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Voids

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Definition

Voids are underground open spaces or cavities that may be of natural or man-made origin. Natural structures include caves, dissolution and collapse cavities in soluble rocks, cambering fissures (or gulls), open fault cavities and lava tubes. Man-made voids include all the different types of mines, habitation, religious and storage spaces, military excavations, tunnels and shafts. When voids are not foreseen in engineering geology they can pose a hazard.

Introduction

Voids or cavities are open spaces in the ground that are commonly encountered as unforeseen ground conditions in engineering geology. In 2012 Donnelly and Culshaw proposed a method for the classification of natural and man-made voids based on their mode of formation which was published in BS5930 (2015). When voids are not foreseen in engineering geology and construction, they can pose a hazards.
In tunnelling and mining they can represent a inrush, flooding or gas explosion hazard. Where they are present on construction sites they may result in unacceptable subsidence or collapse. In hydraulic structures (dams and tunnels) they can lead to structural compromise or failure. Voids may be formed naturally (Figure 1), or be man-made (Figure 2 and Table 1) - (British Standards Institution, 2015). Understanding the differences between natural and man-made voids helps to characterise their geometries, distribution and likely associated hazards. The void type, size, evolution, engineering geology and geotechnical behaviour of the rock mass, hydrogeology, hydrochemical setting and depth determine the best [illegible]

Natural Voids

The most common natural voids occur in the soluble or karstic rocks (Figure 1 – A to F). In order of increasing solubility (and dissolution rates), the common soluble rocks are: dolomite ($MgCa(CO_3)_2$) and limestone ($CaCO_3$), plus the evaporites including gypsum/anhydrite ($CaSO_4.2H_2O/CaSO_4$), halite or rocksalt ($NaCl$) (Gutiérrez et al., 2008; Warren, 2016). Natural karstic voids range in size from those widened by dissolution generating fissures a few millimetres wide to enormous cave systems with volumes of millions of cubic metres (Ford and Williams, 2007). The most common are cave systems caused by the downward passage of water in unconfined conditions flowing to springs/resurgences. However, deep acidic and/or hydrothermal water flow in confined conditions can produce hypogene cave systems. The various origins and the host rock structures (including rock mass discontinuities such as bedding, jointing, faulting and folding) produce complex cave systems both in plan and profile. In addition, cavities can form by cave roof failure and upward migration of breccia pipes (Figure 1 – B, C) forming sinkholes (Waltham et al., 2005). Roof failures in coal mines (Anon 2017) show breccia pipe propagation of up to 20 times the cavity height (Dunrud, 1984); in soft materials, or with basal erosion, a cavity can continue upwards through much greater thicknesses and produce very large sinkholes (eg., Ziaozhai Tienkeng in China). Cavities also occur by dissolution of the rock surface at rockhead beneath superficial deposits (Waltham et al., 2005) (Figure 1 – D, E) or by downward washing of soils into cavities. On a larger scale, salt dissolution at rockhead can produce voids beneath a thick cover of superficial deposits or a bedrock aquifer (Figure 1 - H). In arid areas caves may also develop by downward movement of water through salt deposits (Figure 1 - G). In addition to dissolving, some rocks also expand; anhydrite expands considerably on hydration to gypsum forming near-surface swelling caves.

Voids related to tectonic structures are relatively uncommon, but are most likely within faults and mineral veins (Figure 1 – I, J). At the surface such cavities are generally not a problem, except where they are opened by fault reactivation (Figure 2-J). Underground they are a problem forming conduits for water and gas into tunnels.

Coastal sea caves are common in all rock types due to wave erosion. Voids are also common in breccia and boulder conglomerate deposits. The washing out of the matrix from a volcanic breccia to local springs produced large sinkholes in Guatemala City (Figure 1- O, P). These were triggered by surface water, leakage from water and sewerage infrastructure. Soil piping and voids can also be caused by the natural or induced washing away of sand deposits, both in natural situations and especially in hydraulic structures such as dams. Pipes and voids may also occur in peat (Donnelly 2008). Lava tunnels on the flanks of volcanoes can also pose a hazard to construction (Figure 1 -N). Landslide mass movement and cambering may open fissures and voids (Figure 1 -L), which may be open or covered. Other rock types including sandstones can dissolve producing pseudokarst cavities and sinkholes (Ford and Williams, 2007; Waltham et al., 2005); loess, lateritic, gypsiferous and saline soils and permafrost (Figure 1-M) can also develop voids and be problematical.

