a safe distance). If cavities are suspected, then no one is allowed to walk onto the blasted shot until 24 hours have elapsed. This gives reasonable time for a cavity to manifest itself in the muck pile. If cavities are observed, they are backfilled with good quality stemming material. If no cavities are suspected, then normal blast hole mark up and excavation can start straight away.

3.5.2 Implementation

Once mark up and mining of a shot commences, then standard practice of careful observation when walking on broken muck piles applies and routine inspection for any form of hazard (including cavities) in the work area is carried out.

3.6 Water Inrush

Mining has created large excavations and continues to enlarge voids below the original ground water surface and within a steep sloped caldera. Following very heavy rainfall events, there is a risk of flooding of the mine workings. Around the pits, is a perimeter drainage system that passively manages water from the surrounding catchment during large run-off events. Excess surface water within the pits and groundwater is extracted by a system of sumps and pumps. Dewatering of the pits is also achieved by submersible pumps within dedicated water wells.

The pits are also relatively close to the sea and mine below sea level. The ultimate pit design extends out into the sea beyond the current shoreline. To facilitate this pit extension, a coffer dam will be constructed to prevent inrush from the sea.

3.7 Geothermal Outbursts

Geothermal outburst can occur when hydrothermal pressure exceeds the overburden lithostatic pressure, posing a risk of hydrothermal eruption or rock outburst. This may result in geothermal noxious gas, steam, hot water, mud and/or rock being forcibly ejected under pressure from the rockmass surrounding the excavation. The most significant hazard posed by the geothermal system to the mining operations is the potential for a hydrothermal or phreatic eruption. This was identified by (Geothermex, 1986), as the main hazard in removing overburden during mining.

Bixley and Brown (1988) define a phreatic eruption as follows:

> *"A phreatic eruption occurs in water dominated reservoirs, with water nearly at the boiling point so that any local depressurisation permits it to boil.*
>
> *The large specific volume change involved when it boils provides the mechanism for the steam thus generated to brecciate and eject reservoir rocks so that a zone of rock brecciation accompanies the descending flash point".*

Removal of overburden and dewatering of the pit, changes the hydrostatic conditions behind the walls and below the floor of the pit. This reduction in pressure can initiate boiling in a fluid and can result in an over-pressured situation where fluid pressure exceeds the lithostatic pressure, (Bixley and Brown, 1988). This mechanism can be mitigated by ensuring that sufficient overburden thickness is maintained between the heat source and the surface or affect additional depressurisation.

3.7.1 2006 Outburst

On 30 April 2006, a geothermal outburst occurred in the Phase 7 area, bench 956 final ramp. This outburst damaged Shovel 67, Figure 39, and the operator sustained significant burn injuries. Debris was present over most of the Phase 7 bench (some 400 metres in length), and was expelled to at least 100 metres in height. The dimensions of the crater were some 30 metres wide by 80 metres long, depth unknown.

The outburst occurred by partial removal of a low permeability Argillite cap overlying a dome of higher permeability rock (leached-soaked domain (LSD) and/or boiling zone (BZ) ore type rocks). This dome formed a trap for higher pressure gas and steam. Once the self weight of low permeability overburden rock was less than gas/steam pressure in the underlying boiling zone, the outburst occurred, Figure 39.

Figure 39: 2006 Phase 7 geothermal outburst (Lihir Gold Ltd)

In very simple terms, geothermal outbursts can occur where heat energy is trapped and pressure builds up that exceeds the lithostatic pressure of the rock mass above the trap. The most effective means of reducing the risk of outburst is by reducing the energy in the system. This is achieved by depressurisation, by venting steam from steam relief wells as shown in Figure 40, Figure 41 & Figure 42 below:

Figure 40: Steam relief wells

Figure 41: Steam relief wells on Kapit stockpile

Figure 42: Steam relief wells in Lienitz Pit

3.7.2 Kapit Pit Depressurisation

The location of steam relief wells is shown in Figure 43. Current measured pressures within the Kapit pit range from <2 bar-g to approximately 16 bar-g (Rodriguez et al., 2008). This is equivalent to temperatures between 80 to 300 °C as pressure is directly proportional to temperature. Experience gained from mining in a geothermal environment in the Lienitz pit indicates that this can be achieved successfully and safely when temperatures are reduced to below 120 °C, which is equivalent to a pressure of approximately 2 bar-g. Temperatures measured from cored boreholes drilled for resource evaluation purposes indicate that temperatures in excess of 120 °C are encountered in the Kapit pit from 1064 bench and below. The current life of mine plan indicates this bench will be mined in late 2012. Hence this sets the target for pit depressurization, Fig. 44

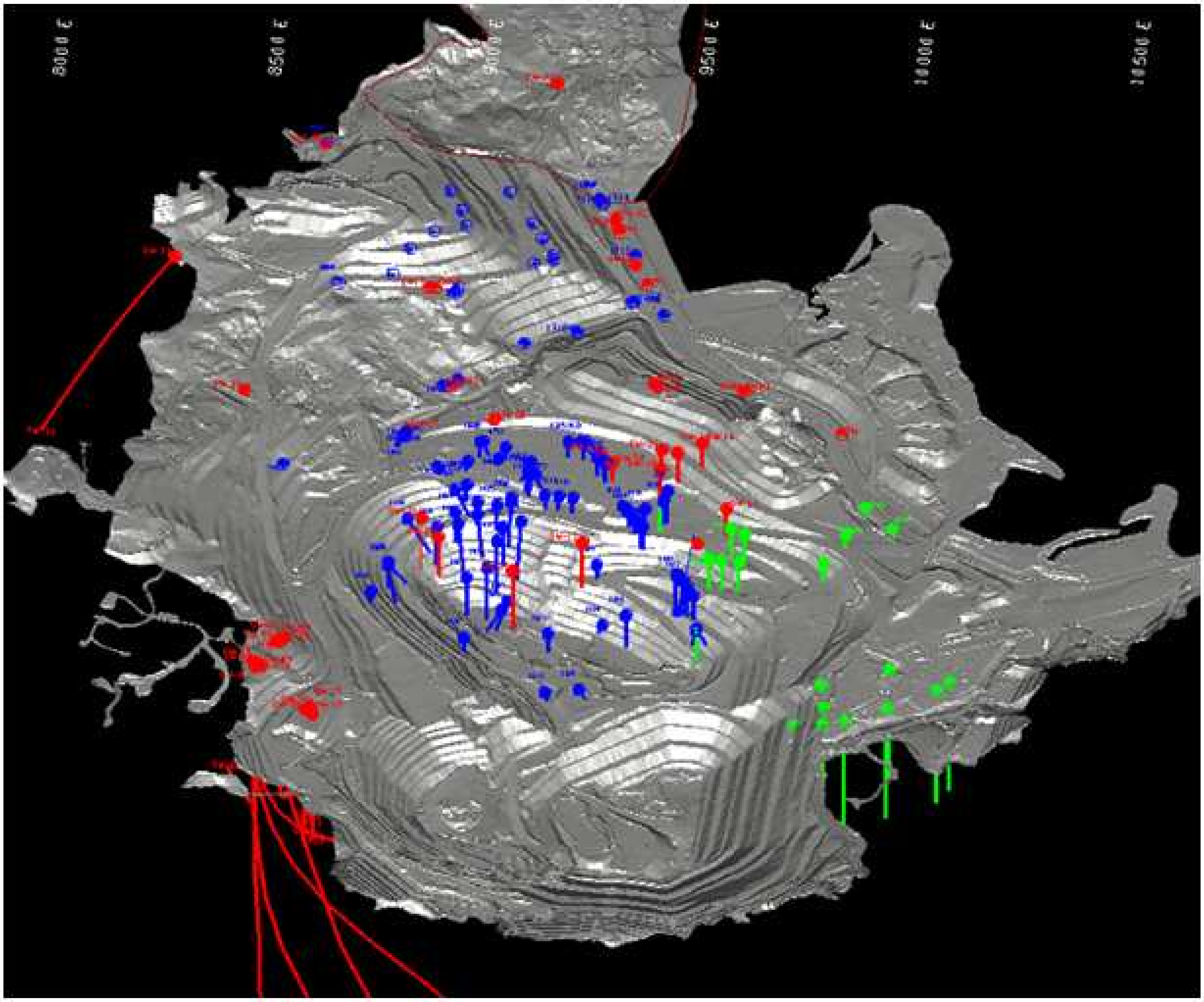


Figure 43: Location of steam wells for depressurization (Lihir Gold Ltd)

The chart below shows the depressurization in the Kapit pit with time since 2004, Figure 44. Pressures have been reduced in general from approximately 12 bar-g down to 6 bar-g. The target to achieve the life of mine plan is to reduce the pressure to below 2 bar-g (equivalent to 120 °C) by the end of 2012.

The key driver to depressurization is mass extraction from steam relief wells drilled into the near surface steam zone and within the final pit shell. This is measured in kt (kilo tonnes) as shown in Figure 45 below, with a target extraction of 250 kt/month.

