Prevention and remediation of sinkholes
Construction in sinkhole terrains

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Chapters 11 and 12 from

Sinkholes and Subsidence:
Karst and Cavernous Rocks in Engineering and Construction
by Tony Waltham, Fred Bell and Martin Culshaw
2005

Springer Publishing, Berlin, and Praxis Publishing, Chichester
ISBN 3-540-20725-2   978-3540-207252
springeronline.com
382 pages, 250 figures

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Prevention and remediation of sinkholes

Design and construction of buildings and infrastructure in karst terrains are influenced not only by the character of the bedrock but also by the nature and thickness of the soil cover. Voids and cavities in both the bedrock and the soil are significant as potential sites for collapse. The possibility of subsidence due to them, whether slow or rapid, therefore has to be assessed prior to the commencement of construction operations. Hence construction must involve the total environment that influences those processes that aggravate sinkhole development in karst and its overlying soils, both on-site and in the immediate environs (Sowers, 1996). Once an assessment has been made, it may be possible to change the layout of a site to avoid the potential hazards. Ground preparation on sites within karst terrain can include remedial work on existing sinkholes and dissolution features, and also works to prevent or minimise the impact of their future development. Landfills on karst provide a special case where the nature and behaviour of the cover soils is critical; any potential hazard of new sinkhole development beneath landfill threatens its integrity with the added risk of serious pollution of local groundwater resources.

Most ground failures in karst are as subsidence sinkholes developed entirely within the soil (though related to fissures within the underlying bedrock). Stabilisation of the soil is therefore a most effective means of preventing future ground failures, besides being the objective of remediation of sinkholes that have already developed in a site.

11.1 SOIL TREATMENT AS SINKHOLE PREVENTION

Many of the conventional techniques of soil improvement, including various methods of grouting and densification, are applicable to overburden on karst (Terashi and Juran, 2000). However, it is essential to note that such soil treatment is only effective when accompanied by appropriate drainage control (Section 12.1.1) so that new sinkhole development is not induced by increased water flows, regardless of whether the soil has or has not been improved (Section 8.1).

11.1.1 Grouting in karst

Innovation within the civil engineering industry has produced a great variety of grouting techniques for the purpose of improving various parameters within ground conditions (Bruce, 1994; Grouting Committee, 1998). Permeation grouting with very mobile grouts is the oldest method, and is still applied widely for soil improvement, along with its variants of hydrofracture grouting (*claquage*) in soils of low permeability and, more recently, jet grouting. Any soil improvement by permeation grouting has to offer the benefits of a more stable soil that is less prone to development of subsidence sinkholes. Techniques are generally not specific to karst situations, but may be limited in application by the scope for major grout losses offered by open fissures in a karst rockhead beneath the soils to be treated. Compaction grouting, which also compacts the surrounding soil, is generally more useful in karst (Section 11.2).

Bulk grouts are relatively cheap slurries consisting of mixtures of cement, sand, gravel and pulverised fuel ash (PFA), that can be pumped via bored holes into ground cavities. They have been widely used to treat areas of potential subsidence, but only have limited application in karst situations. Typically, the amount of cement in a bulk grout is small, as low as 4% of the proportion of sand and gravel, while rock paste is cement-free colliery spoil mixed with water; many PFAs are used in grouts as they are inherently cementitious. Foam grouts are useful for filling large voids, and may be either gaseous emulsions in an ordinary grout or expanding polyurethane foams. All these materials have only very low strength, and their prime purpose is to provide just enough support within a cavity to inhibit small-scale failure of roof slabs, and thereby prevent cavity migration towards the ground surface. Their main use has therefore been in stabilising old mines with thinly bedded and unstable roof spans. Most natural caves in strong karstic limestone have stable arched roofs in massive rock, where low-strength bulk grouting offers little benefit.

Boreholes for the injection of bulk grouts are commonly drilled on a grid pattern with a spacing of 3–10 m. This is good practice for the treatment of abandoned, partially collapsed, pillar-and-stall mines, but is not generally applicable to cavernous bedrock in karst terrain. Natural caves tend to have fewer, more widely spaced, individual conduits than in a typical mine network, and are therefore better treated by site-specific grouting schemes developed to target individual caves. Most natural caves extend far beyond the zone of influence under any engineering site, and uncontrolled filling can lead to enormous grout losses. Shuttering inside a cave can prevent grout waste, and efficient filling may only be possible after works to gain access where there is no natural open entrance. Installation of shuttering allowed the filling of only the critical half of a cave that lay beneath an abutment of Belgium's Remouchamps viaduct (Waltham *et al.*, 1986). However, pattern boreholes have been used to fill soil cavities over karst in Florida (Kannan, 1999).

An added problem with bulk grouting in karst is the inadvertent blocking of natural underground drainage conduits. This can cause back-flooding in adjacent ground or even diversions of drainage flows that then induce new sinkhole development elsewhere; installation of drainage pipes through any kind of grout fill or backfill may be essential. Any grouting of a cave system in gypsum is generally inadvisable (Cooper, 1998). Unless the caves are small, abandoned and very dry, injecting grout into them could divert drainage flows elsewhere. Very high dissolution rates of gypsum in groundwater mean that this could lead to rapid cavity development in surrounding ground. Remediation of a sinkhole in gypsum is therefore especially difficult if it is to avoid threatening adjacent land (Case study #1).

11.1.2 Compaction grouting over cavernous karst

Compaction grouting is defined as the staged injection of low slump grout to improve soil properties. It uses highly viscous grout mixtures of cement, sand, clay and PFA to displace and compress loose soil around an expanding grout bulb. The grouting increases overall density of the soil, and so improves its strength and bearing capacity, and also reduces the soil permeability. Although compaction grouting can be applicable in any type of soil, it has been used most frequently in soils finer than medium-grained sand (Bell, 1993; Grouting Committee, 1998). The benefits of compaction grouting are revealed by increased resistance in an electronic cone penetration test (CPT) carried out before and after grouting (Figure 11.1). The technique has been used to improve soft soils over bedrock of karst limestone, either prior to construction or as a remedial measure to underpin a subsided building. Once soil densification is achieved during remediation works, the growing grout bulb can be used to lift subsided buildings back to their original positions in a karst terrain (Henry, 1987). At many sites, compaction grouting can seal cavities in limestone and heal cover soils more economically than can conventional grouting, and is less expensive than using deep foundation methods (Welsh, 1988).

A site in Pennsylvania had 5–20 m of clay soils over a pinnacled limestone rockhead. Compaction grouting was applied prior to construction, and mean grout take was 6.5 m^3 in more than 800 holes (Stapleton *et al.*, 1995). There was a good correlation between grout take and rockhead depth within a number of buried sinkholes (Figure 11.2), and also with zones of soft clays previously identified by a CPT. Also in the Pennsylvania karst, two low-rise buildings for a business centre in King of Prussia were sited on soft residual soil over cavernous limestone (Welsh, 1988). It was thought that large-diameter bored piles would have to be used for their foundations, but installing the piles at varying depths, socketing them into limestone and proof sub-drilling each one would have proved extremely expensive. Compaction grouting was chosen as an alternative, to fill any voids, compact the cover soil from bedrock up to 1.5 m beneath ground level and to form a column of grout (in essence, a mini-pile) around each grout-hole from rockhead up to formation level. The maximum depth of grouting was 18.3 m, and grout pressures and quantities

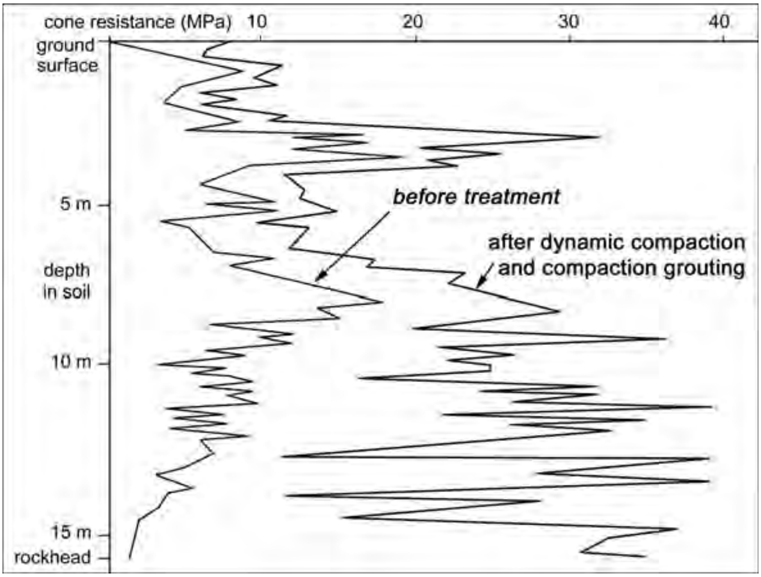

Figure 11.1. End resistance in an electronic CPT in fine sands, before and after treatment by compaction grouting, and also dynamic compaction, at a site over limestone near Jacksonville, Florida.
After Henry (1987).

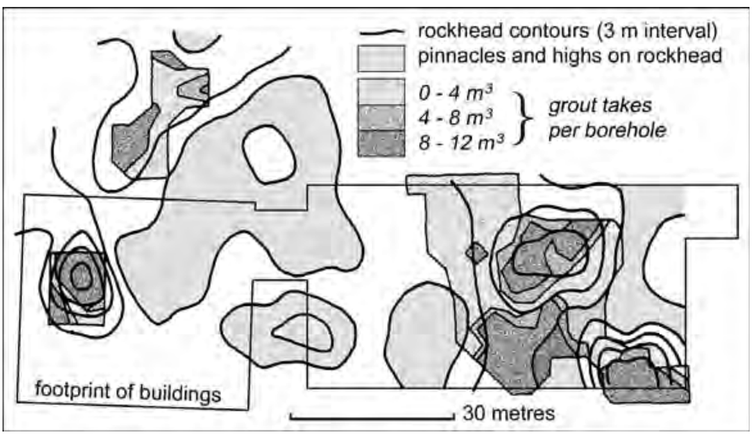

Figure 11.2. Grout takes per borehole during compaction grouting of clay soils within buried sinkholes in a pinnacled rockhead in Pennsylvania.
After Stapleton *et al.* (1995).

were controlled to minimise or eliminate heave; achievement of suitable bearing capacity was checked by a standard penetration test (SPT).

Early in construction of a highway interchange, also near King of Prussia in the Pennsylvania karst, a large number of subsidence sinkholes appeared in the soil mantle after a drought that was followed by a period of intense rainfall (Petersen *et al.*, 2003). This suggested that unpredictable sinkhole activity would continue, even with drainage measures in place. As the depth to bedrock precluded exposure of the throats of sinkholes for direct repair, it was decided to grout near-surface voids in the sinkhole zones, which also would consolidate the soft soils over the rockhead epikarst. A grid pattern was used for grouting, with primary holes at 3-m centres, followed by grouting from secondary and tertiary holes where deemed necessary. The grout-holes extended 3 m into competent limestone bedrock and were grouted upwards in 600-mm stages, taking a total of 48,000 m^3 of low-mobility grout of cement and fly ash. The works were successful but added 10% to the project costs.

After cracks appeared in the driveway and walls of a house in Tampa, Florida, investigation boreholes indicated that the lower layers of a sandy soil had been loosened by ravelling into voids within the underlying limestone (Henry, 1987). Some 218 m^3 of low-slump grout was injected via five holes extending to depths of 9–18 m. Formation of large grout bulbs at depths of 10.5 and 13.5 m then created a controlled lift of a zone 9 m across at the ground surface. The compaction grouting therefore plugged the cavities, densified the soil and restored the distressed building to its original position. Compaction grouting also was used to remediate a sinkhole in chalk that began to develop in overlying soils in the central reservation of England's M2 motorway. Eighty grout-holes were sunk over an area that extended into both carriageways, the work taking five weeks to complete. Compaction grouting sometimes has been used to form plugs in the throats of small sinkholes that are only partially choked with clay soils. As it is rarely possible to determine dimensions for the plug, a generous quantity of grout should be emplaced (Sowers, 1996).

