INVESTIGATION, DESIGN & CONSTRUCTION IN KARST

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Cover Photo: Karst subsidence feature, Co. Cork.

SYNOPSIS

Limestones in parts of Ireland form karst features and these can manifest as subsidence sinkholes, which are generally considered to be the principal hazard to infrastructure and building development. These hazards may appear without warning and might be triggered by changes in groundwater level, by alterations to surface water discharge, or by loading. A comprehensive desk study is an important tool in revealing evidence and risk factors for karst subsidence. Geophysics provides a cost effective means of surveying large areas of ground. Boreholes and probing should generally focus on anomalous features found in the landscape or revealed by geophysics. A risk assessment approach can be used to assess the likelihood of karst subsidence and could be used to provide a rational basis for planning and engineering design. Many engineering solutions for earthworks, drainage and structure foundations on karst have been published and case history examples of the implementation of some of these on Irish roads is described.

INTRODUCTION

The solid geology of much of Ireland is limestone, a rock that may be dissolved by the action of slightly acidic groundwater producing openings in the rock. The resulting landforms are given the general name of karst, defined as follows –

"An area of limestone or other highly soluble rock, in which the landforms are of dominantly solutional origin, and in which the drainage is usually underground in solutionally enlarged fissures and conduits' (Geological Survey of Ireland, 2000)."

The existence of karstic limestone and the development of karst-related collapse features represent hazards to building and civil engineering projects both during and following construction.

This paper draws on published guidelines, experience and methodologies from Ireland and other parts of the world where karst conditions have caused problems for infrastructure and buildings. The published work of the Geological Survey of Ireland provides a useful introduction to the limestone and karst of Ireland, and this is available as hardcopy (GSI, 2000) or from the GSI website (www.gsi.ie). The methods described have been developed for Ireland on a series of road infrastructure projects, particularly N8 Cashel to Mitchelstown.

The paper describes karst conditions in Ireland and a procedure to assess karst risk on building and civil engineering projects. Relevant ground investigation techniques are described and the importance of a thorough desk study to identify evidence that can be used to interpret karst is emphasised. Karst risk factors are identified and a possible risk assessment methodology is described. The risk assessment process can be used to identify locations requiring further investigation where the evidential record is inadequate or where further confirmation is required. The risk assessment could also be used to help demonstrate a designer's compliance with his obligations required under Health, Safety and Welfare legislation (ACEI/IEI/RIAI, 2003).

Case histories of earthworks and foundation solutions from roads projects including N8 Cashel to Mitchelstown, N7/N8 Portlaoise Motorway and N18 Ennis Bypass are described.

KARST IN IRELAND

LIMESTONES

Much of Ireland is underlain by Carboniferous limestones deposited during a major marine transgression that covered the Devonian deposits, and in Ulster, limestone was deposited during the Cretaceous period (Figure 1).

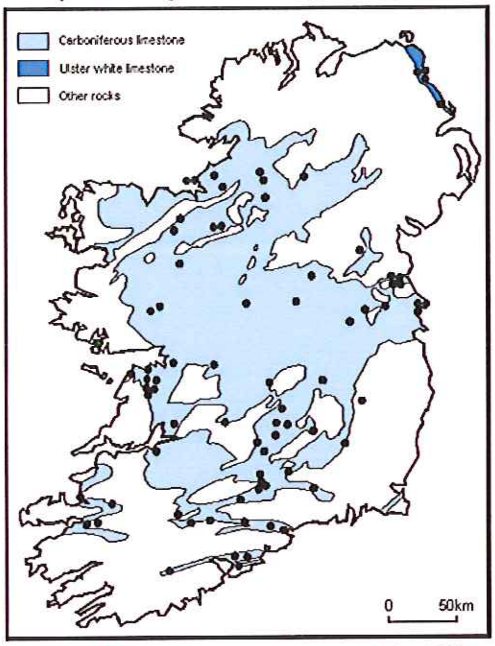


Figure 1: Extent of Limestones in Ireland (GSI, 2000)

The Geological Survey of Ireland (GSI) has described the limestones of Ireland as follows (GSI, 2000) –

"The Carboniferous limestones are normally hard and grey to black in colour, and are found in almost every part of Ireland; the Cretaceous limestone (chalk) is somewhat softer and normally white in colour and is only found in Ulster.'

"Limestones are composed mostly of calcite (calcium carbonate) or dolomite (calcium/magnesium carbonate). Some limestones are almost pure carbonate, others contain substantial proportions of other material – most commonly sand, clay (mud or shale) and chert (very fine grained silica). The non-carbonate material may be distributed throughout the rock, may occur as small nodules (especially of chert) or may be concentrated in distinct beds (most commonly, beds of shale) interbedded with the limestone.

"Limestones can be formed in several different ways and in different geological situations, usually in the sea. Many

limestones are predominantly composed of the calcareous shells or skeletons of marine organisms, but others are formed chemically by precipitation of carbonate from shallow waters. Some form in extensive horizontal layers (beds) which may be as thin as a few millimetres or as thick as several metres. Others form as massive unbedded banks or mounds of fine-grained calcareous debris (mud mounds), which can be many metres thick in the centre, thinning out towards the edges.

"Dolomitic limestones (or dolomites) are rocks which have undergone chemical changes resulting in the replacement of some of the calcium by magnesium. Magnesium carbonate (the mineral dolomite) has a different crystal structure to calcium carbonate and this creates additional void space in the rock which can enhance the development of permeability and, in some cases, karstification.

"The nature of the limestone strongly influences its susceptibility to karstification. Purer limestones are more susceptible than impure (shaly) limestones. Another strong influence is the geological structure: folding of the limestone causes fracturing and the formation of a network of fissures along which water can penetrate and begin to dissolve the rock. In general, pure limestones tend to be brittle, allowing extensive open fractures, while impure limestones tend to deform more readily, sealing up the fractures and impeding water movement. The degree of karstification is significantly reduced where there are inter-bedded shale layers which restrict water movement and where very strong deformation causes resealing of fractures with crystalline calcite."

The end of the Carboniferous period saw a time of uplift and folding, which created extensive fracturing of the limestone, and where the limestone was more brittle this allowed pathways to form for water to percolate through the rock. Rainwater is slightly acidic and this carbonic acid readily dissolves the carbonate of the limestone creating voids known variously as caves, sink-holes/swallowholes/slugaries/sluggeraghs, dolines (small to medium sized closed depression, a few metres to a few hundred metres in diameter and depth). Where the overlying soil material subsides due to an underlying sinkhole in the rock the feature is known as a subsidence sinkhole (see e.g. Waltham et al). Sinkholes function as funnels, allowing re-charge of the karstic aquifer. The resulting landforms are given the general name of karst.

KARST LANDFORMS

Work by the Geological Survey of Ireland (GSI, 2000) indicates that karst features started to develop in Ireland following the formation and subsequent uplift of the limestones at the end of the Carboniferous period some 280 million years ago. Many of these features are now buried, inert and fossilised and this 'paleokarst' or relict karst can be more difficult to identify. In places the covering of glacial soil deposits is several tens of metres thick. The author is aware of one example in Co. Sligo, where geophysics identified an anomalous zone several tens of metres in extent. This was investigated by rotary drilling and the core revealed that the anomaly was a large infilled collapse feature with pieces of limestone rock of various lithologies randomly arranged in a cemented mass. The interpretation placed on this was that a cavern had collapsed and the fallen rock had become re-cemented in situ.

These relict features may be less of a risk to a project than active karst caused by underground water flow in more recent geological times, e.g. episodes following glaciations when substantial quantities of meltwater were produced are likely to have been particularly active, or at the present. An important factor in the development of karst, particularly in the southern counties was the relative lowering of sea level, by over 60 m, which is believed to have occurred during the Tertiary and Quaternary eras of geological time. When the sea level was much lower than the land, karst solution could penetrate well below the present-day water table creating a high porosity and permeability in the limestone bed-rock. When the sea level rose to its current level, the karst voids filled with water, giving rise to highly permeable limestone aquifers.

Where drainage pathways have formed in the limestone, water will be more readily admitted. At these locations sinkholes or swallow holes may be formed, and where there are overburden soils these may be carried away by water into the limestone forming subsidence sinkholes or other features. The range of sinkhole forms has been described by e.g. Waltham et al, Sowers, and others. Anecdotal evidence from Co. Cork indicates that subsidence sinkholes are likely to be small – up to 5m across (Beese & Creed). Records from a 54ha site in Co. Cork with more than 80 individual instances of karst features included one subsidence 4.3m across, but most less than one metre diameter. However because of their unpredictable nature and possibly sudden appearance, sinkholes should be regarded as the principal hazard to civil engineering works.

Karst occurs in many countries across the world and the geological processes forming karst features have been widely studied. Of particular interest are examples of work in countries where substantial civil engineering works have been undertaken such as USA and China. However, care should be exercised in extrapolating from these studies as the mode of formation and present conditions may differ significantly. In particular glaciation of a karst landscape appears to reduce the incidence of karst subsidence (Newton, 1987).

HYDROGEOLOGY

In areas of karst geology water flow underground requires particular consideration; water flow can have a significant effect on ground conditions, and polluted water can move quickly below ground. Special care will be required to protect these features which might provide a direct pathway for pollutants to reach groundwater. For example, in locations of proposed cuttings on a road project, removal of less permeable overburden soils might make the underlying bedrock aquifer more vulnerable.

