Reassessment of Subsidence Risk, Edward South Lode, Waihi Mine, New Zealand

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Summary: Initial assessments indicated that the risk of voids migrating to the surface from the Edward South stopes of the old Martha underground mine at Waihi could be high. However, three new holes drilled above the stopes confirm a good quality rock mass and an absence of voids. These investigations have enabled a reassessment and consequent reduction of the risk of sinkhole subsidence in this area from high to low risk.

INTRODUCTION

Underground mining of gold-silver bearing quartz lodes was carried out for 70 years from 1882 until 1952 in the great mines at Martha Hill, Waihi, located 80km southeast of Auckland. The mine shafts and stopes reached a depth of up to 600 m on 16 levels, with workings extending laterally some 1.6 km. As new reefs were discovered the workings extended beneath parts of the township. Over their long life the mines produced 1,217 tonnes of gold-silver bullion from processing 12.2 million tonnes of mined ore. A new era of mining at Waihi began in 1988 with the opening of the Martha Hill open pit. The mine extracts gold and silver ore remaining in stock-work zones between the previously mined richer lodes.

A sudden collapse crater 40 m in diameter originating from the old underground mine stopes occurred in 1999 near an occupied part of Waihi. It placed in danger several houses and a main street. This crater occurred close to similar crater which formed in 1961. The 1999 collapse resulted in subsurface investigations and risk assessment studies being commissioned by the Hauraki District Council. In December 2001 a further 50 m diameter collapse crater formed in a residential area, swallowing a house, but fortunately without injuring its five occupants (Figure 1). Two other houses were perched on the crater rim. The 2001 collapse led to an acceleration of work to identify the potential hazard posed by the old underground workings at Waihi.

Figure 1. The 13 December 2001 sink hole at Barry Road, Waihi

Assessment Method

Detailed rock mechanics analyses were made for the hazard assessment. The stability of the old underground mine stopes was evaluated in terms of the stope back, hanging wall, footwall and crown pillar failure mechanisms. The collapse crater area study included analysis to simulate the probability of void migration from

unfilled stopes to the surface using the @RISK program. The analyses show that in the cases of the actual collapse craters, the voids have a high probability of migrating to the surface, thus providing a method of testing and authenticating the hazard assessment modelling. Modelling analysis applied to the remaining stopes of the old underground mines show there are additional areas where void migration from unfilled stopes has an assessed high, medium and low probability of reaching the ground surface. The locations of these probabilistic hazard zones were outlined using the @RISK modelling and deterministically by using the dimensions of the historical collapses applied along the length of the stopes.

Consideration of the "incubation period", the time interval between the cessation of mining and the occurrence of collapse, and comparisons with mine subsidence histories overseas, indicates that further collapses are likely to occur over the next 50 years.

Risk assessment estimates made using occupancy levels within the three hazard zones were compared with Societal and Individual Risk criteria. Results indicate that safety within the high and medium zones may be unacceptable.

THE EDWARD SOUTH WORKINGS

The previous assessment of the sinkhole hazard in Waihi associated with the old underground workings at Edward South and other places beneath the town area (Richards et al, 2002), concluded that high, medium and low hazard zones existed over parts of the Royal, Edward South and Empire Lodes. With respect to the Edward South Lode, the report noted that the modelled zone of high and medium probabilistic subsidence hazard above the Edward South Lode warranted further subsurface investigations to determine whether or not a void had commenced migrating to the surface. Although the combined empty stopes of the Edward South Lode were modelled to have a probabilistic hazard rating a little greater than the pre-assigned 10% for a high zone, the hazard was significantly lower than that estimated for much of the Royal and Empire lodes. In addition the Edward South stopes are deep, have a narrow span, and historical records indicate the presence of a good quality rock mass around the stopes. It is therefore possible that the stopes are stable and without upwards migrating voids. It was recommended that the probabilistic hazard ratings above the Edward South lode be regarded as provisional pending the results of additional subsurface investigations, such as drillholes. Evidence that voids are not present may allow the hazard rating to be lowered or removed.

