For this present report we have drawn extensively on the previous work, particularly the well documented and detailed studies by PSM and NWG over the last six years.

2.0 SUBSIDENCE CRATER REVIEW

When carrying out their subsidence crater assessment for the 2002 report, GNS could not find an established method for estimating the probability of subsidence craters forming from unfilled underground mine workings and set about developing one. Under the direction of Dr Laurie Richards, an author of the 2002 GNS report, a methodology was developed to do this. In the technical assessment portion of the August 2002 GNS report, rock mechanics methodologies were developed and used to assess the stability of crown pillars in the stopes of the old Martha underground mine at Waihi. The work, which involved several different crown pillar stability assessment methods, is summarised in Figures 28 to 38 of that report. The stability assessments indicate that given certain realistic rock mass and stope parameters, the crown pillars could be unstable and would tend to collapse (i.e. Fig. 35).

The methodology for assessing the subsidence risk is presented in Figure 36. Using the software program @Risk, the report examines the probability of a roof collapse extending to the ground surface using a predefined collapse mechanism assuming that collapse of weak ground occurs as an upward migrating void, which, depending on the rock cover and rock strength conditions, may or may not reach the ground surface as a zone of subsidence. The ability of a stope collapse to reach the ground surface is calculated as the sinkhole index. When the sinkhole index exceeds 100% then subsidence of the ground surface could occur. The probability of the sinkhole index exceeding 100% is assessed in the void migration calculation utilising numerous iterations of a range of stope size and rock mass input parameters within predetermined bounds defined by a frequency versus dimension relationship in the @Risk software. The probability of a void reaching the surface was then tested against those places where subsidence craters have actually migrated to the surface, and was found to be very high. With this deterministic validation of the probabilistic void migration calculation, we were satisfied that our estimates were realistic.

The diagram on the left side of Figure 36 in GNS 2002 was intended to demonstrate the stope parameters used in the void migration calculation. The diagram was not intended to show how a void migrated to the surface. Rather we envisaged in the 2002 report that the voids migrated to the surface using a chimney caving mechanism as indicated in Figure 30, (c) and (d). As shown in Figure 31 of the 2002 report, a conical (chimney) collapse can migrate upwards the greatest distance. As well, the evidence of subsidence craters both outside (in 1961, 1999 & 2001) and inside the mine (summarised in Fig. 5, PSM125.L88 and NWG Geotechnical Summary – Martha Pit 2007/2008 Figures 7 & 8) show that voids tend to migrate by chimney collapse. We considered that in the underground mine, chimney void migration to the surface was most likely to occur upwards from an empty stope cavity along a line of poor rock mass, such as that provided by the intersection of two through going, sub-vertical faults or shears. We know from mine records that steeply dipping, intersecting faults and shears with various orientations are present in the mine rock mass.

In 2004 Trevor Carter, an experienced and well regarded colleague of Dr. Laurie Richards (lead author of the August 2002 GNS report), made an unsolicited review of the August 2002 GNS Report. In his “review”, forwarded by email, Trevor discussed the methodology we had used, and the review of our report by Tony Taig (Appendix 2, GNS August 2002 report), and forwarded two recent papers he had written on crown pillar stability. The comments by Trevor are briefly summarised here because they are the only detailed written evaluation we have received regarding rock mechanics aspects of our 2002 void migration assessment methodology.

Trevor discussed the rock mass parameters we had chosen and the values we had derived for crown pillar critical span, suggesting that the values he would have derived for these items would be for a poorer rock mass and less stable crown pillars – i.e. collapse of the crown pillars would be more likely in his assessment. As well he suggested that in his experience there are two distinct periods when crown pillar collapse is more probable – a two peak event history with early collapses due to bad workmanship (mining too close to the surface or stopes too wide, or both), followed by late collapses due to wear and tear (i.e. long term collapses due to weathering, loss of support from decay of timbers, ravelling, etc.). Trevor also made comments about his experience with open pits excavated near old underground mine workings.

Following this review and that by Tony Taig, which is included in the August 2002 GNS Report, and because there appears to be no viable alternative, we have elected to maintain the consistency and the methodology of our reporting. We have therefore used the same void migration calculation method for deriving the probability of sink-hole collapse for the North Branch, Mary, No. 2 and Martha stopes in this report, as was used in the August 2002 GNS report. By using this consistent approach we can then directly compare the new estimates for the Martha stopes (Table 1) with those for the other stopes in the August 2002 GNS report.

