Monday, 10th May 2021

REF: Ensham21 - R9

Mr G Gough
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Dear Garry,

Re: Discussion on Sinkhole Subsidence

1 INTRODUCTION

As requested, this technical memorandum provides a discussion on the potential for sinkhole subsidence occurring in the Ensham life of mine extension project area and is an addendum to the subsidence assessment report (Gordon Geotechniques Pty Ltd, 2020[1]).

In addition to overall pillar stability, the risk of roadway (intersection) collapse such that sinkholes develop at the surface should be considered in the life of mine extension project area. Significantly, it is reported in the technical literature that sinkholes are restricted to shallow mining areas and generally only reach the surface at depths <50 m[2,3,4].

As shown in **Figure 1**, the depth of cover in the MDL and North ML areas is significantly deeper, ranging from 130-210 m. In the South ML area, the depth ranges from 80-160 m (**Figure 1**). It is also noted that the shallowest part of the proposed workings in the South ML area is located outside the flood plain.

Furthermore, underground mining has already been carried out in the current underground workings at depths of 40 m, with no evidence of sinkhole subsidence occurring above the excavated roadways.

[1] Gordon Geotechniques Pty Ltd. (2020). Subsidence Report for the Ensham Life of Mine Extension Project.

[2] Mahar, J.W. and Marino, G.G., 1982. Building response and mitigation measures for building damage in Illinois. Proceedings of Workshop on Surface Subsidence due to Underground Mining, Morgantown, West Virginia University, pp. 238-252.

[3] Whittaker, B.N. and Reddish, D.J., 1989. Subsidence: Occurrence, prediction and control, Elsevier, Amsterdam, 528p.

[4] Nielen Van Der Merwe, J and Madden, BV.J. (2002) Rock Engineering for Underground Coal Mining. South African Institute of Mining and Metallurgy. Special Publications Serries 7.

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These observations are confirmed by the following discussion on the mechanism of sinkhole subsidence and supplemented with design calculations for a potential failure to occur. These design calculations were also peer reviewed by geotechnical consultants Mine Advice in 2016[5].