Cap grouting is a means of reducing or sealing rockhead fissures immediately below a soil that may develop subsidence sinkholes by ravelling or collapsing into them (Sowers, 1996). It is similar to compaction grouting as it involves injecting a viscous grout (of cement, sand and PFA mixtures) to form a more or less continuous layer over the karst rockhead, and is also known as closure grouting (Fischer and Fischer, 1995). Primary grout-holes are bored on a grid at 3–6-m centres, and a grout is injected with a pressure of 1.0–1.5× the overburden pressure at the relevant depth (Figure 11.3). Grouting from secondary or even tertiary holes may be necessary to complete the grout cap. Grouting is terminated when refusal occurs at the required pressure in a grout-hole. The grout should set rapidly so that it does not continue to flow and thereby be lost into bedrock cavities; accelerators, such as calcium chloride, alkali carbonates and hydroxides, may be added to hasten setting, especially during cold weather (Bell, 1993). If grout continues to be pumped without any build-up of pressure, a temporary stop can allow some setting and blocking in the outflow zones, so that injection can be resumed the next day to achieve full pressure.

11.1.3 Soil stabilisation for sinkhole limitation

Dynamic compaction, by dropping a 30-tonne weight from a crane, may be used to compact soils that are prone to significant settlement under structural loads. It can

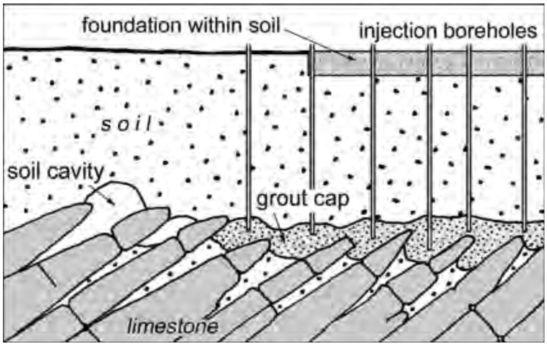

Figure 11.3. Creation of a cap of viscous grout across rockhead fissures by injecting coalescing bulbs of compaction grout through a grid of boreholes.

be used on soil cover over karst, where it can also collapse any voids migrating through the soil (Guyot, 1984). However, though this may retard void formation in soils, it does not necessarily eliminate the cause, so a new void, and then a subsidence sinkhole, may develop in the soil in the future if the conditions are right (Sowers, 1996). Dynamic compaction has also been used to collapse small caves at shallow depths in weak limestones, including the Miami Limestone in southern Florida. However, dynamic consolidation is inappropriate where vibrations could reach adjacent sites to induce new sinkholes (Section 8.3).

Precompression, by preloading a site with a temporary surcharge, is an economical means to consolidate weak and compressible soils. The method has been used on soft soils in shallow solution dolines and filled sinkholes (Sowers, 1996), but its application is limited notably by the long times required for effective pre-loading. Vibrocompaction (or vibroreplacement) can be applied to densify most types of soil within an annulus around a steel shaft that is vibrated into soft ground. As the shaft is withdrawn, coarse granular backfill is mixed into the soil to create a consolidated column about a metre in diameter. Stone columns were used to enhance the performance of soft cohesive soils in wide buried sinkholes within the chalk beneath road embankments in Berkshire, England (Rhodes and Marychurch, 1998). Vibrocompaction can also be used to collapse voids in the soil, but its ground vibrations are smaller than those created by dynamic compaction.

Lime treatment or cement stabilisation can be applied to improve the performance of many soft clays (Rogers *et al.*, 1996). Unconfined compressive strength of clay soils can be roughly doubled by the addition of small proportions of either cement or lime to a clay soil; a rule of thumb for the amount to be added is 1.0% by weight for every 10% of clay minerals present (Bell and Coulthard, 1990). A lime-stabilised layer 150 mm thick usually gives satisfactory performance, and is very effective when created beneath a raft. The site chosen for a motel in Allentown, Pennsylvania, had eight depressions, each about a metre deep, in its clay soil overlying karst limestone (Qubain *et al.*, 1995). Backhoe excavation into some of the depressions revealed that these were old subsidence sinkholes within the overburden soil. There was no surface evidence of sinkhole activity, though soil voids up to 1.2 m across were found. All the depressions were therefore exposed, to a maximum depth of 5.5 m, and all the soft wet clay within them was removed until firm soil was reached. The excavated clay was treated by addition of 5–10% lime, and used to backfill the exposed depressions in compacted lifts of 300 mm, to establish an allowable bearing pressure of 150 kN/m for conventional strip footings.

Some residual soils, derived by weathering from the insoluble components of a limestone, contain appreciable amounts of unstable clays that are subject to swelling on wetting and shrinking on drying. A thin layer of dissolution residue is commonly found immediately above pinnacled rockheads on the limestones of Kuala Lumpur, Malaysia (Tan and Komoo. 1990). Even though this may underlie 70 m of stiffer or harder residual soils, it commonly has negligible SPT N-values; some of these extremely soft clays are probably protected from consolidation by their locations between tall pinnacles. Fortunately, this weak residual soil is irrelevant where bored piles pass through it into bedrock sockets. Soft clay soils, capped by a chert residuum, were also found over a deeply pinnacled dolomite rockhead at a site for a uranium plant at Stillfontein, South Africa (Partridge *et al.*, 1981). The soil and some pinnacled crests were removed to a depth of 3 m, and replaced by a compacted soil raft formed of the stable residual chert. Excavation and fill involved 60,000 m^3 of soil, with compaction by an 8-tonne impact roller, heavy grid rollers and smooth-tyred vibrating rollers, to develop considerable densification of the soil satisfactory for foundations.

11.2 SINKHOLE REMEDIATION

Location of buildings and structures away from open and active sinkholes is always the preferred course of action, but may not be possible on a constrained site or where a sinkhole develops during or after construction. In these situations, sinkholes require complete remediation. The cheap and easy option of simply filling with any available material is almost never stable in the long term. There are far too many cases where small subsidence sinkholes have opened up, to be promptly back-filled, covered and forgotten, until they fail again some years later (Figure 11.4). Unless soil drainage is eliminated or controlled, reactivation of backfilled sinkholes is commonly inevitable.

A programme of land rehabilitation in South Africa's Wonderfontein Valley involved filling some of the large sinkholes that had developed catastrophically in response to de-watering of the karst (Box 8.1). The deep sinkholes were simply filled with available mine tailings, but this was during a period of rising water tables, after mine pumping had ceased (Swart *et al.*, 2003). The fills exhibited small amounts of subsequent compaction, but most performed well until some years later when sub-sidences were reactivated after a period of heavy rainfall. One sinkhole failed during filling, and was only stabilised when coarse rock debris was mixed with the mine tailings on a second phase of filling.

Figure 11.4. A small sinkhole that has been repeatedly filled, without proper treatment, under a much-patched parking lot in Bowling Green, Kentucky.
TW.

The two basic alternatives in most cases of sinkhole remediation are either to completely seal the outlet conduit at its base or to fill with graded material that will remain stable when storm-water drains through it. Sinkhole throats can be sealed with concrete plugs or capped with reinforced concrete where they enter bedrock; the use and type of reinforcement depends on the size of the sinkhole and the type of structure, if any, that will be constructed above or near it. With the drainage outlet sealed, the material used to fill the sinkhole should not be critical, and the only ongoing hazard is from any new sinkhole developed by the diverted infiltration flows. This should be prevented by adequate control of surface drainage, preferably removing all storm-water flows away from the site. Installation of geogrids in sinkhole repairs can be beneficial, especially in the manner in which they effectively delay any subsequent subsidence movements (Section 12.2.1).

A novel method of plugging stopes in abandoned gold mines in South Africa, is called the balloon technique (Parry-Davies, 1992). This consists of drilling 150 to 200-mm holes to intercept the void, and inserting strong inflatable polyethylene balloons via the holes. The balloons are then filled with polyurethane foam to form a lightweight barrier across the void, and this is capped with low lifts of fibrecrete to form a plug thick enough to support overlying backfill or bulk grout. This could be adapted to plug the throats of sinkholes but may encounter problems with cavity shapes that are less uniform than a mined stope.

Sinkhole remediation that allows continuation of its natural drainage is commonly preferable, and simple inverted filter fills can be appropriate to rehabili-

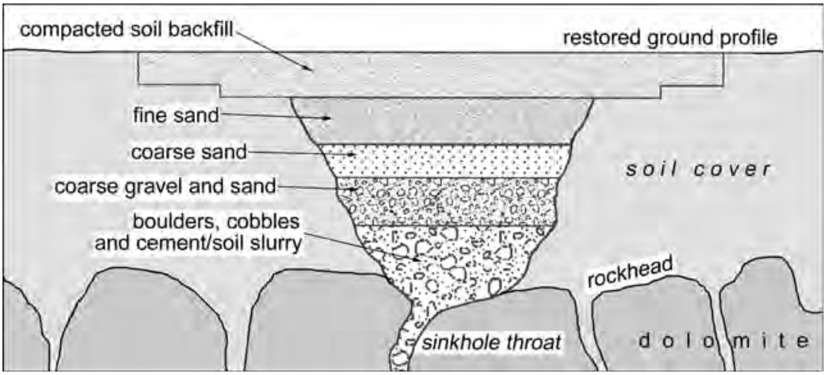

Figure 11.5. Inverted filter fill to rehabilitate a small subsidence sinkhole over dolomite.

tate subsidence sinkholes that are only a few metres deep (De Bruyn and Bell, 2001). The sinkhole is initially filled with boulders and soil-cement slurry to choke its throat (Figure 11.5). Once the slurry has set, unstable material on the sidewalls is removed by backhoe, and further backfilling uses a coarse gravel–sand mixture over the top of the boulders, followed by progressively finer sands. All backfill is placed in layers 150 mm deep that are each densified by small mechanical compactors. Soil around the sinkhole is excavated to a radius of 3–5 m, before being replaced and compacted, with or without incorporation of anchored geogrid.

Small subsidence sinkholes are remediated on appropriate scales. On a site of 57 ha to be covered by a large single-story commercial mall and surrounding pavement, near Clarksville, Tennessee, treatment of numerous sinkholes was based on the depth to bedrock and recognition of a definable sinkhole throat (Vandevelde and Schmitt, 1988). Where a throat was located, it was exposed by excavating the overburden to bedrock, and was then plugged with concrete or rock, before the excavation was backfilled. Where a throat was identifiable but the depth to bedrock was excessive, the suspect area was excavated to a depth based on the immediate ground conditions, and a concrete cap was placed above the throat area. Where the throat was near buildings, a larger excavation was made and the complete floor of the excavation was covered by geogrid, before placement of the concrete cap. At all sites, the excavation was brought up to grade with compacted clay soil. Surface drainage was then redirected to selected sinkholes where disposal wells were constructed into bedrock.

11.2.1 Repairs to large sinkhole failures

A large subsidence sinkhole that develops in the soil profile beneath a road may require a complete remediation to allow the road to be returned to use. The classic sinkhole repair is based on variations on the three-fold concept, that blocks its throat into the fissure in cavernous bedrock, then fills the bulk of the hole then caps the fill with a reinforced structure to carry the road (Waltham, 1989). That model is based

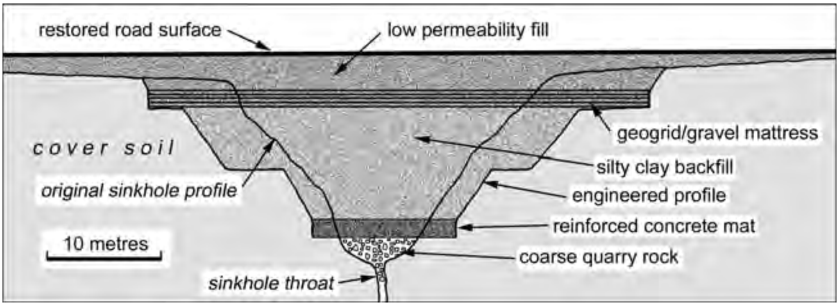

Figure 11.6. Incorporation of a concrete plug and a geogrid mattress in the remedial filling of the sinkhole under a road in the Saucon Valley, Pennsylvania; the scale is approximate. After Bonaparte and Berg (1987).

on a repair to a road in the Saucon Valley in Pennsylvania (Bonaparte and Berg, 1987), where a sinkhole nearly 30 m across had opened in a soil cover at least 15 m deep over karstic limestone where the water table had declined due to nearby mine drainage. The throat of the sinkhole was blocked with quarry rock of 150–300 mm size. This was capped by a small concrete slab that supported the main fill of locally available silty clay (Figure 11.6). A gravel mattress 35 m long and 1.2 m deep contained 13 layers of polyethylene geogrid (with a unit strength of 70 kN/m), and was designed to support the road by sagging while retaining integrity over a void up to 12 m across that may develop during any reactivation and renewed suffosion within the sinkhole. Unfortunately for this "textbook" repair, the sinkhole did open up again in the following year, destroying the road. A second repair placed a reinforced concrete slab 30 m long, which still supports the road today. It appears that bedrock was not exposed in the sinkhole throat, so the plug of undersize rocks sat in the soil profile, where ongoing drainage caused renewed suffosion of both the soil and the plugging material.