3.0 VOID MIGRATION CALCULATIONS FOR NORTH BRANCH, MARY, NO. 2 AND MARTHA STOPES

We have examined the risk of ground subsidence developing from chimney collapses into unfilled mined out stopes in the lodes that extend away from the northeast quadrant of the Martha Mine. This was carried out using the same methodology i.e. @Risk simulations of sinkhole index probabilities as developed for the study of ground collapse in the August 2002 GNS report. The basic model was calibrated by checking the predicted sinkhole indexes against this previous work.

The input data of stope locations, dimensions and volumes and whether filled or unfilled was provided from the NWG mine model, with a little additional data provided from historical records held by Dr. Bob Brathwaite of GNS. Estimates of maximum and minimum stope widths were developed from the stope volume and surface area data provided. Maximum and minimum stope widths for use in the probability simulations were developed from examination of the previous width ranges used for the Royal, Empire and Edward lodes south of the open pit.

The results are presented in Table 1 and the high, medium and low sink-hole hazard areas are shown on Figures 5 & 5a. The rock cover and % rock cover given in the table are best guess estimates based on the cross-section data through the lodes. Where individual stopes are known to have been filled, i.e. Martha Lode stopes F1, F2, F3 and F4 and No 2 Lode stopes 2, 3 and 4, then these have been omitted from the hazard assessment because they are deemed to pose no risk of surface subsidence. Where the collapse of adjacent stopes could combine to form a bigger collapse feature, then this has been examined by combining stopes together in the assessment. The results are also given in the table.

The assessed current annual probabilities of ground collapse (calculated using the same methodology as GNS 2002) within the influence zones of the unfilled stopes follows:

- Mary Lode – 0.04 or 4.0%
- Martha Lode – 0.04 or 4.0%
- No 2 Lode – 0.01 or 1.0%
- North Branch – 0.04 or 4.0%

These probabilities for the Mary, Martha and North Branch stopes are of the same order of magnitude as determined by GNS in 2002 for the Royal and Empire stopes along the southern boundary of the mine. The sink-hole hazard zones associated with each of the lodes are shown on Figures 5 & 5a.

4.0 PEDESTRIAN SAFETY IN WAIHI HAZARD ZONES

The assessment for traffic risk performed by Professor D G Elms (Letter Report to HDC dated 2 Oct 2002 – Appendix 3) concluded that the likelihood of vehicles being directly impacted by a sudden collapse was significantly (two orders of magnitude) lower than the ambient probability of vehicle accidents on NZ roads. Further, by implication, the level of risk posed to the road-using community would be expected to be acceptable to them in a rational analysis. We expect the same to apply to the use of the potential high probability collapse areas by pedestrian traffic in the event that future land use is for recreational purposes, e.g. as reserve areas having walking and cycle tracks.

Professor Elms assumed a car speed of 50 km/hr. For walkers we could assume 5 km/hr. Thus a pedestrian takes 10 times as long to pass through one of the high hazard zones as a car does. This means that the probabilities for a pedestrian are 10 times those for a car, i.e.

Edward	2.96×10^{-9}
Royal	6.14×10^{-9}
Royal	3.68×10^{-9}
Empire	20.36×10^{-9}

The annual probability of collapse on the Mary, Martha and North Branch lodes are essentially the same as for the Royal and Edward lodes. Therefore assuming a similar number of pedestrian trips as traffic, we can apply Professor Elms' assessment logic to show that the risk of death to a pedestrian in a high sink hole hazard zone is about 50 times less risky than a person in Waihi being killed in a car accident. Death due to a traffic accident in Waihi was estimated to be about 1 death in 10 years (Appendix 3). This does not mean that the death of a pedestrian (or cyclist) in a high hazard sink hole subsidence zone could not occur. It could, but its probability is very low and is generally regarded as acceptable in the normal scheme of our daily activities.