Understanding and control of drainage is important in karst areas. Inadequately controlled drainage can trigger previously dormant karst activity. For example if surface water courses are changed and water finds a new route to rock, then dormant or relic karst features might be re-activated. This is generally more likely where surface water drains down through soils above groundwater level and particularly where groundwater level is in the limestone. Conversely, thick overburden with high groundwater level should present a lower risk where runoff is discharged directly to the ground. Inadequately controlled discharge of surface water runoff that alters underground flow paths has the potential to activate new features and cause surface subsidence at new locations. Appropriate drainage design in karst areas includes redirection of natural drainage away from the newly constructed structures, sealing drains and hard surface areas, and avoiding soakaways and distribution systems.

KARST HAZARD

The existence of karstic limestone and the development of karst-related collapse features represent a hazard to projects both during and following construction. The formation of karst features in the limestone itself takes a significant length of time (dissolution rates of a few millimetres per 100 years are quoted), and it is unlikely that a new void would form in the rock or that an existing void in the rock would deteriorate to the stage of collapse solely due to karst processes within the lifetime of a development. However, the activity rate of features in the soil overburden is sufficiently great that landowners often report taking remedial measures at intervals of one to five years. These remedial measures have been reported to consist typically of filling the holes which appear at the surface. Such actions suggest active karst and might indicate existing man interference via e.g. groundwater abstraction. Activation of such subsidence sinkholes generally represents the greatest risk from karst to building and civil engineering projects.

Waltham et al have described two modes of subsidence sinkhole formation based on the two end members of morphologies – suffusion in perfectly cohesionless soils and drop-out in cohesive soils. Real conditions are likely to be more complex.

Suffosion sinkholes form from the top down typically in sandy soils where sand is gradually washed down by flowing water into an enlarged fissure in the rock.

Figure 2: Surface depression, indicator of karst subsidence, several 10s of metres (Co. Tipperary)

The features tend to appear as relatively shallow saucer-shaped depressions. Such features are often visible in the landscape (Figure 2). They may be active or might have been formed historically under different hydrogeological conditions. In some locations depressions are water filled, while others are dry following periods of wet weather. Wet depressions may be seasonal, might be maintained by high groundwater level, or by poor drainage relative to the rate of recharge. Dry depressions suggest good drainage and this might indicate activity. Where these features form in entirely sandy soil profiles, it would be unlikely for there to be cavities.

Drop-out sinkholes (Figure 3) form from the bottom up in cohesive soils or damp sandy soils which can support themselves across a cavity. The cavity initiates at the rock surface and as more material is eroded the cavity enlarges and works its way towards the surface. Under natural

conditions, where groundwater conditions are in equilibrium, it is thought this process might take hundreds or thousands of years. Where man interferes the process can be significantly accelerated, occurring within days or weeks of the interference, and inactive features can become active. It is possible that microgravity anomalies identified in the soil profile are such features. These features might be active or might have been formed historically under different hydrogeological conditions. Where they exist they can potentially become active when groundwater conditions are changed. They may be up to 50m across and 10m deep, though most Irish examples are smaller.

Typically Irish glacial soils are described as cohesive, but will often include more permeable, sandy features, while the cohesive matrix will contain a proportion of silt and sand. It is reasonable to expect such a combination to be susceptible to both suffusion and drop-out.

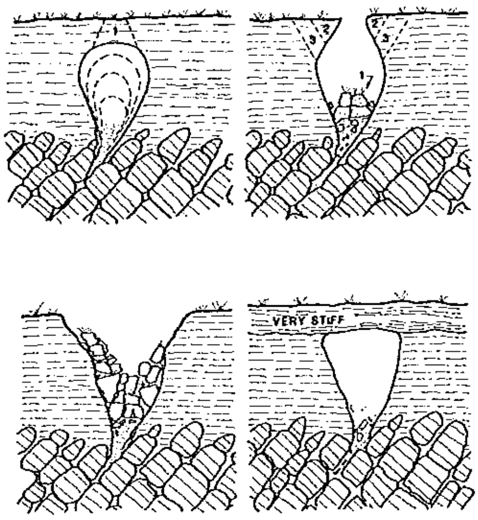


Figure 3: Development of drop-out subsidence sinkhole, showing initial drop-out (1), subsequent collapse (2, 3) & final collapse with debris infill, and effect of stiff surface soil (after Sowers)

The processes by which an existing cavity might develop more rapidly following the interference of man can be described under the following headings –

1) Increased water flow causes soil erosion at a greater rate. Lowering groundwater levels from above to below rockhead will increase the water pressure gradient and increase the flow of water from soil overburden into rock and this would be likely to accelerate the formation of subsidence sinkholes. This may initiate new drop-outs and activate existing features. This is thought to be the cause of most subsidence sinkholes. It will always be combined with (2).

2) Existing water-filled cavities in soil are partly supported by the buoyancy of the water. When the water table in the soil is lowered, effective stresses loading the soil arch increase and the support from water pressure is lost; this might result in collapse where the soil arch can not support the extra load. This process will occur on its own where the water table is lowered within the soil, and it might be combined with (1).

3) Erection of a structure (e.g. structure or highway embankment) or heavy construction plant increases the load on the ground. Where the loaded area includes a cavity the soil arch may be overloaded and collapse.

4) Diversion of surface water drainage will change sub-surface drainage conditions. Where surface water is concentrated to a greater degree than at present, and finds a new drainage pathway to rock, perhaps through an existing cavity or more permeable material within the till, then the flowing water may produce collapse of the cavity or initiate a new cavity. This process is largely confined to the zone above the present water table in soils and where the water table is at shallow depth the effect is likely to be limited.

Man interference accelerating the formation of drop-outs can be divided into two categories –

i. Groundwater lowering – this occurs when –
   - water is abstracted for public/private supply,
   - when groundwater is lowered in a quarry,
   - when groundwater is lowered at and adjacent to an excavation (cutting) as part of road or building basement construction.

ii. Construction –
   - which increases the load on the ground causing collapse when the ground with a cavity can not support the load – structures and earthworks structures (embankments), construction plant (particularly in cuttings where cover to cavities might be reduced);
   - where existing surface water drainage is altered and the downward percolation of water takes new pathways – leakage from drainage ditches, services trenches, areas of stripped topsoil.

Predicting exactly when and where collapse will occur is nearly impossible, as an existing cavity might not be affected while a completely new one might be initiated. However by assembling information that might be interpreted as indicating different facets of subsidence formation a risk assessment can be undertaken.

KARST INVESTIGATION TECHNIQUES

DESK STUDY

This is likely to provide the best source of information and is an essential part of any investigation where karst is suspected. It is also a requirement of IS EN 1997-1 (Eurocode 7). As a minimum the following data sources should be collated for use in a desk study –

- GSI memoirs and 1: 100,000 geological sheets;
- 1: 50,000 Discovery Series Sheets, place names;
- GSI, 6 inch: 1 mile geological mapping sheets, typically dating from late 19th century, and more recently issued Quaternary mapping;
- Aerial photographs;
- The Karst of Ireland. Limestone landscape, caves and groundwater drainage systems (Geological Survey of Ireland, 2000);
- Geological Survey of Ireland Karst Database;
- Other literature sources, e.g. 'Mitchelstown Cave – one of Europe's major caves – its discovery and history', 'The caves of Ireland', by J.C. Coleman, Anvil Books Ltd, 1965;
- Information from landowners.

These sources should be supplemented with aerial photography where this is available, and/or a walkover of the site to examine topographical features. Many topographical features can be slight in nature but all should be collated.

An example of karst subsidence hazard that occurred during works on the original N8 is described below. In 1993 subsidence occurred on the central median of the old N8 approximately 200m west of Skeheenaranky. The collapse occurred as the existing road was being improved and a shallow excavation was carried out (300m in length). The size of the collapse was approximately 3m in width and 6m in depth. Following the collapse investigations including boreholes and geophysics were carried out from the county boundary to the school in Skeheenaranky. The 300m long section where the existing road was to be excavated was investigated in particular. Drilling (eight boreholes) confirmed limestone bedrock at 25m to 49m depth, with an average depth of around 35m. Possible voids within the bedrock, identified by low core recoveries, were found in all boreholes except one. Superficial deposits appeared to comprise mainly 'hard brown gravely sandy clay', with some layers of sand and gravel. However overlying bedrock the soil was described as 'soft brown gravely sandy clay'; boreholes were formed by 'diamond drilling', assumed to describe rotary coring. No problems were encountered elsewhere during the improvement works. Grouting was attempted to fill the voids but without success, possibly suggesting substantial voids, or that grout was washed away by moving groundwater. The remedial works adopted at the location of the collapse was to build a bridge spanning 10m across the void. The collapse has been attributed to a karst-related feature known as a subsidence sinkhole. Although the exact cause of the collapse could not be determined, an 'underground stream' at the location of the collapse may be an explanation (personal communication Michael O'Malley/Petra Roche-Perks, January 2005). The River Funsion runs west of the area in question and there are signs of a stream or springs appearing on the south side of the existing N8. It is noted that from Funsion River to Sheep River (2.5km) there are no streams running from the Galty Mountains across the road, and drainage maybe underground.

The results of the walkover should be collated with the desk study and interpreted aerial photography data, and in the context of highway projects employing HD22 they will form the basis of the Preliminary Sources Study. Upon completion of this process geophysics and invasive investigations should be considered.

GEOPHYSICAL SURVEYS

Geophysical surveying allows large areas of ground to be investigated at relatively modest cost, and because of this provides significant advantages in investigating for karst. By comparison, conventional ground investigation techniques – boreholes, trial pits, probing, etc. – investigate minute volumes of ground, and their use in the initial stages of karst investigation is of limited value.

Geophysical investigations provide data for two aspects of karst investigation –

(i) They provide a simple means of identifying rock head, which may be a factor influencing karst risk.

(ii) They identify anomalous conditions, i.e. ground that is different to its surroundings which might indicate the presence of karst subsidence.