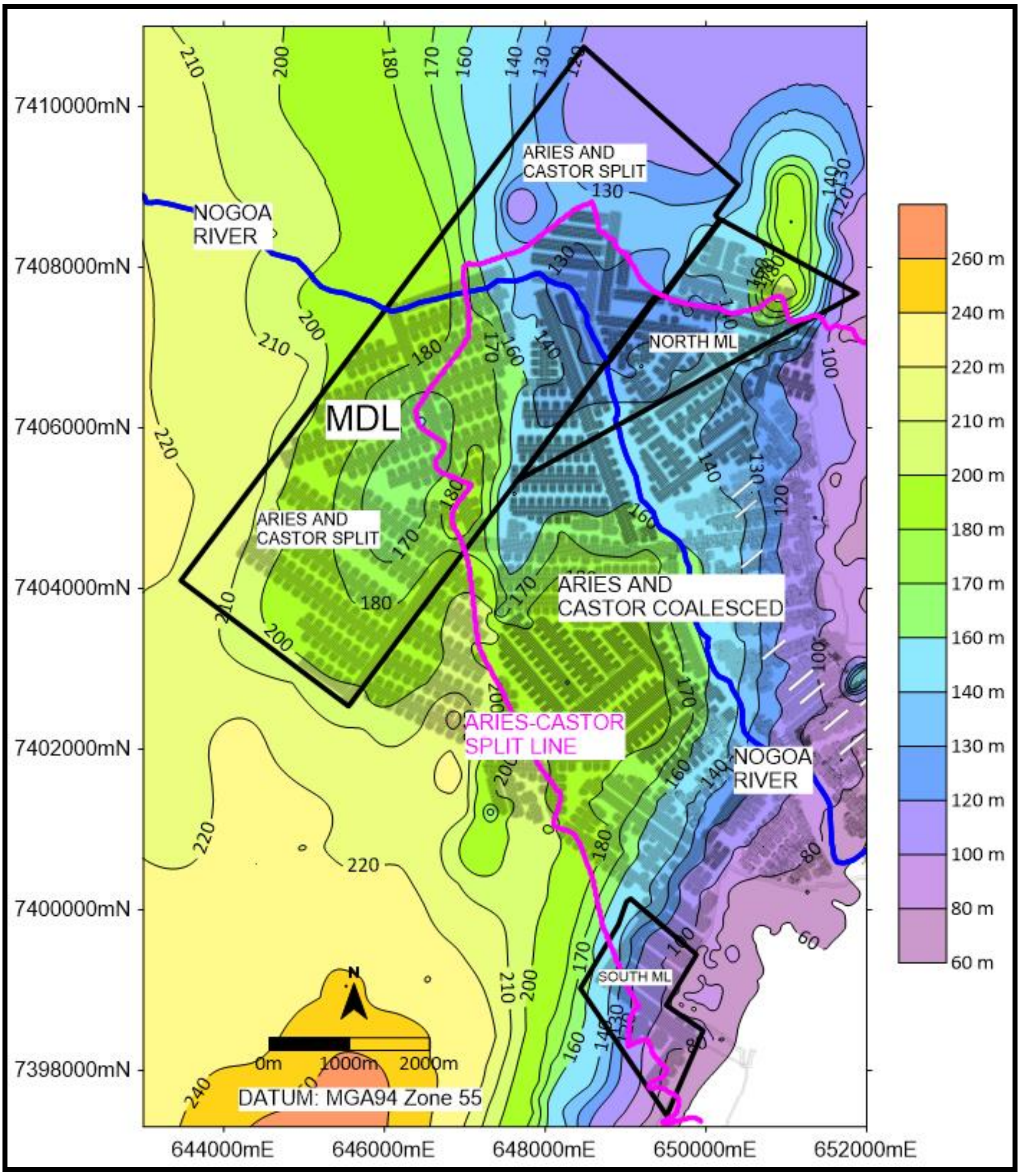

Figure 1. Working Section Depth (GGPL, 2020).

[5] Mine Advice Pty Ltd (2016). Peer Review of Gordon Geotechniques (GGPL) Report to Ensham Coal – Geotechnical Review of the Ensham Mine Plan in Areas 1 and 2 (Dated March 2015).

2 MECHANISM OF SINKHOLE DEVELOPMENT

Whittaker and Reddish (1989) devote an entire chapter to sinkhole subsidence above bord and pillar mines. They present various analyses examining the development and propagation of sinkholes and also review the published literature, supplemented with some case examples.

Whittaker and Reddish concluded that the local geology and the natural strength of the immediate roof are important factors in assessing the potential for sinkhole development. The mining dimensions and geometry of workings are also of equal importance and should be considered in making an assessment of subsidence risks above bord and pillar mines.

Mine Advice (2016) provided further analysis of this aspect and highlight that one of the key issues in regards to sinkhole development through fresh rock material is the extent by which the upwards progression of a roof cavity is truncated by either lithology or natural arching (**Figure 2**). **Figure 2** shows that sinkholes develop with vertical sides rather than any form of natural arching, which will cause the effective span to decrease higher into the cavity.

As discussed by Mine Advice, this failure mechanism is commonly observed in underground coal mines and along with roof lithology acts to restrict the height of roadway roof fall cavities to typically only a few metres (**Figure 2**). This is consistent with observations in the current Ensham underground workings.