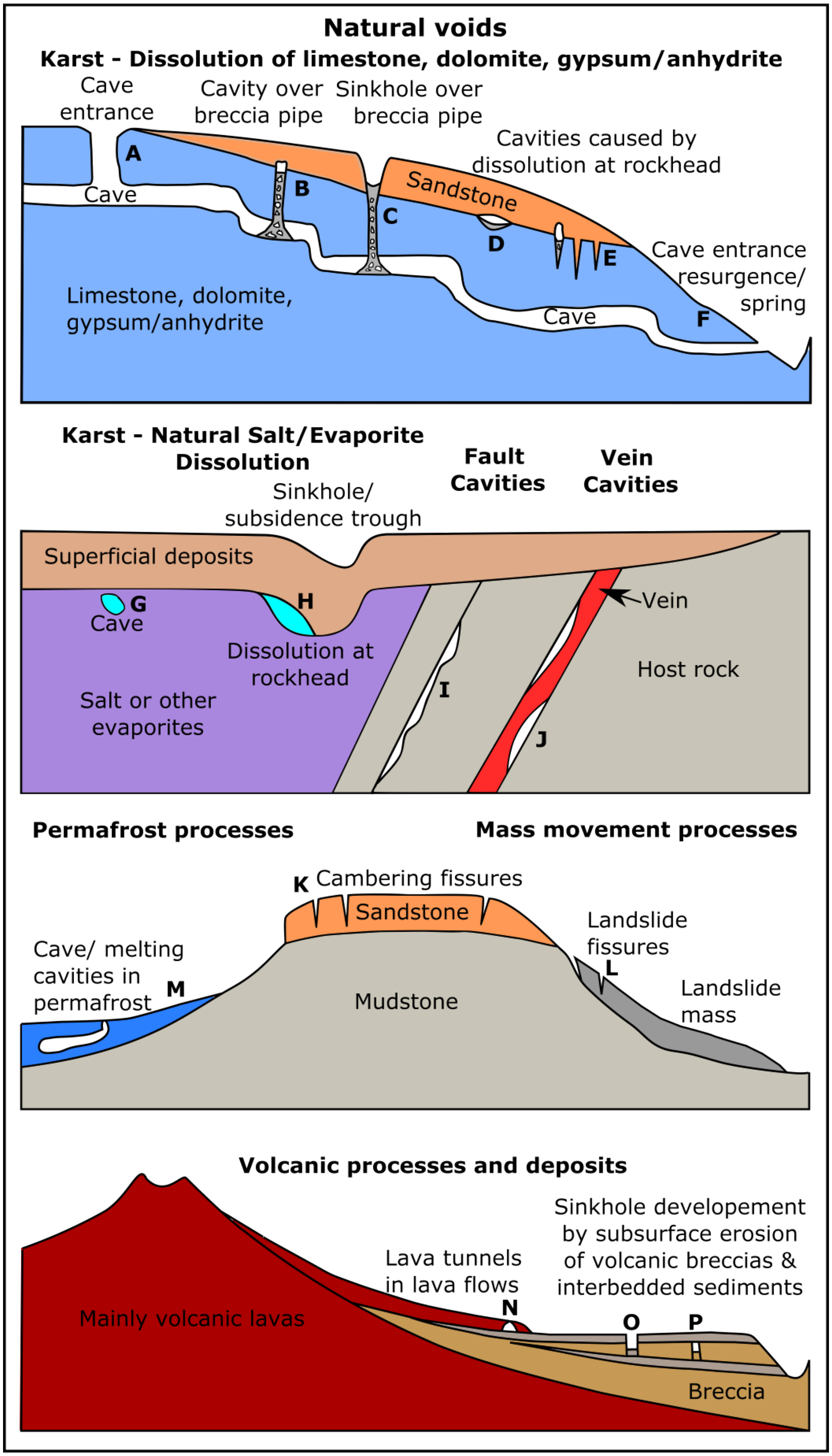

Figure 1. Types of natural voids in various host situations.