Waihi Gold Mine

Table 1 Probability of sinkholes above stopes in Martha, Mary, No 2 and North Branch lodes

Job # 42160447

Stopes nos.	Length m	Stope width m			Volume m^3	Rock Cover m	% rock	Sinkhole index - bulking 33-50%			Sinkhole index - bulking 15-30%			Probability a stope will not collapse (for bulking 33-50%)	Combined Probability of a Collapse on Lode (see pg 61 of GNS 2002)	Annual Probability of Collapse now (t = 0) (see pg 53 of GNS 2002)	Comments
		Min	Mean	Max				Mean	% > 100	Risk	Mean	% > 100	Risk				
Mary Stope																	
1	98	0.90	1.31	3.31	2970.0	73	83	65.4	9.6	M	143	73	H	0.904			
6	59	1.80	3.10	5.10	3376.0	185	93	29	0	L	65.2	5	M	1			
7	20	0.30	0.65	2.65	51.0	209	93	3.3	0	L	7	0	L	1			
8	54	1.80	2.30	4.30	1946.0	195	93	19.5	0	L	44.7	0	L	1			
12	102	1.80	3.05	5.05	10256.0	248	94	38	1.2	M	86.6	30	H	0.9876			
14	68	1.20	2.04	4.04	1811.0	302	95	10.4	0	L	22	0	L	1			
1,2	98	1.80	2.57	4.57	8056.0	73	83	116	64	H	264	100	H	0.357			
1,2,3,4	146	###	2.21	4.21	10480.0	73	83	113	57	H	254.6	100	H	0.426	**1.00**	**0.04**	
1,2,3,4,5	169	1.20	2.21	4.21	15118.0	73	83	143	82	H	320.7	100	H	0.183			
6,9	122	###	3.10	5.10	15129.0	185	93	63.8	7.5	M	140.7	79	H	0.925			
6,9,11	122	1.80	3.10	5.10	26706.0	185	93	136	78	H	190	100	H	0.224			
7,8	73	1.80	2.30	4.30	1997.0	195	93	13.7	0	L	28	0	L	1			
7,8,10	73	1.80	2.30	4.30	9264.0	195	93	88	69	H	109.6	60	H	0.306			
12,15	102	1.80	3.05	5.05	10748.0	248	94	41.3	1.4	M	89.7	35	H	0.986			
7,8,10,13	98	1.80	3.54	5.54	16386.0	195	93	88.1	34	H	140	95	H	0.664			
7,8,10,13,16	166	1.80	3.54	5.54	23333.0	195	93	60.4	5.6	M	134.8	70	H	0.944			
No.2 Lode																	
1	87	1.80	3.86	5.86	7751.0	136	90	52.8	4	M	116.9	59	H	0.96			
5	78	###	1.60	3.60	1578.0	302	95	8.7	0	L	17.6	0	L	1	**0.16**	**0.01**	Stopes at No.2, 2, 3, 4 are filled
1,5	87	1.80	3.86	5.86	9329.0	136	90	69	13	H	140.5	82	H	0.874			
Martha Unfilled																	
1	68	1.80	3.29	5.29	7122.0	170	92	64.6	8.2	M	109.7	63	H	0.918			
2	29	0.90	1.43	3.43	154.0	224	94	3.5	0	L	7	0	L	1			
4	29	1.20	2.05	4.05	521.0	278	95	8.4	0	L	18.6	0	L	1			
5	29	0.90	1.31	3.31	440.0	248	94	10.7	0	L	23.5	0	L	1			
6	44	1.20	1.67	3.67	1150.0	273	95	13.8	0	L	31.4	0	L	1			
8	54	1.20	1.83	3.83	1004.0	327	96	7	0	L	15	0	L	1			
11	20	###	1.50	3.50	299.0	380	96	6.7	0	L	59.4	2.7	M	1	**1.00**	**0.04**	
12	29	1.20	1.94	3.94	1864.0	341	96	24.4	0	L	25.2	0	L	1			
13	56	1.80	3.05	5.05	5060.0	131	90	79	23	H	120	78	H	0.771			
1,3	68	1.80	3.29	5.29	13257.0	170	92	111	64	H	119	74	H	0.365			
1,3,7,9	112	1.80	3.15	5.15	16244.0	170	92	87.8	27	H	166	95	H	0.735			
1,3,7,9,10	112	1.80	3.15	5.15	17019.0	131	90	124	62	H	225	100	H	0.384			
13,14,15,16,17,18	88	1.80	4.22	6.22	17830.0	131	90	144	83	H	195.4	100	H	0.17			
1,13	124	1.80	3.29	5.29	12182.0	131	90	65	7.4	M	147	77	H	0.926			
1,13,3,14	124	1.80	4.22	6.22	24765.0	131	90	133	67	H	247	100	H	0.33			
1,13,3,14,15	124	1.80	4.22	6.22	26238.0	131	90	141	72	H	253	100	H	0.279			
1,13,3,14,15,16,7	173	1.80	4.22	6.22	28723.0	131	90	96.3	32	H	212	97	H	0.684			
1,13,3,14,15,16,7,17,9,10	173	1.80	4.22	6.22	34138.0	131	90	119	56	H	256	99	H	0.44			
1,13,3,14,15,16,7,17,9,10,18	173	1.80	4.22	6.22	34849.0	131	90	121	60	H	261.5	100	H	0.396			
Martha filled																	
F5	127	0.60	0.94	2.94	1936.0	248	94	11.3	0	L	22.4	0	L	1	**0.00**	**0.00**	Stopes at Martha Filled, F1, F2, F3, F4 are filled
6,F6	78	1.20	1.75	3.75	1798.0	273	95	10.5	0	L	21.8	0	L	1			
North Lode																	
1	102	1.80	3.07	5.07	7663.0	127	90	52.2	3.3	M	118.6	56	H	0.967			
1,2,3,4,5	122	1.80	3.50	5.50	19337.0	127	90	118	57	H	232	100	H	0.43			
1,2,3,4,5,6,7	122	###	3.50	5.50	31948.0	127	90	213	99	H	284.6	100	H	0.01	**1.00**	**0.04**	
1,2,3,4,5,6,7,8	122	1.80	3.50	5.50	33453.0	127	90	225	99	H	282	100	H	0.01			