More successful, and only marginally smaller, was the repair of a caprock sinkhole under a road in the town of Macungie, also in Pennsylvania (Dougherty and Perlow, 1988). This sinkhole opened up to 26 m across and 13 m deep, though the karstic dolomite is 30 m down beneath its cover of shale and soils (Figure 11.7). It occupied the site of a large sinkhole containing a pond, which had been filled with mixed soil and rubbish, and then forgotten, when it was in farmland about 20 years before the road and houses were built over it. The repair was based on experience at the nearby Saucon Valley sinkhole (which had occurred 30 months previously, and at the time had its first repair intact). The throat was choked with 800 m^3 of large dolomite boulders (up to 1 m in size) tied with a lean-mix concrete (Figure 11.8), though the bedrock fissures could not be exposed because adjacent apartment blocks prevented any deeper or wider excavation of the unstable hole (Figure 11.9). This conical plug was capped with a reinforced concrete slab 900 mm thick (Figure 11.10), before soil was placed to restore grade. The replaced road remains stable today, with only the slightest of settlement – which can be ascribed to compaction of the soil fill.

Sinkhole remediation that does not accommodate drainage is likely to require

Figure 11.7. The unstable sides of the Macungie sinkhole, in Pennsylvania, below an investigation drill-rig that found rockhead at a depth of 30 m.
Photo: Percy Dougherty.

Figure 11.8. Chunk rock being placed at the lowest exposed point in the Macungie sinkhole.
Photo: Percy Dougherty.

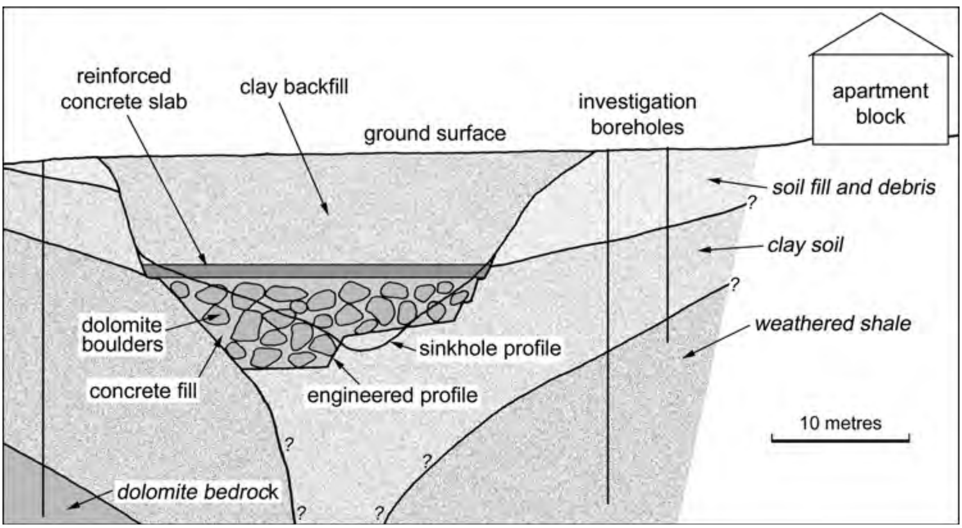

Figure 11.9. Cross section through the Macungie sinkhole with its engineered remediation and backfill.
After Dougherty and Perlow (1988).

Figure 11.10. Pouring the last of the concrete into the plug of chunk rock in the Macungie sinkhole, before rebar was laid as reinforcement to a cast concrete cap.
Photo: Percy Dougherty.

subsequent repair. When a sinkhole 30 m long and 12 m wide appeared in 1997 beneath a railway in Missouri, it was filled with rock as an emergency response; this was followed shortly by 40 m^3 of grout injected through 12 bored holes that reached just to rockhead 15–20 m down (Abkemeier and Stephenson, 2003). The track subsided again in 1999, and 84 m^3 of grout (of cement, fly ash and sand) was injected through boreholes that reached down to cavities in the bedrock limestone. Further reactivation occurred in 2002, when a new sinkhole grew to about 35 m across. At the same time, a large flow of sand-laden water entered an adjacent quarry, the deepening and drainage of which had induced infiltration through the soils beneath the railway. A new programme of compaction grouting in the sandy soils immediately above rockhead did not stop the flow into the quarry. Consequently, a grout curtain was formed 110 m deep and 60 m long between the railway sinkhole and the quarry. This reached down to conduits in the limestone that would appear to be the outlet for suffosion from the sinkhole, and were only sealed by injecting molten asphalt. With water flow into the quarry visibly reduced, the cause of the sinkhole appears to have been removed, and its remedial fill should now be stable.

These three examples demonstrate the importance of treating the real root of a subsidence sinkhole failure by adequately choking its outlet into bedrock through either one or more fissures. Engineered fill with a 150 mm grain size will rarely prove adequate in any reasonably mature karst; chunk rock of 1 m diameter is more appropriate. An unbonded plug of large rocks allows the natural drainage through to the bedrock fissure, while a massive cemented plug diverts drainage elsewhere, with the potential for opening a new fissure and adjacent sinkhole. This is not an issue where a road structure carries drainage away from the plugged sinkhole. While geogrid installed beneath a road may be invaluable for eliminating the instant appearances of open holes, it does not constitute a repair in itself. In a long-term repair of a large sinkhole in thick soil, geogrid can only serve as a warning mechanism where the perceived risk of subsequent reactivation does not warrant the costs of a large concrete slab.

11.3 LANDFILLS IN SINKHOLE KARST

The ideal landfill site should be hydrogeologically acceptable, should pose no potential threat to surface water or groundwater quality when used for waste disposal, and should have a sufficient store of material suitable for covering each individual layer of waste. With their dissolutionally opened ground fissures, karst terrains afford the least protection to groundwater from pollution by leachate, and any proposal for locating a landfill on them requires that the site investigation determine the full character of the karst before the project goes ahead (Hall *et al.*, 1995).

A site near Madison, Florida, demonstrated the crucial need for thorough investigations prior to landfill emplacement within a karst terrain (Hoenstine *et al.*, 1987). Operation of the site began in 1971 after a very cursory investigation that consisted of a number of shallow auger holes and examination of the appropriate local soil map and descriptions. Variable thicknesses of the Hawthorn Group, with an upper sand and a lower clay, overlie cavernous Suwannee Limestone beneath the site. Agricultural and industrial hazardous wastes were deposited in the landfill, even though no plastic liner had been installed under the site, and leachate soon contaminated some of the local wells. Investigation revealed that the clay unit had been breached by the ravelling soil voids that were migrating upwards from the limestone and into the sand (Figure 11.11). These were incipient subsidence sinkholes, but prior to any surface failure they created flow paths from the overlying sand into the underlying limestone, thereby allowing contaminants from the landfill access to the limestone aquifer. Pollution had therefore reached the limestone, and had migrated for 2 km through the aquifer, with slugs of contaminants moving from the landfill after periods of heavy rainfall. Construction of that landfill site had been inadequate by modern standards.

A landfill was placed over karst near Chattanooga, Tennessee, after an extensive ground investigation with boreholes and a resistivity survey found no voids within the soil cover 3–15 m thick (Tinjun *et al.*, 2003). Twelve sinkholes were cleaned out to expose their bedrock throats, which were then choked with rock and soil, and capped by graded backfill. Limestone pinnacles were found across the site in greater numbers than had been anticipated from the geophysical survey, and all were removed to 1,500 mm below formation level. The entire site was then sealed with

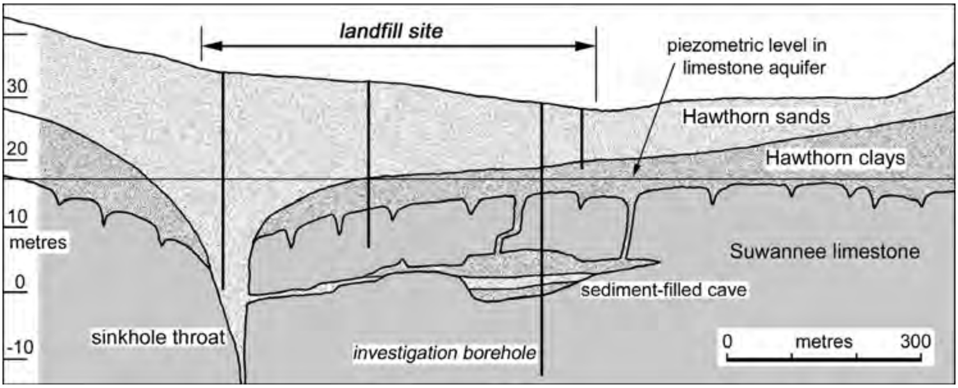

Figure 11.11. Profile through a buried sinkhole beneath a landfill site in Florida, with subsurface details conjectured from minimal borehole data.
After Hoenstine (1987).

a clay liner 600 mm thick. Liners constructed with one or two drainage layers, to convey contaminants that have percolated into the liner to a leachate collection system, have been recommended for use in karst terrains (Mitchell, 1986; Davis, 1997).

Any landfill installed in karst terrain is exposed to risk from sinkholes. Development or enlargement of a sinkhole beneath a landfill could mean that the bottom liner becomes unsupported and eventually collapses into the sinkhole. Geosynthetic reinforcement can be incorporated in liners to mitigate this risk, particularly at sites that have a thin soil cover (Siegel *et al*., 2001). A landfill in Missouri was closed with an impermeable cap that was required to extend over a sinkhole almost encircled by the landfill (Stelmack *et al*., 1995). Bedrock was sandstone overlying limestone, and the sinkhole was a caprock failure with a partial fill of natural soils and inert wood waste. A double layer of geogrid was installed across an area 30 m square beneath the composite layered cap that covered the entire site. This was designed to resist cap failure by spanning a new soil void 2 m across or by surviving 300 mm of settlement by the entire sinkhole fill 15 m in diameter.

An alternative to geogrid emplacement may be grout improvement of the soil, especially where needed for remediation of an existing site. A landfill in the Appalachian Great Valley of Pennsylvania stood on alluvium overlying residual clay totalling 4–18 m thick over cavernous limestone, and there was concern that sinkholes could develop at the toe of the cap after the landfill was closed (Mirabito *et al*., 2001). Consequently, compaction grouting was used as a preventative measure against development of dropout sinkholes in the soils between the landfill and the limestone. The purpose of the grouting was to densify and strengthen the sediments so that they would be less likely to collapse. Low-slump grout, consisting of cement, fly ash and sand, was injected into holes at various depths, staged upward from 1.5 m below rockhead and into the soil cover.

11.3.1 Sinkholes as pollution sources

The conduit flow that characterises karst aquifers provides potential for rapid and unattenuated pollutant transmission, thereby reducing the effectiveness of dilution and dispersal. Karst aquifers have strongly anisotropic permeability, and exhibit major variations in flow patterns and aquifer properties that reflect the maturity of the karst, the lithology and fracture spacing, and the position within the groundwater flow system. Sinkholes constitute pathways for contaminants to enter an aquifer, thereby adversely affecting groundwater quality. Flow velocities through a conduit system can be measured in kilometres per day. Contaminants entering a sinkhole will therefore pollute the associated aquifer very rapidly. Counts of faecal coliform units increase in the groundwater of cavernous limestone in Kentucky after storm events where surface water entered the aquifer rapidly through sinkholes (Ryan and Meiman, 1996). Over a longer timescale, a pollution plume from a landfill has been recorded to extend within 3 months over a distance of 30 km through karstified limestone (Hagerty and Pavoni, 1973).