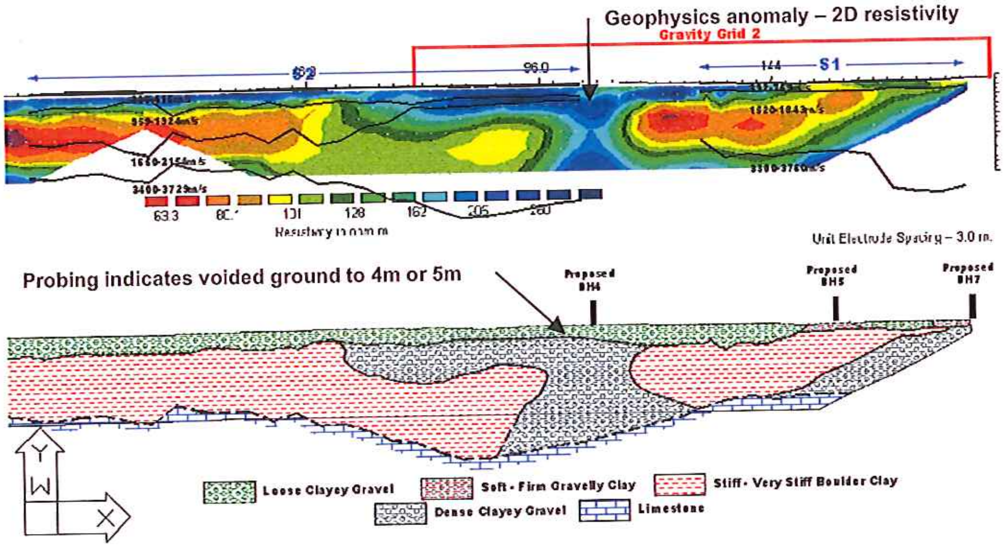


Figure 4: ERT profile across subsidence feature (N8 Cashel – Mitchelstown)

A variety of geophysical methods can be used and generally the advice of a specialist should be sought. Some techniques include –

2-D electrical resistivity (ERT) surveys are excellent at mapping soil and rock type, and will identify rockhead, which is an important initial step (Figure 4). It can provide an indication of weathered/karstified limestone but is unlikely to identify individual cavities.

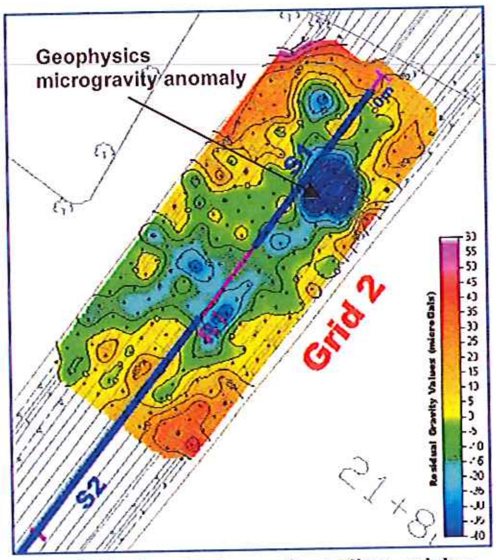


Figure 5: Contoured microgravity readings, red=low, blue=high (N8 Cashel – Mitchelstown)

Surface seismic surveys measure the velocity of seismic waves through the ground and these can be correlated with density and stiffness, allowing interpretation of voids or loose/weak soils.

Microgravity surveying will identify zones of low density, e.g. voids, and has good depth range. Cavity size can be modeled, but zones of varying soil thickness might be misinterpreted as cavities. It will be expensive for large areas.

An example of a microgravity survey of a karst feature on the route of the N8 in Co. Tipperary in Figure 5 with zones of low readings (red) and high readings (blue). A borehole in the low zone encountered solution weathered limestone with clay infill at depth, while adjacent GI encountered good quality limestone at shallow depth.

Ground probing radar records the reflected electromagnetic signal from boundaries between different material types and can resolve even small cavities, but is very limited by clayey soil cover and has limited depth range.

Note that geophysical anomalies may have different interpretations, and for example, microgravity anomalies may not necessarily be cavities and might be non-hazardous zones of lower density soil and an assumption regarding the void filling (air/water) will need to be made.

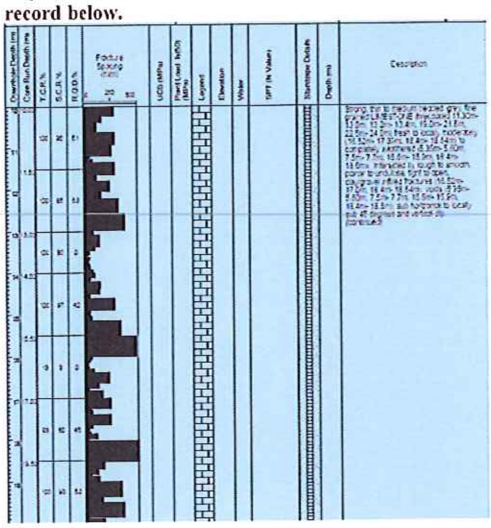
An example of an ERT profile across the same area of subsidence as the microgravity feature in Figure 5 on the route of the N8 in Co. Tipperary is shown in Figure 4.

Subsequent probing indicated soft/loose/voided ground to a depth of 4m to 5m. The ERT shows the infill in green and blue over a much wider and deeper zone of bedrock depression and clay infill associated with weathering of the underlying limestone. The excavation of the soft ground is shown in Figure 8.

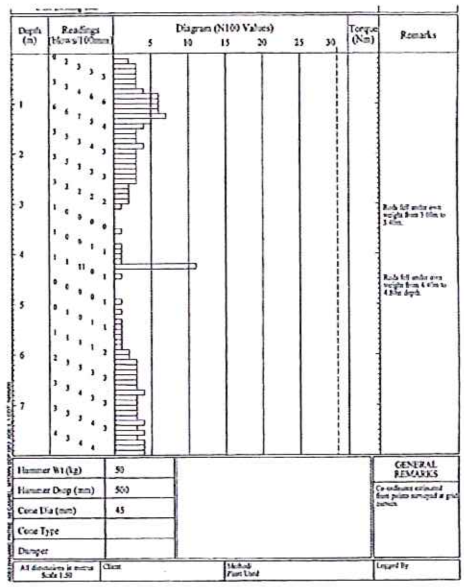
CONVENTIONAL INVASIVE TECHNIQUES

Conventional investigations should be designed to systematically investigate geophysical anomalies and other features identified from the desk study and geophysics, as well as providing more general information regarding soil and rock conditions. Generally, it is unlikely that vertical boreholes located following conventional principles will encounter essentially vertical sinkholes by chance. Substantial evidence of karst is unlikely to be confirmed without the focus provided by earlier work.

Figure 6: Rotary core showing brecciated rock and clay infill (a) core photographs above, (b) borehole record below.



Rotary coring is necessary to confirm rockhead interpreted from geophysics and to provide evidence of karstification of the rock (Figure 6), though this is often indicated by poor core recovery and care must be taken if soft infilling sediments are to be recovered.



counts and suggesting voided soil.

Cable tool boring will provide general soil profiles and unusually low SPT blowcounts might be indicative of karst subsidence. Waltham et al report that in Florida ravelling is indicated by continuous vertical zones with N ≤ 2 in cohesive soils, or N ≤ 4 in granular soils. These values might be correlated with dynamic probe blow counts, and such probing could provide a more cost effective alternative to boreholes (Figure 7).

Experience in Ireland, where many tills are stony, indicates these techniques might be of limited use. Cobbles and boulders will always prevent probing and backfilled subsidences may not be easy to probe. However all instances of probes or SPT tools falling under their own weight warrant further consideration and can be considered indicators of subsidence. It is emphasised that any anomalous observation that might indicate a karst feature must be considered. Low or zero SPT N-values within otherwise firm or stiff cohesive till should be assumed to represent voids. Incremental blow counts should always be reported as required by IS EN 22476-3:2005 for SPTs, and IS EN 22476-2:2005 for dynamic probes. It will be easier to identify voids when SPT blow counts are recorded for each 75mm or 100mm as previously required by BS1377.

Trial pitting provides the clearest means of investigating near surface incidence of karst subsidence or possible sinkholes (Figure 8). It includes a larger volume of ground, allows collapse debris to be examined and the

nature of the subsidence to be investigated. Undertaken as part of the construction work it allows soft or loose infill to be removed and replaced with more competent fill material.

Figure 8: Trial pit investigation of subsidence sinkhole, showing soft organic infill (Co. Tipperary)

KARST RISK ASSESSMENT

BASIS FOR RISK ASSESSMENT

During the design process all the collected data should be considered and the implications of karst on the proposed development should be studied using a risk assessment approach; the level of acceptable risk might increase with decreasing sensitivity of a structure, and the subsequent investigation and site works should be designed and performed accordingly. Clayton (2001) has described how geotechnical risk can be managed and it is suggested that all ground investigation can be useful seen in this context. In simple terms a ground investigation might provide the data to select the foundation concept for a structure, or to assess how much excavated soil and rock might be used as engineering fill. Karst subsidence is more difficult to assess and it can be difficult to reach definitive conclusions. Presently even the hazard posed by karst subsidence in Ireland is unclear. An incident occurred on the N8 at Skeenarinky, Co. Tipperary in the early 1990s which could be considered a near miss, while there are many unrecorded incidents of subsidence in rural areas, which cause no damage. Karst is a factor considered in design in Cork, Limerick and Tralee, but in the absence of significant development the risk in other areas is unknown.

The risk assessment approach has the value of allowing decisions to be made by collecting and considering a wide range of relevant data using a rational framework.