5.0 GROUND DEFORMATION AT WAIHI

5.1 General ground deformation near mines

There is an extensive literature on ground surface subsidence, mainly related to underground mining of coal seams, with less information on ground movements near open pits. It is clear that either can cause significant ground surface movements extending some distance away from a mine.

Much of the ground subsidence literature on underground mining relates to coal mining where extensive, sub-horizontal coal seams have been substantially mined out, causing variable widespread subsidence with a mainly vertical downwards component of movement at the surface. This type of subsidence can reach the surface relatively quickly, especially where the mined coal seam is “shallow” and where unsupported, longwall mining methods are used, but is not directly applicable to the situation at Waihi.

In some urban areas affected by underground mine creep subsidence movements, generally from mining coal seams, there are pragmatic restrictions on the type of buildings and services that can be constructed. For example, resilient, sheet clad, timber framed buildings constructed on piles with a crawl space above the ground so that the building can be re-levelled or relocated, are acceptable, whereas brittle brick or concrete buildings generally are not. Although creep movement has not reached this level in Waihi, and may not do so, the accurate monitoring recommended in Waihi, in our view is necessary for long-term assessment and to assist in development of planning measures for building and infrastructure close to the mine.

Chimney subsidence from steeply dipping or vertical voids, such as that occurring at the Martha underground mine, has formed roughly circular subsidence craters and distinctive concentric ground cracking extending some distance away from the “crater”. The width of high, medium and low hazard zones have been set up to encompass the observed ground subsidence and cracking from the 1999 and 2001 events (Figures 5, 8 & 9). However, any unfilled stope voids will tend to close up with time, mainly by lateral movements normal to the void. These movements are likely to be very slow, complex, episodic and may involve block movements which exploit through going rock mass defects such as faults and shears. They would be a combination of small vertical subsidence and lateral movements which may be concentrated on sub-surface rock mass defects such as shears and faults.

In addition to conventional slope failures, the long-term creep ground movements associated with open pits appear to depend on rock mass properties and the size and depth of the pit. Initially movements can tend to be rebound types of movements due to rapid unloading as the pit is excavated. In the long-term these can translate into slow, inelastic creep displacements towards the pit, especially when long-term strain softening is considered. They could also be expressed at the surface as a combination of small vertical subsidence and lateral movements which may be concentrated on sub-surface rock mass defects such as shears and faults. Thus it will require specialist interpretation of detailed measurements to determine whether or not the observed surface movements can be attributed to the open pit, the old underground mine, or a combination of both.