Groundwater recharge via sinkholes bypasses the purifying processes that normally takes place within the soil, and attenuation of pollutants is reduced significantly. The sinkhole plain of south-western Illinois, in which there are some 10,000 sinkholes, has chronic and widespread bacteria-related groundwater quality problems due to the rapid recharge to its shallow karst aquifers (Panno *et al.*, 1997). The major source of pollution has been private septic systems, of which 10% illegally discharge raw sewage directly into sinkholes or sinking streams.

An additional impact of pollution is created by acids, derived from landfill leachate or any other pollutant, that can attack carbonate rocks and enlarge solution features. A milk factory at Allansford, in Australia, disposed of dairy waste with little or no pre-treatment into a series of injection holes directly into karstic limestone (Shugg, 1998). About 300,000 m^3 of this waste had been disposed of annually for over 50 years, creating a pollution plume that extends more than 2,500 m through the upper 30 m of the aquifer. The waste is a mixture of soluble and suspended organic material that ferments and produces an anaerobic, odorous black sludge, along with methane and carbon dioxide. Initially, the pH of the effluent is 3 or 4, which may be further reduced by the CO_2 produced, so that it has potential to dissolve the limestone. Consequent structural collapse of the aquifer was considered, but total dissolution by the waste is unlikely to have exceeded 500 m^3, which even if concentrated around the injection wells should have minimal impact on ground stability.

11.3.2 Landfill within sinkholes

Though landfill over sinkholes may be a necessity in an extensive sinkhole karst, there can be very few cases where landfill or waste disposal that fills up inside an existing sinkhole can be considered appropriate. Unfortunately, sinkholes fall to natural temptations to improve land usability and value by filling any inconvenient depressions. They offer the added benefit of very convenient disposal sites, and

Figure 11.12. Uncontrolled landfill in a small subsidence sinkhole in the covered karst of Newfoundland, Canada.
Photo: Derek Ford.

numerous sinkholes around the world are filled with uncontrolled waste of all kinds (Figure 11.12). Under any attempt at control, engineered liners would prove excessively uneconomical in most sinkholes, if they were intended to achieve long-term stability. Even if a liner could be installed in a sinkhole, leachate drainage is impossible without expensive maintained pumping.

An even greater pollution hazard is created by illegal dumping of waste into open sinkholes. Sinkholes are frequently filled by farmers with relatively inert rubbish, though too many have a rich mixture of animal carcases that contribute foul and undiluted liquids to the underlying aquifer. Even more hazardous is the illegal practice of fly-tipping, where all manner of waste is dumped out of sight, usually during nocturnal visits. Sinkholes adjacent to country roads are especially prone to fly-tipping (Figure 11.13), and a tanker-load of cyanide waste dumped down a roadside sinkhole in the Mendip Hills karst of southern England is only the most horrific of many examples. In such situations, the best hope is that the target site is an old solution sinkhole or a mature subsidence sinkhole that has a substantial thickness of soil on its floor and choking its drainage outlets. After 14,000 litres of diesel spilled into a sinkhole from a traffic crash on the freeway across Kentucky's sinkhole plain, treatment of the sinkhole soil recovered only part of the lost fuel (Stephenson *et al.*, 2003). Flow paths and conduit routes are well known in this karst (Quinlan and Ewers, 1989), but none of the diesel reached

Figure 11.13. Fly-tipping of waste in a deep caprock sinkhole that is conveniently adjacent to a moorland road across the Llangattwg interstratal karst, U.K.
TW.

down-flow monitoring sites. It would appear that the unrecovered fuel was attenuated within the thick soil of the sinkhole, but the same could not be anticipated for the great majority of karst sinkholes.

A sample study in the karst of Virginia found more than fifty dumps in sinkholes, even though state law specifically prohibits dumping refuse, garbage and dead animals in caves or sinkholes (Slifer and Erchful, 1989). The statistics suggest that there are more than 1,300 sinkhole waste dumps in Virginia, of which over 600 are likely to represent a serious threat of aquifer pollution. While such statistics are not available for karst regions worldwide, the Virginia figures would appear to indicate the scale of this sinkhole hazard in many or all karst terrains, especially those that are semi-urbanised or densely populated.

12

Construction in sinkhole terrains

Lowland terrains of soil-mantled cavernous karst provide some of the worst conditions possible for civil engineering and construction. The soil cover may not offer a sound foundation medium because it can fail slowly or rapidly by suffosion into the underlying karst, with consequent development of destructive subsidence sinkholes. Foundations carried to bedrock avoid this sinkhole problem, but encounter the twin difficulties of extremely irregular rockhead profiles and the possibilities of open caves that may collapse within the bedrock. An engineering classification of karst ground conditions (Waltham and Fookes, 2003) offers a general view of what sort of difficulties may be anticipated or encountered within a particular karst terrain (Chapter 10). Rockhead in juvenile karst is generally sound except for isolated fissures or shallow caves: in youthful karst, rockhead only gives rise to minor problems due to its irregularities that usually can be dealt with by the use of piles or rafts; in both karst classes, small sinkholes can be spanned by rafts or piles with reinforced ground-beams. Pinnacled rockhead in complex and extreme karst may mean that piles are required to found buildings or structures in competent rock; caves commonly extend to 10 m or so in width, and therefore necessitate adequate probing below pile tips and may need filling with mass concrete.

For any construction site, the engineer has to choose between founding structures within the soil profile or on bedrock. The options are usually dictated by the thickness of the soil cover, the complexity of the karst with respect to cavity and rockhead profiles, the drainage conditions that may influence the site's susceptibility to development of subsidence sinkholes, and the scale, value and sensitivity of the built structure.

12.1 CONSTRUCTION ON SOIL OVER KARST

In the densely populated lowland terrains, where the largest share of construction activity proceeds, most areas of karst are mantled by soil covers more than a few metres deep. In these areas most small buildings and nearly all roads and railways are founded within the soil, by reason of economics. Large or sensitive structures are founded on bedrock, regardless of its depth, and most karst terrains with thinner soils are in upland regions where construction activity is less. There are various types of ground treatment that can be used to enhance the behaviour of the soil cover (Chapter 11), but engineering works have to continue on the soil profile while ensuring that new subsidence sinkholes do not and can not undermine or reduce the integrity of the new structures.

12.1.1 Control of drainage

The vast majority of new sinkholes, formed as subsidence features within the soil profile, are induced by man's activities, largely by disturbing the natural ground drainage (Chapter 8). The prime concern of every engineer working on karst is therefore to control the site drainage. The key factor is proper disposal of all storm-water, especially that off built structures, so that it is carried off-site or is channelled directly into bedrock. Where drainage is allowed to infiltrate the soil profile, it will eventually and inevitably drain down into bedrock fissures, thereby causing suffosion of the soil, and ultimately the development of subsidence sinkholes. On any site in a karst terrain, except in some juvenile types of karst, design codicils should ban soakaway drains, require the use of flexible lines and junctions on all water and drainage elements and require diversion of all inbound drainage flows. However, soakaways or dry wells can be used if they are sealed into open fissures and cased below rockhead. Sites should be landscaped in such a way as to prevent concentrated ingress or ponding of water. The backfill in service trenches should be compacted so that it has a permeability close to that of the surrounding ground. Storm-water ditches and canals should be lined over critical areas and should discharge well away from any development, and water-retaining structures should be underlain by impermeable membranes to prevent accidental infiltration into the ground.

The large areas of impermeable black-top on any major highway can shed massive quantities of run-off that must be captured by effective drainage to avoid infiltration to the soil all along the highway shoulders. Engineered options include paving of drainage ditches, lining the interface between subgrade and sub-base, and also the sides of the pavement box, with an impermeable membrane, and installing sub-base drainage into managed catch basins (Moore, 1984, 1988). Natural sinkholes can be utilised to dispose of storm-water, as long as they are regularly cleaned of any debris that might impede drainage into them. Many are lined or filled with chunk rock to maintain their stability when large flows drain into them, and many others are engineered with debris traps and conduits through the soil cover (Figure 12.1); it is essential to ensure that their subsurface structure carries drainage directly to bedrock without scope for diversion into the soil (Figure 8.4). It is also better that disposal wells constructed in existing sinkholes should be remote from buildings.

On highways and building projects alike, pipelines, storm sewers and culverts should not be bedded in permeable material such as crushed rock since this provides

Figure 12.1. A shallow sinkhole in Bowling Green, Kentucky, engineered to take storm-water drainage from an urban area directly into an underlying limestone cave without eroding the soil cover.
TW.

a conduit for adjacent surface drainage. Inadequate or inappropriate site drainage is usually disastrous over time (Section 8.1). Flexible plastic pipes are appropriate for many modern service installations over karst, as the breakage of old clay-pipes by the smallest movements induced by small-scale suffosion creates a water input, increased suffosion and an inevitable sinkhole within the soil profile. Soil voids and incipient subsidence sinkholes are commonly intercepted during trench excavation for wastewater, storm-sewer and fuel pipelines. As soon as a void is exposed, it should be inspected so that remediation can be designed to maintain the integrity of any buildings or structures on site, while at the same time preserving the hydrogeological character of the void to minimise impact on the quality of groundwater resources (Pope, 2001). Appropriate remedial measures include sealing the face of a trench with concrete, installing a durable PVC pipe across the base of the trench to permit continued drainage flow across, or encasing wastewater or storm-sewer pipes in concrete along the length of a void plus 1.5 m at either end.

12.1.2 Foundations within the soil over pinnacled bedrock

Spread footings, as either pads or strips, distribute the load of a structure to the subsoil over an area sufficient to suit the ground properties; their sizes are therefore increased for higher loading and on weaker soils. They usually provide the most economical type of foundation structure, but the allowable bearing pressure must be chosen to provide an adequate factor of safety against shear failure in the ground and also to ensure that settlements are not excessive. Spread footings are commonly appropriate on firm to stiff residual soils and also on alluvial soils that floor many solution sinkholes, but they can cause excessive settlement on some soft, compressible, residual soils on karst. The major hazard on karst is where they can lose integrity if a soil cavity migrates upward to develop below them.

A problem that may arise due to loading by a building or structure where the rockhead is pinnacled is that of differential settlement, especially where large pinnacles extend upwards into a soft soil. A stiff soil between tapering pinnacles forms a down-facing wedge that may offer additional resistance and support. However, where pinnacles or floaters (broken pinnacles forming blocks within the soil) approach the surface, differential subsidence may be significant. If the soil's potential compaction suggests that differential movement may be 10–25 mm, a building of flexible construction may be appropriate. Many houses on the soil-covered karst west of Tampa, Florida, stand safely on conventional shallow spread footings, notably where the soil cover has been shown by ground radar survey to be free of any ravelling failures.

A single-story commercial mall covering 70,000 m^2 on karst near Clarksville, Tennessee, provides a fine example of construction on shallow foundations (Vandevelde and Schmitt, 1988). Within the 57 ha site, 29 sinkholes included a few wide solution dolines, many suffosion sinkholes and some small dropouts; surface run-off was towards these sinkholes, until it was re-directed to a number of them away from the buildings, where disposal wells were installed. The buildings were designed with steel frames and masonry walls on spread footings bearing on firm to stiff residual soils or on compacted structural fill. After the site had been stripped, the subgrade in the building and pavement areas was proof-rolled with a pneumatic-tyre roller, which was also intended to reveal any unsuitable ground conditions and incipient dropouts. The subsidence sinkholes were cleaned out, plugged and back-filled (Section 11.2), and the excavation was brought up to grade with compacted residual soil. Potential settlement of most of the buildings was estimated to be < 20 mm, but would be greater where compacted fills had been placed; where fill was more than 15 m deep, settlement of 75–130 mm could take place. At sites of maximum settlement, it was recommended that walls and floors had flexible joints, service pipes were assembled with extra care and detailing was appropriate for such subsidence (I.C.E., 1977).

12.1.3 Extended foundations on rafts and mattresses

A raft permits construction of a satisfactory foundation in materials whose strength is too low for the use of spread footings. Its chief function is to spread the building load over a maximum area of ground and thus reduce the bearing pressure to a minimum. In addition, a raft provides a degree of rigidity that reduces differential movements in the superstructure, and is capable of spanning small new subsidence sinkholes that may develop in the soil beneath it. Critical to its integrity in spanning new sinkholes is the extent of reinforcement within the concrete (Figure 12.2); this is designed in conventional manner with respect to the anticipated load and to the maximum unsupported span that can be anticipated. A raft can provide adequate support for a building founded on variable soil conditions across natural fills in old

Figure 12.2. Double weldmesh reinforcement for a concrete slab, cast as foundations for an ornamental lake with a bridge and pagoda, on deep soils over pinnacle karst at Shilin, southern China.
TW.

sinkholes or across placed fills in younger sinkholes, though it is still desirable that fills should be properly compacted when placed.