New Drilling Investigations

Three holes, ES1 to ES3, were drilled above the Edward South Lode between 6 September and 11 November 2002. The sinkhole hazard has been reassessed based on the information from these drillholes. Figure 2 shows the location of the three drillholes. The two shallow inclined holes, ES1 and ES2, were drilled to check for near-surface voids that may have migrated from the stopes towards the ground surface (Figure 3). An example of this type of void can be seen in drillhole RDH6 (Figure 4 & Opus 1999) above the Royal Lode in the Seddon Street area where there is a zone of 17m of lost core at least 60m above the top of a filled stope.

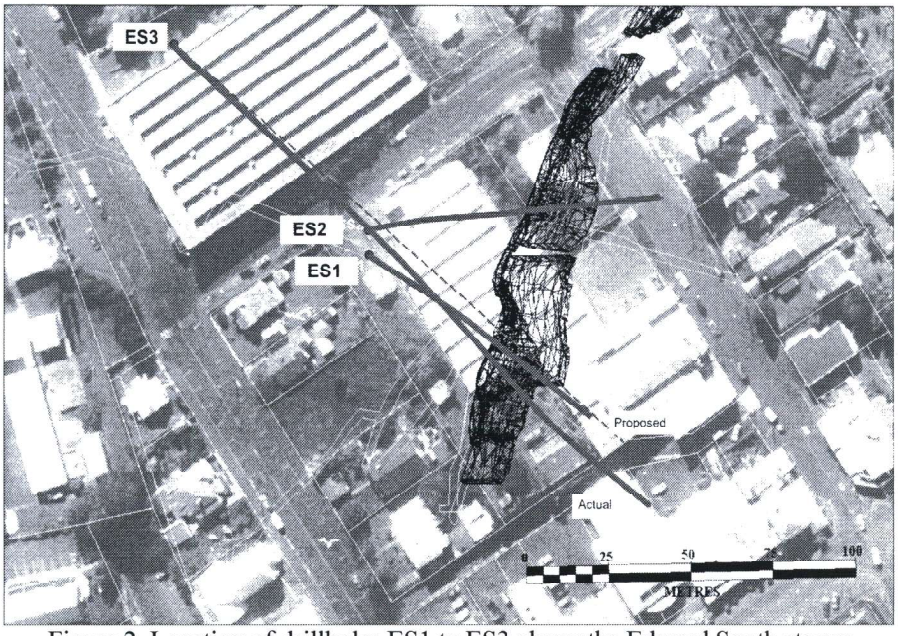

Figure 2. Location of drillholes ES1 to ES3 above the Edward South stopes

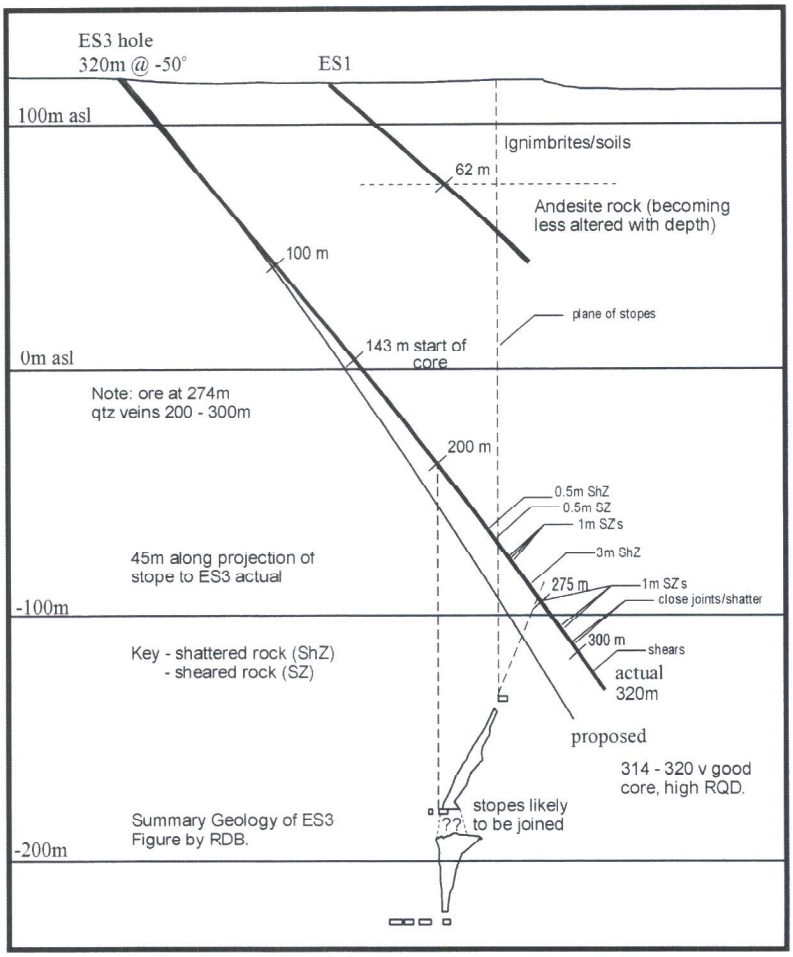

Figure 3. Summary geology for drillhole ES3

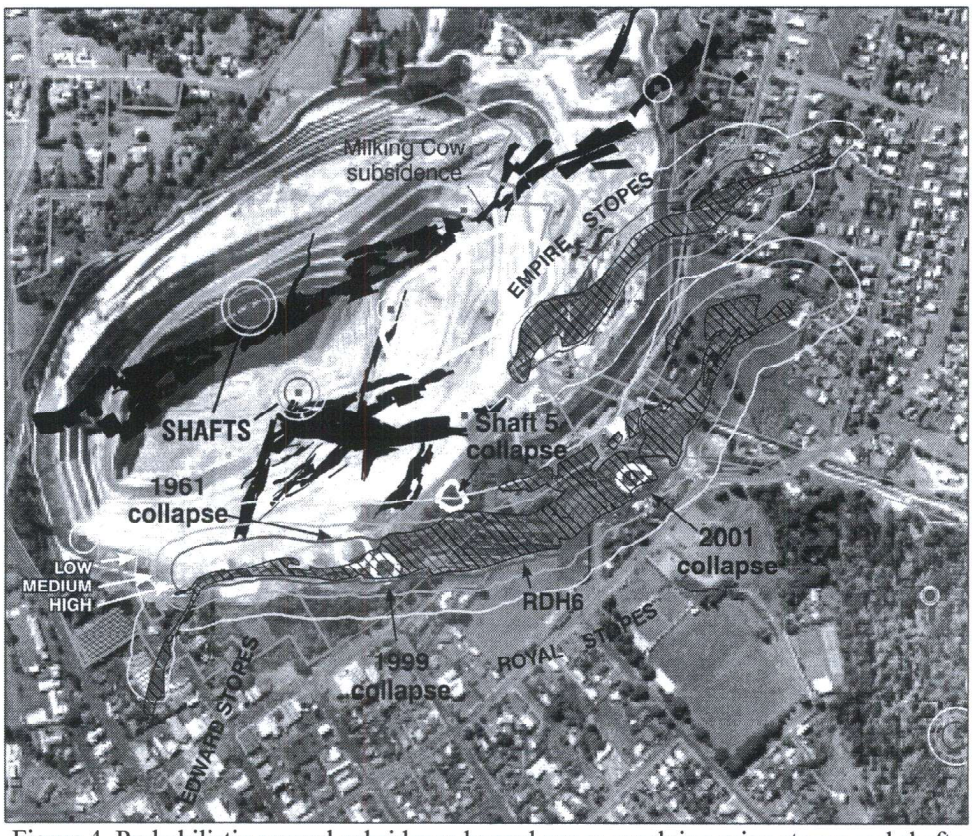

Figure 4. Probabilistic ground subsidence hazard zones overlying mine stopes and shafts

