Sinkhole development on mine flooding

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Abstract

The development of dropout dolines during large scale dewatering operations is a well known and well understood phenomenon. Dropout dolines form due to soil collapse into an underlying void over bedrock fissures, typically in limestone, dolomite or gypsum rocks. During the rapid dewatering of calcareous strata dropout dolines have been known to develop and are a known risk during dewatering operations, when groundwater levels are rapidly reduced in the overlying overburden, resulting in high vertical groundwater flow gradients and changes in in-situ stress conditions.

This paper presents an atypical case of the development of a dropout doline during mine flooding. Dropout dolines typically form rapidly, in a matter of minutes, collapsing into a void that has evolved over a considerably longer timeframe. The case reported in this paper is associated with a former metalliferous mining operation in Ireland where the orebody is situated within a Carboniferous dolomitic limestone host rock. Dolomitisation and mineralisation occurred during the early Carboniferous and karst development took place during the Tertiary when groundwater levels were lower and humid climate conditions allowed active karst formation. The karst features subsequently became infilled with weathered rock and sediments during the Quaternary.

The presence of karst (palaeo) was known prior to mining and a number of features were identified. No doline development was observed during mine development and operation, although dewatering was undertaken to facilitate development. Following the cessation of mining, dewatering operations ceased and groundwater levels recovered to pre-mining levels. The dropout doline is believed to have developed immediately following the recovery of groundwater levels..

In this paper the chain of causation will be explored and the remedial solution that was implemented to facilitate the continuation of the original land use will be described. The paper will conclude by identifying the risk factors that should be considered during future similar mine closure operations.

Keywords: karst, sinkhole, doline, closure.

Introduction

Limestone terrains are often known for the presence and development of karst landforms, through the dissolution of rock and the development of a well-connected underground drainage network. These landforms may be covered by allogenic sediments such as glacial till or by residual soils. A common hazard in karst terrains is the potential for the overlying soils to be transported into an underlying bedrock opening so that a void migrates progressively upwards by progressive collapse to form a dropout doline (Waltham et al 2010). In February 2014 a sinkhole or dropout doline appeared after a night over heavy rain in a field above the worked out mine. The doline was elliptical in plan, measuring ca. 13m along its long axis, ca. 8 m along its short axis and ca. 7 m in depth (Figure 1). The sinkhole was steep-sided with no bedrock visible in its walls or base, both of which were composed of sandy glacial till.

Figure 1 Sinkhole a few days after development.

Geology

The area is underlain by a sequence of partially dolomitised Lower Carboniferous limestones which was subject to extensive, but episodic, karstification during the Tertiary Period, 65.5 – 2.6 million years ago (Drew & Jones 2000 and Coxon & McCarron 2009). During the early Tertiary a karstic drainage system developed in the area, with water movement concentrated along predominantly north-northwest to south-southeast and north to south trending strike slip faults. At this location, a north-northwest to south-southeast trending fault zone, known as "The Main Fissure", was mapped underground. This sub-vertical feature pinches and swells over very short distances both along the dip and strike, with weathered areas up to 8 m wide being recorded. It is of note that the Main Fissure is situated below the doline (Figure 2) and the long axis of the doline aligns with the trend of the fissure. In contrast to the north-northwest to south-southeast and north to south trending features the east to west trending faults tend to be tight and there has been minimal water movement along these structures and hence an absence of karst development.

By the mid-Tertiary karstification had reached a depth of at least 40m in the Galmoy area and solution dolines had developed in which organic clays accumulated (Coxon & McCarron, 2009). Evidence from underground mapping indicates that karstification had developed to ca 90 m depth in some areas. During the Quaternary the climate oscillated between cold (glacial) and warm (interglacial) stages, however by the start of the Holocene, about 12,000 years ago, the area was ice free and the voids in the limestone that had formed in the Tertiary had become clogged with sediment and there was no longer any active groundwater circulation. In this area the limestone is covered by approximately 5 m of sandy glacial sediments with a well-developed clay matrix, known locally as Boulder Clay.

