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MITIGATION OF CATASTROPHIC COLLAPSE FAILURE OF ROADS CONSTRUCTED ON A KARSTIC LIMESTONE ENVIRONMENT

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Abstract: Buxton is well known around the world for its mineral water, but another aspect of Buxton that goes hand in hand with its mineral water is its karstic limestone environment. This paper concerns the redevelopment of 3.8ha of farmland for residential use and the challenges faced by that environment.

From a global perspective it can be said that the following conceptual collapse mechanisms exist within a karst environment:

- Collapse of an existing cavern within the bedrock, with the resulting void migrating to the surface;
- The limestone dissolving within the lifespan of the development, to create a cavern which subsequently collapses, with the resulting void migrating to surface;
- Erosion of the superficial deposits into cavernous limestone, which creates a sinkhole at surface. A sinkhole being defined as:
  - A funnel shaped depression in the land surface generally in a limestone region communicating with a subterranean passage developed by solution;
  - Closed depressions in the land surface that are formed by solution of near surface limestone and similar rocks and by the subsidence or collapse of overlying superficial material into underlying solution cavities.

A series of non intrusive (geo-physical) and intrusive ground investigations were undertaken in a number of phases in order to carefully characterise and construct a 3D subterranean ground model.

Once the solution features within the karstic environment were characterised, it was concluded that the most environmentally economical and sustainable way to carry out construction of the roads throughout the karstic environment was to bridge the solution features.

A high tensile, low creep geosynthetic was designed to span a 'design solution feature'. The geosynthetic was incorporated into the makeup of the roads and hardstandings to mitigate the risk of the collapse of the roads.

Keywords: anchorage length, flexible pavements, geotextile, limit state design, reinforced road, subgrade.

INTRODUCTION

This paper documents the approach taken to identify the potential for catastrophic collapse mechanisms to affect a proposed residential development in karstic limestone terrain. Particular emphasis is placed on how the identified risks were assessed and how an economic solution of incorporating a high tensile strength, geotextile, into the road makeup was adapted in order to mitigate against Ultimate Limit State (ULS) failure.

The site in question comprises a 3.8 hectare site and is situated on the outskirts of the historic market town of Buxton, Derbyshire in the United Kingdom, with the proposal to redevelop farmland into 103 residential properties. From a regional geology perspective, the site is indicated by Aitkenhead et al. (1985) as being located very close to an unconformable contact between units of the Monsal Dale Limestone of Dinantian age (Lower Carboniferous) and Millstone Grit of Namurian age (Upper Carboniferous). The development is noted as being on the edge of superficial deposits of head. Figure 1 shows the site location in context with the solid geology and Figure 2 shows the site orientation over the unconformity.

Buxton is world famous for its spring water, which is sourced from a subterranean reservoir hundreds of metres below ground level. The result of thousands of years of underground water flow is considered to be responsible for the formation of many significant cave systems in the Buxton area, one of the most famous being Poole's Cavern, situated less than half a mile to the south of the site (Figure 1). Accordingly the development required consideration with respect to the potential for karstic limestone features and underground void systems which may have consequences for the immediate and long term stability of the project or the ground water resource.

COLLAPSE MECHANISMS IN KARSTIC LIMESTONE

From a global perspective it can be said that the following conceptual collapse mechanisms exist within a karst environment:

- Collapse of an existing cavern within the bedrock, with the resulting void migrating to the surface;
- The limestone (or other susceptible bedrock) dissolving within the lifespan of the development, to create a cavern which subsequently collapses, with the resulting void migrating to surface;
- Erosion of superficial deposits into cavernous limestone, which creates a sinkhole at surface. A sinkhole being defined as:
  - A funnel shaped depression in the land surface generally in a limestone region communicating with a subterranean passage developed by solution (Glossary of Geology 1960);