5.2 Terminology

To reduce confusion, we qualify our use of the general term “subsidence” and instead describe the main type of ground movement, where possible following the four descriptions outlined in 5.3 below. In cases where the ground movement may be related to more than one of the four ground movement types listed, we will describe the combination of movement types which we consider are involved.

In engineering terms Risk (R) is defined as the product of the probability (P) of a hazardous event occurring by the consequences (C) if it does occur. i.e.

$R = P \times C$

Consequences are typically defined as damage (economic loss) or loss of life that would likely result if the hazardous event actually occurred. We note that in this definition risk is not the same as probability.

5.3 Deformation at waihi

At Martha Mine where there has been a combination of historical, deep underground mining and more recent excavation of the open pit, there is likely to be a complex interaction of ground movements between the two mines, which may extend some distance from both mines. At this stage there is visible linear cracking in Haszard and Seddon Streets (photos 1 to 4). That in Seddon St. is being monitored by NWG using crack width measurements with proposals to strengthen the monitoring system by recording the total spatial movement of selected points with time. As well there is deformation which is not being monitored, such as that in Haszard Street.

The monitoring in Seddon St. shows total crack width movements in the range 1 to 10 mm in the first six months of 2008. The assumption of a continuing rate of movement would result in 0.2 to 2 m of total movement over 100 years. Movement rates may increase following the start of lake filling as increased water pressures cause declining effective strength within the slope and around stopes, leading to additional movement. The current amount and rate of movement is not life threatening, but is sufficient in time, to damage buildings and services and has already done this. The footpath, kerb and channel (in Seddon Street) and a water main (in Haszard Street) have required repair because of this ground deformation. At this stage there is a lack of accurate knowledge of where else outside the mine boundary, similar or smaller movements may be occurring. Accurate and detailed monitoring is required to determine this, and to pick up possible future movements, if they occur.

In our view there is a high probability that small, long-term creep deformations due to both the old underground and the open pit mines could occur in adjacent parts of Waihi. However, without accurate monitoring information we cannot accurately assess how much and over what area the creep movements might occur. Given that this study is focussed on stope subsidence hazard we have not regularly received or reviewed the monitoring data related to pit wall movement which may assist interpretation of the nature of the movements. In our view, based on the observed cracking, there are insufficient accurate movement data available away from the pit perimeter. Therefore we recommend initially monitoring points in an area above where the open pit and the underground mine stopes are close to each other and could interact. We recommend that a set of survey monitoring pins along lines are established and accurately (± 2mm) surveyed for their x,y,z coordinates on a regular basis (three monthly initially then declining as the behaviour is better understood) within this area to establish movement (or lack of it) over the forthcoming years. Our suggested monitoring lines are shown on Figure 5b and are discussed in Section 5.5 following. They should include as many as possible of the settlement monitoring points already installed and being monitored in Waihi (Figures 7 & 7a).

A network with a similar purpose has been established in Taupo urban area to monitor possible subsidence ground movements related to nearby deep geothermal steam extraction for a proposed electricity generation plant. This network of pins is set into road kerbs, initially at 20m centres, is monitored at 6 monthly intervals, and a movement history has been established prior to any deep geothermal steam extraction from the adjacent Tauhara area. In our view the Taupo monitoring network serves as a working model of what is required in Waihi.

5.4 The types of ground deformation near Martha Mine at Waihi

In brief there are several, possibly complexly interacting forms of ground movement at Martha Mine, all of which can be referred to as “subsidence”. These are:

1. The small, gradual surface settlements of up to ~260mm due mainly to lowering of the groundwater table in the open pit (Figure 7b), but also influenced by rock mass relaxation due to mining and the subsurface geology. The extent of this ground settlement is monitored with levelling surveys and reported annually to HDC. These movements have influenced much of the town and are considered to have a very low impact – see Figure 7, which is Figure 42 from the August 2002 GNS report. Figure 7a shows the location of the levelling survey pins.;

2. Sudden collapse craters into old underground mine workings. The extent of this high risk hazard was assessed by GNS in 2002 for the Royal, Empire and Edward stopes to the SE, South and SW of the open pit. The “Martha Stopes” to the north-east of the open pit have now also been assessed for this form of sudden collapse in this report (Figures 5 & 5a). Recent observations by Newmont during construction of the Pit 64 cutback indicate that as with previous collapses (in 1961, 1999 and 2001) that have reached the ground surface the chimney caves have formed directly above the stopes rather than along the 30° angle of draw. (Ref Newmont Geotechnical Summary – Martha Pit 2007/2008 Figures 7 and 8) This recent observation is consistent with the definition of the location of the high hazard ground subsidence zones directly over the stopes developed during the initial study by GNS in 2002. (GNS August 2002) and continued in this report.