To be most effective, rafts should be laid on beds of granular material to reduce friction between the ground and the structure. Post-tensioned rafts have been found to tolerate more than 25 mm of differential movement under individual houses built on unstable soils over karst limestone around Tampa, Florida (Kannan, 1999). These were placed on soil stabilised to a nominal depth of 3–5 m. This scale of movement would not have been tolerated by conventional strip footings, but excessive movements can also break a light raft. Some of the worst sites, where ravelling and suffosion of the soil indicated significant potential for new sinkhole failure, were given additional treatment by compaction grouting above rockhead.

A reinforced raft will be able to span or cantilever over unsuspected small cavities and sinkholes that develop beneath them. For low buildings, up to four stories in height, it may be possible to use an external, reinforced, ring beam around a central raft that is only a lightly reinforced raft, as a practical and economical foundation structure. Stiff reinforced concrete rafts were used as foundations for houses at a site in southern England, where a number of pipes of different diameters occur in the chalk (Rhodes and Marychurch, 1998). The rafts were designed to span 3 m if a pipe collapse occurred within the footprint of a house, and to cantilever 1.5 m at the edges. Even so, a house plot generally was rejected if a pipe was found within the plot that was greater than 2 m in diameter.

Extensions to foundations can improve their ability to span small new sinkholes that may develop beneath them. Beams of reinforced concrete connected spread footings, to form a rigid frame supporting a large house on karst in Nashville, Tennessee, after three small subsidence sinkholes developed during the ground works phase of construction (Mishu *et al.*, 1997). The same concept can extend to bridge foundations. A new bridge carries the Ripon bypass across the River Ure, on the gypsum karst of northern England, and was therefore designed and built with protection against any future ground subsidence (Cooper and Saunders, 2002). The bridge has a strengthened heavy-duty steel girder construction on supporting piers with oversize foundation pads that can span a future small subsidence feature. Furthermore the design incorporates a sacrificial concept, so that it will withstand the loss of any one pier without collapse. Some highway bridges in Pennsylvania stand on shallow foundation pads within the soil, after cap grouting of the rockhead to mitigate against subsidence due to soil suffosion into open fissures in the limestone (Knott *et al.*, 1993). These bridges are stable, but others in the same state have failed where sinkholes have undermined shallow footings (Box 8.2).

A cellular raft can be built to a sufficient depth that the weight of excavated ground equals the weight of the building, which therefore imposes no structural load. These foundations are described as buoyant, compensated or floating, and should give rise to no meaningful settlement. They can be used in karst terrains where there are deep residual soils that are soft and highly compressible, but their ability to span a new sinkhole opening beneath a building is largely a function of the extent of reinforcement within the structural concrete.

Engineered mattresses of compacted soil have been used where the natural soil mantle is of variable nature and/or thickness above pinnacled karst bedrock. A mattress limits both total and differential subsidence by spreading the imposed load to an acceptable level on the underlying soil. It constitutes a relatively impermeable layer, thereby limiting the ingress of water, and so reduces the risk of subsidence sinkholes developing. It also forms a relatively strong layer that may bridge any small cavity that develops beneath it, especially if the compacted soil is reinforced by geogrids. Mattress design relates to the thickness and geotechnical properties of the soil, and also to the sensitivity to subsidence of the planned structure. The method of construction depends on the site conditions and the fill material available.

Experience in South Africa has shown that sites over shallow pinnacled rockhead, where gravel or waste rock is available as fill, are best treated by excavat-

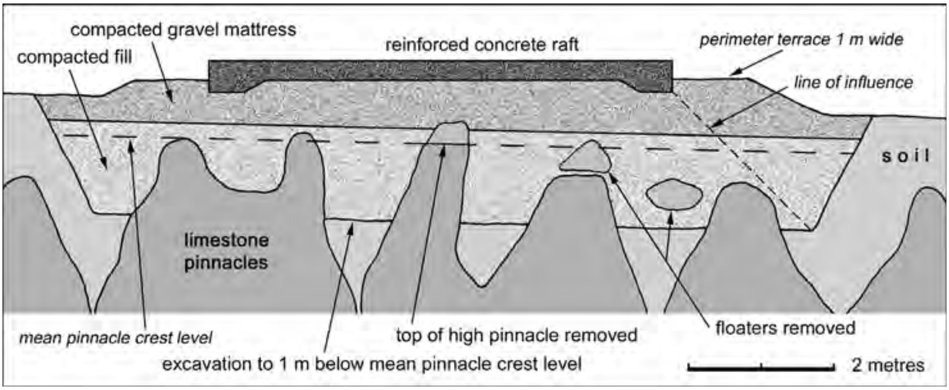

Figure 12.3. An engineered gravel mattress that extends over bedrock pinnacles and intervening soil-filled fissures.
After Wagener (1985).

ing the soil cover to a depth of 1 m below the tops of pinnacles and removing all floaters (Wagener, 1985). At some sites it may be necessary to remove by blasting the tops of pinnacles that protrude above their general level. Additional excavation may be required where pinnacles are spaced far apart, or where soils are very loose. The base of the excavation is first levelled, and then lifts of fill are placed and compacted with a small vibratory roller. A layer of waste rock is placed about 200 mm above the tops of pinnacles and similarly compacted. Uncontrolled ingress of water must be avoided during compaction, and ten passes of the roller is usually sufficient. Soilcrete or lean mass concrete can be used as an alternative to waste rock. Then, the mattress is built up to the required level (above ground level to provide good drainage) preferably using selected gravel compacted to 95% modified dry density (Figure 12.3). Alternatively, houses can be founded on light rafts with thickened edge beams on mattresses of lesser thickness. On sites with a thick soil cover over the pinnacles, mattresses consist of properly compacted gravel or waste rock, provided the latter is capped by a layer (greater than 1 m thick) of less permeable material to limit water ingress into the underlying karst.

12.1.4 Sinkhole flooding

Storm events can cause the temporary flooding of sinkholes where their capacity to drain to bedrock is exceeded. This can threaten infrastructure and development that occupies the wide solution dolines, depressions and sinkholes in lowland polygonal karst. It is a significant hazard on Kentucky's Sinkhole Plain. Most sinkhole flooding occurs where the internal sinks are choked with debris and/or sediment, where catchments have been increased by development works, or where back-flooding emerges from conduits impeded by sediment or breakdown. The latter may be uncontrollable without implementation of major engineering works; some large

Figure 12.4. A shallow sinkhole within a car park in Bowling Green, Kentucky; drains within the road surface carry storm water directly into the limestone, but their limited capacity makes flooding inevitable after heavy rainstorms.
Photos: TW and Alan Glennon.

karst depressions and poljes in both western China and Bosnia are now drained by tunnels where they can feed into adjacent depressions at lower altitudes. The first two causes of sinkhole flooding may be reduced or eliminated by appropriate drainage management that is initiated during site development.

In most terrains of polygonal karst, storm drainage cannot be completely removed, and it must be directed into available sink points within the natural sinkholes. Selected sinkholes can be engineered to behave as retention ponds (Figure 12.1), as topography generally limits the scope for built retention ponds. These and all other sinkholes may require engineering of their internal sinks so that they become efficient disposal wells that transfer drainage directly to the karst conduits; they must avoid imposing flows through the soil cover that could promote development of new subsidence sinkholes (Figure 8.4). Failure to maintain the drainage outlet can allow frequent flooding of the sinkhole, which may be acceptable in agricultural land or in car parks (Figure 12.4) but cannot be tolerated where buildings are placed.

Increasing urbanisation accelerates run-off from impermeable surfaces, thereby increasing flood frequency in sinkholes, and requires detailed planning to protect new and existing structures (Kemmerly, 1981). Measures that have been used to control sinkhole flooding include the construction of channels to drain into sinkholes, the installation of drain pipes into sink points, the transfer of stormwater from one sinkhole to an adjacent drainage basin or sinkhole, the installation of grids and gabion filters to prevent debris blockages and the enlargement of sinkholes by excavation to increase drainage or retention capacity (Crawford 1984, 2001; Moore and Amari, 1987; Barner, 1999). Urban development on karst around Springfield, Missouri, led to the city adopting an ordinance that would protect the drainage capacity of sinkholes and prevent their flooding. This included the requirement for a hydrogeological report, prior to any proposed construction works, that assesses the susceptibility of the cover soil to erosion, the relationship between sinkholes and the overall drainage area, the capacity of sinkholes to take storm-water and the impact of the construction works on sinkholes. It also prohibited buildings within the sinkhole floodplain areas, prohibited installation of basements, banned the use of heavy plant that may compact soils and reduce the permeability of sinkhole floors, demanded reinforcement of foundations and required wider easements between buildings. Where measures were not implemented correctly, periodic sinkhole flooding has persisted (Barner, 1999).

12.2 ROADS AND RAILWAYS ON KARST

Most highways, both road and rail, across lowland karst are founded on the soil cover, as economics generally preclude extensive foundations to bedrock. In mountainous karst terrains, highways are commonly cut into rock. They may therefore encounter almost any kind of foundation requirements and may require precautionary works with respect to both subsidence sinkholes in the soil profile rock cavities and open cavities within karst bedrock.

Construction of a series of motorways in the classical karst on the limestone of Slovenia encountered many difficulties with caves and sinkholes in bedrock (Case study #3). Many caves were found when they collapsed during blasting operations; they were either capped with concrete slabs (Figure 12.5), or were filled after any interior sediments had been removed and replaced by compacted rubble (Slabe,

Figure 12.5. Solution sinkholes exposed during construction along a highway footprint in Slovenia, one cleaned out ready for filling, the other with a concrete plug forming its floor. Photos: John Gunn.

Figure 12.6. A sediment-filled cave in the wall of a road cutting in Slovenia, seen when it was first exposed and later with a masonry wall across its sediment fill.
Photos: Tadej Slabe.

1997; Knez and Slabe, 2002b). Caves exposed in the sides of road cuttings were walled up to avoid rock fall (Figure 12.6).

Ground investigation for a major road improvement in England revealed pipes in weathered chalk, both at outcrop and beneath the cover of Tertiary and Quaternary sediments. The pipes, up to 20 m in diameter and 7 m deep were filled with clays, sands and gravels derived from cover sediments (Rhodes and Marychurch, 1998). Where pipes of less than 1 m diameter occurred beneath bridge sites, the infill was excavated and replaced by structural fill or mass concrete. Pipes up to 8 m across were spanned by reinforced concrete rafts, with diameters double that of the pipes, transferring the load to the adjacent chalk. Where a pipe was wider than 8 m, a bridge was founded on piles into chalk no closer than two pile diameters beyond the pipe to avoid pile–pipe reaction. A geogrid-reinforced granular blanket was used to support embankments over small pipes filled with medium dense sands and gravels. Smaller pipes with a soft cohesive fill beneath embankments were covered by a concrete cap, and soft fills in larger ones were improved with vibro-replacement stone columns capped by geogrid mattresses.

Deep soil-filled fissures (grikes) in strong limestone may require grouting or filling with mass concrete. Alternatively, a graded rock-blanket formed beneath subgrade level throughout a fissured zone can prevent the loss of sub-base material and minimise the effects of strains in the surfacing materials. While grouting, sealing or capping fissured karst may stabilise the ground immediately beneath a highway, it may also divert local drainage to initiate formation of new subsidence sinkholes in adjacent land. Placing of a new highway embankment may act in a similar manner, and may also cause its own undermining by new sinkholes if it is permeable and has no controlled internal drainage. Successful design was applied to a road through cone karst in Puerto Rico that had to cross 12 large solution dolines between the cones; each of these had active drainage through its soil floor into the limestone beneath (Vasquez Castillo and Rodriguez Molina, 1999). It was appreciated that the new road embankments should not impede the natural drainage, so the dolines were investigated individually, by drilling, geophysics, dye tracing and pump testing, to estimate their drainage capacities and storage requirements. Soft sediments were then cleared from the road footprint across the doline floors, and were replaced by geotextile-lined filters that transferred highway drainage efficiently into the limestone. Unstable cavities in shallow bedrock were collapsed by surcharge loading prior to construction of the embankments, which have subsequently retained integrity.