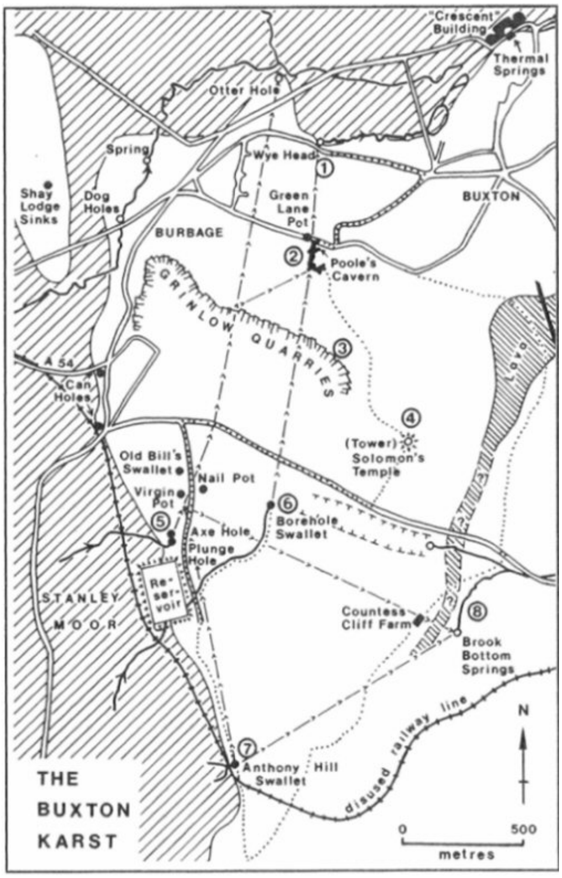

Figure 1. Illustrating the site (labelled as Otterhole) in context with the solid geology (The Namurian is indicated by diagonal hatch) and known karstic features. Taken from Ford & Gunn (1992)

- Closed depressions in the land surface that are formed by solution of near surface limestone and similar rocks and by the subsidence or collapse of overlying superficial material into underlying solution cavities.

From a development perspective, it was vital that the potential for any of the described collapse mechanisms to occur, either during construction or its 120 year design life, were identified with the associated risks established and designed out if necessary.

KARSTIC FEATURES ON SITE

Early on in the planning phase, visual evidence of a karstic environment was identified through several site visits. The most notable of which being the Otterhole Resurgence, where groundwater flowing from west to east through the pervious limestone, meets the impermeable mudstone and is forced to the surface. The resurging waters collate in Otter Hole Pool, before continuing as a stream flowing into the River Wye to the east of the site. A sinkhole termed the Resurgence Swallet was also noted to the north of the site. These features are shown in Figure 1. Other karstic features are described below.

Otterhole Resurgence Cave

To the immediate west of Otterhole Hole Pool, the surface topography is karstic in nature with notable depressions and irregular relief. Desk study searches identified that the otterhole resurgence was a recorded cave feature, which had been surveyed internally in the1960's by Derbyshire Caving Association, who typically described this small cave system as comprising a 1.5m high, 0.3m to 0.45m wide entrance point at the resurgence continuing as typically horizontal, less than 1m diameter and smooth sided conduits, which widen out in two localities, the largest comprising the "final chamber", a 7m long, 5m wide and 2m high cavity (dimensioned on Figure 2), beyond which no further access was achieved. The approximate orientation and extent of the cave system was recently surveyed during the development planning stage and the approximate extent of the final chamber with the narrow connecting conduits shown on Figure 2. This survey managed to proceed past the "final chamber" by approx. 8 linear m, through a very narrow diameter conduit which continued westwards and upstream through a further chamber, before becoming inaccessible, due to a reduction in the tube width to <0.2m.

At the time of the survey, the majority of the conduits and chambers were noted to have a typically 100mm deep and moderate water flow. The water which flows out of Otterhole Resurgence is considered to be sourced from the south west and may also be in connectivity with Stanley Moor, circa 1.5 km to the south south west of the site and