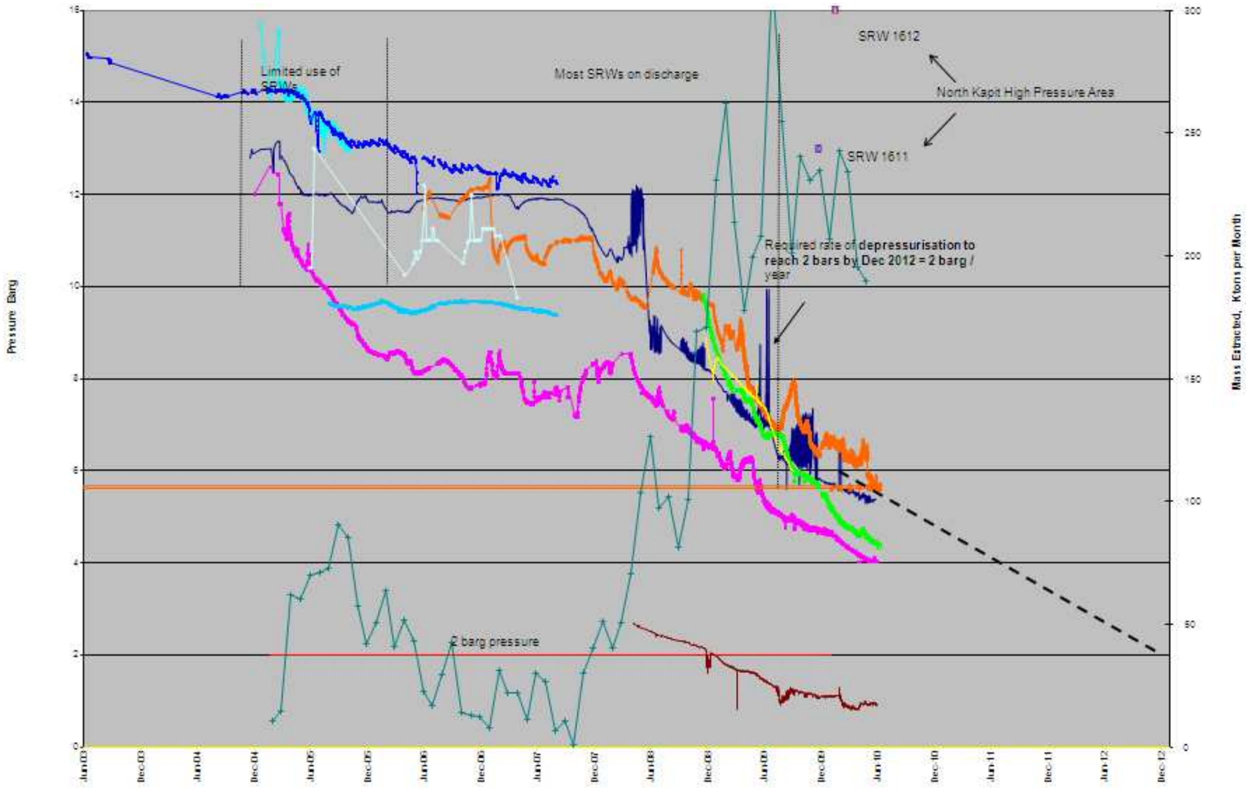


Figure 44: Kapit pit depressurisation monitoring (Lihir Gold Ltd)

Mass extraction from steam relief wells since Jan, 2008 is shown in Figure 45.

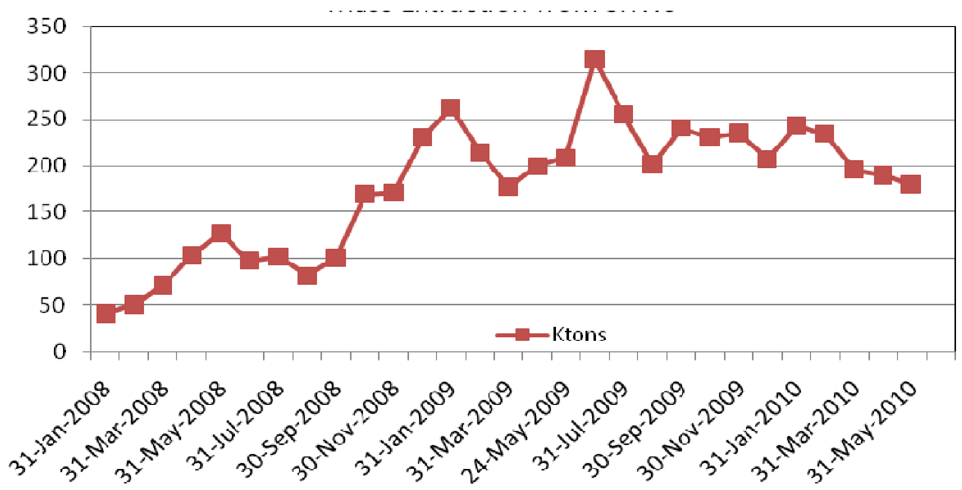


Figure 45: Mass extraction from steam relief wells (Lihir Gold Ltd)

Process flow for geothermal outburst management is shown in Figure 46.

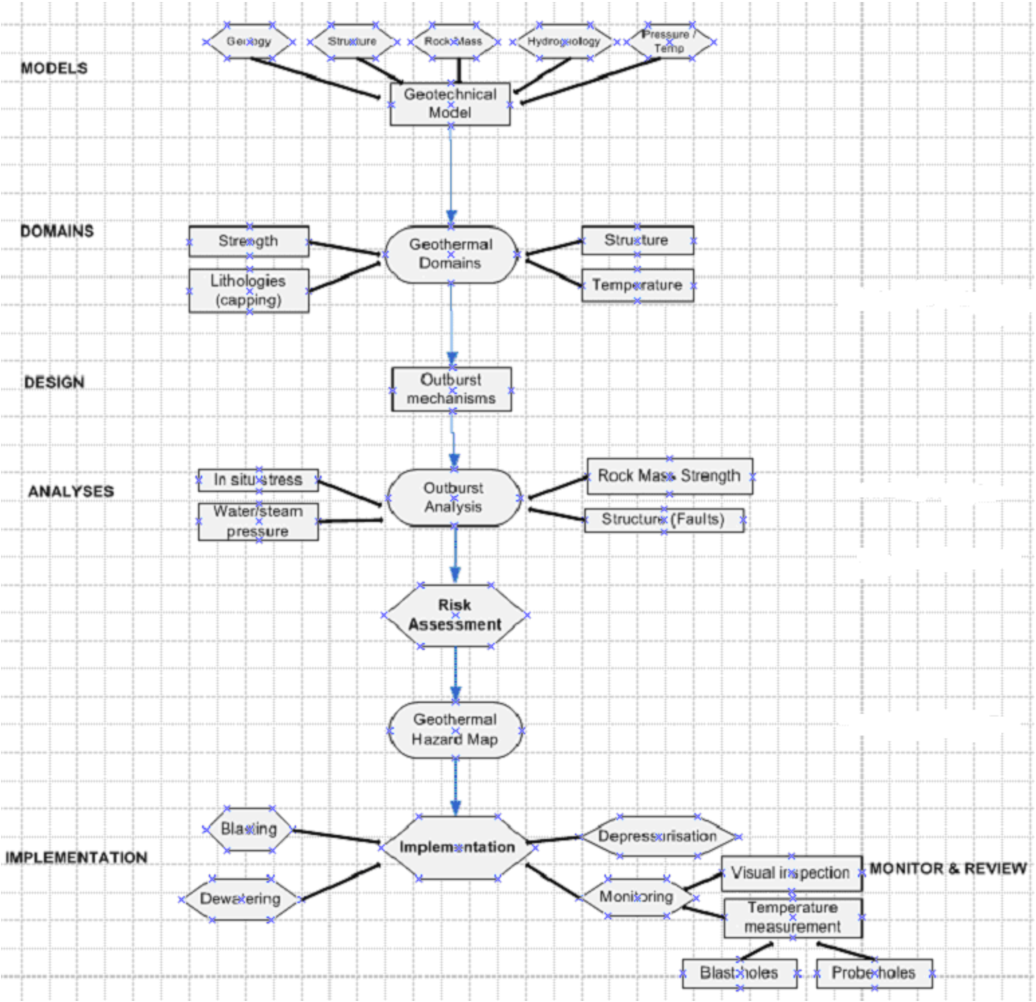


Figure 46: Process flow for geothermal outburst (Lihir Gold Ltd)

3.7.3 Potential Geothermal Outburst Area

These risks are controlled by the PGOA (Potential Geothermal Outburst Area) procedures that demarcate mandatory separation distances between personnel and operating plant, (Villafuerte et al., 2007). An example of separation distances is illustrated in Figure 47. Other precautionary measures include the use of bulletproof glass, thermal cameras and gas detectors. Geothermal risks are managed by a dedicated Mine Geothermal team.