Man-made Voids

The near surface in many areas is riddled with known and unknown man-made voids (Table 1 and Figure 2) classified into broadly similar categories by Parise et al., (2013) and by Donnelly and Culshaw in British Standards Institution – BS5930 (2015, Table F.1). They range from water supply tunnels (Qanats) dating back 3000 years to catacombs, storage and habitation excavations, military tunnels and stores, transportation tunnels, sewers and infrastructure tunnels (Table 1 and Figure 2 A, B, C, D, F).

Many urban and rural areas are undermined by /mines for metalliferous deposits and industrial minerals including sandstone, sand, limestone, gypsum, pozzolana, chalk, flint, stone and coal, iron ore and salt to mention but a few (Figure 2 – E1, E2, E3). Clearly the list of minerals and geographic locations are extensive; if there is a useful mineral or rock, even near surface beneath a town, it is likely to have been worked.This has left a legacy of voids and potentially unstable ground that needs to be identified, investigated and mitigated. The majority of these industrial rocks, minerals and fuel minerals are stratiform and were (or still are) worked by shafts, inclined drifts and near horizontal adits (Figure 2, L, M, N). Older small workings were commonly extracted from bell pits or dene holes (Figure 2 - I). Larger workings are extracted mainly by room and pillar working, though longwall working is generally the favoured method for deep coal working (Figure 2 – L, Q). Longwall workings tend to produce subsidence bowls, which may have marginal fissures and fault reactivation causing open fissures and steps in the ground surface (Figure 2 – K, L) (Donnelly, 2009). Room and pillar workings may collapse by roof failure causing a breccia pipe to migrate towards the surface and break through as a crown hole (Figure 2 – Q, O, P). In deeper mines these collapses may choke up before reaching the surface. A typical breccia pipe may propagate up to 20 times the extracted seam thickness dependent on the profile shape of the failure and bulking factor of the rock (Dunrud, 1984) (Figure 2 - P).

Mining for precious metals also dates back to antiquity. Many of the metalliferous deposits occur in veins, whose extraction is largely by shafts or adits with removal of the vein from above and below to form stopes; these may emerge at or be very close to the surface forming a subsidence hazard (Figure 2 – E2).

Early salt extraction used natural brine springs, but later boreholes and pumps were installed (wild brining) producing underground cavities (Figure 2 -H) and significant subsidence (Cooper, 2002). Modern salt extraction is by pillar and stall mining (Figure 2- E3, Q), or by controlled brining from large deep dissolution cavities, generally at many hundreds of metres depth (Figure 2- G). Commonly these cavities are reused for gas and waste storage, though some are made specifically for gas storage. Not all “controlled” cavities have proved successful and notable collapses have occurred in the USA (New Mexico and Texas) (Johnson, 2003) and UK (Preesall and Teesside).

Triggering mechanisms for void collapses

Ingress of water is by far the most common triggering mechanism and spates of collapses forming sinkholes (over natural and mining cavities) have been induced by heavy rainfall and flood events. Burst water pipes or leaking sewers also trigger collapses. Road and hard-standing drainage into gulleys and French drains can allow water infiltration and subsidence along the drainage system. Engineering can also induce voids to collapse by changing the in groundwater levels due to groundwater abstraction , dewatering and recharge. Vibration is another triggering mechanism particularly during engineering or earthquakes, or next to roads and railways, but also during borehole investigation and subsequent construction/mitigation.