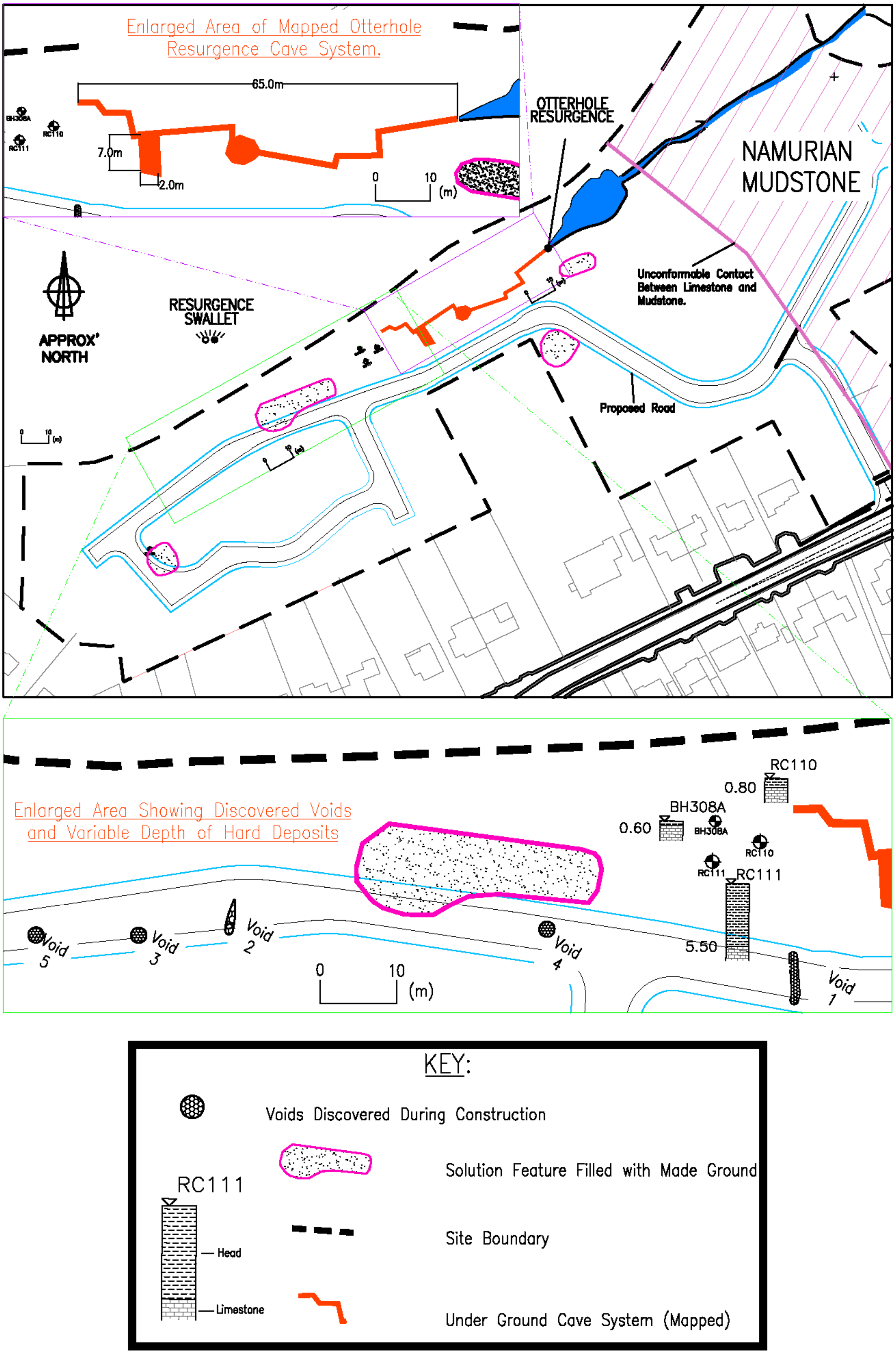

Figure 2. Site layout (proposed housing excluded for clarity) with enlarged areas showing notable items.

60m higher in elevation. A notion supported by dye testing at two sinks in Stanley Moor, proving connectivity with Otterhole Resurgence. This possible connectivity between Stanley Moor and Otterhole is illustrated in Figure 1 (Ford & Gunn (1992))

Sinkholes

In addition to the infilled sinkhole described above, anecdotal evidence (later confirmed by trial pits) suggested that other areas of the site historically had sinkhole features, subsequently backfilled with made ground. The largest of which was located adjacent to the north-western boundary and was 10m long, 4m wide and 4m deep, although no previously visible water feature was noted. The locations of these features are given in Figure 2.

SITE INVESTIGATIONS

It was considered imperative that the presence and extent of any potential voids underlying the development were thoroughly investigated in order to define the degree of risk. In this regard the site investigation was based on the following key aspects:

- The investigation of the known caves/karstic features;
- Exploration to determine the presence of further subsurface voids;
- Determination of the geometry, depth and nature of the voids.

The actual site investigation undertaken (with respect to void investigation) is summarised in Table 1.