3. Pit wall movement. The movement and stability of the walls for the entire open pit are being continuously monitored and assessed in near real time by NWG using a Geotechnical Management System (Maton 2004 – Appendix 1), which includes measurements from three total survey stations to numerous monitoring prism points. We understand that the results of this monitoring are reviewed regularly for HDC by Open Pit Reviewer Mr John Ashby who advises HDC on pit wall stability.

   The pit wall movement monitoring is used to assess the short and longer-term stability of the pit walls. Concerns over the stability of the south wall have resulted in moving the Cornish pump house so that work can be undertaken on a south wall cut-back to a long-term, stable angle (PSM125.R28 and PSM125.R34 Reports). Following completion of the cutback works, the open pit walls are expected by NWG to be stable with acceptable levels of stability under static, lake filling and earthquake loading conditions, and thus have a low probability of failure. The continuation of total station pit wall monitoring into the foreseeable future provides assurance that slope movement which may possibly lead to a slope failure, would be detected, evaluated and dealt with as it occurred.

It is noted that some of the creep movement cracks in the surface of Seddon Street lie outside the previously defined low subsidence hazard zone and are parallel to the southern high wall rim, in a similar manner to tension cracks associated with slope instability. These cracks are shown in Photos 1 to 7 and their locations are shown in Figure 5. They are discussed in more detail below. Our current knowledge of the movements does not permit reliable differentiation between pit wall instability and stope collapse as the cause(s) of this movement, but their nature, alignment and extent coupled with observations presented by Newmont (Ref Newmont Geotechnical Summary – Martha Pit 2007/2008) indicate that pit wall movement cannot be ruled out at this stage and a precautionary approach to their interpretation is warranted.

4. Gradual vertical, lateral and rotational ground movements caused by creep of large “blocks” of ground as they adjust to the various underground and open pit mining excavations, as outlined by Trevor Maton in Appendix 1. These movements appear to be mainly associated with the southern and eastern perimeter areas of the open pit above the old underground mine workings and where the rock mass is noticeably poorer than in the northern and western walls of the pit. The movements have caused what are at this stage relatively minor surface deformations at several locations. However, there is potential that these ground movements could slowly enlarge over a period of many years to eventually reach more than a metre or so of overall displacement. The known ground movements in Seddon St. are being monitored monthly by NWG using a micrometer distance measurement between two pins. These cracks are generally outside both the extensive pit wall total station monitoring being carried out by NWG and are too complex to be effectively monitored by the annual vertical surface settlement monitoring being carried out to determine the ground response to groundwater lowering for the open pit excavation.

As noted, there are small linearly oriented ground displacements related to type 4 above, extend some distance beyond the open pit and are presently noted in Seddon and Haszard Streets, in places well outside the collapse crater low hazard zone and some 120m from the rim of the open pit (Figure 5). Subsidence and ground cracking is also seen at and near the net ball courts and a few other places. Our present interpretation is that these slow ground movements are low impact (and low risk) and are gradual surface movements, possibly due to adjustments and rotations of large rock mass blocks. They appear at this stage to fall within the general definition for low hazard described in the 2002 GNS report - *“there may be minor surface settlement and ground cracking deformation*” (p35, August 2002 GNS report).

Of these four types of ground movement, types 2 and 3 can in some situations be rapid and thus high impact and risk, while types 1 and 4 are considered to be low risk. Type 4 differs from type 1 by having an unknown level of potential for the deformations to become increasingly large, possibly reaching up to a few metres of total movement in time, whereas at least part of the type 1 deformations may tend to reverse when the open pit is flooded and the groundwater table reaches former levels. The degree of movement from type 4 is potentially damaging to buildings and services, but because of its slow rate of movement, it is not a threat to life. The magnitude of these deformations can be expected to decrease with surface distance from the open pit and from the underground mine stopes. We recommend accurate survey monitoring to measure the magnitude and extent of these possible movements against time.