The deep hole, ES3, was drilled to see if a void was propagating up from the widest part of the Edward South stopes. Figures 3 & 5 show the drillholes in relation to sections through the stopes. Figures 2 & 3 are based on

Torckler 2002. Logs and photos of the drillhole core have been prepared by Opus International Consultants. Core recovery parameters are generally excellent, especially considering the fact that the holes are inclined. Apart from core losses in superficial materials, the only areas of lost core indicated in the logs are in ES1 between 63.20 – 63.90 and 65.75 – 66.20 in andesite rock. ES3 was cored from 143m to 320m with the logs showing only a very small zone of less than 100% total core recovery between 307 and 308m where total core recovery is about 95%. The drillhole data clearly indicate undisturbed ground conditions without evidence of voids. An assessment of the geological conditions indicated by the drillhole logs and core photos is summarised in Figure 3.

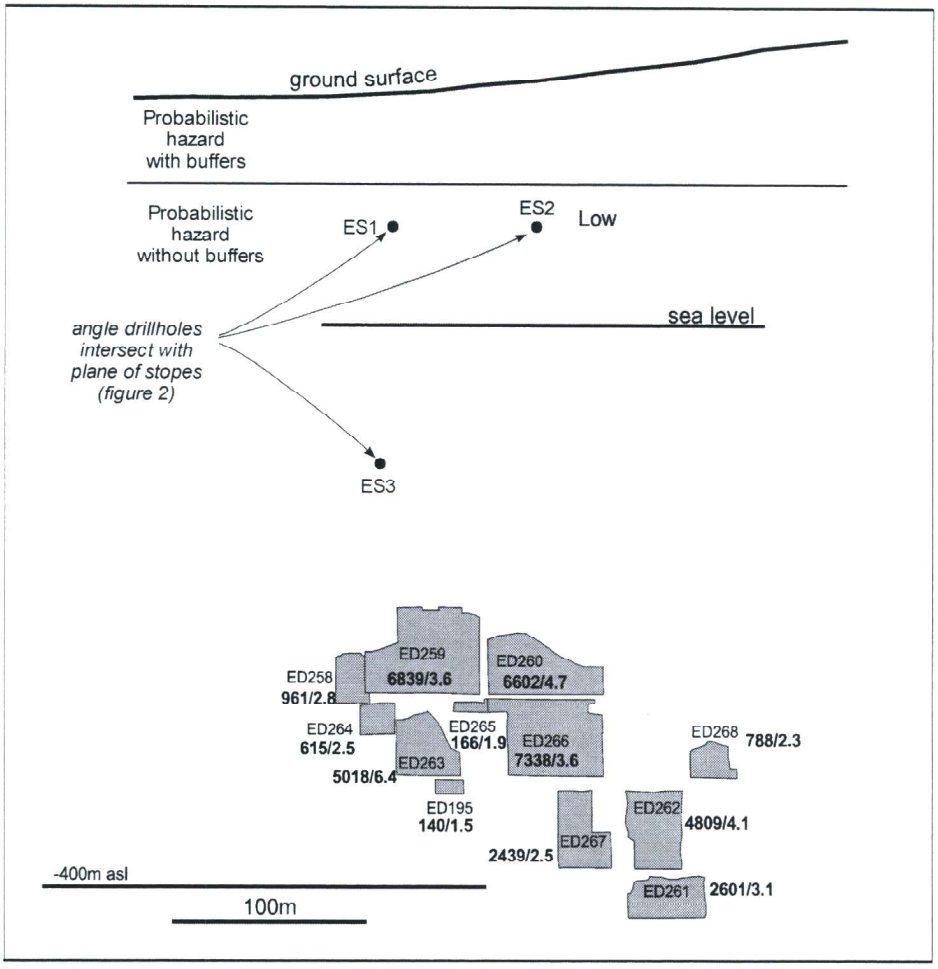

Figure 5. Edward south long section showing stope identifier, volume, average thickness and surface hazard.