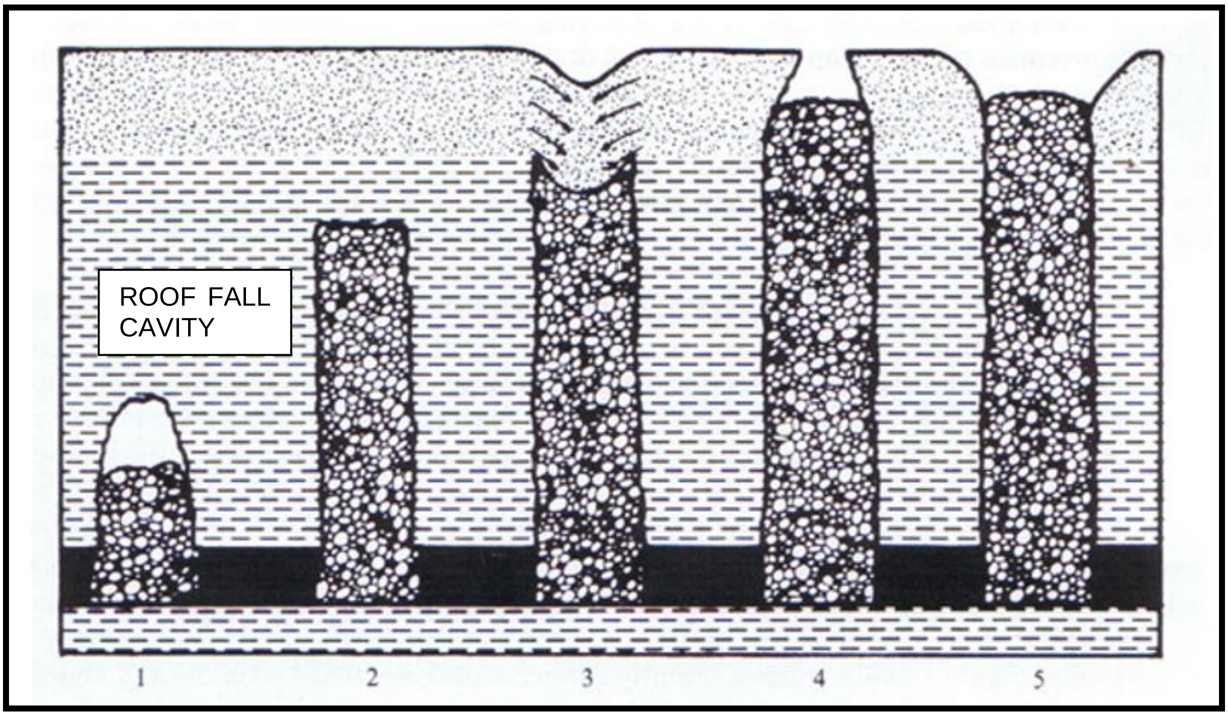

Figure 2. Illustration of Suggested Sinkhole Development Mechanism (Whittaker and Reddish, 1989).

3 RISK OF SINKHOLE SUBSIDENCE TO THE SURFACE

The risk of sinkhole subsidence of shallow workings to the surface has been assessed using a limiting equilibrium analysis as detailed below. As detailed earlier, experience elsewhere indicates sinkholes due to intersection failures generally reach the surface at depths <50 m. The analysis is presented in Brady and Brown (2006[6]) as follows:

For **dry** conditions:

$$F_1 = 2\frac{c'(a + b\cos\alpha)}{\upsilon ab\cos\alpha} + \frac{k\tan\phi'}{(2h - b\sin\alpha)} * \left\{h^2 + \frac{(h - b\sin\alpha)^2}{b\cos\alpha} + \frac{2}{a}\left[h(h - b\sin\alpha) + \frac{b^2\sin^2\alpha}{3}\right]\right\}$$

For **saturated** conditions:

$$F = F_1 - \frac{2\upsilon_w\tan\phi'}{3\upsilon(2h - b\sin\alpha)} * \left\{\frac{h^2 + (h - b\sin\alpha)^2 - 2d(2h - b\sin\alpha - d)}{b\cos\alpha} + \right.$$

$$\left.\frac{2}{3a}\left[3h(h - b\sin\alpha) + b^2\sin^2\alpha - 3d(2h - b\sin\alpha - d)\right]\right\}$$

where:

	F, F_1	= factor of safety
	c'	= cohesion in kPa
	ϕ'	= friction angle in degrees
	a	= intersection width 1 (metres)
	b	= intersection width 2 (metres)
	k	= average of the horizontal to vertical stresses
	α	= seam dip in degrees
	υ	= rock density in kN/m^3
	υ_w	= water density in kN/m^3
	d	= water table depth (metres)
	h	= thickness of fresh rock (metres)

For the Ensham mining area, cohesion (c') and friction angle (φ') values of 0 kPa and 30° have been used respectively, assuming the failure mode is along joints, with some surface roughness. The roadway width is 6.5 m and the seam dip 3°.

The stress value (k) has been reduced to 1.2 for the shallower depth of cover. This value is also consistent with the in-situ stress measurements presented in Brady and Brown (2006).

The analysis has been carried out for both dry and saturated conditions.

[6] Brady, B.H.G. and Brown, E.T. (2006) Rock Mechanics in Underground Mining. 3rd Edition.

To maintain a Factor of Safety of >2 in wet conditions, at least 12 m of fresh rock is required for 6.5 m wide roadways (**Figure 3**).

Ensham technical personnel applied a conservative minimum 20 m of fresh rock for the extraction of bord and pillar panels in the southern part of the mining area. In this area, the total depth of cover including weathered rock, was 40 m.