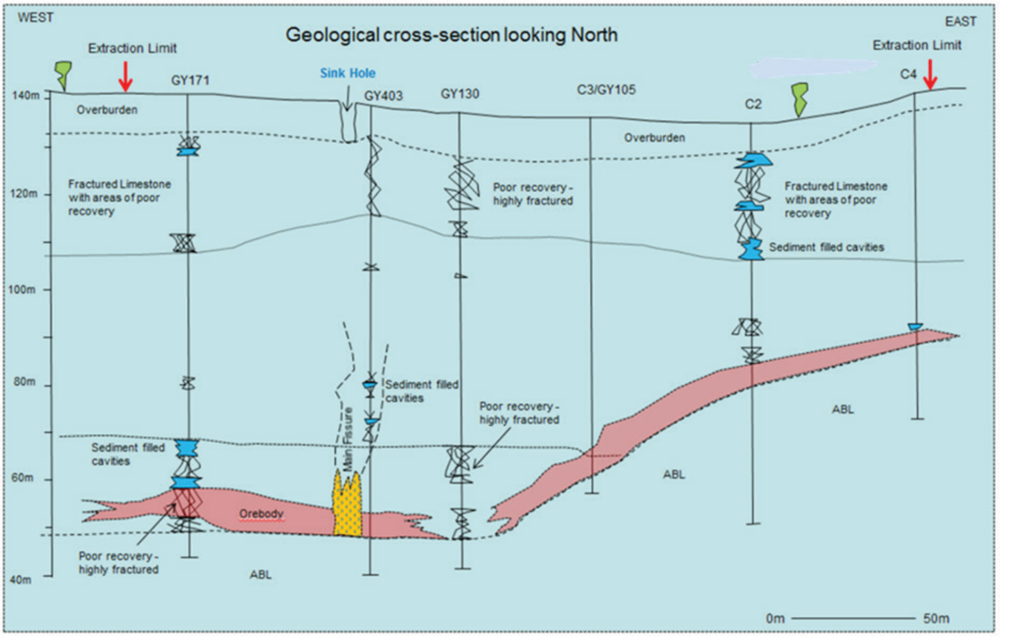

Figure 2 *Relationship between the mine workings and the sinkhole.*

Groundwater Regime

The Galmoy mining district occurs within a tightly-bounded block of Carboniferous Waulsortian dolomitised limestone (the "Galmoy Block"). All of the orebodies occur close to the southern end of the Galmoy Block, in close proximity to the east to west trending G Zone Fault Zone. During mine dewatering, the boundaries of the block acted to localise the area of drawdown, which was very well defined around the mine area. Groundwater recharge to the Galmoy Block is mostly derived from infiltration of precipitation and local runoff. Most of the block has a natural recharge of between 200 and 350 mm/year.

Dewatering, and underground mining, commenced at Galmoy in the middle of 1995. Mining continued until 2012 and dewatering ceased in 2013. The recovery of groundwater levels was rapid and the water-table had recovered to pre-mining conditions by March 2014.

Potential Mechanism of Doline Formation

Closed depressions, commonly referred to as sinkholes or dolines, are the commonest landform in karst areas. There are six broad types of sinkhole, which are described in Waltham et al (2010) and in all cases focussed vertical groundwater movement and bedrock dissolution are essential precursors to their formation.

In solution sinkholes there is dissolutional lowering of the bedrock surface with drainage focussed on a central fissure or fissures. Environmental change may lead to solution sinkholes being filled with sediment and buried sinkholes are common in Ireland. The formation of collapse sinkholes requires focussed dissolution of bedrock at depth leading to the growth of a void in the roof which ultimately fails. Cap-rock sinkholes are a special type in which the collapse propagates upwards through non-limestone cover rocks. There are two types of subsidence sinkhole, dropout and suffosion, which have a common origin. A fracture in the bedrock is enlarged by dissolution until it reaches a size sufficient for turbulent flow and the transport of sediment. Where the superficial deposits overlying the bedrock are non-cohesive, they gradually slump into the enlarged fissure forming a broadly conical suffosion sinkhole. Where the superficial deposits are cohesive the basal sediment is washed into the bedrock fissure forming a void that grows upwards from the bedrock-overburden interface to form an arch. The arch grows until a threshold is reached where it is no longer able to support the overburden and then collapses to form a dropout sinkhole with near-vertical sides.

It is considered that the sinkhole at Galmoy is a dropout doline formed due to a combination of the following factors.