At some sites on mantled karst, adequate soil stabilisation may be unrealistic, and the expensive alternative is founding a road or railway on deep bedrock. For many years a railway trackbed stood on soils 10–20 m thick over karst limestone in the coastal plain of North Carolina. A new reservoir, on the soil cover and behind a 10 m high earth dam adjacent to the railway, then modified the local drainage regime and within two years of impoundment initiated numerous subsidence sinkholes around and underneath the trackbed (Erwin and Brown, 1988). As more sinkholes developed through the soil cover, temporary repairs and diversions over a period of 14 years, involved sinkhole filling, bedrock grouting, dynamic compaction of the cover and temporary draining of the reservoir. The railway is of military strategic importance, so a permanent solution was sought; it was rebuilt on a land bridge, 1,240 m long, across the entire sinkhole zone. This stands on bored piles (caissons) 1,200 mm in diameter that were founded on rockhead or were drilled up to 5 m into bedrock; probing established 1.5 m of sound rock under each end-bearing pile and no voids more than 150 mm high in the next 1.5 m of underlying limestone. Despite drilling dry for the piles, eight sinkholes, the largest 9 m in diameter, developed during construction works; these were simply filled with compacted soil, as the piles did not rely on soil pressure for lateral support.

Pipelines are increasingly being built as efficient modes of bulk transport. When buried in the soil they impose very modest additional loads on ground, and their main impact on a karst terrain is likely to be the disturbance during their construction. The new oil pipeline from the Caspian Sea to the Mediterranean crosses the gypsum karst near Sivas, Turkey, where a sinkhole hazard was recognised and evaluated during route selection. Small subsidence sinkholes pose no risk to the pipeline, but a few large natural collapse sinkholes are known in the area (Figure 3.18). Though the likelihood of a large collapse was considered to be very small, the consequence of such an event would be very serious, because a pipeline fracture over a new sinkhole would be economically disastrous and environmentally catastrophic. Maximum collapse width in a single event was considered to be 25–40 m, and the pipe, 1.067 m in diameter, was modified to a steel thickness of 22.6 mm as a precautionary measure for the entire route across the karst, so that it could safely span 44 m, even with a worst-case soil wedge balanced on the exposed pipe (Arthur *et al.*, 2004).

12.2.1 Geogrid as a sinkhole defence

Synthetic plastic reinforcement incorporated within a road structure offers an economical alternative to placing concrete slabs where soil and sub-base undermining by new subsidence sinkholes is a perceived threat (British Standards, 1995). Though geosynthetics are available in various forms, heavyweight geogrid is most applicable

Figure 12.7. Heavy paralink geogrid being rolled out onto a road sub-base as a protection measure against sinkhole development in the underlying soil.
TW.

to bridging sinkhole voids (Bonaparte and Berg, 1987); it is produced with tensile strengths up to 400 kN/m along its length (and typically 40 kN/m across its length). Geogrid can be rolled out during sub-base construction to cover any area prone to sinkhole failure (Figure 12.7).

A programme of full-scale tests and numerical modelling showed the value of geosynthetic sheets with a tensile strength of 200 kN/m in spanning dropout sinkholes up to 4 m across (Villard *et al.*, 2000). The material is now used under sections of trackbed for France's TGV high-speed railway. The same study also found that the surface subsides as a shallow dropout where the geosynthetic lies beneath a cover thickness less than 75% of the underlying void width, while soil arching supports an undisturbed surface over a thicker cover (Figure 12.8). In either process, the geogrid delays surface collapse, and thereby provides a window of opportunity for remedial action before any suffosion sinkhole can increase in size, though it cannot be relied on to span large dropout failures.

The new Ripon bypass was built across gypsum karst in northern England, where new sinkhole events average one per year within an area of a few square kilometres. The road line was constrained by topography and existing land use. Grouting of cavities proved not only impractical, because of their size, but also undesirable, as it would have led to accelerated dissolution of gypsum under adjacent ground (Cooper and Saunders, 2002). Geogrid was therefore incorporated in the roadbed structure, designed to provide support for at least 24 hours after being

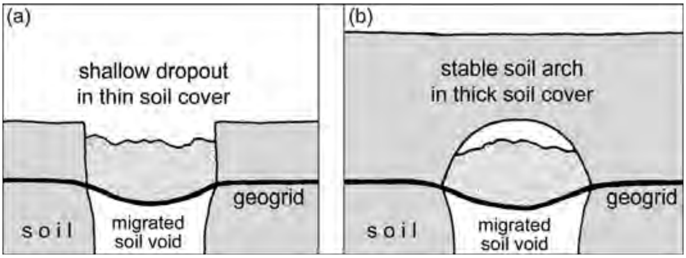

Figure 12.8. Sinkhole prevention by geogrid installed within soil profiles: (a) development of only a shallow dropout where cover is thin; (b) development of a soil arch in a thick soil over the geogrid.
After Villard *et al.* (2000).

undermined by any new sinkhole subsidence. A cluster of 51 small subsidence sinkholes in glacial drift were found during upgrading of Britain's North Wales Coast Road across a limestone outcrop (Nichol, 1998). Loose material was removed from sinkholes within the road footprint and was replaced by crushed rock or concrete, and drainage outfalls were directed into surface watercourses away from the zone of subsiding ground. Heavy geowebbing was then installed 1 m below the road surface along the complete section affected by sinkholes, and this has ensured that two subsequent subsidence events developed so slowly that remediation of the causative new sinkholes could be taken before they threatened road traffic.

While geogrid installed beneath a road may be invaluable for eliminating the sudden appearance of a sinkhole, it does not constitute a complete repair of a new or existing sinkhole (Section 11.2). Within a long-term repair of a large sinkhole in thick soil, geogrid can only serve as a warning mechanism where the perceived risk of subsequent reactivation does not warrant the cost of a large concrete slab.

12.3 FOUNDATIONS ON KARST BEDROCK

A characteristic of karst terrains is that the rock surface where exposed, or the rockhead beneath a soil cover, may be extremely irregular, with deep fissures, cutters or grikes between residual blocks, clints or pinnacles of intact rock. Typical cavernous limestones are strong enough that structural loads can be placed on most pinnacles, as long as they are not detached, undercut or cavernous. Where numerous pinnacles occur near the ground surface, a raft of reinforced concrete can be used to span between pinnacles. This extends the concept of the soil mattress (Figure 12.3), except that the entire structural load may be borne by the rock pinnacles. Such a raft is normally only feasible where the soil cover is less than 3 m thick. A reinforced raft also retains its integrity when soil is subsequently washed out of the fissures by unintended input of drainage (Figure 12.9). Most bridge footings within Pennsylvania are founded on spread

Figure 12.9. A concrete foundation, directly on dolomite bedrock in South Africa, that has retained integrity after an open fissure has been exposed beneath it when its soil fill was washed out.
Photo: Dave Haskins.

footings or mats placed directly onto limestone where it lies under less than about 3 m of soil (Knott *et al.*, 1993). Prior to construction, any irregularities in the bedrock surface had been filled with lean concrete, to provide more uniform support for the shallow foundations.

Where soil is 3–7 m thick, a structure may rest on beams that transfer loads to short piers down to the tops of individual pinnacles. If this type of foundation is used for larger and heavier structures, it is necessary to proof-drill the pinnacles (Partridge *et al.*, 1981). Pinnacles that are potentially undersized or unstable may require assessment by probe drilling splayed at 15° from the vertical from the point of foundation (Foose and Humphreville, 1979). Extension beams can be incorporated into a raft to transfer its load to available pinnacles where they are lacking at critical locations (Figure 12.10). A television station in South Africa was founded on a grid of beams that included extensions to reach stable pinnacles outside the building's footprint (Figure 12.11). Fortuitously, the pinnacle tops were at a uniform level on

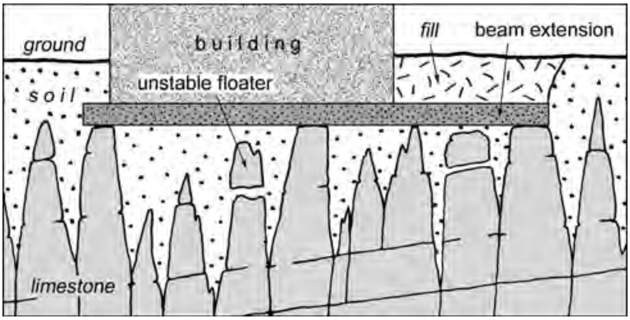

Figure 12.10. Foundation raft or ground beams with extensions to reach stable rock pinnacles in a deeply fissured limestone rockhead.

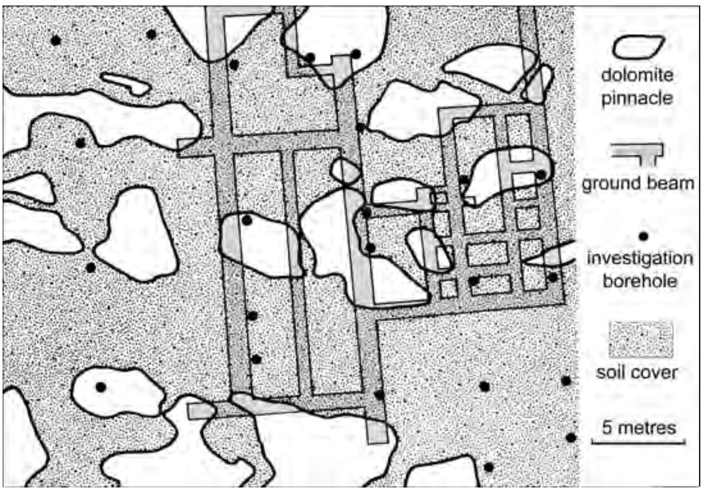

Figure 12.11. Plan view of ground beams designed and extended to reach stable dolomite pinnacles to support a building at Zeerust in South Africa; soils reached more than 20 m deep between the pinnacles.
After Brink (1979).

an old erosion surface, and were completely exposed by removing just 1 m of soil cover, leaving soils that reached depths of at least 20 m between the pinnacles (Brink, 1979). Massive concrete rafts, reinforced with steel girders, support a power station in Illinois by bridging over fissures and weak soil zones between pinnacles of sound limestone (Swiger and Estes, 1959).

The alternative to spreading loads onto available pinnacles is to improve the ground beneath individual footings or piles. The most common means of rock reinforcement is by dentition, whereby concrete or masonry infill is placed in open fissures and cavities in or just below rockhead (Figure 12.12(a)). Deeper fissures may be cleaned of soft soils before being packed with permeable backfill prior to capping

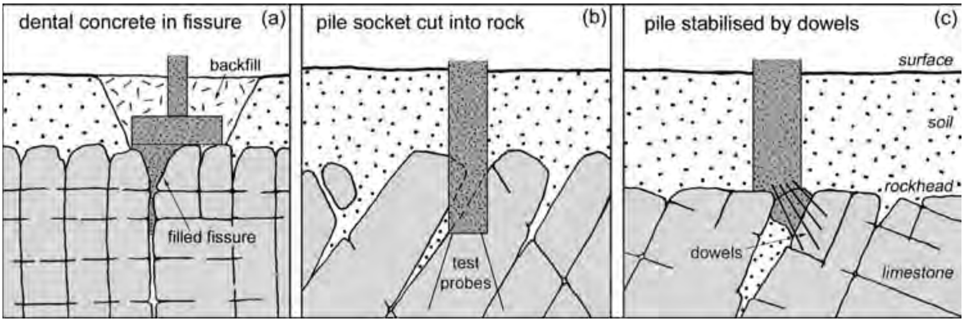

Figure 12.12. Pile integrity in karst achieved by treatment of rockhead fissures: (a) dental contrete filling in a wide fissure; (b) pile socket cut into rock and probed beneath; (c) pile stabilised by dowels through concrete fill.
After Sowers (1986).

with concrete or stonework; adequate drainage should be provided within the engineered fill. Steel dowels up to 3 m long may be drilled into adjacent bedrock and grouted in place to reinforced dental concrete (Figure 12.12(c)). They can be useful in thinly bedded limestone with complex fissure patterns where low loads are needed to increase stability and where the discontinuity surfaces are at least moderately rough. Deformation in the rock mass loads the untensioned dowels until sufficient stress is developed to prevent further strain. Pre-tensioned rock bolts, up to 8 m long, may be used as reinforcement to enhance the stability of discontinuous carbonate rock masses, however, their normal purpose is to induce compression in the rock mass and thereby improve shearing resistance on potential failure planes, so their application is limited in karst with open or soil-filled fissures. Every karst site is different, and many sound structures are site-specific adaptations (Sowers, 1986).