Classification of Parise et al., 2013 A-F and subcategories	**Man-Made Voids**
A- Hydraulic underground excavations	A1 Drainage; A2 Water inception structures; A3 Underground water ducts; A4 Cisterns; A5 Wells; A6 Hydraulic distribution works; A7 Sewers; A8 Ship and boat canals; A9 Ice wells/ snow-houses; A10 Tunnels or ducts of unknown function
B- Hypogean civilian dwellings	B1 Permanent dwellings; B2 Temporary shelters; B3 Factories, B4 Warehouses, stores, cellars; B5 Underground silos; B6 Stables/animal shelters; B7 Pigeon-houses; B8 Apiaries; B9 Any other kind of civilian settlement
C- Religious excavations	C1 Temples, wells, shrines, churches etc. C2 Burial places
D- Military and war excavations	D1 Defensive works; D2 Galleries and passages: D3 Mine and countermine tunnels; D4 Firing stations; D5 Stores; D6 Accommodation and command infrastructure; D7 Civilian war shelters.
E- Mines	E1 Quarries ([+]also called Stone Mines) –stratabound
	E2 Metal Mines – vein and stratabound
	E3 Other mines, including coal mines, salt, gypsum mines etc – mainly stratabound
	E4 Non-specific exploration tunnels
	E5 Underground vegetable production
	[2]Former mines used for storage
	[2]Mines created for waste disposal and radioactive waste disposal facilities
F- Transport excavations	F1 Tunnels for vehicles or pedestrians
	F2 Transit works, non military
	F3 Railway and tramway tunnels
	F4 Non-hydraulic wells and shafts
G- Other works	[2]Telecommunications tunnels
	[2]Boreholes
	[1]Dissolution caverns: brine caverns for salt, oil, gas storage, plus pressurised air power plant storage
	[1]Dissolution channels, near surface brine runs

Table 1. A-G Classification of man-made voids based on Parise et al. (2013); and the Donnelly and Culshaw classification in British Standards Institution – BS5930 (2015, table F.1); [1]brine cavities after Cooper (2002); [1,2] not in Parise et al. (2013)