The drill core photos show that the andesite rock mass in the vicinity of the Edward South stopes in ES3 generally has a *good* rock mass classification (using the CSIR Geomechanics Classification), with a range from extensive areas of *very good* to small areas of *poor* rock mass. The zones of poor rock are plotted on Figure 3. The rock mass from the start of coring at a downhole depth of 143m to the first significant (0.5m wide) shatter zone at 236.5m is generally good to excellent. There is another 0.5m wide shear zone at 246.5m, but the first wider zone of poor rock mass begins at 256.5m. The rock mass vertically above the upper Edward South stope, as seen in the ES3 drillcore logs between 200m and 256m (Figure 3), has full core recovery and generally good to excellent rock mass rating parameters (Total and Solid Core Recoveries 100% apart from very minor lengths, and average Rock Quality Designation of 62%). In our experience and judgement a void is unlikely to propagate upwards through such a good rock mass with so few defects. In our assessment the ES1 and ES3 drillholes (Figures 3 & 5) clearly indicate that no void is propagating upwards from the southern end of the Edward South stopes. In addition the good to excellent quality rock mass present vertically above the stopes at this point (Figure 3) is most likely to prevent void propagation.

REVISION OF SINKHOLE HAZARD

In our judgement, where it is clear from the drilling that there is no void, and where the rock mass quality appears to be good enough to prevent a void from forming, the low hazard rating can be removed. In addition the stopes at the southern end of the Edward South lode are too small (total source volume of ED258, ED264 and the small southern tip of ED259 is less than 2,500m^3 and the average stope span is less than 3m - Figure 5) for a void to migrate upwards through ~300m of rock to the surface. On the basis of this evidence the low hazard zone

has been removed from the southern end of the Edward South stopes to the point where stope ED259 (Figure 5) increases suddenly in height and volume. The extent of the revised low hazard zone is shown on Figures 4 & 5.

The ore lodes in the Martha Mine are often associated with faults or shears. The ES3 core photos show the quartz lode beginning at about 274m with associated shatter and shear zones on both the hanging and footwall sides. The ES3 drillhole intersects the lode some 47m above the top of the stope (Figure 3). Most of the poor rock mass seen in the ES3 drillcore is located on the footwall side of the lode extension. By comparison, the crown and hanging wall rock mass conditions are much more favourable than those in the footwall. It is the hanging wall rock in this case that provides stability and will inhibit or prevent upwards void migration.

Hazard assessment for Edward South stopes

The supplementary drilling program has confirmed the previous impression that the rock mass above the Edward South Lode stopes is better than the general quality of rock above the upper areas of other lodes. As noted (Richards et al, 2002), the Edward South stopes are also at a greater depth than is typically the case at Waihi and has smaller stope thicknesses (2.3 to 4.7m in top stopes). As well this area is outside the area of previous subsidence.

A method was developed for assessing the probability of voids migrating through to the surface (Richards et al, 2002). This involved a collapse model which assumed that the shape of the migrating void approximated to a frustum of a tapered rectangular solid section. The collapse geometry is controlled by weak sheared surfaces at the contacts between the ore and the country rock on the hangingwall and footwall and by an angle of break on the lateral edges of the void. The height to which the void can migrate depends on the length of the stope, the angle of break and the bulking properties of the rock. Stopes with moderate to high probabilities of void migration to the surface (0.1 to > 10%) were found to be located mainly in the areas of previous subsidence.

Figure 5 shows the layout of the stopes in the Edward South Lode. Stope ED258 and 259 effectively act as one stope since there is no significant vertical pillar between these. The top stopes ED258/259 and ED260 have low probability of caving to the surface. Historical information indicated that *Arches under 9 level at the top of stopes ED264, 265 and 266 were shot out in 1935 and 1937.* The hazard assessment therefore considered the possibility that all the stopes shown on Figure 5 had effectively amalgamated and the total volume of all the stopes would be available to receive caved material. Hangingwall or stope back failure along the length of the top three stopes combined (ED258, ED259 and ED260) resulted in a high probability of caving through to the surface when analysed using our @RISK model.