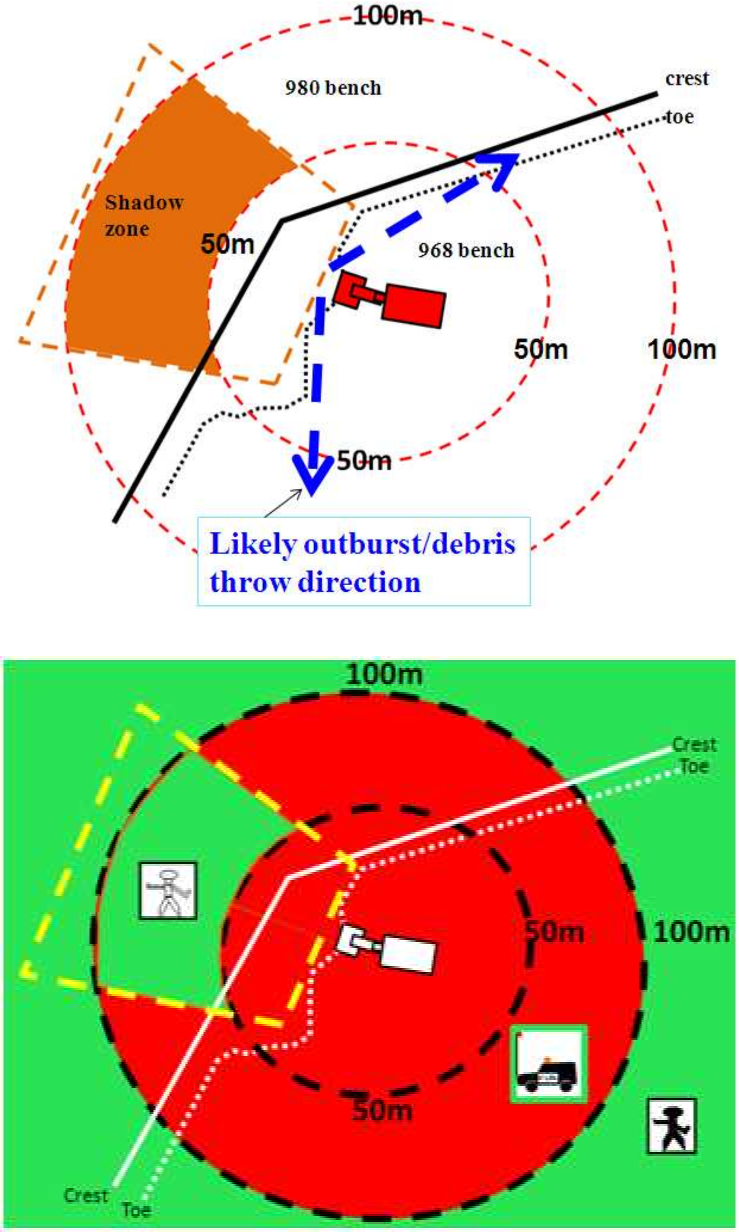


Figure 47: PGOA exclusion zones around operating plant (Lihir Gold Ltd)

3.8 Earthquakes/Tsunami

Lihir Island is a volcanic seamount and the Lihir Gold Mine is located within the caldera of a volcano believed to be extinct. The mine is situated in an area of moderate seismic activity and has been subjected to various seismic investigations. The most recent comprehensive study was undertaken as part of the coffer dam studies in late 2009. From USGS records of all earthquakes from 1973 to present, the strongest event within 200 km radius of Lihir was a M8.2 earthquake on 16 November 2000 with an epicentre approximately 109 km SSW of Luise Harbour and depth of 33 km. The second strongest event on the same USGS record was a M7.7 earthquake on 9 September 2005 centred 190 km SSE of Lihir at a depth of 90 km. These and smaller events have been felt at Lihir but have not inflicted infrastructure, property or topographic damage.

Notwithstanding the above, earthquakes will continue to be felt at Lihir and their potential for causing damage to pit walls, natural slopes and other infrastructure is real as is the potential for earthquake-generated tsunamis to threaten Luise Harbour. As such, they are included in the design criteria for pit slopes and the coffer dam at Lihir.

A tsunami (large wave) may be triggered by an earthquake. As Lihir operations as a whole and the pits at Lihir are proximal to the sea, a formal risk management strategy comprising an emergency response plan and evacuation procedure has been developed and implemented based on the national tsunami hazard mitigation program (NOAA US dept).

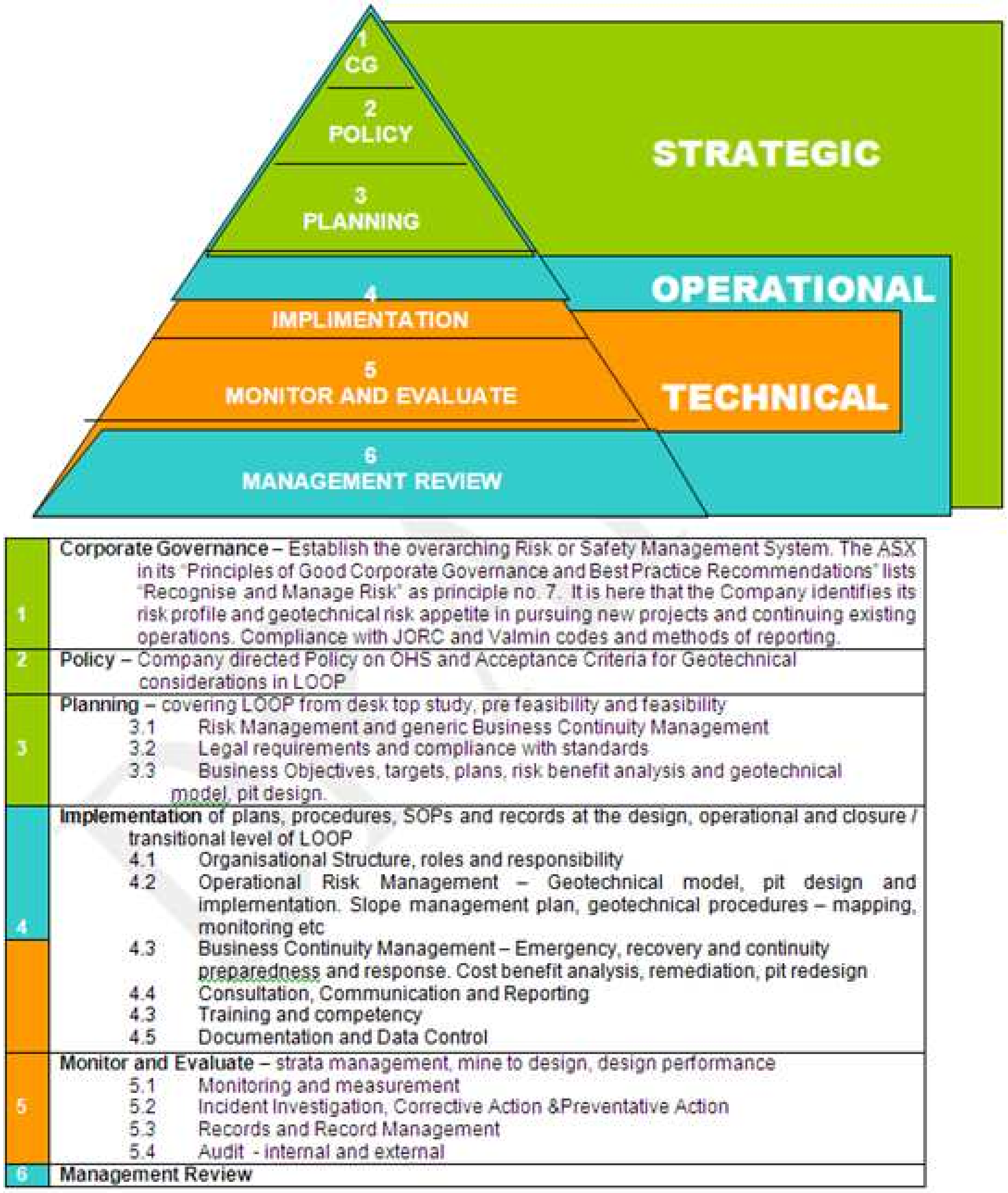
Failure debris from the Kapit Landslide in 2006 spilt into the sea and caused a wave surge in Luise Harbour which over turned a boat in the small boat harbour causing the loss of one life. This hazard is mitigated by continuous instrumentation and observational monitoring of the landslide area.

4 Geohazard Control and Risk Management

Lihir Gold Mine is implementing management and control systems as shown in Figure 48 below.

Figure 48: Management system framework (Lihir Gold Ltd)

The Guidelines for Open Pit Slope Design (CSIRO, 2009) show a methodology for a geohazard risk control which aligns well with the above system and provides the guiding strategy for the GMP as in Figure 49 below:



1	**Corporate Governance** – Establish the overarching Risk or Safety Management System. The ASX in its "Principles of Good Corporate Governance and Best Practice Recommendations" lists "Recognise and Manage Risk" as principle no. 7. It is here that the Company identifies its risk profile and geotechnical risk appetite in pursuing new projects and continuing existing operations. Compliance with JORC and Valmin codes and methods of reporting.
2	**Policy** – Company directed Policy on OHS and Acceptance Criteria for Geotechnical considerations in LOOP
3	**Planning** – covering LOOP from desk top study, pre feasibility and feasibility 3.1 Risk Management and generic Business Continuity Management 3.2 Legal requirements and compliance with standards 3.3 Business Objectives, targets, plans, risk benefit analysis and geotechnical model, pit design.
4	**Implementation** of plans, procedures, SOPs and records at the design, operational and closure / transitional level of LOOP 4.1 Organisational Structure, roles and responsibility 4.2 Operational Risk Management – Geotechnical model, pit design and implementation. Slope management plan, geotechnical procedures – mapping, monitoring etc 4.3 Business Continuity Management – Emergency, recovery and continuity preparedness and response. Cost benefit analysis, remediation, pit redesign 4.4 Consultation, Communication and Reporting 4.3 Training and competency 4.5 Documentation and Data Control
5	**Monitor and Evaluate** – strata management, mine to design, design performance 5.1 Monitoring and measurement 5.2 Incident Investigation, Corrective Action &Preventative Action 5.3 Records and Record Management 5.4 Audit - internal and external
6	**Management Review**

Figure 49: Methodology for managing the risk of geohazards (CSIRO, 2009)

The bulk of the GMP focuses on the Operational and Technical elements of the strategy. These elements are equivalent to the tactical planning and operational stages of the mining process. This chapter focuses on the Strategic elements and describes how it is translated into practice at the mine.

The risk management principles guiding the GMP follows AS/NZS ISO 31000:2009 Risk Management - Principles and Guidelines (Standards Australia, 2009), Figure 50.