Integrity of individual footings that bear onto bedrock is only assured where sound rock has been proven beneath their loading points to a depth adequate to span any unseen cave within the karst rock. Depths to which drilling or probing must prove intact rock relate to the intact and mass properties of the karstic rock, and guidelines related to rock types can only be approximate due to the extremely variable nature of karstic ground (Table 7.1). Though rigorous proving of rock is essential under pad foundations that impose high point loads on the rock, the same does not apply to strip or raft foundations that are adequately reinforced. These distribute loads onto sound rock and are able to span small voids, and the same applies to structures on multiple pad footings that incorporate sacrificial design, whereby any one can fail while the structure retains integrity. Wide caves at shallow depth create the main hazard where stable arches cannot develop in their roof profiles, and these may require filling with concrete (Section 11.1.1). Where the cave has to continue to carry drainage, partial filling may be required, and this is normally only practicable where the cave is accessible, either naturally or by an engineered entrance (Figure 12.13).

The poorly cemented Miami Limestone, which is widespread in southern

Figure 12.13. A masonry wall built beside the underground stream inside the St. Augustine's Cave in Ireland in order to reduce the unsupported span beneath a main road that stands on a concrete slab.
TW.

Florida, may lose much of its strength in the weathered zone, and so not present the strong rockhead that is typical in most karst terrains. Low-rise concrete buildings have exhibited major settlements with foundations on this soft, porous, oolitic limestone where it has been subject to dissolution, leaving it leached and highly porous, with little induration remaining in the 2 m below rockhead (Sowers, 1975). One building was surrounded by a crack in the more intact surface crust and settlement exceeding 100 mm was recorded. Standard penetration tests (SPTs) carried out at the site revealed blow-counts of 1–2 for the weakened limestone. Reinforced rafts can be used at such sites, but end-bearing piles would require founding on a deeper horizon of higher strength. Though these conditions do not apply on limestones with high intact strength that form most karst terrains, they are replicated in the softer chalks of northern Europe and also in some younger and poorly indurated coralline limestones that form coastal karsts and raised terraces.

12.3.1 Driven piles and pin piles

Where the soils beneath a proposed structure cannot provide adequate support, the structural load can be transferred to the underlying bedrock by means of piles. Driven piles of steel H-section or small-diameter concrete can be hammered through the soil profile, until they meet refusal at or close to rockhead. Alternatively, non-displacement piles of steel or concrete can be grouted or cast into pre-drilled

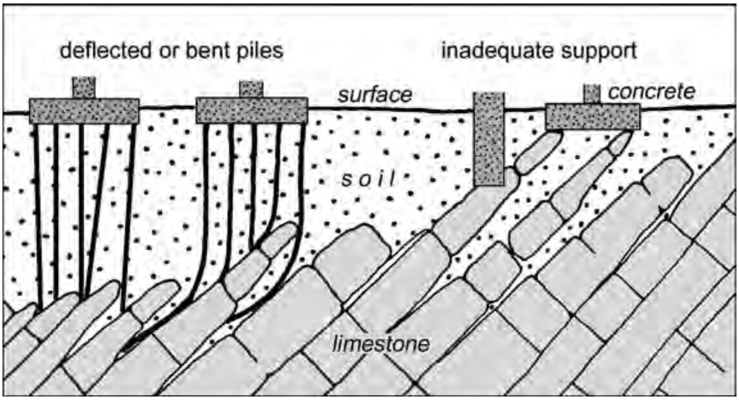

Figure 12.14. Unsafe foundations on pinnacled rockhead in karst due to deflected or bent driven piles and to footings on inadequate pinnacles.
After Sowers (1986).

holes. A third alternative is the use of large-diameter bored piles (Section 12.3.2). The choice of pile normally depends on the local ground conditions, but any type can present special difficulties in karst terrains (Wyllie, 1999).

Steel piles driven to rockhead successfully support numerous bridges on variable karst terrain in Pennsylvania (Knott *et al.*, 1993), and H-piles 350 mm in section can carry loads of over 1 MN. However, rockhead relief, with or without pinnacles, that is characteristic of karst, commonly creates difficulties in placing end-bearing piles on rockhead of strong limestone. Piles frequently have to be founded at different elevations, while floaters and detached pinnacles can both make pile diving difficult and also threaten pile integrity where driving refusal on them leads to their mistaken interpretation as sound rockhead (Figure 12.14.). Driven piles may fail to find a sound footing on sloping rockheads, where a tendency to move along open fissures or pinnacle faces can cause bending of steel piles and deflection of concrete piles, especially in steeply dipping limestones (Sowers, 1975). There may be occasions on driving high capacity piles, when the pile continues to penetrate slowly under repeated hammer blows. It is difficult then to determine whether the pile is progressively fracturing, the pile tip is crushing or the pile is bedding into the rock, though dynamic pile driving analysis, which measures wave propagation generated by each hammer blow, may help interpret what is happening (Sowers, 1996).

Non-displacement piles are formed by drilling holes, then inserting steel H-beams or narrow rebar structures, and filling with concrete. Also known as pin piles, minipiles or micropiles, they can be used in karst ground where it is uneconomic to install driven piles. They normally have diameters of 125–300 mm, consist of steel reinforcement with cement grout, and gain their supporting capacity largely from skin friction (Tarquinio and Pearlman, 2001: Dotson and Tarquinio, 2003). Steeply sloping rockhead surfaces can easily deflect a drilling bit, so drilling should progress slowly and carefully to allow the bit to cut into the bedrock, after which a normal drilling rate can be resumed. Holes may be lined with casings that are or are not left in place. Casings can prevent loss of concrete into karst voids when casting or grouting a pile into a drilled hole. Alternatively, uncased holes can be useful where voids require to be filled simultaneously with the pile grouting. Holes through soil and floaters may collapse during drilling, thereby preventing any casing being installed down to rockhead, so an eccentric bit can be used to produce a larger hole with the casing being installed simultaneously.

A benefit of micropiles is that they distribute structural loads and may therefore perform well where karst offers non-uniform and potentially cavernous ground conditions. Heavy silos were to be placed on bare limestone karst in Greece, but a programme of compaction grouting failed due to heavy losses of grout with minimal benefits (Sotiropoulos and Cavounidis, 1979). They were therefore successfully founded on 1,256 micropiles of 800 kN capacity, 142 mm in diameter, averaging 11 m long and each taking 1–4 tonnes of grout. They were also used in covered karst in Tennessee, where soft soils, 6–9 m thick, overlie strong limestone that contains open caves (Heath, 1995).

It may be argued that piles should only be used in karst areas when other foundation structures are not feasible. Though piling may be difficult in karst, end-bearing piles have the benefit of transferring structural loads to bedrock and thereby avoiding the major hazard from subsidence sinkholes in unstable soil cover. Piling through ground in which there are notable voids may precipitate collapse of the voids and in turn lead to piles being buckled or even sheared, but any piling in bedrock creates safer foundations than those found in the soil over the same cavernous ground. However, it may be inadvisable to use piles in ground that contains beds of cavernous gypsum, because its relatively rapid dissolution could create new voids and so destabilise a piled structure (Cooper, 1998).

The lateral stability of piles passing through collapsed zones or through large voids is also open to question. Cast pin piles have been placed successfully through caves in Greece by using expanding sleeves to contain concrete columns within the voids, while not filling the entire cave systems at unnecessary expense (Sotiropoulos and Cavounidis, 1979). The pin piles were used to transfer loads through caves found within 4 m depth beneath the base of large-diameter caissons supporting bridge piers (Figure 12.15). A sleeve was lowered down the bored hole and expanded to twice its diameter when filled with concrete to create a wider unconfined column with a bearing capacity matching that of the narrower, confined pin pile. Comparable textile sleeves, without the widening capacity, have been used on micropiles (Heath, 1995). There must always be an element of doubt over the integrity of such sleeved piles through inaccessible caves, and the larger capability of modern drilling rigs means that they can generally be replaced by cased holes of larger diameter.

Piles that are placed through soil cover to a pinnacled rockhead on limestone will require to be of greatly variable lengths. Steel H-piles that are easily cut or welded can be advantageous, as pre-cast concrete piles are difficult to shorten or splice. It has been found that the mean length of end-bearing piles can be about 30%

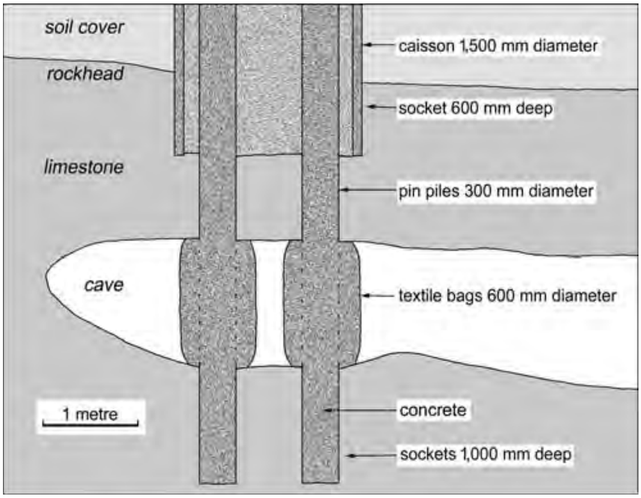

Figure 12.15. Textile bags used to form oversize concrete columns where a cast-in-place pile is bored through an open cave.
After Sotiropoulos and Cavounidis (1979).

longer than the mean rockhead depth determined during ground investigation (Foose and Humphreville, 1979).

12.3.2 Bored piles and caissons

Conventional large-diameter bored piles can be used where heavy structural loads have to be carried. Although drilled shafts may represent the only type of viable deep foundation at some sites on karst, they are expensive. Extra costs may accrue due to additional depths to reach sound rock because of the occurrence of fissured rockhead, buried sinkholes or caves, due to additional rock excavation through weathered zones, due to sloping rockhead surfaces or shale horizons or due to an inability to de-water (Destephen and Wargo, 1992). Also known as caissons or piers, bored piles are normally 1–2 m in diameter and carry loads of 1–5 MN. Most cavernous karst limestone is strong enough to carry the high end loads of bored piles, once the rock is proven to be free of voids immediately beneath the pile. Some of the softer limestones, including most chalks, cannot carry such high point loads, and bored piles are commonly inappropriate on them.

Pile shafts are sunk by conventional methods, normally by large drilling machines, though hand-dug shafts are still used in some difficult ground. Once the shaft is cleaned out to reach solid ground, a rebar cage is lowered into it and the concrete is then cast in place. A casing is normally needed for temporary support through soil, but may be extracted as the concrete is placed. These piles are largely end-bearing. Though part of their load may be carried by skin friction, this is normally minimal where they are through weak soil onto strong limestone bedrock. They are normally socketed about 1 m into sound rock, and rarely need to be belled out on strong karst limestone. With their high end loads, proving of sound rock beneath them is critical in karst, where open caves could diminish or destroy pile integrity (Section 12.3.3).

High-rise buildings commonly stand on large bored piles, because no other pile type has the necessary bearing capacity. Once selected for a project, there is then normally no alternative to boring the pile shafts however deep is required to found them on stable rock. Pinnacled rockhead can therefore provide appalling ground conditions, especially where it is very well developed in tropical karst terrains (Figure 5.3). Adjacent piles on building sites in Kuala Lumpur, Malaysia, have reached rockhead at depths of 5 m and 80 m, where the first pile found a stable pinnacle, but the second passed down a deep soil-filled fissure. Even in less mature karst in Alabama, some pile borings 900 mm in diameter have encountered bedrock on one side of the hole 25 m before it was encountered on the other side, where the site happened to be over the steep wall of a karst fissure (Cooley, 2002). Such unexpectedly deep piles can be required on any site where a deep buried sinkhole breaks the rockhead, and such can occur in almost any karst (Chapter 5).