Table 1 Site Investigation undertaken

Technique	No. Tests	Purpose
Internal Cave survey of Otterhole Resurgence	1	Investigation of existing features
Geophysical Investigation by Electrical Resistive Tomography	7 profiles between 90m and 250m	Exploration to determine the presence of further subsurface voids
Dynamic Probing	72	Determination of the geometry, depth and nature of the voids
Trial Pits / Trenches	31 / 12	
Cable Percussion Boreholes	10	
Rotary Boreholes	15	
MineCam survey	1	

Investigation of existing features

This phase involved an internal survey of Otterhole Resurgence Cave and the identification of various infilled sinkholes and was discussed in the karstic features section.

Exploration to determine the presence of further subsurface voids

A geophysical survey utilising Electrical Resistance Tomography was undertaken in order to identify potential underground voids. Seven profile lines ranging between 90 and 250m in length were used to survey the ground using both dipole-dipole and wenner configurations.

The results identified a ground profile in typical accordance with Table 2, in addition to numerous low and high resistivity anomalies. Strong anomalies were associated with the known caverns associated with Otterhole resurgence and strong anomalies were also associated with areas underlying the proposed development, which were typically concentrated in the northern area of the site and to the west of Otterhole Resurgence. Figure 3 shows the line which passed over the northern area of the site, including the otterhole resurgence caves.

A trend was identified with a number of the anomalies, with respect to these typically comprising a strong low resistivity at between 6m to 10 mbgl, with this low resistivity link extending to the ground surface, see Figure 3 as an example. It was considered that these represented infilled voids, where the infill comprised either water or clay.

It was considered likely that the Otterhole Resurgence caves comprised part of a buried network of dissolution features connected by a series of underground conduits too small for human access.

Determination of the geometry, depth and nature of the voids.

The geophysical investigation identified 37 No. anomalies which were investigated by intrusive means, as detailed in Table 1. The intrusive investigations typically proved that the majority of the anomalies were contained within the Head deposits and demonstrated a localised deepening of the soft to firm clay, which in 6 No. exploratory holes showed deposit depths increasing from the average of 2.30mbgl to up to 5.50mbgl. A key aspect with respect to this localised deepening was how abrupt this step change in clay depth occurred, a factor well illustrated in the area to the immediate west of the Otterhole Resurgence Caves, where three boreholes at centre spacing's of less than 7m, show that the clay thickness varied from 1.0m to 5.5m and back to 1.5mbgl (shown in Figure 2).

A further finding within the head deposits was the presence of a small (less then 300mm) open void in one trial pits, logged between 2.2 and 2.5mbgl and contained completely within the superficial deposits.

Investigation of anomalies within the limestone was achieved with rotary cores and identified that the anomalies typically corresponded with open fissures in the limestone, which were typically less than 100mm wide and ranged in orientation from sub vertical to sub horizontal. One exception to this was observed in a borehole (RC110 shown on Figure 2) to the immediate west of the mapped passage associated with the Otterhole Resurgence caves, which identified a void at approximately 6.0mbgl. This was subsequently investigated, through a standpipe, with a MineCam and revealed a solution feature of non uniform shape, almost ‘christmas tree’ like, with lateral ‘fingers’ extending out from a central core and of estimated diameter ranging between 0.5m to a maximum 2.0m. This feature appeared to comprise a conduit which continued laterally towards the Otterhole Resurgence.

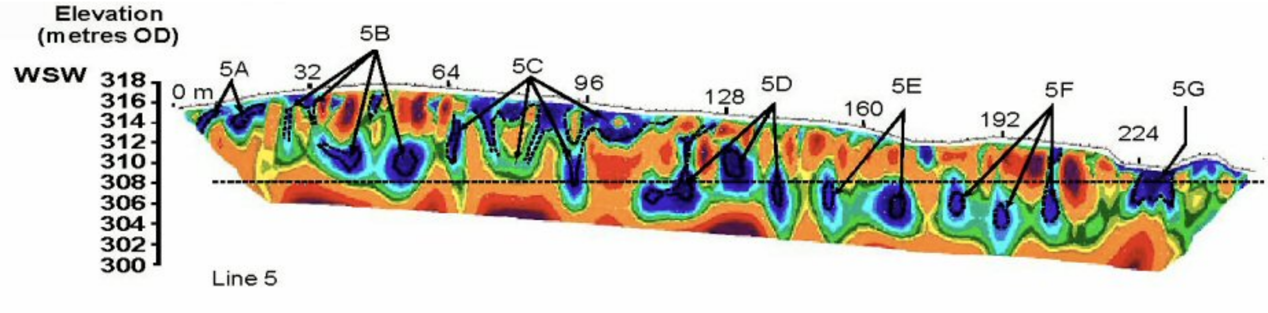

Figure 3. Example of strong low resistivity anomalies indicating likely infilled voids at 4m to 6mbgl. Anomalies 5E, 5F and 5G are associated with the Otterhole Resurgence caves).