The first step in the investigation of sites where karst is a potential problem is to collect available data related to karst as part of the ground investigation process. The initial phase of this work is a desk study. This is generally regarded to be the most cost effective part of ground investigation and is an established element of good practice (BS 5930:1999; IS EN 1997-1:2004, Clayton, 2001; NRA DMRB HA34 and HA22; Site Investigation Steering Group, 1993). Collation of desk study data should continue throughout the design process.

The desk study provides essentially information regarding the ground in the region. The information obtained from the desk study will allow the design of site specific ground investigations. Unlike others countries with karst (see e.g. Carroll County Water Resource Management Manual and Ordinance (CCWRM) 2000, or UK Planning Policy Guidance PPG14 for development on unstable ground (UK DoE, 1990, DTLR, 2002)), Ireland has no specific regulatory requirements regarding development in karst regions, and no specific programme of investigative works is recommended. However, GSI (2000) provides a list of desk study sources and recommends that, following a desk study, the ground investigation should include, inter alia, geophysical surveys, trial pitting, rotary percussive boreholes (boreholes that produce no core but which should identify cavities), rotary cored boreholes (to produce rock core), down-the-hole logging using various geophysical and other techniques, and in-situ testing.

From a review of relevant geotechnical codes of practice and other references the following can be learned –

IS EN 1997-1:2004 (Eurocode 7) requires that the detailed specification of the design situation should include 'caves and other underground structures', and 'solution cavities, such as swallow holes or fissures filled with soft material, and continuing solution processes' (2.2(2)). This requires that these features are identified prior to undertaking detailed design. The code also requires that design investigations shall be carried out to provide information for an adequate design, to plan construction and to identify difficulties, and particular attention should be paid to natural or man-made cavities. It is a further requirement that existing groundwater levels shall be established during the investigation (3.2.3(1) to (9)). No specific programme of investigative works is recommended, however IS EN 1997-2:2007 includes a section on planning of ground investigations, though again without specific recommendations for investigating karst.

BS5930:1999 gives no recommendations for a specific programme of investigative works in karst areas.

BS8004: BS8004:1986 notes that ground movement independent of applied foundation loads may be caused by

solution of the ground by percolating water, but provide no guidance on investigations or design solutions.

Tomlinson (7th edition, 2001) suggests that karstic conditions comprising pinnacles and promontories of strong limestone surrounded by soil-filled joints might best be investigated with trenching supplemented by probing with non-coring drilling.

Wylie (2nd edition, 1999) notes that identifying karst solution features requires integration of a range of techniques, principally desk study activities such as researching past experience, collecting historical records, viewing aerial photographs and walkover, with geophysics and drilling. The need to select appropriate geophysical methods and their limitations are discussed.

From the above it can be seen that there are limited specific recommendations for ground investigation prior to undertaking civil engineering works in karst regions of Ireland. Waltham et al (2005) have presented recommendations for investigating karst areas based on wide experience in the field. In addition to desk study, they suggest a combination of geophysical techniques with invasive work to validate and confirm geophysics findings. This might be regarded as normal good practice for ground investigation in Ireland.

The data collected from investigations is used as the factual basis for a risk assessment. The factors described below can be considered, though the relative importance is likely to vary from project to project. For Ireland, it has not been possible to assess which factors are most significant, and further work collating data from a number of projects in different karst regions is needed.

The risk from karst to construction projects has been studied in Ireland (e.g. Beese and Creed) and around the world (e.g. Waltham et al, Newton.), and these studies have suggested risk factors though evidence can be complex and in cases contradictory. One factor upon which authorities are agreed however are the roles of groundwater lowering and surface water drainage in causing karst related subsidence.

RISK FACTORS – GROUNDWATER AND DRAINAGE

Most subsidence sinkholes appear to be caused by lowering groundwater, and the incidence of such features appears more pronounced when groundwater level is lowered below rockhead. This process is probably caused by increased effective stresses and reduced buoyant support of the soil arch, together with surface water flowing down through the soil along preferential pathways whose location is determined by underlying local fissures in limestone rockhead that allow water flow into subsurface drainage channels. Flowing water may preferentially flow through more permeable soils and can cause seepage erosion particularly where hydraulic gradients are higher where water flows out of soil and into a fissure in rock. It might be noted that groundwater may not flow vertically through the soil. Lowered groundwater is likely to occur e.g. where cuttings are formed taking the road below the original rockhead profile. Locations affected in this way should be considered generally to be 'high' karst risk locations. An essential component of any investigation for karst is to monitor groundwater levels both in rock and superficial soils, and this monitoring should continue for at least a full annual cycle.

Another significant factor in causing subsidence sinkholes is collection and disposal of surface water, where this is allowed to discharge through the soil to a water table at depth. It is recommended that design of drainage addresses this risk and the mitigation measures will likely vary depending on the assessed karst risk. Risk factors relating to groundwater and drainage can generally most easily be managed during the design and construction process.

RISK FACTORS – GEOLOGY

New subsidence sinkholes might develop naturally without construction activity taking place, and as a first approximation it is considered that the following factors are considered to assess karst risk for a project. These risk factors relate to the geology and ground conditions and include the nature of the underlying rock and its structure, and the depth and type of overlying soils (Waltham et al, 2005). These factors can be used to assess karst risk to a proposed scheme and will allow specific risk mitigation measures to be included in the design, and during construction.

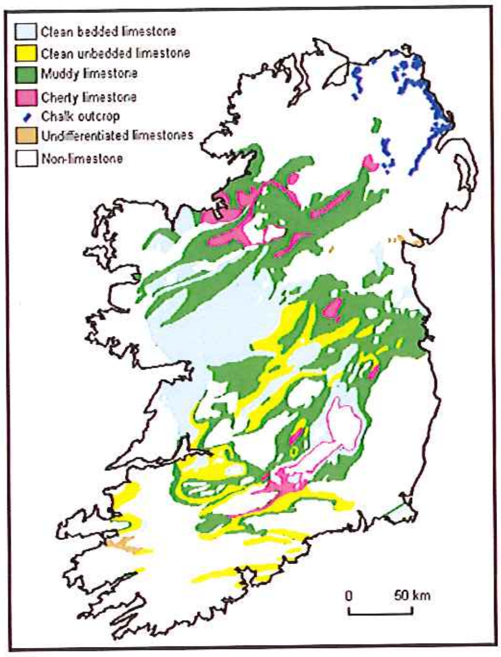


Figure 9: Geology of Ireland showing pure & impure limestones (GSI, 2000).

The following geological risk factors have been suggested in the literature –

Rock type – pure limestone are more brittle than impure limestones (comprising argillaceous limestones and containing layers of mudstones etc), and more prone to fracturing allowing the development of solution enlarged drainage channels. Evidence from the GSI karst database suggests karst features are twice as common on pure limestones as on other limestone types. One approach would be to rank these risk factors, so in the Irish context have the highest risk ranking, impure limestones would have a lower risk ranking and non-soluble rocks a zero ranking (Figure 9). Hence non-carbonate rocks will generate a zero karst risk. Information can be taken from GSI mapping, and supplemented with borehole data when this is available.

Rock structure – the presence of a boundary of limestone with an impermeable rock makes karst development more likely because there would be no subsurface flow in the impermeable rock. Relatively impermeable rock might be defined as non-carbonate rocks, and where such a boundary occurs within the project it should be included in the assessment. For risk ranking, an adjacent boundary with a non-carbonate rock should be given a higher risk rating, while the absence of a boundary would generate no additional risk. Hence only boundaries will enhance karst risk. Information can be taken from GSI mapping (Figure 10).

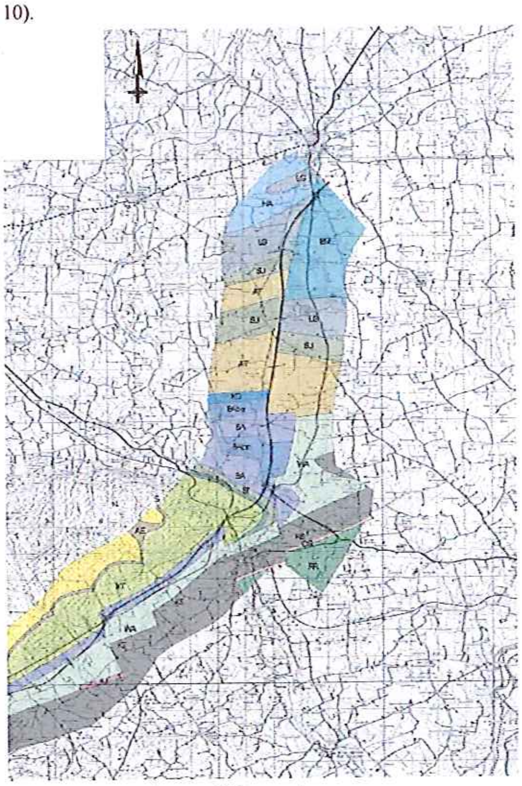


Figure 10: Faulting on GSI mapping

Depth of overburden – evidence indicates subsidence sinkholes are more likely to form where the depth of overburden is small and that where the depth of overburden is great (more then 60m to 100m) they are rare. The depth ranges can be assessed based on geophysics or after borehole investigations have been completed and rock head has been proved. The depth ranges considered in this part of the assessment might usefully be related to the typical depth of ground investigation exploratory holes, say 20m. Evidence suggests that most sinkholes form where cover is less than 5m, and this depth range could be given the highest risk rating; where rock has been found at 5m to 20m depth a lower ranking would be allocated, and where rock is at greater than 20m or no rock has been identified in a borehole to this depth, the lowest ranking is applied. It should be noted that collapses have occurred where cover to rock was 25m to 50m.