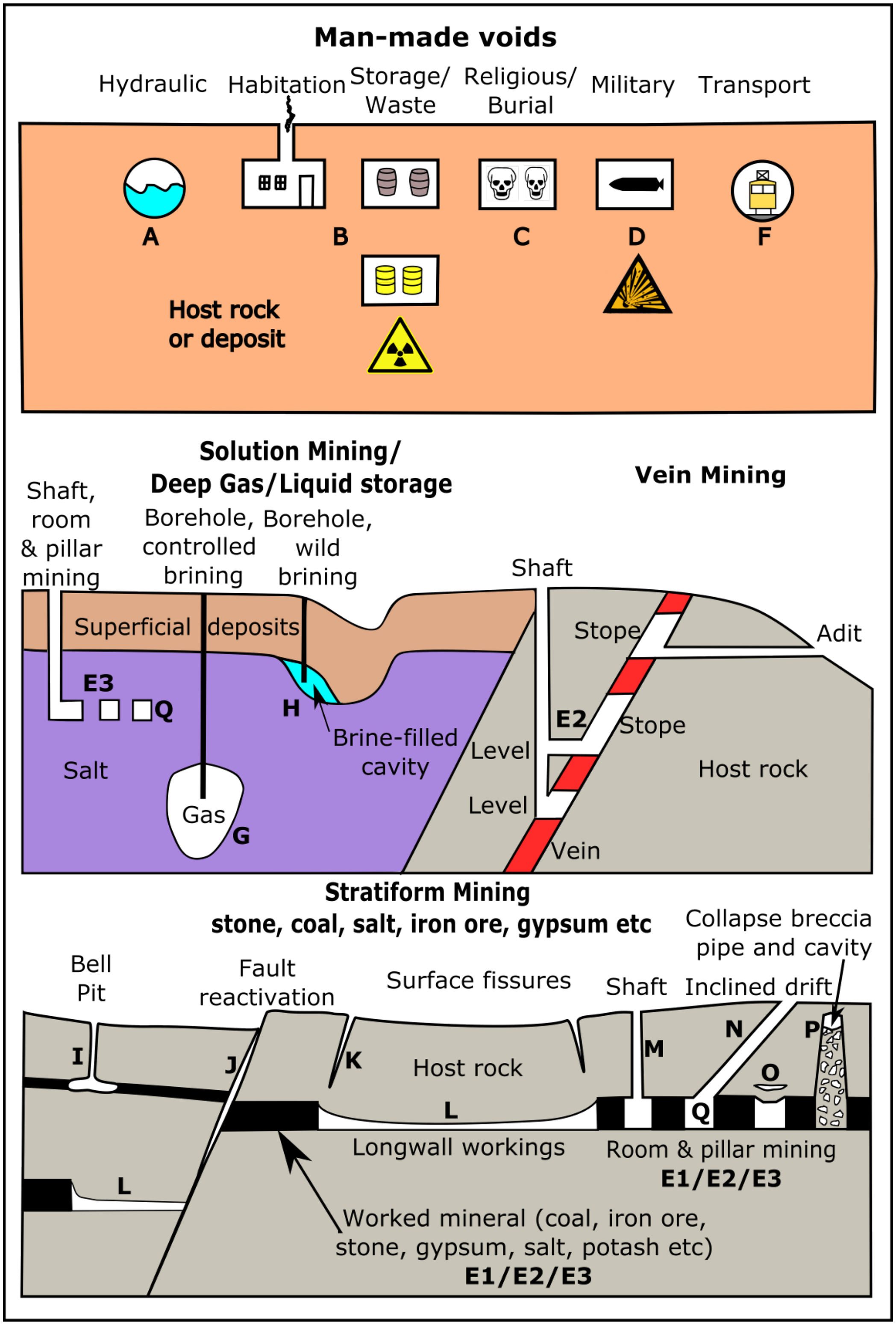

Figure 2. Types of man-made voids Designations A, B, C, D E1, E2, E3 and F are noted after Parise et al. 2013 in Table 1, other letters are for identification only in the present text.

Investigation of voided ground

Many voids have a pattern related to their underlying cause, such as a joint-controlled cave system, a vein or the pattern of room and pillar workings. The related subsidence pattern gives information about the geometry of the cause and the area's susceptibility to collapse. The pattern can commonly be determined from topographical surveys, air photograph analysis and LiDAR interpretation. Boreholes and probing have traditionally been used to detect and locate voids, but drilling holes stands very little chance of encountering the target without knowledge of the likely void location derived from previous studies or a geophysical investigation (Table 2). For borehole investigations the automated recording of penetration rates can help with the assessment of voided ground. It is important that investigation holes are properly grouted otherwise they can aggravate the problem they are investigating.

Investigation techniques for voids		
Method	Problems/benefits	Uses
Topographical and field survey	Shows void pattern if partly collapsed	Site characterisation
LiDAR	Shows void pattern if partly collapsed	Site characterisation
Boreholes	Drilled on a random pattern or on a grid there is great scope to miss the target	Mine workings, caves, man-made voids
Boreholes and void sonar scanning	Good range underground if cavity is penetrated	Mine workings, brine cavities etc
Probing	Inexpensive compared with boreholes	Collapsed ground, cavity fill and voids
Boreholes and borehole camera	Short range dependent on clarity of water/air in cavity	Mine workings, caves, fissures, faults
Resistivity tomography	Good on greenfield sites, poor on previously developed sites	Voids, breccia pipes and rockhead
Microgravity	Good on greenfield or previously developed sites	Large voids and breccia pipes
Ground Probing Radar (GPR)	Shallow depth of penetration attenuated by clay	Near surface voids and fissures
Seismic	Suitable for mine workings; confused by irregular karstic features and steep dips	Mine workings and salt dissolution voids
Cross-hole seismic	Requires an array of boreholes	Voids, shafts, caves
Passive seismic tomography (PST)	Good for large cavities at depth.	Voids, karst, mine workings, man-made cavities
Electromagnetic (EM) conductivity	Images near surface voids	Caves, shafts,
Natural Potential (NP) profiling	A complementary technique	Caves, mine workings, man-made cavities.
Self Potential Tomography (SPT)	Depth penetration to about 20 m	Shallow air or water filled caves; shafts
Internal surveying/LiDAR scanning	Requires access to void.	Caves, any dry accessible and safe cavity

Table 2. Investigation techniques for voids.

Mitigation of voids

Where potentially unstable voids are found near the surface, induced collapse and filling is a simple cost-effective mitigation method. Where coal (or other mineral) remains at shallow depth as pillars surrounded by partially collapsed ground, complete excavation can be cost effective with the mineral value offsetting excavation costs.