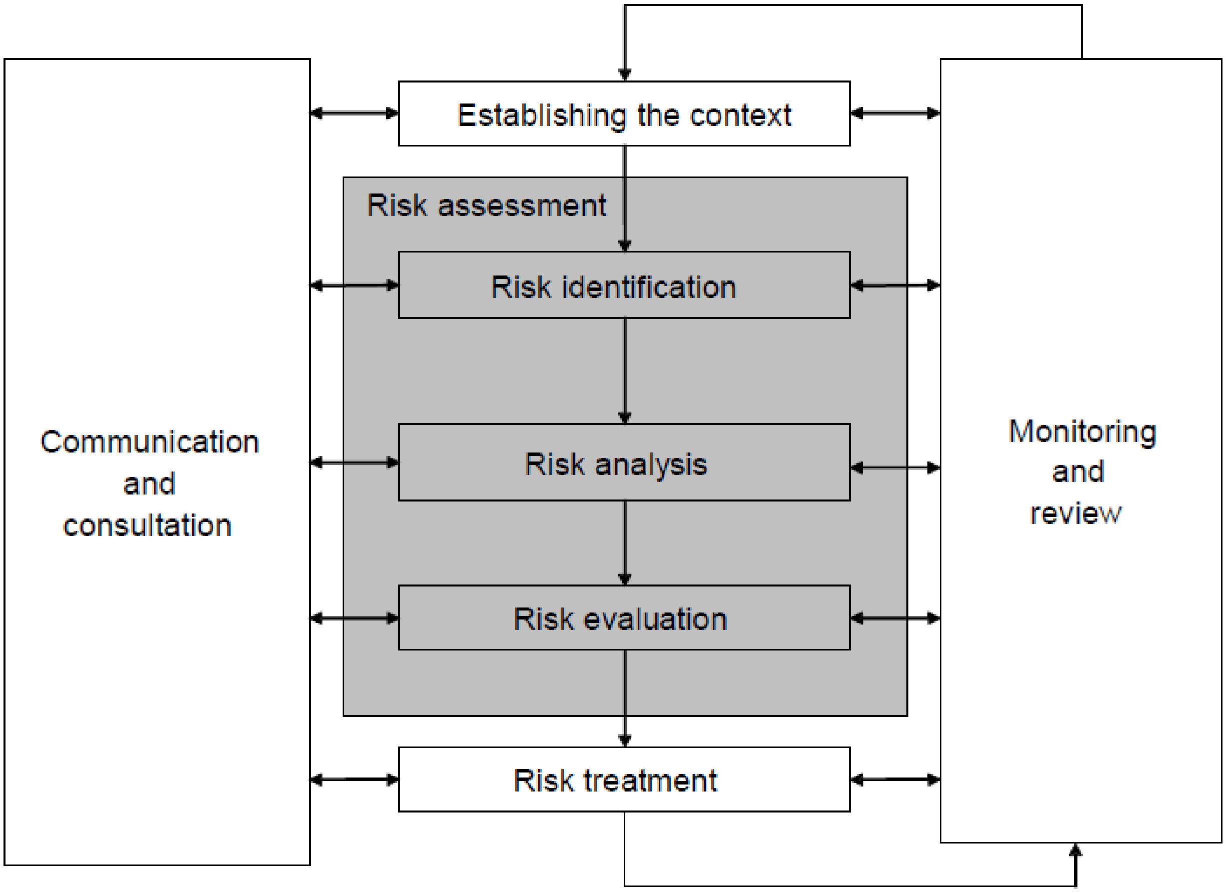


Figure 50: Contribution of risk assessment to the risk management process (AS/NZS ISO 31000:2009)

In more detail, the GMP aims to follow the risk management process to:

- identify the types of geohazards,
- analyse the risks, determine consequences and probabilities and hence quantify risk
- evaluate the risks against company's qualitative risk matrix
- treat the risks by:
  - establishing geohazard control and prevention systems,
  - specifying monitoring / detection systems,
  - specifying contingency actions,
- monitor and review by:
  - identifying change agents responsible for review of the mine plan,
  - identifying triggers for changes in ground conditions that require urgent response,
  - provide a basis for document control and management of change to ensure that changes to mining are evaluated and the GMP updated, and,

- set out methods of audit and review needed to show the effectiveness of the GMP and confirm that risk is being managed to a level acceptable to the company.

4.1 Mine Geohazard Management

The mine has an objective to develop performance standards for activities associated with major hazards.

- To ensure major mine hazards are managed to as low a level as reasonably practicable
- Provide confidence in achieving business outcomes
- Meet regulatory obligations

Bow-tie risk assessments are typically done, for all major mine hazards, Figure 51.

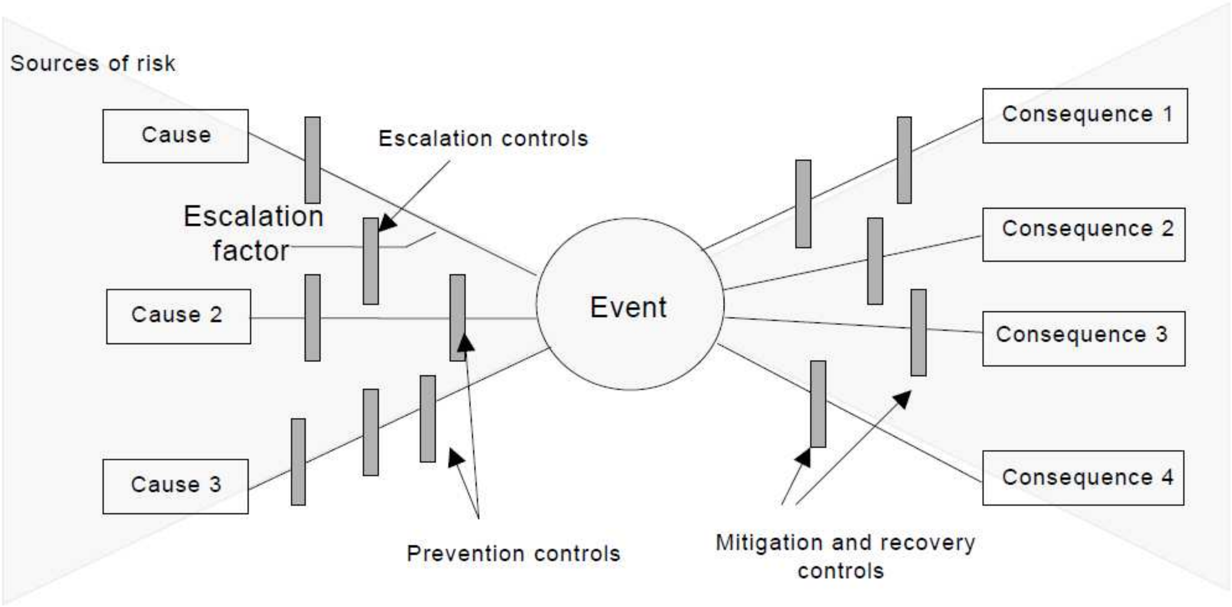


Figure 51: Bow tie risk assessment framework (AS/NZS ISO 31000:2009)

Bow-tie risk assessments were completed for the following geohazards:

- Slope failure
- Land based waste dumping
- Earthquake and tsunami
- Geothermal outburst
- Water inrush

The risk matrix shown in Fig 52 below was used for semi-quantitative analysis for above mentioned hazards:

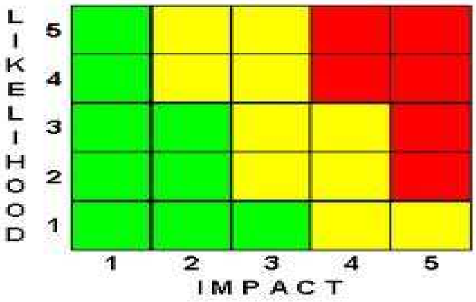


Fig 52: Risk matrix for semi-quantitative analysis

Table 5 shows the risk rating for each of the geohazards.

Table 5: Geohazard vis-à-vis Risk Rating

Name of Geohazard	**Risk Rating Range**
Slope failure	12-16
Land based waste dumping	9-12
Earthquake and tsunami	10-15
Geothermal outburst	12-16
Water inrush	10-15

4.2 Operational Risk Management

Once mining is underway and designs are being implemented, two principal techniques are used to manage risk:

- Job Safety Analysis (JSA)
- Zero 3 Tasol

Both tools use a qualitative risk assessment method.

Once a geohazard has been identified, the probability and consequence of occurrence and level of associated risk are assessed through team based risk assessment.

4.3 Change Management

Any change to slope designs or the mine plan that could alter the geohazard framework, requires a review of the GMP as part of the Change Management process. This review can be initiated by anyone and will be undertaken in accordance with the site Management of Change System.

4.4 Roles and Responsibilities

4.4.1 Organisational Structure

The Mining Department includes a dedicated Geothermal and Geotechnical Section. The Geothermal & Geotechnical Section is responsible for providing geothermal, geotechnical and hydrogeological advice to the mining operation. The section consists of four teams who work together to collect and analyse important geoscientific information relating to all geothermal, hydrogeological and geotechnical issues.

The teams manage the following aspects:

- Geotechnical Projects - slope investigations to derive optimum slope angles for safe pit designs,
- Geotechnical Operations - safety issues related to mining in a complex and unique geotechnical environment.
- Mine Geothermal - safety issues related to mining and working in a unique geothermal environment.
- Hydrogeology – ground water and surface water related risks.

Figure 53 shows the basic reporting organizational structure (org chart). The three groups report to the head of the section, Superintendent of Geothermal and Geotechnical, who reports directly to the mine manager.