Figure 11: Active Subsidence Sinkhole (Co. Tipperary) from walkover (extent outlined, note infilling & cracking at right centre)

Type of overburden – this seems to determine the form of subsidence feature rather than the likelihood of occurrence; sandy soils tend to migrate downwards (suffosion) into the rock gradually forming a saucer-shaped depression, while soils with cohesive soils (and this may include damp sandy soils) are more likely to fail unexpectedly forming so-called drop-out sinkholes. It is suggested that a low ranking be applied where only sandy soils are found above rockhead, with a higher ranking for mixed and/or cohesive soils. Typically for most parts of Ireland, there are few areas of purely sandy soil and most soil overburden will be either cohesive till (boulder clay) or mixed till and glacial sands/gravels.

Ground relief is also thought to influence development of karst (Waltham et al), with low incidence of subsidence in areas of higher relief compared to valleys. An explanation might be that valleys form over more erodable, karstified limestones, where subsidence is more likely, while hills are formed by more resistant limestones.

RISK FACTORS – FIELD EVIDENCE

In addition to the geological factors described above, field evidence should also be considered. For karst in Ireland the following sources are suggested –

- GSI Karst database;
- API interpretation;
- Walkover survey;
- Local or anecdotal evidence, place names.
- Geophysical surveys;

The GSI Karst Database is an inventory of karst features known to GSI, i.e. those identified by field mapping or reported, but is not comprehensive. Data was compiled from a variety of sources including maps, literature, and company records, and it can be regarded as a record of previous field investigations. The database should be queried and features from it included in the assessment.

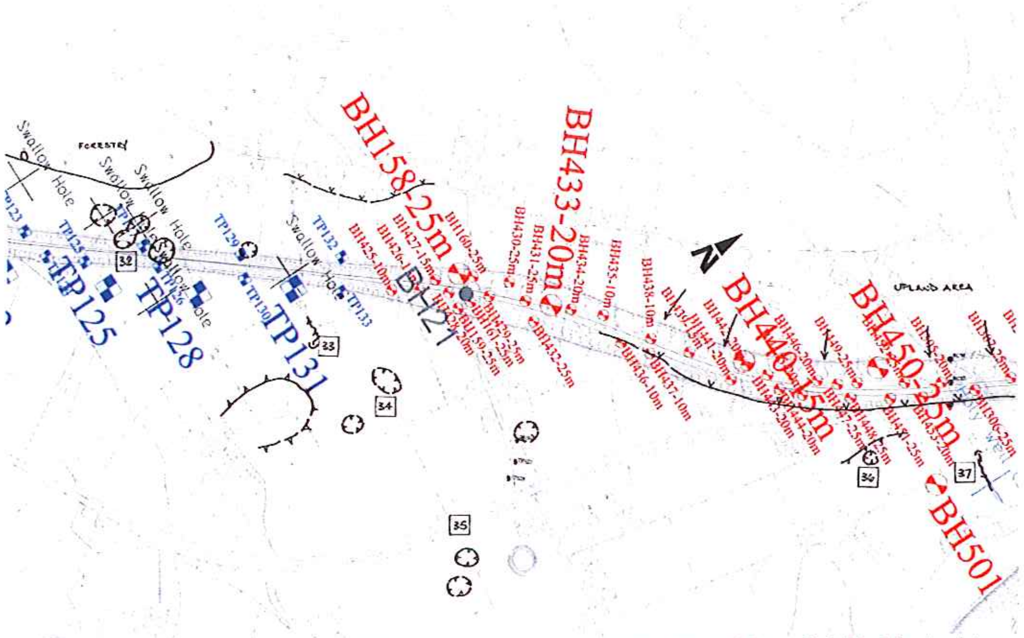


Figure 12: Plans with GSI database and API/walkover features.

Stereographic pairs of aerial photographs allow surface topography to be viewed in three dimensions and landforms to be interpreted. In particular changes in surface slope produced by depressions and ridges are accentuated. In the present context, subsidence sinkholes are interpreted to appear as depressions some tens of metres across and a few metres deep; these features are clearly revealed by aerial photographic interpretation (API), and all such depressions should generally be interpreted as subsidence sinkholes in the first instance. API might also reveal the presence of dry valleys (valley shaped features apparently formed by watercourses, but where there is no watercourse present), which are characteristic of karst regions, and which may also be identified from large scale topographical mapping.

A walkover survey of the project area should be undertaken following the desk study and API. These studies will identify locations of interest which require further more detailed examination, and when time is limited these can be prioritised. The features identified should be plotted on site plans and might usefully be photographed, particularly where there is evidence of activity (Figure 11).

The following information on place names has been taken directly from 'The Karst of Ireland', (GSI, 2000), which references extracts from 'The Origin and History of Irish Names of Places' (by P.W. Joyce. Published by Appletree Press), and provides the following definitions for Irish in place names, which may be indicators of karst features.

'*Poll*: a hole of any kind. Topographically it is applied to holes, pits or caverns in the earth, deep small pools of water, very deep spots in rivers or lakes, etc. In the beginning of anglicised names it is always made *Poll*, *Poul*, or *Pull*, and as a termination it is commonly changed to *Foyle*, *phuill*, *phull* by aspiration of the 'P', and by the genitive inflexion. Diminutives: *Pullen, Polaun, Polleens, Pollagh, Pullagh*.

'There are several words for a cave: *poll, polltalmhan* (poultaloon), *dearc* (derrig) or *derc* (a cave or grotto), *cuas* (anglicisations: *Coos, Coose, Cose, Cous, Couse*). Sometimes the 'C', is changed to 'H', e.g. *Hoosh*. Diminutives: *Coosan, Coosane, Coosaun, Coosheen*. In addition: *Uagh, Uaimh* (genitive: *Uamha, Uamhain*) and *Uath* are very common, the latter denoting an occurrence in a cave. Anglicisations: *Nahoe, Nahoo, Nahoova, Nahone, Nahoon, Oovan, Owen* (occasionally).

'Indications of water are numerous: *Uisce*, anglicised to *Iska, Isky, and Isk. Turlough*: dried lake. *Tobar, Tiobrad:* well (*Tober, Tipper, Tubber, Tubbrid*). *Uaran, Fuaran*: fresh or cold water springing from the earth (*Oran*).
In addition the terms 'slugary', 'slugaries', 'sluggeragh' may be used locally to describe 'swallow holes'.

Table 1: Karst risk assessment (values used for N8 Cashel - Mitchelstown

Geological factors			
Underlying rock	Clean limestone = 2	Muddy Limestone = 1	Sandstone = 0
Overburden depth	0 – 5m = 3	5m – 20m = 2	>20m = 1
Nature of overburden	Cohesive = 2	Granular = 1	
Boundary with impermeable rock	Yes = 2	No = 1	
Ground investigation factors			
Walkover/API/GSI features	>15 per 5km = 3	1 to 15 per 5km = 2	<1 per 5km = 1
Geophysics anomalies	>15 per 5km = 3	1 to 15 per 5km = 2	<1 per 5km = 1
Landowner observations	>15 per 5km = 3	1 to 15 per 5km = 2	<1 per 5km = 1

Landowners and occupiers can be the most useful source of information regarding active karst subsidence. Farmers will notice holes appearing in their fields, and are likely to infill them where they present a hazard to tillage operations or a risk to livestock. For the N8, a landowner questionnaire included the questions –

- 'Any history of local flooding or unusual drainage features?'
- 'Do you have any places on your land subject to subsidence or any places that have been filled in?'

Responses to these questions together with annotations on the landowner site plans proved useful in identifying active subsidences and sinkholes (or slugaries/ sluggeraghs). Subsequently these features were annotated on to site plans, which provided the most convenient means of collating data (Figure 12). For the N8, it was noted that some known features were not identified by landowners as active features, perhaps because the landowner had not been in occupation for long enough. It should be noted that landowner interpretation of what is a sinkhole might not accord with conventional geological understanding.

Numerical values can be assigned to each of the risk factors and these values could be combined to provide a basis for quantitative rankings, though presently there appears to be insufficient data to properly weight the various factors. The risk ranking used for N8 Cashel to Mitchelstown is shown in Table 1. A qualitative approach appears more appropriate with each part of the site ranked 'low', 'medium', or 'high' risk. An extract from the karst risk assessment is shown in **Error! Reference source not found.**. The design measures adopted for each situation will vary from project to project. For the N8, the risk assessment was used to identify areas requiring further investigation, to identify sections of the route where managed drainage were proposed and highlight sections of the route where karst subsidence features might be found, providing a means of satisfying the designer's H&S obligations and indicating where earthworks solutions might need to be implemented.

Since the work on N8, Cooper et al (2011) have described methods of avoiding karst hazard and present a method of calculating a sinkhole susceptibility rating.

COMPARISON OF GEOLOGICAL FACTORS WITH FIELD EVIDENCE

The results of risk ranking based on geological features might be compared with the results of hazard mapping based on field evidence. From previous work, generally the correlation is good or moderate. Instances of poor correlation have occurred where shallow overburden occurs over impure limestone away from a boundary with impermeable rock, and there is little evidence of karst activity. This would seem to indicate that shallow rock is not in itself a significant factor and, and clearly for features to form the underlying rock needs to be karstified.

DESIGN & CONSTRUCTION

EARTHWORKS

The design will need to ensure that the works are safe to build and that they are stable during operation. Ground investigation in all its forms may identify locations where risks are known to exist, but more commonly the risks will not be immediately apparent. Prior to construction works starting in earnest a thorough walkover should be undertaken to identify any features missed by the ground investigations. At this stage the contractor will have possession of the site and will have mobilised plant so trial pitting/trenching operations to investigate anomalous features should be undertaken where this has not already been completed. Once earthmoving starts, any areas of subsidence should be noted, made safe and investigated to avoid accidents.