Where accessible caves or man-made caverns are likely to be unstable, walls of brick or concrete can be used to support the roof (Waltham et al., 2005). Piling through cavities can support overlying structures, but care is needed to prevent obstruction of the natural water flow (Waltham et al., 2005); Small voids can be mitigated with appropriate foundations to span any likely failure.

Grouting is the common method of dealing with voids (Warner, 2004). Dependent on their size strong cement grouts may be utilized, but for large mine workings low cement grouts with a filler of pulverised fuel ash (PFA) or sieved colliery spoil have been successful (Anon 2017) For abandoned salt mines cement, PFA and brine mixtures have been used to prevent further dissolution. For voids in hydraulic structures grouting can be difficult and where highly soluble rocks such as gypsum and anhydrite are present it may be impossible, though some chemical grouts have been used with some success. Grouting voids in cave systems may be problematic and can cause ethical issues for cave conservation. In some cases the voids and related caves may be too big to grout, or grout may be lost, unless a grout curtain is used. Furthermore, grouting may affect the natural groundwater flow and induce dissolution in adjacent areas; this may be highly problematic in the more soluble rocks such as gypsum, anhydrite and evaporites. Foam grouts can also be utilised to fill moderately large spaces where the roof is stable (Waltham et al., 2005).

Ingress of water into the ground can trigger cavities to develop into sinkholes. Sustainable drainage systems (SuDS) using infiltration, unlined drainage gulleys and French drains should be avoided where voids are suspected. Reinforced and flexible services should be installed, preferably in lined trenches so that if a failure occurs the water is directed away from sensitive structures to places of safe drainage. Fluctuations of groundwater levels within voided ground can also trigger collapse; abstraction from boreholes and irrigation can not only lower the local groundwater level, but also add considerably to the amount of water infiltration triggering collapse. Similarly, open loop ground source heat pump systems both abstract and return water to the ground with the likelihood of affecting voids and causing their collapse.

With all these methods it must be appreciated that in some places the natural or man-made voids may be so severe that they are impractical to mitigate and complete avoidance of that ground is the only option.

Summary and Conclusions

Voids are commonly present in the near surface where they commonly encountered as unforeseen ground conditions and hazardous ground during civil engineering. Voids may be of natural occurrence, commonly associated with soluble (karstic) rocks including limestone, dolomite, gypsum, anhydrite and salt. They also occur naturally associated with some volcanic rocks (breccias and lavas) or associated with landslides, cambering, soil piping and some tectonic structures including faults. Man-made voids are particularly common in the near subsurface and here they range from ancient to modern excavations for habitation, religious use, military use, transport, plus water supply and storage. In addition to these and present at depths from the near surface to the deep subsurface, voids associated with mining are particularly prevalent representing the extraction of coal, iron ore, salt and a long list of industrial, precious and metalliferous minerals. Each commodity has its own preferred method of extraction, stratiform deposits being largely worked by room and pillar or longwall working; steeply dipping deposits may have been worked by digging levels and stopeing. Some soluble rocks, such as salt and evaporites, are commonly worked by solution mining. The wide range of natural and man-made voids that could be present need to be considered before any engineering is undertaken. By understanding the engineering properties and geotechnical behaviour of the host rocks, local history and form of any mineral deposits, ground can be characterised and then investigated using techniques including geophysics and boreholes. In most situations voids can be mitigated by grouting or filling, but in some circumstances avoidance is the best course of action.

Cross references

Borehole
Borehole investigations
Designing site investigations
Dewatering
Drainage
Drilling hazards
Engineering geological mapping
Engineering geomorphological mapping
Evaporites
Failure
Faults
Gases
Geological hazards
Geophysical methods
Grout/grouting
Hazard assessment
Hydrogeology
Infiltration
InSAR
Landslides
LiDAR
Limestone
Karst
Mass movement
Mining hazards
Permafrost
Risk assessment
Sabkha
Sinkholes
Site investigation
Subsidence
Tension scars
Tunnels
Vibrations

Volcanic environments

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