- The presence of a palaeokarstic void system, the Main Fissure, which had been filled with sediment;
- Lowering of the local water-table by dewatering and intersection of the Main Fissure in the mine which together allowed the flow-path down the fissure to be reactivated. Groundwater flowed down the fissure towards the mine, taking with it some of the fissure sediment fill and opening void space within the fissure. The process was enhanced by concentration of surface drainage at the location of the Main Fissure due to a depression in the rockhead (the solid rock surface under the overburden) along the Main Fissure and an up gradient catchment associated with the Main Fissure;
- The development of open voids within the glacial till due to washout of material through fractures (i.e. palaeokarst features) in the bedrock associated with the Main Fissure; and
- Exceptional rainfall over the preceding period and infiltration, coupled with the spreading of agricultural water on the field sometime in the 24 hour period before the sinkhole appeared, which increased the weight of the overburden and acted as the trigger for collapse into the void which formed the sinkhole.

Scoping calculations of the potential for collapse of a soil voussoir arch based on the range of likely soil properties (density, thickness, cohesion, friction angle, void radius and groundwater flow velocity) at the site were undertaken using the method published by He et al (2003). The conditions were found to be consistent with a marginal stability condition, i.e. consistent with the potential for the formation of a dropout doline.

The timing for the development and formation of the doline may be considered in four stages as illustrated on Figure 3):

A. Development of palaeokarst (65.5 million to 12,000 years ago): Evidence from mid-Tertiary organic clays in buried sinkholes in the area indicates that there was an active karst at this time and it is considered likely that groundwater was circulating through the Main Fissure. There may have been subsequent periods of active karstification but by 12,000 years ago all the voids in the limestone that had formed in the Tertiary had become clogged with sediment and there was no longer any active groundwater circulation through them;

B. Pre-mining (12,000 to 20 years ago): During the Holocene there was slow groundwater flow at shallow depth through immature fissures some of which are likely to have been slightly enlarged by dissolution to form channels and conduits. The water-table would have been similar to that which it has recovered to following cessation of dewatering with very low hydraulic gradients and consequent low groundwater velocities which would have been insufficient to entrain and transport sediment. Hence, no void could have formed in the overburden at this stage;

C. During Mining: During the mining stage dewatering had the effect of lowering of the water-table and increasing the water velocity (especially during periods of recharge) giving rise to a greater washout potential. The higher velocity water flows in the Main Fissure accelerated the removal of sediment and water through this route and it is likely that voids formed in the Main Fissure allowing sediment to be moved down from the overburden and development of a void at the base of the overburden; and

D. February 2014: Upon cessation of mine related dewatering the water-table began to return to its original pre-mining stage level. Importantly, as water was no longer being removed from the mine, active circulation of groundwater ceased and the rainfall recharge gradually filled up all of the voids with a consequent steady rise in the water-table. Observations of turbid water in some wells for a short period suggests that there may have been a final phase of sediment mobilisation as the water-table approached pre-mining levels and groundwater started to flow through