Table 2: Karst Risk Assessment for Earthworks (as used for N8 Cashel to Mitchelstown)

E'wks elem	Cut / Fill	Height/ Depth	Rock Type	Depth of o'burden	Cover	B'daries with imperm rock	Geo Risk Rating	Geo Risk Ranking	AP features	Geophys features	Shallow Geophys features	Landowner Obs GSI D'base Walkover	Evidence-Based Risk Rating	Evidence-Based Risk Rating (shallow MG only)	Correlation between Geological and Evidence-Based	GW lowering	KARST RISK
		m	S'stone =0 Impure L'stone=1 Pure L'stone=2	0-5m = 3 5-20m = 2 >20m =1	Gran=1 Cohes/ mixed=2	Yes=2 No = 1	Min = 0 Max = 24	High Medium Low	<1/ 5km=1 1-15/ 5km=2 >15/5km=3	<1/ 5km=1 1-15/ 5km=2 >15/5km=3	<1/ 5km=1 1-15/ 5km=2 >15/5km=3	<1/ 5km=1 1-15/ 5km=2 >15/5km=3	Min=1 Max=27	Min=1 Max=27	Good Moderate Poor	High Medium Low	V. High High Edium Low
EW1	Cut	11.5	2	3	2	1	12	High	3	3	3	3	27	High	Good	High (10.0-10.5m)	very high
EW2	Emb	6	2	2	2	1	8	Medium	3	3	3	3	27	High	Moderate	Low	medium to high
EW3	Cut	4	2	3	2	1	12	High	3	3	3	1	9	Medium	Moderate	Medium	medium to high
EW4	Emb	4.5	2	2	2	1	8	Medium	3	3	3	3	27	High	Moderate	Low	medium to high
EW5	Cut	4	2	2	2	1	8	Medium	1	3	3	3	9	Medium	Good	Medium	medium
EW6	Emb	11	2	2	2	1	8	Medium	3	3	3	3	27	High	Moderate	Low	medium to high
EW7	Cut	6	2	1	2	1	4	Low	2	2	2	2	8	Medium	Moderate	Medium	low to medium
EW8	Emb	<2	1	1	2	1	2	Low	1	3	3	1	3	Low	Good	Low	low
EW9	Cut	4	1	1	2	2	4	Low	1	2	1	1	2	Low	Good	Medium (0.0m-2.0m)	low

Notes

1. E'wks elem – earthworks element ie cut or fill section of route
2. o'burden = overburden ie soil material over rock
3. Gran = predominantly granular soil; Cohes = predominantly cohesive or clayey soil
4. B'daries with imperm rock = Boundaries with impermeable rock
5. Geo Risk Rating = Geological risk rating
6. Geo Risk Ranking = Geological risk ranking
7. AP features = potential karst features identified from aerial photographic interpretation (API)
8. Geophy features = all potential karst features identified from geophysics
9. Shallow geophys features = features identified from shallow microgravity geophysics only
10. Landowner obs = landowner observations; GSI d'base = GSI database features; Walkover = walkover features
11. GW lowering = relative extent of groundwater lowering (related to cutting depths and existing GWLs)

Stripping topsoil will often reveal areas of fill where a farmer or landowner has backfilled a subsidence; these should be investigated. Risks to earthworks can be divided into those where natural ground will form the sub-formation to the road and those where fill will be placed. In the latter case, and for higher fills, it is likely that the extra load applied by the fill will highlight soft or voided zones thereby revealing subsistence. However well-constructed fills will generally be safe in the long run as they will have the capacity to arch over smaller voids. Precipitation will tend run-off fills and no water courses will be present, so no surface water should be directed to the ground below an embankment and this reduces the risk of causing the erosional processes leading to sinkholes and subsidence.

Figure 13: Exposed limestone rock surface (Co. Cork) showing deep soil-filled slot/grike.

Where the ground forms the sub-formation two conditions might be considered. Rock can be revealed and in general will have an uneven surface, perhaps with deep soil filled slots or grikes where rock has dissolved along natural structural features (Figure 13). These should be exposed, cleaned and backfilled with mass concrete to provide even support to the road pavement; a typical detail used for several roads projects is shown in Figure 14.

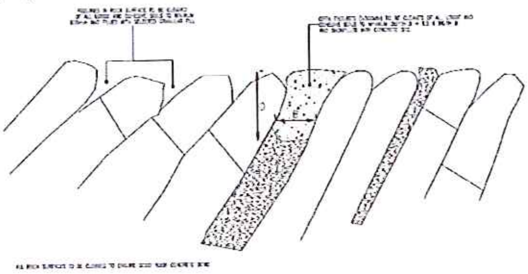


Figure 14: Typical detail for pavement dentition in karst limestone

Soil at formation might be considered to pose a risk of collapse and calculations considering cohesive soil's undrained strength (see e.g. Bolton, 1979) show that firm clay soil will support a cavity of 5m diameter at shallow depth, which would be dangerous were it to collapse. This form of assessment provides a reasonable upper bound estimate of void sizes for design and confirms the need to investigate and where necessary treat all shallow microgravity anomalies below the footprint of new works.

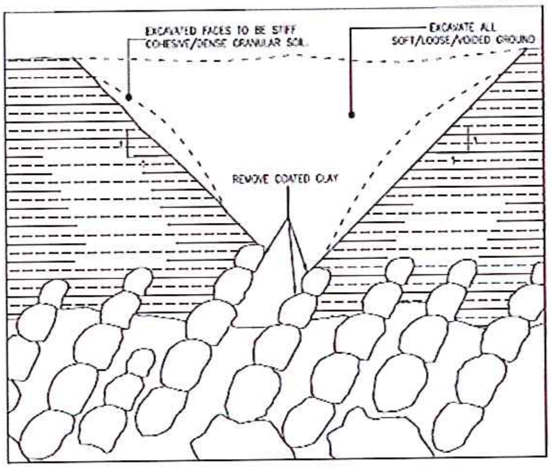
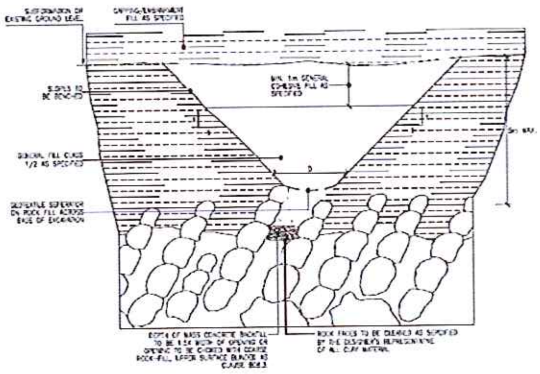


Figure 15: Typical detail for backfilling sinkhole over shallow limestone (depth to rock < 5m); above (a) excavation of subsidence to remove soft material and expose stiff cohesive/dense granular soils; below (b) treatment by backfilling with well-graded granular fill to maintain drainage flowpath to rock



Where karst subsidence is identified over shallow rock, treatment is straightforward. The subsidence should be excavated to confirm its nature and remove soft material that may have collected in a depression. Once rock has been exposed it may be possible to identify where water percolating from the ground surface is entering the rock. It is sensible to allow this water path to remain so that no new drainage paths, which might promote further subsidence, are generated. The excavation should be backfilled with compacted well-graded crushed or broken rock (NRA SRW Class 1A or 1C) with capping or embankment fill over the treated area. A typical detail is shown in Figure 15.

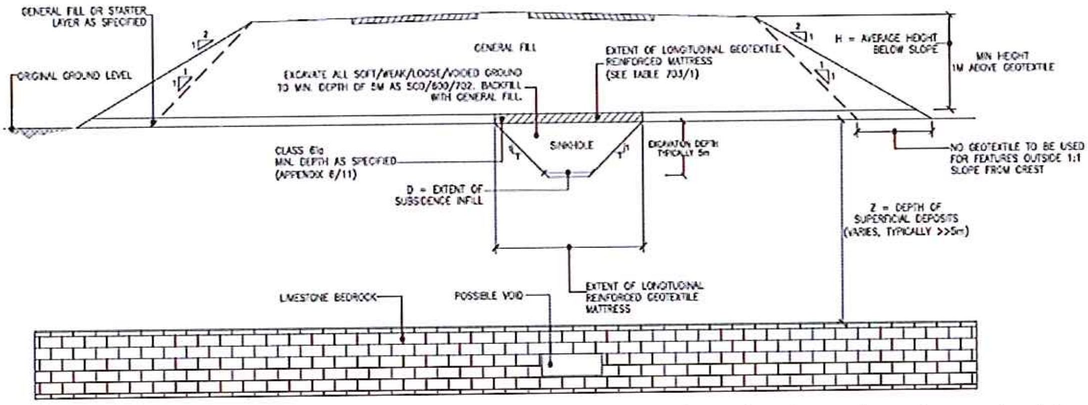


Figure 16: High-strength geofabric reinforcement over karst feature.

Preference should be given to excavation and positive remediation of subsidences as described above. But a measure, which might be adopted perhaps where rock is deeper, is to reinforce the earthworks layers below the pavement formation with high-strength geofabrics. These can be designed to span suspected voids and the design challenge is to estimate the void size. Case history evidence should be used where possible, e.g. Beese and Creed recorded the largest subsidence in their database for Co. Cork was of the order of 5m across, or results from micro-gravity surveys might be used.