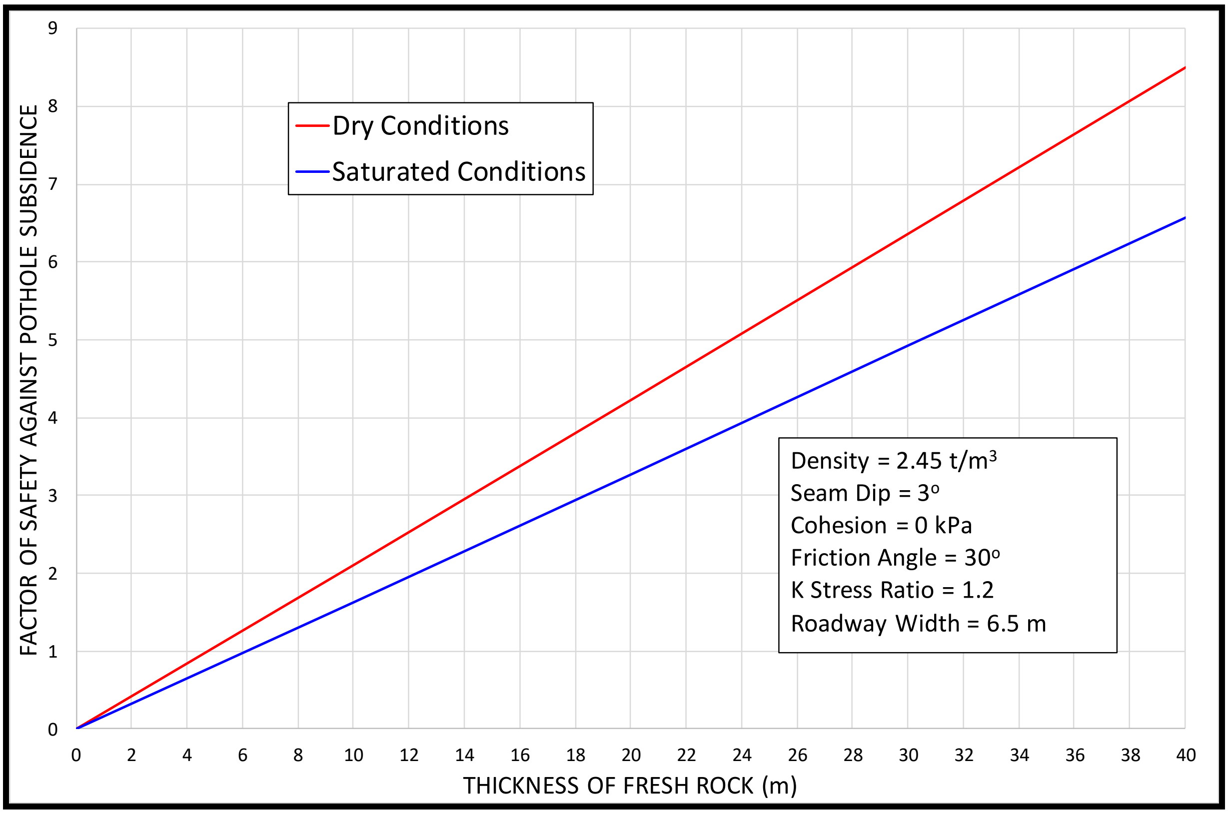

Figure 3. Limiting Equilibrium Analysis for Sinkhole Subsidence – 6.5 m Wide Roadways.

For a large intersection with an average span of 14 m, the side dimensions would be 9.9 m. In this case, the required thickness of fresh rock would approach 20 m in saturated conditions, applying a Factor of Safety of 2 (**Figure 4**). For a 15 m wide bell out, this approaches 30 m (**Figure 4**).

These calculations endorse the conservative design criteria of a minimum 40 m depth of cover and a Factor of Safety of 2 applied to the Ensham underground workings.