Drilling of the three holes, ES1 to ES3, indicates that a continuous void has not developed above the line of the three stopes ED258, ED259 and ED260. However, ES3 has sampled a relatively small section at the southern end of this total length and there may be undetected sections of caving ground to the north of ES3 above part of stopes ED259 and ED260. It is noted that lengths of stope shorter than ED260 or ED258/259 become geometrically stable before they can reach the ground surface and any smaller sections of caved stopes are therefore not significant with respect to their possible effects at ground surface. Also the new investigation holes ES1 and ES2 show that a void from these stopes has not migrated up to within 100 m of the ground surface.

REVISED RISK ASSESSMENT

The hazard zones are defined as (Richards et al, 2002):

Low probability **L**	Sinkhole probability less than 0.1% - but there may be minor surface settlement and ground cracking deformation (where there are adjacent high and medium hazard zones).
Moderate probability **M**	Sinkhole probability 0.1 to 10%
High probability **H**	Sinkhole probability >10%

In our judgement the investigation drillholes ES1 to ES3 may not entirely disprove the presence of a migrating void, but they have allowed a reduction of the hazard zone to low and a decrease in its length (Figures 6 & 7). Within the assigned low hazard rating the probability of a sinkhole reaching the surface is less than 0.1%. Using the methodology established (Richards et al, 2002) the annual probability of a collapse forming at the surface in the low hazard zone is 0.00004 (4×10^{-5}) or 0.004% (Table 1).

Fatal Accident Rate (FAR) is the probability of death per hour x 10^8. FAR for Edward South lode with a Low hazard rating is 0.018. This is two orders of magnitude less than the FAR due to an accident at home = 2, the FAR due to an industrial accident = 6, and the FAR due to a car accident = ~50. Although the FAR due to a

subsidence is an involuntary risk, it is a great deal less than the ambient rate that we all accept in day to day voluntary activities.

Societal Risk. The factory/warehouse building located within the Edward South lode low hazard zone was occupied by up to 88 people until recently. The annual probability of a collapse at any point on the Edward South lode is estimated to be 8×10^{-6} (column C of Table 1). Assuming a severe case where there are 90 people working in the area of a 40 m diameter collapse, and that if a collapse occurs there will be a 20% fatality rate. The 90 people are there 8 hours per day, 5 days per week. Then there is an annual probability of less than 8×10^{-6} 8/24 x 5 x 52/365 that there would be 18 fatalities, or $<1.9 \times 10^{-6}$. This gives a point on the ANCOLD (Australian National Committee on Large Dams) derived societal risk diagram (Figure 6) which is within the acceptable risk area.