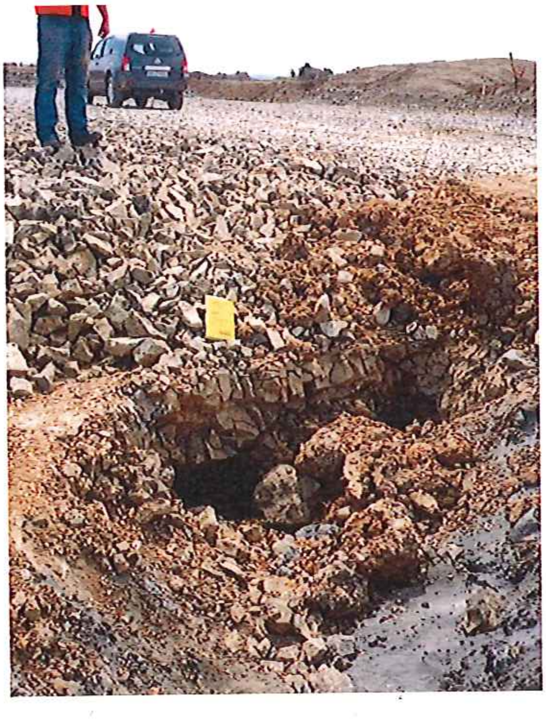


Figure 17: Solution cavity in limestone (N8 Cashel to Mitchelstown)

As an alternative the road can be constructed as a reinforced concrete slab designed to span voids. This option has been adopted in the UK for a section of road near Derby on Triassic gypsum (Cooper et al, 2011), and similar solutions have been adopted widely for new motorways in China (Waltham et al, 2005).

Earthworks properly reinforced with geotextiles can be designed to prevent ultimate limit state failure, i.e. collapse, but it is unlikely that serviceability will be maintained and ultimately repair will be required. A design method is described in BS 8006-1:2010 (8.4) and an example of a design solution proposed for the N8 as well as other projects is shown in Figure 16. Similar solutions have been adopted for sections of new road constructed over gypsum near Ripon, Yorkshire, UK.

N8 Cashel to Mitchelstown

For the N8 Cashel to Mitchelstown, despite the widespread evidence for karst features close to the route, little evidence was found during construction. An example of a solution cavity in rock is shown in Figure 17. This was remediated by backfilling with rockfill similar to the example shown in Figure 18.

Figure 18: Remediation by excavation and backfilling with coarse rock fill (Co Cork)

DRAINAGE

Poor drainage design can be a cause of karst subsidence and where subsidence is a risk attention should be given to drainage details. In higher risk areas, the following measures were recommended on the N8 –

- All collected water should be carried to defined outfalls and not allowed to run-off and seep into the ground where it will increase the risk of activating subsidence.
- Run-off from roads should be collected and carried in sealed or lined drainage systems (drainage trenches lined with an impermeable liner) to discharge at watercourses.
- Attenuation ponds should be lined.
- Cut-off ditches collecting diverted surface water drainage should be lined.
- In particularly high risk locations drains should be constructed from long (6m) steel or PVC pipes which will span voids avoiding the risk of leaks from broken pipes or from over-rotated joints.
- To prevent very coarse grained starter or basal drainage layers providing drainage conduits, starter layers in high karst risk sections should be were constructed of the finer, well-graded Class 6C selected granular fill (following Wagener and Day). The granular layers will provide enhanced drainage compared to cohesive till soils and Class 2C fill allowing consolidation settlement.
- Over the edge drainage was permitted as it was considered unlikely to produce concentrated flows.

Kerbs and gulleys could be used to collect and manage rainfall on the road pavement but their adoption for rural motorways is likely to prove costly.

Water collected and flowing in the more permeable backfill around pipes and other buried services also presents a subsidence risk as the concentrated flow caused may induce new subsidence, and these should be treated similarly to drainage pipes.

FOUNDATIONS

Earthworks are more resilient than most road structures in that they can accommodate a degree of ground movement before failure. Modern structures tend to be less tolerant of differential movement and more extensive design measures are required to ensure satisfactory performance. Wylie (1999) presents a useful introduction to the problems of building on karst and describes typical design solutions.

Figure 19: Typical ground profile of till over karst limestone

In areas of Ireland prone to karst, ground conditions typically comprise cohesive till over limestone bedrock (Figure 19). Where rock is close to surface and above groundwater level, the most convenient foundation solution is to excavate and found on rock. Some excavation of rock and dentition work is likely to be needed and the method has the great advantage of enabling the foundation conditions to be verified simply. Foundations might also be designed to span voids or slots in rock as typically these will be no more than 1m to 3m wide (Figure 20). As dissolution rates in limestone are typically low there should be no increase in risk to the structure during its design lifetime. The risk of there being a large cavern beneath the foundation should always be considered.

Figure 20: Shallow foundation spanning karst limestone surface (Co.Cork)

Most bridge and smaller structures can be founded on stiff till provided this is found within a few metres of ground surface. The risk is that the till may be affected by subsidence and hence not provide a safe foundation. Two broad solutions might be adopted –

i. Take foundation loads to rock below any affected soil, and ensure the foundation in rock will be stable.

ii. Treat voids in soil and or provide a structural solution that bridges any small voids.

The first option will generally require piled foundations, either permanently cased through subsidence prone soil or pre-formed, and with a socket in rock designed to provide sufficient resistance through rock socket friction alone spreading load into the surrounding rock with no reliance placed on pile toe resistance, which would be absent in the presence of an underlying void in the rock. Risk can be further mitigated by employing a larger number of small (or mini) piles with a rigid pile cap that enables load to be shared between the piles without risking stability (Figure 21). The work by Long and Collins provides guidance on pile design in Irish rocks.

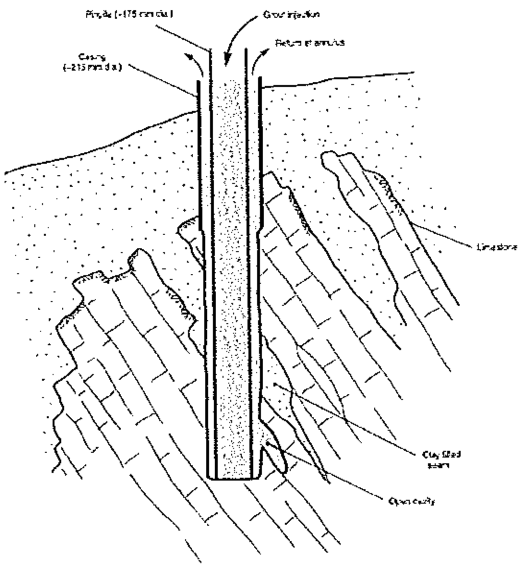


Figure 21: Typical mini-pile design in karst limestone (Wylie, 1999)

Where large diameter piles, carrying heavier loads and relying on pile toe resistance, are employed then measures should be taken to verify the integrity of the rock beneath the pile toe. In either case pile load testing can be undertaken to verify pile performance.

Where rock is deep, then piled foundations become more expensive and other solutions should be considered. Grouting near surface soils to create a load bearing 'mattress' of improved ground can be considered. Alternatively where voids are shallow dynamic compaction to collapse voids and soft/weak ground may be an option.

N8 Cashel to Mitchelstown

For the N8 Cashel to Mitchelstown, constructed by Roadbridge – Sisk jv (designer PH McCarthy/Hyder/Agec), eleven structures out of a total of more than 60 were judged to be founded on ground where there was a risk of karst subsidence based on the risk assessment carried out. Depths to rock based on ground investigation information varied from around 5m to 30m. At these sites additional probing, comprising c.1450 rotary percussive air flush nominal 80mm diameter open holes with a total of more than 16750m drilling was specified in Appendix 6/11. Probe hole spacing was typically 2.5m on a rectangular grid, with additional probes in suspect locations. The requirement was to prove rockhead and identify zones of voided, soft or weak soil.

Presence of soft, weak or voided soil was determined based on the rate of progress of drilling and the volume of grout take compared to hole volume when holes were grouted. The procedures had not been specified and were developed on site. While not ideal it does seem sensible to consider all factors for a particular site or project before establishing assessment criteria. Upon completion probes holes were grouted by tremie to fill the hole and voids encountered. In most cases the foundations were reinforced concrete pads but two overbridges were designed with reinforced soil abutments. The project design also included provision for various ground improvement techniques: excavation to expose rock and filling identified voids, ground stabilization by drilling and pressure grouting, and soil stabilization using interlocking soil/cement columns, but none of these was required.

Probing allowed the foundation designs to be confirmed at all sites except for structure S05 where weak soil zones were encountered between 17m and 20m depth, these were confirmed with cable percussion boreholes and SPTs. It was also discovered that rockhead varied greatly between 20m depth and 40m depth over relatively short plan distances of 2m to 5m. The evidence strongly suggested karst in the limestone with likely active voids in the overlying soil and on this basis the proposed pad foundations were changed to driven piles founded in rock.

M7/M8 Portlaoise Motorway

The M7/M8 Portlaoise Motorway was constructed by Dragados, SA and Ascon Limited and their designer

was Roughan & O'Donovan/Faber Maunsell. Overbridge S25 carries a county road over the new M7. Ground conditions at the site comprise around 10m till over limestone. Rotary boreholes at the north abutment and pier revealed a deeply weathered and karstifed profile. Cavities and clay filled voids were identified in the limestone, and lengths of hole with no recovery and quick drilling rates were assumed to represent voids. The rock was described typically as very strong moderately weathered dolomitised or sparry limestone with calcite, cavities, clay infill and honeycombing. A zone 2.9m thick of gravel and cobbles with clay infill was identified. Further investigations confirmed the presence of cavities in the rock to a depth of 25m. It was concluded that intact rock, described as very strong dolomitised limestone with calcite could be relied on between 26m and 30.9m depth at the north abutment and from 15.0m to 28.2m depth at the north pier (Figure 22). Rock at greater depth was also judged to be affected by karstification.