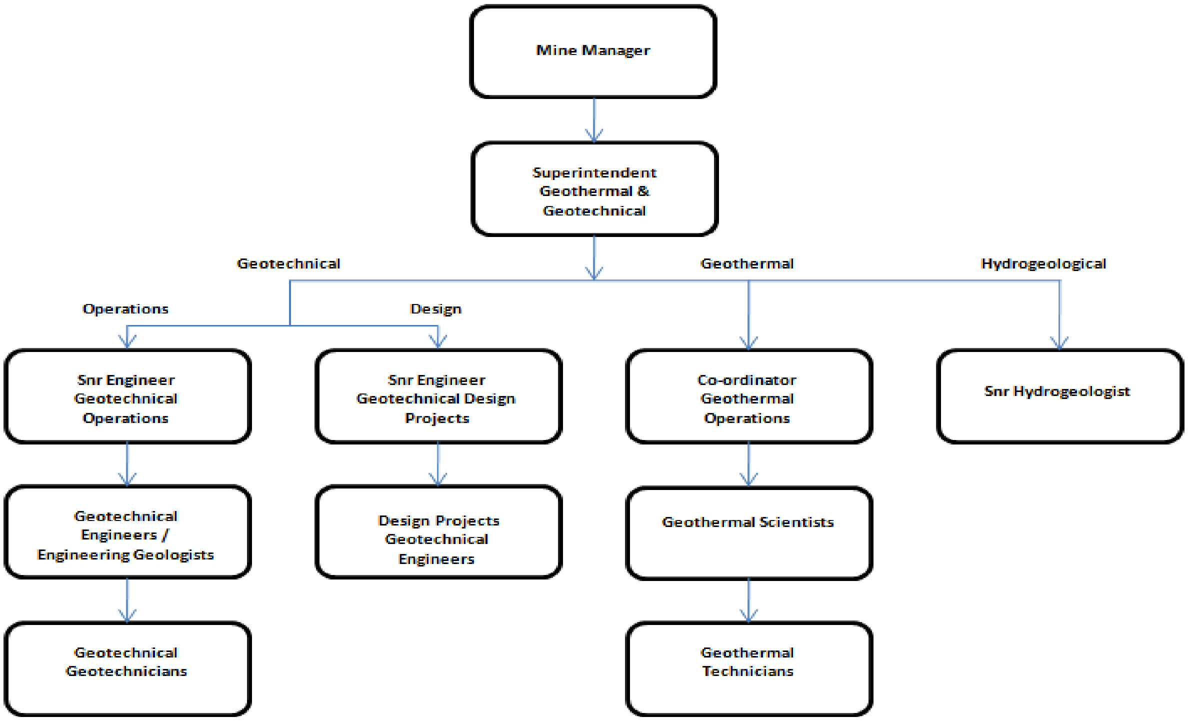


Figure 53: Geothermal and geotechnical organisational structure (Lihir Gold Ltd)

4.4.2 Responsibilities

The responsibility for all mining activities and associated risk management lies with the Mine Manager with delegates appointed by the Mine Manager to monitor condition of associated mine areas and risks. Mine geotechnical and geothermal responsibilities relating to mine planning, design and operations are shown in Table 6.

Table 6: Responsibilities of people involved in geohazard management at the mine (adapted from Guidelines for Open Pit Slope Design 2009, Section 12.3.2.6)

Responsible Person	**Responsibilities (to ensure that:)**
Mine Manager	Suitably trained and qualified personnel are formally appointed to key positions associated with geohazards: Geotechnical & Geothermal Supt, Planning Supt, Operations Supt, Drill & Blast Supt. Legislation is complied with for example the Papua New Guinea Mining (Safety) Act and Mining Regulations. All geohazards are identified and controlled to tolerable levels by the appointed staff, management systems and GMP Resources are made available to achieve a high quality geohazard management performance

Operations Superintendent / Project Managers	Operations are conducted in accordance with the relevant regulations. Standard operating procedures are geotechnically sound and are implemented, and work practices are regularly monitored Regular liaison occurs with Mine Planning, Geology, and Geotechnical & Geothermal staff. Daily mine production activities including geohazard related inspection/issues are properly managed (pit, waste dumps and surface drainage).
Mine Planning Superintendents (strategic & tactical)	Mine planning and design to address relevant geotechnical, geothermal, geological, meteorological and topographical issues. Define mine phase schedules to allow timely preparation of geotechnical inputs. Incorporate geotechnical design parameters into optimisations and detailed designs.
Geotechnical & Geothermal Superintendent	The Geotechnical & Geothermal section is provided with adequate staffing levels. Adequate training is given to all GMP personnel. Suitable equipment and monitoring instruments are supplied and maintained to the specification required Regulations are complied with. GMP is developed, implemented and complies with LGL policy. Audit, review and quality assurance programs are carried out regularly and documented. Ensure daily mine production activities, data collection and communication including geothermal and geotechnical issues are properly managed in accordance with the site's GMP.
Snr. Geothermal Scientists (Co-ordinator Geothermal Operations)	Ensure geothermal related maps and data are kept up to date and available when required. Defining risks related to geothermal hazards. Implementing projects and actions to mitigate their impact on production, costs and safety. Design and implement drill programmes for steam relief wells to depressurise future mining areas.
Snr. Geotechnical Engineers (Operations & Design Projects)	Required geotechnical data is collected, analysed and interpreted and models formulated. Ground and slope performance monitoring systems are used and maintained. The GMP is implemented and complies with LGL policy and statutory requirements. All credible slope failure modes are considered. All ground stabilization measures and slopes are designed and implemented based on geotechnical analysis. All geotechnical related incidents are inspected, evaluated, recorded in a database and reported appropriately Regular liaison occurs with Mine Planning, Geology, and Mine Operations staff. Audit, review and quality assurance programs are carried out regularly and

	documented Defining geotechnical risks and implementing projects and actions to mitigate their impact on production, costs and safety. Develop awareness training packages for geotechnical hazards and PGOA.
Snr. Hydrogeologist	Develop a Water Management Plan that identifies and controls the risks related to ground and surface water and potential impact on production and safety. That the required hydrogeological data is collected, analysed and interpreted and models formulated. Water monitoring systems are used and maintained. Regular liaison occurs with Mine Planning, Geology, and Mine Operations staff. Audit, review and quality assurance programs are carried out regularly and documented Monitoring results are analysed and any anomalies reported.
Geotechnical Engineers & Mine Geothermal Scientists	Standard operating procedures and work instructions are followed. Geohazard conditions in the mining areas, and in particular at active faces, are inspected and monitored regularly. That the required geotechnical data is collected, analysed and interpreted. Monitoring results are analysed and any anomalies reported. Assist with pit design modifications based on new structural or other geotechnical information. All geohazard related incidents are inspected, evaluated, recorded in a database and reported appropriately Liaison with Mine Planning, Geology, and Mine Operations staff on a daily basis. Deliver awareness training for geotechnical hazards and PGOA
Geo-Technician (Geotechnical & Geothermal)	Standard operating procedures and work instructions are followed. Suitable equipment and monitoring instruments are installed and maintained to the specification required. Monitoring data is collected to the agreed scheduled and quality standards.
All employees/ contractors	No work is undertaken without an authorized plan. Safe operating procedures and work instructions are followed. Awareness training for geotechnical hazards and PGOA has been received and understood. All geohazards are identified and reported to their supervisor and/or geotechnical staff. Ground conditions are inspected prior to and during work activities.
Consultant (Geotechnical, Geothermal & Hydro-geological)	Recommend/advise as appropriate - design plans, geotechnical investigation requirements, field investigations, laboratory testing, data collation and storage (if required), data interpretation, analysis and derivation of geotechnical design parameters (e.g. stability modelling). The consultant may also provide operational input, advice, mentoring, due diligence audits and reviews.

4.4.3 Trigger Action Response Plans

Geohazard conditions in the pit and surrounding areas can change daily, hence it is important that Mine Personnel are well informed and aware of developments as they occur and the risks they may be exposed to. Therefore, personnel who have not worked in the pit for more than a month are required to re-familiarise themselves with pit conditions through their supervisors.

Trigger Action Response Plans (TARP) for specific hazards or areas have been prepared and are accessible.

General advice from geotechnical specialist is sought in determining magnitudes of allowable movement triggering response (TARP activation).

4.5 Communication & Reporting

An overview of the content of the GMP is required to be communicated to all company and Business Partner site personnel having involvement in or exposure to the hazards identified in the GMP.

This would be done by incorporation of current general strategies into geohazard awareness training packages or in more specific presentation on failure investigation, remedial works under JSA to those involved, as well as routine update and distribution of geohazard plans.

Two forms of communication are required:

- Ad hoc reporting and communication of any geohazard
- Routine reporting of inspections and interpreted data

4.5.1 Geohazard Reporting

4.5.1.1 Verbal Reporting

In line with Section 45 of the PNG Mines Act "Every person employed in or about a mine who becomes aware of anything in the mine which is likely to cause injury to a person or to the mine shall report the fact to a person in authority". In summary, any geohazard that is observed needs to be reported to a Supervisor and/or to the Geotechnical & Geothermal Section.

Significant incidents are entered into Sitesafe (Cintellate).