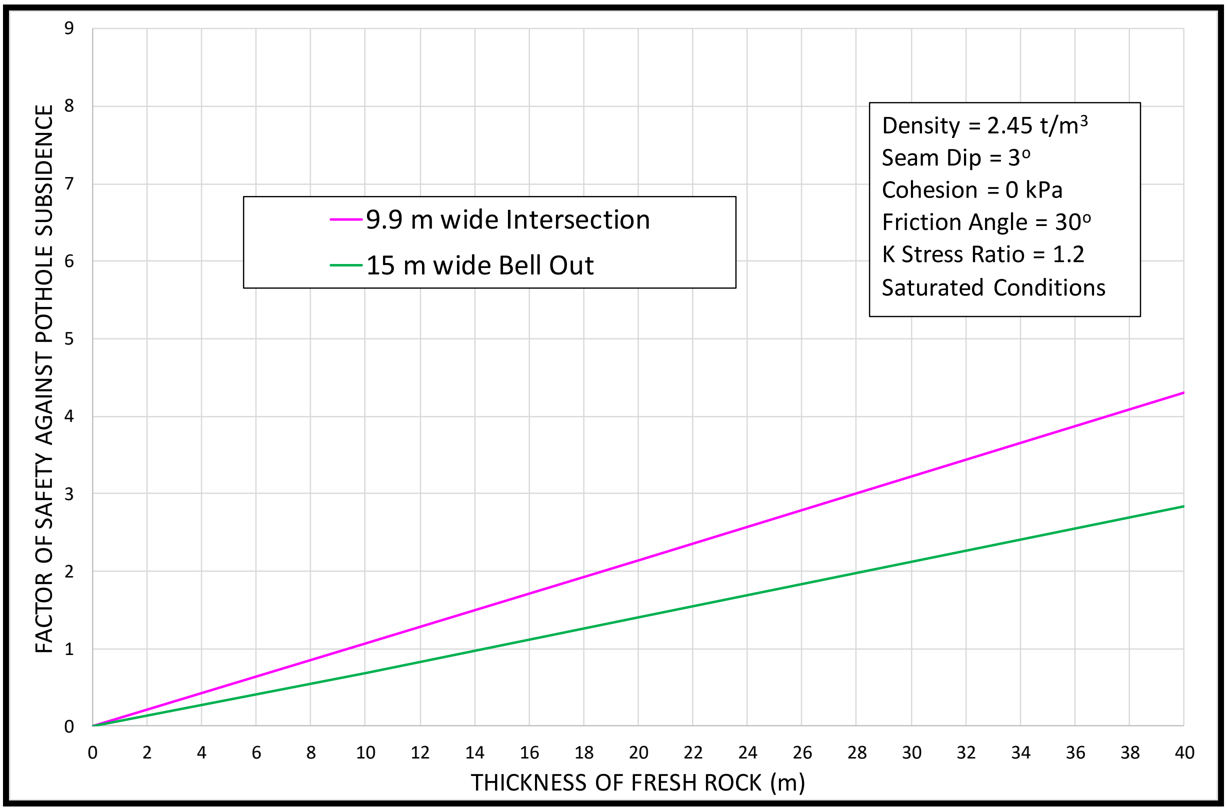

Figure 4. Limiting Equilibrium Analysis for Sinkhole Subsidence above Roadways and Bell Outs.

4 DESIGN PEER REVIEW

The mine design and sinkhole subsidence analysis presented above for the current Ensham underground workings was also technically peer reviewed by Mine Advice (2016).

In their review, Mine Advice highlighted that in the Ensham underground workings very high roof stability associated with bell-outs, which even in seam split conditions, are only influenced by skin falls rather than the development of major roof cavities into the stone above the coal seam (**Figure 2**).

Mine Advice further highlighted that the development mining process at Ensham relies on the maintenance of high levels of roof stability in unsupported plunges greater than 10 m in length in 6.5 m wide roadways. This gives a clear indication of the stabilising influence of the local geology and natural strength of the immediate roof at Ensham, considered by Whittaker and Reddish (1989) to be the key aspects in assessing the potential for sinkhole development.

The impact of very low levels of horizontal stress due to the proximity to nearby highwalls was also considered by Mine Advice. They concluded that in a competent rock mass, the significance of the low stress field is that the potential for buckling type or stress-driven roof deterioration is reduced to negligible levels. Furthermore, in a poorly jointed but competent rock mass, a low stress environment is unlikely to result in kinematic roof instability leading to sinkhole development.

In summary, Mine Advice (2016) concluded that there may be the potential to reduce the conservative fresh rock criteria of 20 m currently used at Ensham even further to as low as 10 m based on a more detailed assessment of the geological information.

5 CONCLUSIONS

Based on mining experience at shallow depths of cover in the current Ensham underground workings, as well as experience at other mining operations around the world, the risk of sinkhole subsidence occurring in the project area is considered to be negligible.

Yours truly,

N.G.Gordon.

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