5.5 Recommended Additional Ground Movement Monitoring

As the possible type 4 gradual ground movements beyond the pit perimeter are not being effectively measured at present, we recommend that systematic on going monitoring, similar to that presently being carried out in Taupo, should commence in Waihi. This monitoring should accurately pick up the extent and directional magnitude of these movements, if any, so that a better assessment of any ground movements can be made. Three dimensional (x, y, z co-ordinate) monitoring of similar accuracy to the total station monitoring being carried out by NWG for the open pit walls would be ideal. Where practicable the open pit monitoring using total stations could be extended into parts of Waihi. However, the lack of suitable vantage points for a total station theodolite to see into all the key parts of Waihi township and the requirement of having numerous prisms close to the ground for this system to be effective, suggests that other options, such as the Taupo model, may be preferable. GNS experience using a total station to monitor on-going landslide movements in near real time in Taihape township, show that the total station survey system with prisms can be effective (see www.geonet.org.nz/landslide/LandslideResources/TaihapeLandslide).

In town areas one disadvantage is that prisms attached to houses, poles and other cultural features may not show the real ground movement when this is small and slow. For example, the actual ground movement of a crack, such as that in Photo 1, where it passes under a house, may not be accurately reflected by monitoring a prism attached to the house. In this case, the ground movement is masked by the house or structural feature. Further these structures can introduce their own spurious movements related to climate (temperature and moisture) changes. Thus for accurate ground movement monitoring, we recommend having a pin or prism attached on or as close as possible to the ground surface. This is the case in Taupo where metal pins are cemented into kerb lines along the edge of roads. Here they give ready access for repeat surveys and for placing additional pins when extension or more detailed monitoring is required. As well this system of pins is low maintenance and does not require a continuous monitoring set-up, as a total station system does.

Initially the monitoring points in Waihi could be set at 20m centres along suitably oriented streets in areas near the underground mine and the open pit rim, with additional points installed either side of visible “cracks” and other known surface deformations. The monitoring frequency of these points could initially be set at 3 months and then adjusted to be more or less frequent depending on the rate of movement being observed. As well there should be regular assessment of the need to adjust the length of the lines or for additional rows and points to monitor new or expected areas of deformation.

We recommend initially the linked monitoring lines shown on Figure 5b.

5.6 Future Ground Movements

5.6.1 Estimating the extent of slow (type 4) ground movements

The slow, type 4 ground movements may be caused by the old underground mine workings, the open pit, or a complex interaction of both combining to affect the adjacent rock mass and its defects, such as shears and faults. The relative contributions from the underground mine and the open pit to surface deformations are likely to vary according to the proximity of each and the prevailing subsurface ground conditions, particularly where through-going crush and shear zones can be exploited.

With reference to Figure 6 (Fig. 41 of the August 2002 GNS report), the angle of draw is defined as the vertical line between the edge of the mine opening – in the case of the underground stopes on the Royal or other lodes, and the line connecting the opening (stope) edge to the limit of significant displacement. The angle of draw is typically in the range 10 to 30 degrees. The cracking in Seddon Street is “linear” (rather than having a circular sink hole appearance) and has an alignment roughly parallel with the open pit rim. It has a maximum angle of draw of about 28 degrees from the base of the Royal stopes, or about 60m from the southern edge of the low hazard zone from the Royal stopes for the 1999 collapse cross-section (see Fig. 8), or extending out 30 to 80m from the edge of the low hazard zone for the 2001 collapse cross-section (Fig. 9). The linear alignment of these cracks roughly parallel to the open pit wall, the direction of their movements and their location outside the hazard zone related to stope subsidence, is suggestive that pit wall movements may be involved with generation of the cracking.

As well as adding complexity to interpretation of observed surface cracking, small, long term relaxation movements of the ground due to the open pit might be expected to extend some distance from the pit rim. Such ground movements would be type 4, low risk ground movements. Using basic rock and soil mechanics estimates, the zero deformation limit could possibly extend to about 250m (the pit depth) from the edge of the pit but would be expected to lie within and may be considerably less than this figure.

In Seddon Street the possibility that the observed cracking is influenced by stope collapse cannot be ruled out. The ground deformations at the NE end of Seddon Street and the Millenium Wall (Photos 4 & 5) appear to be north side down extensional features (Photo 4), possibly related to the 1961 and 1999 collapse craters, the Royal stopes, and/or to the open pit wall movements.