4.5.1.2 Geohazard Maps

Two types of geohazards maps are updated regularly (often daily) and communicated to mining operations personnel:

- Geotechnical hazard map, Fig. 54
- Geothermal hazard map, Fig. 55

These maps are posted in prominent locations:

- Mine crib room
- Daily Mine Production meeting room

They are discussed at the Daily Mine Production meeting (0830 Hrs)

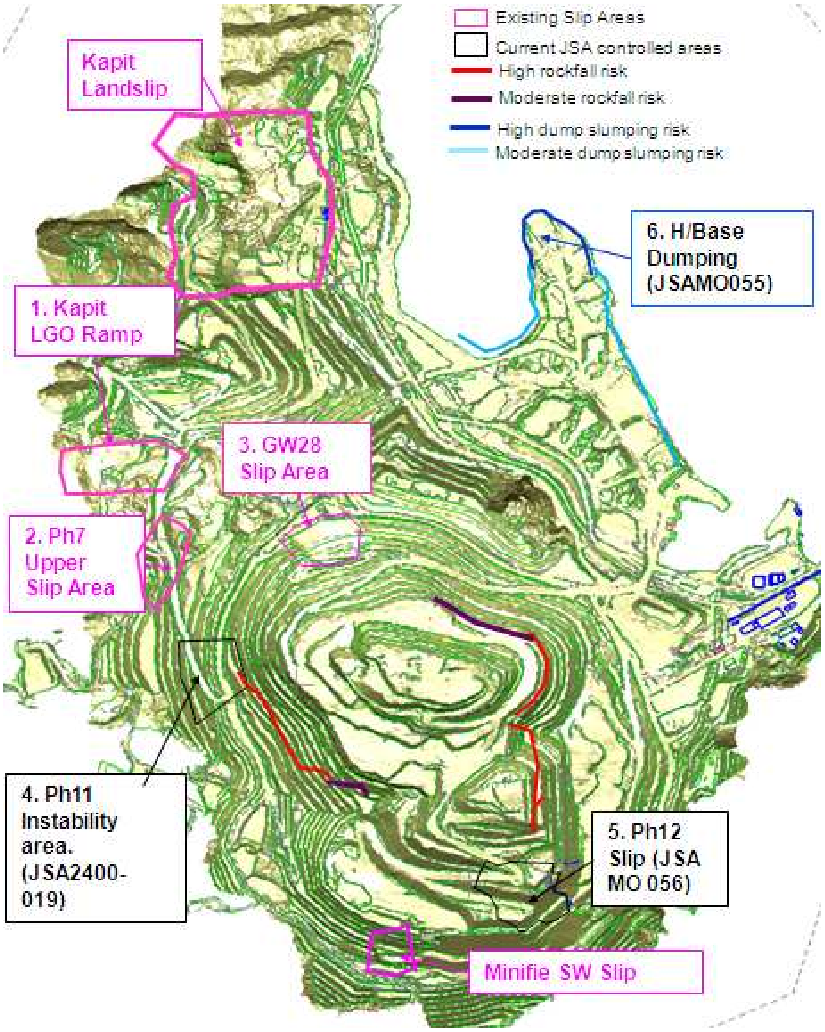


Figure 54: Geotechnical hazard map (Lihir Gold Ltd)

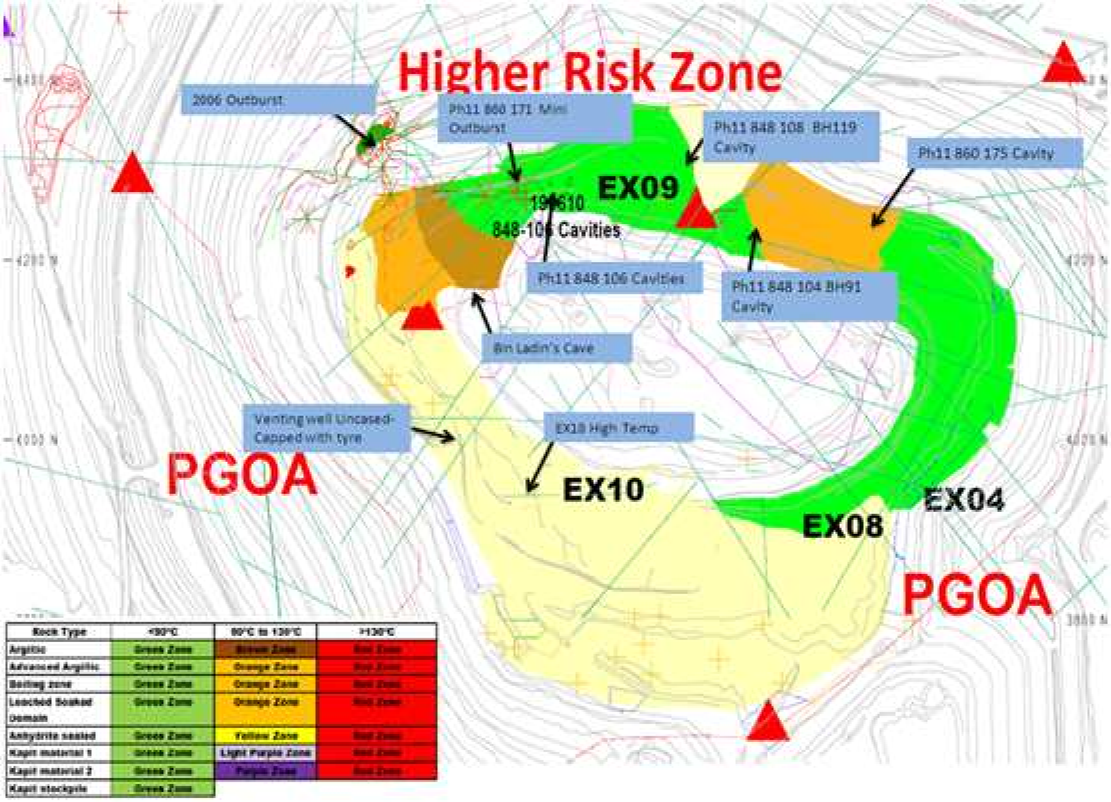


Figure 55: Geothermal hazard map (Lihir Gold Ltd)

4.5.1.3 Geotechnical Zapsheets

Zapsheets are issued where there is a risk of injury to personnel or damage to equipment and the communication of this information make up part of the risk reduction measures. They can be used to communicate geohazards in the pit. Supervisors are requested to present these Zapsheets at start-up meetings, pin up on notice boards and run through as personnel return to site meetings.

Zapsheets are distributed via email and discussed at safety toolbox meetings and stored electronically both in email and original formats.

4.5.1.4 Geohazard Reports

Comprehensive records are kept of any geohazard phenomenon in the pit – i.e. outbursts, failures, cracking, blast damage, etc. Each incident is investigated, the level of risk determined, and risk reduction measures and actions recommended. These actions are communicated immediately to appropriate personnel and/or communicated at the morning production meetings.

Databases of the following geohazard incident types are kept:

- Slope failures
- Geothermal outburst

Standard reporting templates have also been developed for the two incident types.

4.5.2 Wall Inspection and Wall Sign Off

For final wall, interim wall and associated action recording/documentation of signoff, the geotechnical engineer or trained nominee inspects and prepares wall sign-off as evidence of design compliance.

4.5.3 Status Reports

Routine reporting on the status of various elements of the GMP is shown in table 7 below:

Table 7: Routine reporting on the status of various elements of GMP

Report Title	Frequency	Description
Daily slope monitoring report	Daily	High level summary report of areas of concern
274 – geotechnical pit	Weekly	Statutory requirement Geotechnical hazards in the pit and slope monitoring review
274 – geothermal pit	Weekly	Statutory requirement Geothermal hazards in the pit, status of SRWs and temperature monitoring review
Slope monitoring interpretation	Fortnightly	Making interpretation of data for decision making
Slope monitoring instrument status	Monthly	Adequacy and functionality of instruments
Hydro monitoring data review	Monthly	Making assessments for decision making
General slope monitoring review	6 monthly	Comprehensive review of slope monitoring data and slope performance
Kapit Depressurisation	6 monthly	Comprehensive review of the progress with depressurization

4.5.4 Slope Design Reports

Every slope design study is reported comprehensively. The report includes the data upon which the models are based, a summary of the analyses performed and the finding and recommendations are made.

4.6 Corrective and Preventative Actions

Lihir Gold Mine has an incident reporting and management system as part of its Safety Management Plan (LGL-SMP-001). This includes incident investigation using the ICAM methodology and the development of corrective and preventative actions.

All corrective actions pertaining to geohazards are now recorded in a GMP Actions Log.

This tabulates actions arising from various sources such as:

- any geohazard incident, e.g. slope failure, rockfall or outburst,
- audit or review,
- risk assessments, e.g. bow tie.

In addition to the reporting of geohazards or incidents, any person may report a non-compliance with the GMP. These will be reported to their supervisor and where necessary, a corrective action is raised as a hazard or incident report and communicated to site personnel.

Geohazard events are documented via incident report and findings and corrective measures assigned as actions and closed out only when completed or addressed in the GMP. Actions should only be assigned following consultation with the assignee, ensuring a practical plan can be devised and acted upon in a time-bound manner.

4.6.1 Audit and Review Requirements

An audit and review program contains three main aspects:

- Sighting of the GMP document
- Compliance with GMP control activities as summarised in the plan, and
- Effectiveness of the GMP in terms of adequately addressing the risks and reducing the potential for geohazard incidents

The internal audit and review program includes:

- A formal audit plan and annual schedule prioritised by risk (i.e. high and significant risk events).

- A defined audit methodology to identify deficiencies, assess the risks of the deficiencies, and provide recommendations for their acceptance or correction.
- Appropriately trained, competent and independent personnel.
- An audit findings report that recommends corrective or preventative actions to be taken shall be submitted to the Mine Manager,

4.6.2 External Audits and Reviews

The G&G section uses a number of external consultants on a regular basis to perform:

- Technical work, often as part of the design process:
- Review and audit of risk management of geohazards.

Care must be taken that the two roles are kept separate and impartial.

It is recommended that where a consultant is used to perform investigations for a particular cutback that, apart from internal review by the company, a further independent consultant is engaged to conduct reviews of their work.

4.6.3 Audit and Review Schedule

Table 8 below lists the schedule for audits and reviews.