Figure 22: Rotary core photograph – M7/M8 Structure S25 north pier

The designer considered that the karstified/weathered limestone could not be relied upon to provide a safe foundation. For the North Abutment a single row of large (750mm) diameter piles with a 1.5m deep rock socket were designed. Load spread below the socket was assessed to require a depth of rock equivalent to 3D or 2.25m giving an overall requirement for sound rock of 3.75m and less than the available thickness of 4.9m. The bored cast in place rock socket piles were extended to the surface with H-piles to avoid the difficulties of forming piles through voided ground. For the North Pier, two rows of steel H-piles were proposed. A toe level of 16m depth was specified to ensure minimum 1.0m penetration into intact rock, leaving some 12m intact rock to provide load spread above the deeper weathered limestone. Piles were designed following methods described in Tomlinson (1995), CIRIA Report C181 and advice in BS8004:1986.

To verify the design static pile load testing comprising a preliminary pile test and a working pile test on the composite rock socket and driven steel H-piles at the North Abutment and North Pier respectively. Settlements at 1500kN working load varied from 3mm to 4mm and were around 10mm for the maximum test load of 3750kN. Dynamic load testing was performed on all driven H piles during restrike and cross hole sonic logging was used to confirm integrity of rock socket piles. The completed structure is shown below (Figure 23).

Figure 23: M7/M8 Structure S25

N18 Ennis Bypass

The N18 Ennis Bypass was constructed between 2005 and 2008 by GAMA Construction / Strabag (designer Mott MacDonald) and is located to the south of finest karst terrain in Ireland, the Burren. It runs in a north – south direction to the east of Ennis and much of the route has a shallow cover of till over limestone bedrock, though about 30% of the route comprises soft soils. Three phases of ground investigation were undertaken with rotary and cable tool boreholes, trial pitting and geophysics. Geophysical surveys, comprising microgravity and 2D resistivity surveys were undertaken at all structure locations. A number of cavities were identified from the ground investigation data. Many of these were found between -5mOD and -15mOD and were considered to represent the activity when sea level was at a lower elevation than today of between -10mOD and -15mOD. Where microgravity anomalies were investigated they proved to represent a variety of features - infilled or partially infilled karstic cavities, zones of increased weathering with infilled

discontinuities, local areas of thicker superficial deposits, or argillaceous limestone lithologies.

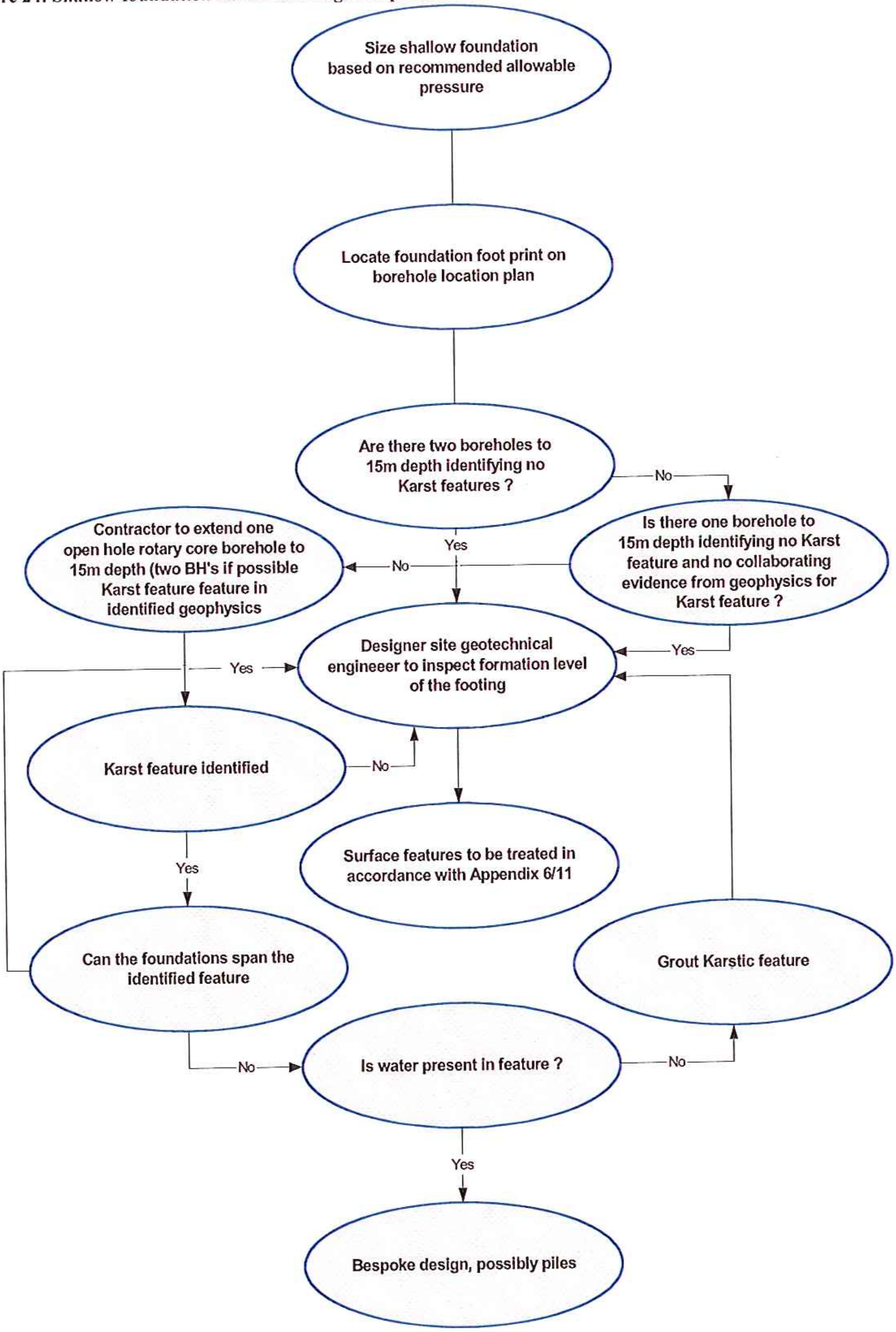
The designer recognised the difficulties of designing for karst and specified methods to treat fissures and karst cavities found below the road sub-formation using geofabrics, granular fill, grout, mass concrete or a spanning reinforced concrete slab.

For each structure the evidence of karst gathered from microgravity survey, 2D resistivity survey and from boreholes was tabulated. For shallow foundations on moderately weak or slightly weathered limestone or better an allowable bearing pressure of $750kN/m^2$ was adopted. Also specified in Appendix 6/11 was a karst risk mitigation procedure for shallow foundations where features were identified during design or encountered on site (Figure 24). The procedure is self-explanatory and provides a systematic means of confirming whether shallow foundations are appropriate or whether a bespoke foundation solution will be needed. The 15m borehole depth should be considered a site specific parameter.

Piled foundations were designed as rock socket piles following CIRIA R181 and UK HA BD70/03, with rock socket friction assessed using the method described by Rowe and Armitage. In areas of suspected karst, piles were designed to provide sufficient capacity in rock socket friction alone and to take account of varying rock depth a minimum length of rock socket was specified rather than a toe elevation.

Finally means of treating karst features found in cutting side slopes and potentially causing instability were specified. Typically the treatment comprised removal of soil and infilling cavities with concrete with weepholes provided to enable free drainage of any groundwater. Provision was made to use gabions or reinforced soil for larger features.

Figure 24: Shallow foundation karst risk mitigation procedure



CONCLUSIONS

Limestones are found beneath much of Ireland and based on reported observations there is widespread evidence of karst. Presently there are no specific guidelines for investigation or construction in karst regions of Ireland and the nature of the karst risk is uncertain. Karst drop-out subsidence is potentially the most significant threat where cohesive tills are found over karstified limestones. The principal challenge to those building roads is to define the nature of the problem prior to construction, providing

Ground investigation should be considered as part of the risk management process for any development and investigations for karst should be included. The various components of a desk study provide the most cost effective means of initially assessing karst risk. Surface features possibly indicating subsidence can be identified in the field and from stereographic aerial photography which enables the comprehensive coverage necessary for a road scheme. Geophysical surveying provides a cost-effective means of providing comprehensive coverage of relatively large areas and its use should always be considered in karst environments. Different geophysical techniques should be considered depending on the features anticipated, ground conditions and other evidence.

Conventional invasive ground investigation should be used to investigate the anomalies revealed by desk study and geophysics. Good quality rotary coring is required in rock to recover clay infill to solution cavities. Rotary drilling is necessary to prove rockhead. Cable tool holes enable soils to be investigated and SPTs with relatively low values should be considered as evidence suggesting karst subsidence. It is important to record and consider blowcounts for each 75mm or 100mm penetration. Dynamic probing enables wider coverage of suspect sites, and again low or zero blowcounts should be considered to provide evidence of karst subsidence. Trial pitting or trenching provides the best means of properly investigating near surface features.

All data should be brought together using a risk assessment and this provides a rational basis for decision making on engineering projects. A weighting used on the N8 project has been presented but at present the appropriate weighting of the various risk factors is uncertain and requires further work. A risk assessment provides a rational basis for deciding where specific measures should be adopted, if only on a relative basis within an individual project. While site specific measures for individual features, particularly at structures, might not be extensively required and is generally justifiable, over-cautious specification of drainage measures can be costly.

Design and construction solutions to enable road construction across karst terrains are described widely in the literature (e.g. Cooper et al, Sowers, Wagener & Day, Waltham et al and Wylie). Examples of measures that were specified and employed for the N8 have been described and implementation of specific measures that were successfully employed on the M7/M8 and N18 have also been described.

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