In Haszard Street the deformation movement is “compressional” north side up with a small right lateral movement, indicating a different mechanism, such as graben-type block adjustment associated with a small outward movement of the pit wall, or rotation of a rock mass block towards the open pit wall (Photos 1 and 2).

The recommended survey monitoring is considered to be what is required to accurately determine the extent and type of deformation movement which may be occurring outside the Open Pit. The lines may be helpful in assessing the possible causes of the ground movement, such as whether they are block movements related mainly to the abandoned underground mine workings. As well, the rate and amount of movement may help determine the level of risk. For example an accelerating movement rate may typically indicate that a rapid failure is on the way, whereas movement that reduces with time typically indicates a settling down and an improving degree of stability or reduction in risk. The recommended monitoring is intended to cover all these possibilities and is likely to be required for the medium to long-term future, for many years after mine closure.

At this stage we have no reason to expect that the deformation hazard might increase above the Edward South stopes. The Edward South stopes are relatively small in volume, they are deeper than most of the other areas, and investigation drilling shows that the rock mass above them is of good quality. They are within the low hazard zone established previously (Figure 5). As well, the two inclined investigation holes above the Edward stopes are being regularly monitored by OPUS for down-hole movements. The accurate surface survey monitoring points recommended in this area are an additional assurance method for checking the potential subsidence hazard in this occupied part of Waihi township.

5.6.2 Possible extent of long-term ground movements

Figure 10 illustrates the extent of the Martha and Royal lode excavations below the deepest part of the open pit. On the Figure 10 cross-section, the Martha lode extends at least 250m below the greatest depth of the open pit, while the 250m deep Royal lode excavations are present to the south and stop some 70m beneath the pit perimeter. Given that the Martha lode excavations average about 10m in width and the Royal average 4m, there is a combined total stope width of about 14m which may tend to close up with long-term rock mass deformation. Allowing approximately 40 to 75% of this void space to be unfilled and available for lateral movement, it is possible that there could be a few metres of long-term lateral closing movement of the south pit rim relative to the north, resulting in a narrowing of the north–south pit width. This lateral movement is likely to be variable depending on void space available and subsurface geology. As well it could have associated surface deformation adjustments over a lengthy period, possibly hundreds of years.

5.7 Possible remote sensing DInSAR monitoring

In 2007 GNS employed a remote sensing specialist Dr Sergei Sampsonov. This opened the possibility of using satellite-borne synthetic aperture radar (SAR) images to detect and measure the subsidence movements in Waihi. DInSAR uses two or more SAR images to generate maps of surface deformation using differences in two-way travel times of the waves returning to the satellite. Once the ground, orbital and topographic contributions are removed the interferogram contains the changes of the surface caused by an increase or decrease in distance from the ground pixel to the satellite. One fringe of phase difference is generated by a ground motion of half the wavelength that is about 3 cm for ERS, RADARSAT and ENVISAT satellites and about 10 cm for ALOS. Phase shifts are resolvable relative to other points in the interferogram only, but absolute deformation can be inferred by assuming one area in the interferogram (for example a point away from expected deformation sources) experienced no deformation, or by using a ground control (GPS or similar) to establish the absolute movement of a point.

The advantage of DInSar is that it potentially offers monitoring of ground deformation over a complete area, rather than along lines as measured by surveying. GNS agreed with HDC to trial the DInSAR technique at Waihi (Appendix 4) in April and May of 2008 and this has been done. However, the results are equivocal as it appears any ground movements at Waihi may be too small to be measured using the technique. This is possibly good news for Waihi, but remains to be confirmed by this technique. Better accuracy measurements using DInSAR could possibly be achieved in Waihi if an accurate terrain model, such as Lidar, was available. We are informed that a Lidar (accurate air borne infra-red height scanning measurements) survey has been completed in Waihi by Environment Waikato. Once this Lidar data becomes available, GNS has undertaken to make a further assessment of the potential for using DInSAR for monitoring ground movements in Waihi

Photo 5. Ground cracking due to lateral northward movent and subsidence, evident along the base of the Millenium Wall in Seddon Street, Sept 2008.

Photo 6 View of surface cracking near the open pit rim which is being monitored with wire extensometers. View looking west.

Photo 6 & 7 Open ground cracking with north (pit) side up, close to the pit rim and east of the Judges Kauri.