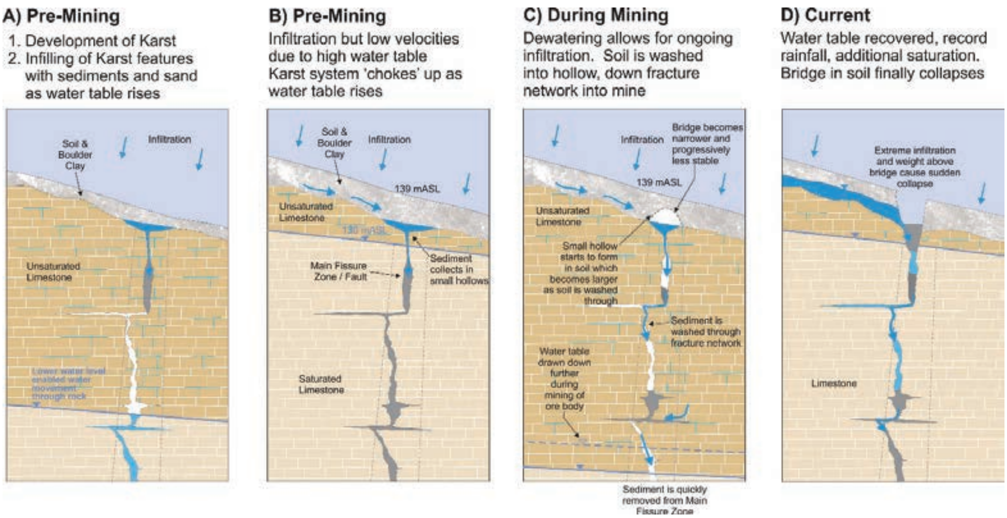

Figure 3 *Sinkhole formation mechanism.*

pre-mining paths. It is likely that the void within the overburden had grown to a size whereby the arch was close to the instability threshold. The period of heavy rain, possibly assisted by application of water to the field, increased the weight of the overburden to such an extent that the unstable arch collapsed suddenly, giving rise to a 'dropout sinkhole'.

Remediation

To remediate the sinkhole and allow the return of the field to agricultural use, a permeable plug was recommended to conserve the drainage pathway and to help alleviate the formation of further sinkholes in the vicinity. This was achieved (Figure 4) through the use of a simple bridging mechanism (≈1 m diameter boulders), over the throats between the limestone pinnacles which were exposed through excavation; the lower section comprising a permeable rip rap and ballast plug encapsulated in a geotextile. The upper section of repair entails compacted layers of rock fill/glacial till and a final capping layer of appropriate subsoil and topsoil to rehabilitate the agricultural surface.

Conclusion

The sinkhole that occurred at Galmoy can be classified as being a dropout sinkhole, most likely occurring as a result of: water infiltration into the underlying Main Fissure due to the bedrock depression above it and lowering of the water-table by mine dewatering; the washout of the sediments within the fissure zone into the mine workings; the formation of a void and voussoir arch at the base of the overburden material as the sediments were washed through; and, heavy rainfall immediately prior to the collapse that acted as the trigger for the collapse of the arch in the overburden above the void.

The particular combination of features in this instance, comprising the Main Fissure developed by enhanced weathering along a dominant north-northwest trending structure which facilitated an increased depth of karst development, created a subsurface geomorphology which concentrated flow towards and through the Main Fissure in the vicinity of the sinkhole prior to the system being choked. The Main Fissure is a unique feature within the mine and so comparable conditions are unlikely to occur elsewhere in the vicinity of the mine. This provides a unique set of circumstances that coincide at this particular location and which are not (to our knowledge) repeated elsewhere in the vicinity of the mine. It is considered that the potential of future sinkhole development in this area will remain at historical background levels.

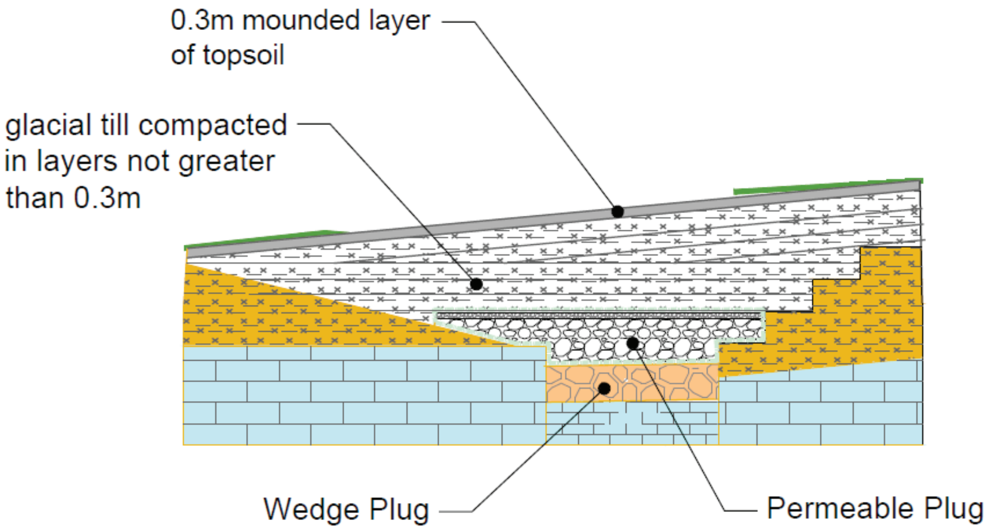

Figure 4 *Implemented approach to sinkhole remediation.*

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