Table 8: Schedule of audits and reviews

Aspect	By who	Timing
Internal Audit of GMP	Supt G&G and another independent Supt.	Every 6 months
External Review/Audit of GMP & adequacy of Geohazard Management.	Supt G&G External expert consultant	Every 12 months, but dependant on risk /change
Review Geohazard and Risk Management procedures	Supt G&G and another independent Supt.	Every 12 months, but dependant on risk /change
Internal review of SOPs related to Geohazard management	Supt G&G	Every 12 months
Geotechnical Audit – monitoring, hazard identification, GMP compliance / review	Supt G&G External expert consultant (includes geotechnical pit inspection)	Every 12 months, but dependant on risk /change
Review Pit Slope Design/Re-design -Minor	Internal G&G Mine Manager Approval	Prior to implementation As required
Review Pit Design/Re-design -Major	Supt G&G Mine Dept sign off process Mine Manger Approval External expert consultant	Prior to implementation As required
External Review/Audit of PGOA procedures & adequacy of controls for geohazard outburst.	Supt G&G Mine Geothermal Coordinator External expert consultant	Every 12 months

4.6.4 Responsibility and Accountability

The Superintendent Geotechnical & Geothermal (G&G) is responsible for managing geohazards and ensuring that the audit and review program defined in the GMP is complied with.

4.7 Training and Required Resources

Two types of training are required:

- Competency based training to operate and update the GMP
- Awareness training for all people who may be exposed to the geohazards

4.7.1 Competency Training

4.7.1.1 Training Requirements

The Mining Manager is accountable for ensuring that professional and supervisory personnel under his control are suitably trained and inducted to a level commensurate with their site duties.

4.7.1.2 Competence and Skills

Competent staff is being engaged to implement the GMP. Competency can be gained from specialist training, experience or on the job training. The level of competence required dependents on the risk associated with each task.

4.7.1.3 Continuous Improvement Training Programs

It is necessary to apply considerable mining experience and professional judgement when establishing and maintaining the geohazard management plan at Lihir. With experience, it will be possible to successively refine the plan over time to maintain an acceptable standard of working conditions. An integral part of any GMP is a competent grasp of the current relevant literature. The company's training policy allows for geotechnical and geothermal staff to undergo further training in the form of postgraduate studies and via attendance to relevant internal/external conferences and workshops.

4.7.2 Awareness Training

As part of the induction process before working in the pit, personnel shall receive some awareness training on the types of geohazards they may be exposed to and how to identify them.

Two training packages are delivered by members of the Geotechnical Section to personnel working in the pit:

- Geotechnical hazard awareness
- PGOA awareness

4.7.2.1 Geotechnical Hazard Awareness

A Lihir specific package has also been developed: Geotechnical Hazard Awareness, which is presented to every person working in the pit (with an MO permit).

This training package “Geotechnical Hazard Awareness” includes the following sections:

- Basic Geotechnical – Hazards, slope failure, rockfall, cavities.
- Observing and Reporting Geotechnical Hazards,
- Current Control Strategies – Monitoring Systems at Lihir.

Personnel working within proximity (1 to 1 – Height/Distance rule) of high walls or crests are required to be trained (Geotechnical Training Presentations and ACG “Down to Earth” video) to a level of competence adequate to allow early identification of geotechnical hazards, correct assessment of safe working distance from crests or toes, and appropriate response to impending slope failure.

A future improvement is the geotechnical hazard awareness training video (ACG –“Down to Earth”) will be shown in the general mining induction for all mine workers.

4.7.2.2 Geothermal Hazard Identification Training

All personnel working in the pit (with an MO permit) receive PGOA awareness training as part of the Mine induction process. Thereafter, a refresher every 6 months is required.

The training package “*PGOA Awareness”* includes the following sections:

- Basic Geothermal – Hazards, outbursts, geysers, boiling mud, steam.
- Observing and Reporting Geothermal Hazards,
- Current Control Strategies – Depressurisation, probe holes, geodomains, separation distances.

A register to track the numbers and names of personnel having successfully completed the course has been developed and managed by the Geothermal & Geotechnical Section.

4.7.2.3 Emergency Drills

Minimum requirement is 1 drill per year for:

- Slope failure
- Geothermal outburst
- Land based dumping

4.7.3 Personnel Requirements

As part of the Mining Operations Induction, all employees and contractors who are to work in the areas covered by the GMP view a geohazard awareness video presentation on slope stability and safe operation.

4.7.3.1 Mine Geotechnical Engineers

Geotechnical qualifications other than an engineering degree are acceptable for persons performing the function of the geotechnical engineer e.g. engineering geologist or geologist with specific pit geotechnical experience.

4.7.3.2 Geotechnical Operations

- 1 * Senior Geotechnical Engineer (residential) - >7 years operational geotechnical experience. Expat.
- 3 * Geotechnical Engineers (FIFO) - > 3 years geotechnical or mining experience. PNG nationals.
- 2 * Senior Geotechnician (FIFO) – 5- 10 years mining & geotechnical instrumentation experience. Expats
- 2 * Geotechnician Leading Hands (FIFO) – 2-5 years geotechnical instrumentation experience. PNG nationals.
- 4 * Geotechnicians (FIFO) – 1 years geotechnical instrumentation experience. PNG nationals.

4.7.3.3 Geotechnical Design Projects

- 2 * Senior Geotechnical Engineer (FIFO) - >7 years operational geotechnical experience. Expats.
- 2 * Geotechnical Engineers (FIFO) - > 3 years geotechnical or mining experience. PNG nationals.

4.7.3.4 Mine Geothermal Scientists

Geothermal qualifications other than a science degree are acceptable for persons performing the function of the geothermal scientist e.g. mining engineer, geotechnical engineer or geologist with specific pit geothermal experience.

4.7.3.5 Mine Geothermal

- 2 * Senior Geotechnical Engineer (FIFO) - >7 years operational geotechnical experience. 1 expat, the other PNG national.
- 3 * Geotechnical Engineers (FIFO) - > 3 years geotechnical or mining experience. PNG nationals.
- 2 * Geotechnicians (FIFO) – 1 year mining or geotechnical instrumentation experience. PNG nationals.

In addition to the above, a pool of PNG National Geology Graduates rotates through each team over a 3 year period, typically spending 6 months with each team.

4.7.4 Specialist Support

Occasions had been arising and might arise in future as well when an external specialist is required to visit the mine site to provide assistance with an area of concern. Until the specialist advice has been offered, the risk would be managed as outlined in the GMP to ensure no employees or equipment are exposed.

At the conclusion of any specialist site assessment, a close-out meeting with all relevant parties comprises a team-based risk assessment to quantify on-going risk. Actions required as part of a formal risk management strategy are then formulated. Preliminary recommendations are provided by the specialist on how best to manage the risk, for effective control or elimination. Information from a subsequent report is then to be conveyed to each person having an accountability for, or direct interest in, the outcomes of the specialist site inspection and team-based risk assessment updated accordingly.

4.8 Records and Related Documentation

4.8.1 Document Control and Record Storage

All site operating procedures including the GMP and associated SOP’s are stored in the site’s document control system Discovery intranet site under Lihirsafe.

All other pertinent GMP documents, records, monthly reports, data files and manuals are filed in a common directory on the site network W:\Minetechnical\ GeoTechnical or Geothermal & Dewatering.

4.8.2 Controlled Documentation

All documentation relating to the GMP implementation and related procedures, Job Safety Assessments (JSA) and Risk Assessments (RA) documentation are controlled documents which may not be altered or modified without following a document control process. This ensures that all modifications or alterations are reviewed and approved by the Mine Manager in consultation with the Superintendent(G&G) and modifications and changes are formally communicated to all persons who may be involved in the planning, design or implementation of the activity, or who may be impacted by the activity.

4.8.3 Other Documentation

At present, the geotechnical section uses two systems for controlled documentation. These include:

- LGL Discovery intranet site under http://lgodiscovery.lglgold.com/Docs/DMCS/default.aspx and
- W:\ drive under Geotechnical \Safety \SOPs (Drafts and Working Copies)

4.8.4 Working Data Management

Geotechnical data is stored in the LGL W:\ drive under Geotechnical and Geothermal sub-folders. A directory exists to store all related monitoring and GIS data. The structure has been established so that ongoing documentation and data collected can be easily sourced and audited.

Data and information for distribution to other sections within the mining department is stored in the MineSight hub in the LGL W:\Common\Mining\MINESIGHT_HUB Geotechnical and Geothermal sub-folders.

4.8.4.1.1 Software Packages

Geotechnical staff uses the following specialised software packages:

- MineSight (Groundwater and structural modelling)
- Quick Slope (Prism data)

- Swedge (Analysis)
- Dips (Analysis)
- Slide (Stability Modelling)

4.8.4.1.2 MineSight Data

MineSight data is made up of layers. These include:

- Cracks,
- Cavities,
- Dewatering drain holes,
- Final wall mapping (structure),
- Final wall signoffs,
- Geotechnical Zapsheets,
- Geotechnical records,
- Transducers,
- Inclinometers,
- Extensometers,
- Crack Pins, and
- Wall monitoring prisms.

The benefit of having the data in layers is that the individual layers can be overlain to retain an integrated and informative overview of various geotechnical aspects and issues relative to the pit and geology.

5 Summary of Significant Contributions and Expected Improvements

The author along with his technical team worked tirelessly to collect available records and data, interact with various departments, carry out field visits, hold discussions with experts, study relevant literature and pooled together individual experiences to formulate a comprehensive Geohazard Management Plan for the mine, discussed above. Table 9 below shows the significant contributions that the team made in this onerous exercise vis-à-vis the major discrepancies/ shortcomings in the previous plans. It also captures the expected improvements and constraints in a continuously evolving scenario as more information become available to the mine operator for reviewing and updating the current GMP.