GROUND CONDITIONS

From the site investigation it was possible to classify the typical ground conditions, as shown in Table 2,

Table 2. Summary of the typical ground conditions identified by the site investigation.

Description	**Depth (mbgl)**	**Average Strata Profile (mbgl)**
Brown slightly clayey TOPSOIL.	0.25m – 0.60m	G.L. - 0.35m
Soft to firm orange brown CLAY with occasional gravel to boulder sized fragments of limestone. (Head Deposits)	0.30m – 3.0m (locally up to 5.5m, see text for discussion)	0.35m – 2.30m
Firm brown CLAY with LIMESTONE fragments, grading into a strong LIMESTONE. (Monsal Dale Limestone)	>10.0m	2.30m – depth (base not proven)

Interpretation with respect to geology and hydrogeology

The authors consider it likely that the conduits underlying the northern area of the site and cavern features associated with Otterhole Resurgence were mainly formed by increased surface water run off associated with glacial meltwater. Aitkenhead et al. (1985) indicate that the head deposits identified at the site are of periglacial origin, associated with the Devension phase of glaciation. As such, it can be considered that the site was affected by a considerable increase in surface water runoff sourced from these meltwaters. It is postulated that some of this surface water flow found a preferential route to the groundwater, by exploiting areas of closely spaced joints (observed during the site investigation) within the blocky limestone, which over several hundreds and thousands of years of periglacial conditions, led to the formation of solution dolines (see Figure 4) opening up and then continuing as underground conduits.

It is considered that the speed and quantity of water flow over the ground surface and through the conduits will have varied considerably over time. When the prevailing conditions changed from relatively high to low energy water flow a transition from predominant dissolution / removal of blocky limestone, to deposition of head deposits from the clay sediment laden water will have resulted. A process which would gradually lead to the formation of the clay infilled voids, or buried dolines (Figure 4). The presence of a void beneath the overlying clay infill, as identified by the geo-physical investigation may suggest that some conduits continued to carry groundwater flow after surface water entry ceased. As such it was considered that some of the conduits may have been partially infilled by head deposits, only to be subsequently cleared by further groundwater flow, a scenario which may lead to the formation of dropout dolines (Figure 4).

DISCUSSION

Potential collapse mechanisms

Compilation of a ground model and hypothesis on the formation of the conduits and associated infilled voids allowed the potential collapse methods in karstic limestone to be reviewed in line with the conditions on the site and the risk of these occurring at the site to be determined.

Collapse of an existing cavern within the bedrock, with the resulting void migrating to the surface

Historically this collapse mechanism appears to have occurred on the site which explains the sinkholes infilled with made ground identified shown on Figure 2. The extensive ground investigation did not indicate that there were any significant sized caverns (where significant was deemed as being greater then a 1.0m diameter conduit) other than the chambers associated with the Otterhole Resurgence cave. As such only these chambers required consideration with respect to potential collapse of a cavern.

Guidance in Waltham et al (2005) suggests that the thickness of strata over a cavity, needs to be at least 70% of the cavity width, less than this and collapse may occur even without additional loading. As such it was considered that the chambers linked to the Otterhole Resurgence cave, having less then 3.5m strata cover, had a residual risk of collapse, although given the current relative stability of these features and the associated limited impact any collapse would have, this area was considered acceptable for Public Open Space use.