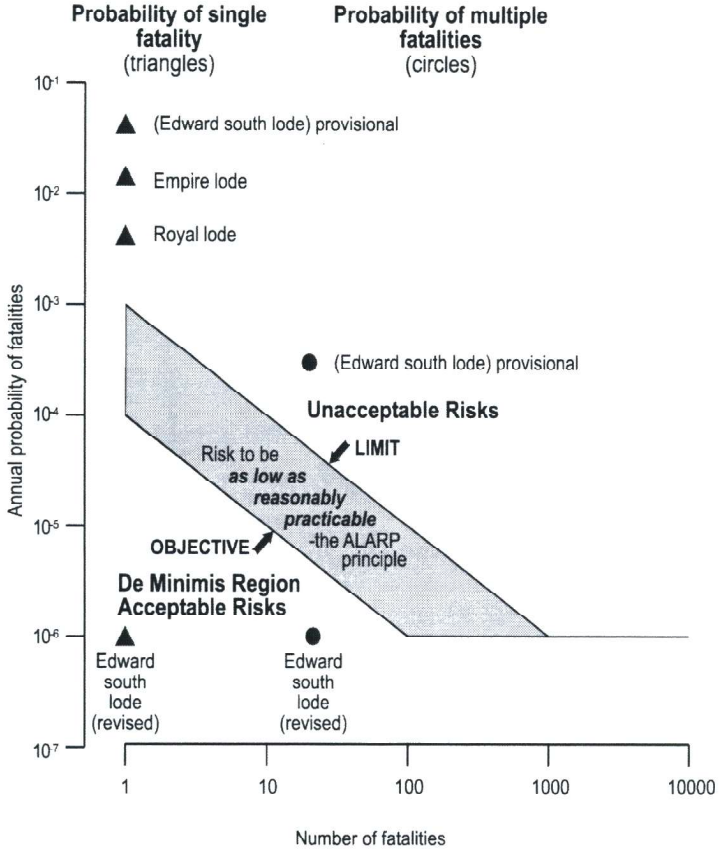

Figure 6. Comparison of risks

Individual Risk. As noted there is a 20% probability that a future sinkhole might cause one fatality and the occupants are there 24 hours per day, then individual risk is calculated as in Table 1 and plotted on Figure 6.

Table 1. Derivation of individual risk

	A		B	C	
Lode	Annual probability of crater forming on lode now	Length of lode low hazard(m) from Figs. 4 & 5	Aspect ratio with 40m diameter crater	Annual probability of crater forming at any point on lode	Annual probability of a fatality of a person on the lode
				(A x B)	(0.2 x C)
Edward	<0.00004	~200	40/200 = 0.2	$<0.000008 = < 8 \times 10^{-6}$	$<0.0000016 = 1.6 \times 10^{-6}$

CONCLUSIONS

1. The three investigation drillholes have high core recovery and do not show evidence of caving ground. They indicate a good quality rock mass at depth (drillhole ES3), and give qualified assurance that voids are not migrating upwards.
2. In order for a void to propagate to the surface from the top stopes of the Edward South Lode, failure needs to occur along a substantial length of the stope. Data from the drillholes indicate that this is not the case. A

pessimistic assumption was made that the top three stopes had combined because the intermediate pillars had been mined. The rock mass above the Edward South top stopes appears to have remained stable since 1937 when the last arches were shot.

3. Historical information indicates that the arches above ED264, ED265 and ED266 were shot out in 1935 and 1937. This would still leave a substantial body of solid rock between ED263 and ED 266. The previous assumption that all the stopes in the area (ED258, ED259, ED260, ED264, ED263, ED265, ED266, ED195 and ED267) had combined may be an unnecessarily pessimistic assumption, given the lack of evidence for void migration from the recent drilling program. Modelling void migration using a smaller number of stopes combined together gives a lower probability of void migration reaching the surface.
4. Based on the new drillhole and other evidence presented, the earlier provisional classification of the area above the Edward South Lode as High hazard can be reduced to Low. As well the southern extent of the hazard zone can be decreased since the deep and shallow drillholes ES3 and ES1 clearly show that a void has not developed in that area. In our judgement the hazard rating for the entire Edward South lode cannot be completely removed by considering the three drillholes, as a small uncertainty remains. The Low hazard classification of the remainder of the lode is recognition that the three drillholes do not fully investigate the entire length of the Edward South lode. There remains a greatly reduced possibility that an upward migrating void may be undetected in the region below or between ES1 and ES2.
5. Individual and societal risk estimates indicate that the risk to people living and working in the low hazard zone remaining above the Edward South lode is within acceptable risk limits.

LIMITATIONS OF THE STUDY

The study has approximations and limitations that are inherent in attempting to model complex processes and ground conditions. The authors have applied their engineering and geological judgement and best endeavours to an imperfect knowledge of subsurface ground conditions and past events. The estimated probability rating of various subsidence events has a relatively high level of uncertainty because of the uncertain nature and properties of the ground through which the voids migrate before they reach the surface. As well, a lack of accurate knowledge of the processes by which the voids migrate increases the uncertainty. However, the model derived for void migration has been tested and validated against the three subsidences that have occurred, and against the void located in drillhole RDH6. The authors are satisfied the void migration model gives good indicative and useable hazard assessment results.

ACKNOWLEDGEMENTS

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