Table 9: Major discrepancies, significant contributions and expected improvements and constraints

Geohazards	**Major Discrepancies in the existing Plans**	**Significant Contributions**	**Expected Improvements and Constraints**
Slope failures and rockfall	Incomplete SOPs, less qualified manpower, inadequate training, less instrumentation, limited communication, ambiguous change management methodology	SOPs reviewed and updated, manpower requirements in terms of qualification, experience and number were defined, training requirement and minimum standards were established, instrumentation strategy and concentration were defined, communication plan with clearly defined roles at all critical levels was formulated, methodology for change management was established	The comprehensive Geohazard Management Plan would ensure that all geohazards are controlled and managed by the competent personnel by compliance with the SOPs, putting in place more effective designs & their implementation, enhanced communication, monitoring and control. This minimises the risks to safety and health of persons apart from damage to equipment, property and environment while achieving production targets. However, the unique geotechnical and geothermal environment in which the mine had been operating since inception and is likely to continue for the next over 20 years at the present level of reserves, would require the mine operator to
Landslides(on natural slopes)			
Land based dumps and stockpiles			
Subsea slope failures (barge dumping)	No Management Plan	The Management Plan was rewritten in line with the other plans and a new site was defined for systematic and controlled dumping of waste.	
Geothermal outbursts	Less qualified manpower, inadequate training, less instrumentation, limited	Manpower requirements in terms of qualification, experience and number were defined, training requirement and minimum	
Cavities (includes H_2S			

and CO_2 gas)	communication, ambiguous change management methodology	standards were established, instrumentation and monitoring strategy was defined, communication plan with clearly defined roles at all critical levels was formulated, methodology for change management was established.	continuously invest in well qualified and experienced manpower, appropriate training, state-of-the-art technology and instrumentation, collection and timely interpretation of data, rigorous monitoring and regular reviews of their systems, procedures and practices. The mine faces a tough task in training and retaining the local manpower from the island and thus needs reliable back up plans to manage the situation, in case of shortage or absenteeism.
Inrush – surface and groundwater and the sea	Very sketchy Plan	The Management Plan was rewritten in line with the other plans. In addition, emergency response and evacuation procedures were also established.	
Earthquakes and tsunami	Management Plan contained only few instructions		

6 Conclusion and Recommendations

The geological environment in which the Lihir Gold Mine in Papua New Guinea is being operated makes it a unique mining operation in the world in terms of some uncommon geohazards which if not managed effectively, would not only risk the operations but also the health and safety of persons employed therein.

The investigation of the slope failure that occurred in October, 2009 at Lihir Gold Mine highlighted that while 'engineering controls' did respond to the deteriorating situation, the 'administrative controls' mostly failed, underpinning the critical role of human factor in the management system. The unusual rate of displacement shown by the prism installed in the area under question was ignored by the geo-technical staff. The audio-visual alarm that triggered in the dispatch room also went unattended. However, on the other side, a stark visual inspection by the night Supervisor detected a crack developing on the drainage bench and immediately prompted withdrawal of persons from the site just before the failure, thus saving some lives. There was also a clear lack of appreciation of the impact of 'change' when the drain was relocated from the front of the bench to its back some time ago thus resulting in increase of pore pressure and contributing to the failure. Risks associated with such a 'change' had not been properly assessed.

This apart, it was also learnt that the individual geohazard management plans had been developed over different periods and held at different management levels. As such, they did not integrate well with each other in terms of delineation of staff responsibilities, monitoring and reporting protocols.

The aforesaid discrepancies prompted the mine operator to review the individual management plans for each geohazard and formulate a comprehensive 'Geohazard Management Plan' for the mine.

The technical team lead by the author worked together to tie up all these loose ends and formulated a comprehensive Geohazard Management Plan for the entire mime. It is believed that effective implementation of this Geohazard Management Plan would surely enable the mine operator to manage these geohazards more efficiently. However, the implementation of this plan needs to be closely monitored and processes regularly audited both internally and externally. While sufficient resources and an adequate number of competent persons would be the key to its success, documentation controls are also needed to capture, store and retrieve data for decision making. As more information and data become available, this Geohazard Management Plan would need to be revisited and up-graded as and when necessary.

In view of the above, it is recommended that:

- A comprehensive Geohazard Management Plan be formulated to integrate all the existing geohazards for better management and control
- Well qualified, experienced and adequate number of personnel should be engaged in the management of geohazards
- Safe Operating Procedures (SOPs) should be established for each major and critical task
- Job Safety Analysis (JSA) should be conducted for each critical activity
- Hazard-prone areas should be identified and categorised to decide the type and concentration of instrumentation as well as frequency of monitoring
- Persons should be trained in hazard identification, response and communication
- Trigger alarm thresholds should be reviewed more frequently in an ever evolving geohazard environment
- Any change should be managed through a proper ‘Management of Change’ process clearly defining the authority approving such change
- A Communication Plan should be developed to prompt timely and appropriate communication to persons responsible for taking decisions in case of need or emergency
- The systems, procedures and practices should be audited both internally and externally at regular intervals by experts and the GMP should be reviewed after any significant change, development or input.

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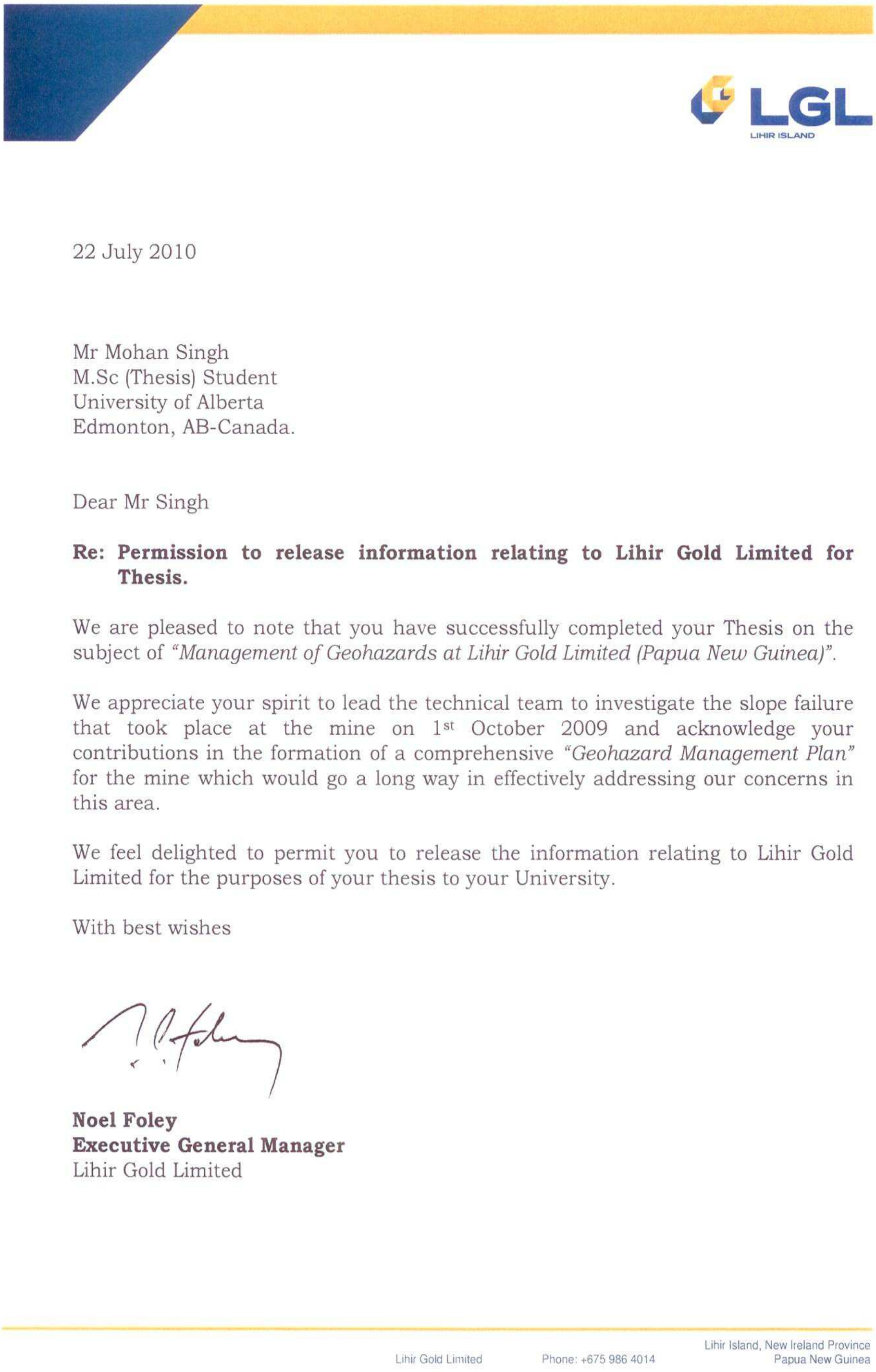
Appendix

Letter of permission and appreciation from LGL



LGL
LIHIR ISLAND

22 July 2010

Mr Mohan Singh
M.Sc (Thesis) Student
University of Alberta
Edmonton, AB-Canada.

Dear Mr Singh

Re: Permission to release information relating to Lihir Gold Limited for Thesis.

We are pleased to note that you have successfully completed your Thesis on the subject of *"Management of Geohazards at Lihir Gold Limited (Papua New Guinea)"*.

We appreciate your spirit to lead the technical team to investigate the slope failure that took place at the mine on 1st October 2009 and acknowledge your contributions in the formation of a comprehensive *"Geohazard Management Plan"* for the mine which would go a long way in effectively addressing our concerns in this area.

We feel delighted to permit you to release the information relating to Lihir Gold Limited for the purposes of your thesis to your University.

With best wishes

Noel Foley
Executive General Manager
Lihir Gold Limited

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