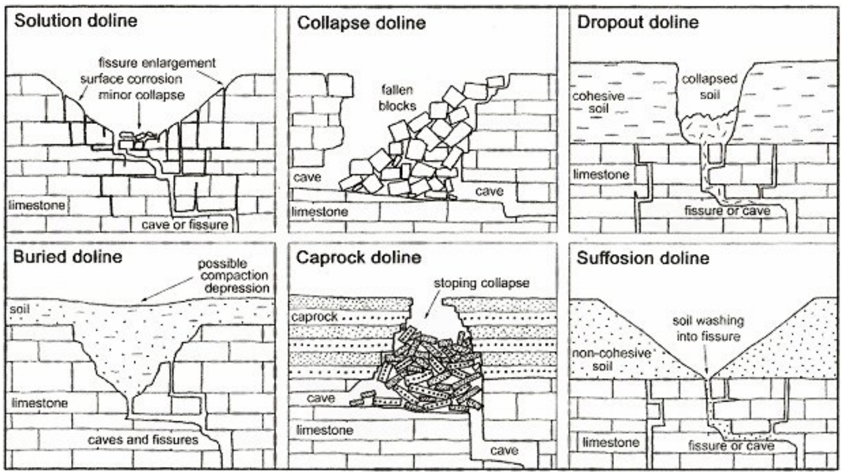

Figure 4. Diagrams illustrating the six main types of dolines (taken from Gunn 2004)

Limestone dissolving within the lifespan of the development, to create a cavern which subsequently collapses

The rate of dissolution of limestone is very low. Various authors (Waltham (1989), Sowers (1996) and Buhmann & Dreybrodt (1985)) have reported typical rates at between 30cm and 100cm per 1000 years. Therefore for a development with a design life of 120 years, the envisaged average dissolution would likely be less than 10cm. It was therefore hypothesised that the creation of a cavern which would lead to a collapse would not be possible over the lifespan of the development. Although ongoing limestone dissolution may exaggerate the erosion of superficial deposits (see below).

Erosion of superficial deposits into cavernous limestone, which creates a sinkhole at surface

The formation of sinkholes through erosion of infilled sediment and subsequent formation of a dropout doline was considered to comprise the main risk to the development. It was also considered possible, albeit low risk given the quantum of investigation, that there were voids within the ground which had not been completely infilled with head deposits, or the infill had been partially removed.

CATASTROPHIC COLLAPSE MITIGATION

In consideration of the above, it was deemed diligent to design into the development, protection against the formation of a design void, by erosion of the sediment infill, leading to catastrophic collapse of highways and building foundations. As discussion of the building foundations is beyond the scope of this paper, only the highways will be considered.

To protect the highway (layout shown on Figure 2) and cause minimum disturbance to the underground water flow regime, it was considered that the most appropriate approach was to install a geosynthetic material immediately below the road sub base. Given consideration of risk and consequence of failure versus cost, it was considered appropriate to design the highway protection based upon Ultimate Limit State failure only, i.e. catastrophic collapse, as opposed to the Serviceability Limit State. This approach would mean that in the event of a design size void opening up beneath the geosynthetic, the fabric would strain and take up the load, resulting in a surface depression. The purpose of the geosynthetic in this instance was not to permit ongoing use of the road regardless of void migration, but instead to be used as a mechanism of preventing collapse and the associated danger to the public, whilst providing a visual indicator that void migration had occurred and that treatment of the void / road repair would be required. It was deemed that a <200mm maximum surface depression should be adopted for this design approach, as this would allow the general road integrity to remain, whilst providing clear visual indication of a subterranean problem.

A woven geotextile was determined as the ideal medium, given that it gave the most economic means of facilitating the tensile strength, with the benefit that the fabric would retain the granular sub base, without addition of a further separation material, as may be required with a geogrid.

In order to determine the size of the design void the findings of the site investigation were considered. Sowers (1996) suggests that a sinkhole may have a potential diameter of approximately 2/3 the thickness of cohesive drift deposits above the fractured/karst limestone. Considering Table 2, the average thickness of the Drift deposits in the road area was 2.3m, giving a potential sinkhole diameter as 1.5m, however, it was also noted that the depth of drift locally deepened to 5.5m, which if taken as the thickness of cover then the design void size would become 3.7m, which had considerable financial implications. It was possible to rationalise the design void to a maximum diameter of 2m, which was identified as the absolute maximum size of an open conduit, considering the results of the MineCam investigation. In context with the site investigation, which had identified only one open void of 0.3m and with the <1.0m diameter conduits associated with the Otterhole Resurgence cave, this was considered appropriate.

The design of the geotextile was undertaken in accordance with BS8006. The final design requiring a geotextile with 88.4kN/m tensile strength at 6% strain, with minimum 4.5m length embedment required to prevent pull out failure.

CONSTRUCTION

Prior to commencement of the road construction, it was understood by the Client and Contractors, that even with the extensive site investigations there was potential for the highway construction and sewer installation to encounter voids during these excavation works. Accordingly during construction 5 No. voids were encountered (locations shown on Figure 2) which upon discovery, the immediate area was cordoned off until a Geotechnical Engineer could inspect them and determine the way forward.

Table 3 shows the primary dimensions of the discovered voids. A number of voids (notably 3 and 4) were only very shallow features and were simply excavated out and replaced with compacted limestone fill. Others were more substantial and required further investigation to determine the full extent. The further investigation comprised CCTV inspections, which were sufficient to identify the extent of the voids via remote photography and video, all three voids were similar in nature and considered to comprise drop out doline features. Figures 6 and 7 show a photograph of void 1 and a cross section through it. Void 1 comprised the largest cavity encountered during construction.

Table 3. Primary dimensions of voids discovered during construction

Void No	MaximumWidth (m)	Maximum Length (m)	Base depth (mbgl)	Strata void located in
1	0.8	4.5	4.0	Limestone
2	0.8	1.5	4.5	Clay
3	0.5	0.5	0.5	Limestone
4	0.5	0.5	0.5	Limestone
5	1.0	4.0	4.5	Limestone

Figure 6. Photograph of Void 1

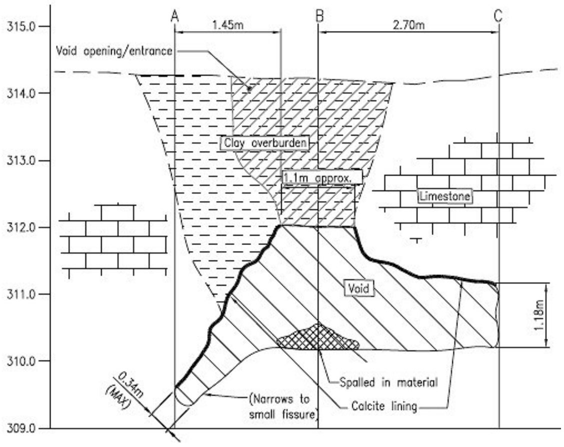

Figure 7. A section through Void 1 (viewing north to south, from left to right)

All the voids were dry and the upstream and downstream ends of the conduits were infilled with sediment, except for narrow fractures (typically less than 100mm in diameter) which appeared to continue beyond sight. These voids were backfilled with a 100mm drainage layer at the base, to permit future water flow and then a low slump concrete mix, before placement of the geotextile and then completion of the overlying road construction. A photograph of the geotextile installation is shown in Figure 8.

Figure 8. Geotextile installation under road

CONCLUSIONS

This project has demonstrated that by undertaking thorough pre-start research and appropriate site investigations, the risks towards construction in karstic terrain can be assessed. High tensile strength geotextiles provided a means of protecting the highways from the residual risk of dropout dolines. The finding of open voids during the installation works indicates regardless of how much site investigation is undertaken, there is always a risk, as was realised in this case, that small diameter voids will not be detected. In this instance the assumed design void was sufficient to account for the construction findings.

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REFERENCES

Aitkenhead, N., Chisholm, J.I., Stevenson, I.P. 1985. Geology of the country around Buxton, Leek and Bakewell – Memoir for 1:50 000 geological sheet 111 (England and Wales). National Environmental Research Council, London;

Buhmann, D., Dreybodt, W. 1985. The kinetics of calcite dissolution and precipitation in geologically relevant situations of karst areas. In Chemical geology **53** pp109-124;

BS 8006. 1995. British Standard: Code of practice for Strengthened/reinforced soils and other fills. BSI, London;

Ford, T., Gunn, J. 1992. Caves and Karst of the Peak District. 2nd edition. British Cave Research Association, London;

Glossary of Geology 1960

Gunn, J. 2004. Encyclopedia of Caves and Karst Science. Fitzroy Dearbon, London;

Sowers, G. F., 1996 Building on Sinkholes – Design and Construction of Foundations in Karst Terrain. American Society of Civil Engineers;

Waltham, A.C. 1989 Ground subsidence. Blackie & Son Ltd, New York,

Waltham, A.C., Bell, F.G., Culshaw, M. 2005. Sinkholes and Subsidence. Praxis Publishing Ltd, Chichester.