12.3.3 Proof testing for piles in karst

Cavities at shallow depth constitute a potential hazard on any karst site where structural loads are imposed. However, they are totally critical to the integrity of piles that carry large point loads onto rock, and commonly do so at depths well below the ground in areas of deep rockhead. It is therefore essential to prove the competence of the rock below the level at which any piles are founded.

At any pile site, karst limestone should be assumed to contain dissolution cavities until it has been proven otherwise. In many cases, the position at which a pile is to be sunk should be probed or drilled prior to the pile being emplaced. Where the structural design leaves no options on the locations of bored piles, it may be more economical to drill the pile shaft first, as far as a socket into sound rock, and then probe the floor for the shorter distance to prove intact rock beneath.

The depth of probing required beneath any pile site should depend on the maximum size of any caves that are likely to be present (based upon local knowledge or the class of karst, as in Chapter 2), on the bridging capacity of the rock mass (based upon rock strength and the nature of its fractures and discontinuities) and also on the load and stress to be applied. The first two factors are very difficult to assess within natural ground (Section 7.3), and therefore it is only possible to present the very broadest of guidelines that can be generally applicable (Table 7.1). Engineering practice may be based on local knowledge of specific karst areas, and should therefore produce more useful local specifications, but there are some surprising variations in available published data (Table 7.2). Guidelines that probing should reach a depth of, for example, up to three times the pile diameter below foundation level are based on concepts of the bulb of pressure and take no account of the width of an unsupported cave span; they may prove inadequate in karst terrains with large caves (Section 7.3).

A displacement pile that is driven onto or into limestone may punch through thin layers of intact rock overlying dissolution cavities. In such cases, and assuming that the pile is not damaged, driving must continue until rock of adequate strength provides the resistance for bearing capacity to be satisfied. A bored pile can be continued down through ribs of sound rock and intervening caves, though careful drilling may be needed to re-enter solid rock through any sloping floor of a large cave.

Where any cavities are revealed by a ground investigation beneath the intended site of a building or structure, then relocation to lie over non-cavernous ground is the best solution, if that is possible. If not, further investigation of the cavity or cavities may be required to determine their size and condition, and there may be benefit in using down-hole cameras. These can view either radially or axially, with focusing and rotation of the head controlled from the surface. The heads have their own light source, and some models can work under water, where ultrasonic scanners also have application in flooded caves. Once the location and dimensions of a cavity have been determined, appropriate remediation can be designed. Filling can be achieved by bulk grouting (Chapter 11). However down-hole camera images can be difficult to interpret, and if the caves are large, direct exploration after gaining access is preferable. This is particularly valuable where shuttering can be placed in a cave to prevent grout loss into areas of no structural significance, and where soft cave sediments may require removal before they can diminish the integrity of concrete poured over them.

12.4 TUNNELS THROUGH CAVERNOUS GROUND

Construction of tunnels in karst can encounter caves at any depth beneath the ground surface. Rock collapse may have already occurred or potential collapse may constitute a significant hazard, and remedial measures can match those of surface works that found on cavernous rockhead. Unstable sediment and debris is normal inside caverns, where it may require precautions and treatment comparable to surface sites that are prone to development of subsidence sinkholes. The very varied difficulties that can be posed by large caves have led to recommendations for probing ahead by up to 50 m on tunnel headings in some of Greece's karst (Marinos, 2001).

A large cavern in the path of a tunnel presents a difficult problem, and inevitably delays excavation. Particularly where excavation is by a tunnel boring machine (TBM), the tunnel may have to be relocated or diverted around a large cavern, as it is technically impossible to head a TBM out of a rock wall into an open space. A number of railway tunnels in the well-developed karst of south-west China have had to be re-routed around large caves (Chen, 1994). Some smaller caves can be filled. A cave breached at mid-height by the TBM driving the Trebišnjica hydro-tunnel, in Bosnia Herzegovina, was filled with 386 m^3 of concrete to provide a solid floor over which the TBM could advance (Milanovic, 2000). Tunnels in both China and Herzogovina have been successfully advanced over concrete arches that have been built with spans of up to 15 m inside caves. Concrete filling of caves may only be

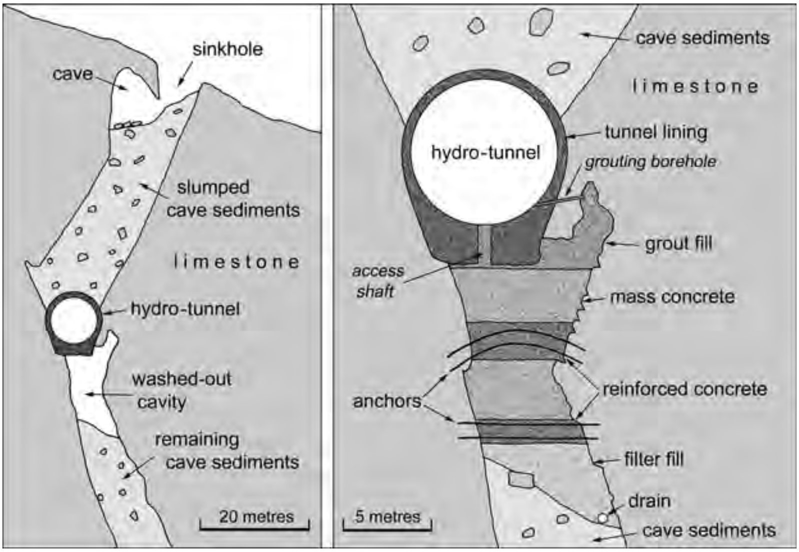

Figure 12.16. Sections through the Capljina hydro-tunnel where it passes through a filled cave in the limestone of Bosnia Herzegovina, with a detail on the right showing remedial works that were required.
After Milanovic (2000).

feasible where shuttering has been built to prevent potentially enormous concrete losses into extensive cave systems and also to prevent concrete blocking active conduits where free drainage must be maintained. Tunnels in both China and Germany have been built through open caves by retaining the tunnel lining as a protective roof, covered with a blanket of granular debris to reduce the impact of breakdown blocks falling from the unsupported cave roof.

Caves that are full of sediment may offer slightly more scope for driving tunnels through them. Advance grouting of the cave fill, either through a cone of drilled holes (spiling), or by site-specific remediation where man-access is created into the cavern, is essentially an extension of the techniques of soft-ground tunnelling. Remedial works may also be required where a tunnel passes close above a large cave with a potentially unstable roof. A tunnel driven through cave sediments may encounter problems after construction, especially where any water leaks from a hydro-tunnel. Water losses from the Capljina tunnel, part of the massive Trebišnjica hydro-scheme in Bosnia Herzegovina, caused erosion of the cave sediments through which it passes (Milanovic, 2000). Sediments washed from below the tunnel threatened its integrity over the emptied cave, and sediments washed from above opened a sinkhole at surface level. Remediation was by sinking a hole through the tunnel lining for man-access into the cave below, where reinforced arches were built inside the cave to support mass concrete placed up to the tunnel floor (Figure 12.16). The sediment above the cave was left untreated, but it stabilised when the water input was eliminated.

Though tunnels pass far beneath most sinkholes, buried and filled features can reach significant depths. Clay-filled pipes were encountered in the Dodoni tunnel more than 100 m below ground level in northern Greece (Marinos, 2001). The filled chimneys intersected during construction of the tunnel outlet works at the Sanford Dam, Texas, were ancient sinkholes over breccia pipes that extended down to a gypsum bed where the collapsing cavities had originated (Eck and Redfield, 1965). The tunnel passed through two of the pipes, of which the larger was filled with uncemented loose sand, which tended to run and cause up to 3 m of overbreak.

Groundwater commonly causes major problems during tunnel construction through cavernous limestone (Marinos, 2001). Face stability may be threatened, and removal of wet muck can be difficult, though control of the massive inflows of water is generally the major problem. The Gran Sasso tunnel, through limestone in Italy, ran into dissolution cavities on a fault zone, which produced inflows claimed to be up to 6 m^3/s (Calembert, 1975). More than 30,000 m^3 of sand and limestone debris entered the tunnel in the same inrush. There is a broad correlation between the scale of likely inflows from karst and the maturity of the karst, but data is not yet accrued to quantify flows with respect to the engineering classification of karst (Chapter 2), and exceptions are always possible where large individual conduits are breached by tunnels. In addition, tunnel construction can lead to de-watering, thereby reactivating old sinkholes and inducing new subsidence sinkholes in any soil cover, as occurred above the Canyon tunnel in Sri Lanka.

12.5 DAM CONSTRUCTION IN SINKHOLE KARST

Sinkholes and caves present numerous problems in the construction of large dams, among which bearing strength and water-tightness are paramount. Long, deep and expensive grout curtains are commonly required to impound water on karst (Bruce, 2003). These become particularly complex where large caves are breached and require individual filling or sealing, but the far-reaching subject of karst hydrogeology lies beyond the scope of these pages. Wide experience has been gained in building numerous dams and sealing their reservoirs in the mature limestone karst of Croatia and Herzegovina (Milanovic, 2000, 2003). There are more than 5,000 dams and reservoirs in the extensive karst terrains of southern China, with examples built, both on the surface and underground, in almost every conceivable situation (Lu, 1986). Most of these dams have been successful, though about one-third of them suffer from serious leakage. Many have failed completely, either collapsing or retaining no water at all, but most of these are the smaller projects built by rural communities and local engineers (Smart and Waltham, 1987). Reservoir impoundment is also significant in inducing new subsidence sinkholes in covered karst that is in China or elsewhere (Section 8.1.1).

Most sound limestone is a strong material with a high bearing capacity, and sufficient bearing strength generally may be obtained within a cavernous rock mass by distributing loads to bear on the more solid rock. For a dam, this may require deeper excavation than otherwise would be necessary. The extent of dissolution

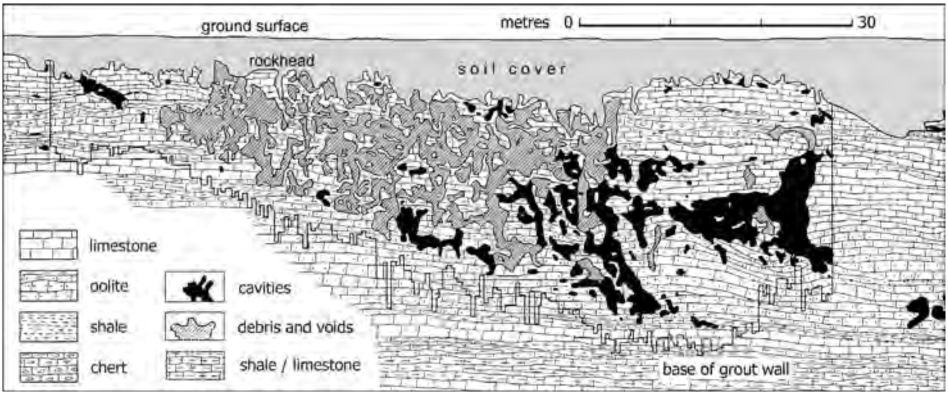

Figure 12.17. Cross section along the grout wall under one part of the Hales Bar Dam, Tennessee, where a zone of extensive, open and soil-filled, fissures and caves lay within the limestone.
After Schmidt (1943).

cavities, both open and sediment-filled, that may lie beneath a river valley in limestone karst, was demonstrated by those revealed during grouting works beneath the Hales Bar Dam in Tennessee (Schmidt, 1943). While much of the dam-site limestone had only a scatter of dissolution cavities, two zones contained networks of dissolution features to depths of more than 30 m below the original bed of the river (Figure 12.17). Extensive grouting programmes, extended in later years, all failed, and the dam was eventually demolished. Besides creating massive reservoir leakage, such cavernous ground can threaten the structural integrity of a dam, but usually only at limited specific points.

Only after construction of Turkey's Keban Dam was completed, a large cave was found under one of its abutments (Bozovic *et al*., 1981). A whirlpool developed in the new reservoir over where rapidly leaking water scoured open a previously soil-filled sinkhole. Subsequently, the rifts and shafts of the newly opened cave were followed to a depth of 45 m where they opened into a large chamber that extended beneath the dam footprint. The rock was weak (taking 2.1 t/m of grout through boreholes), and the cave roof was unstable. A shaft and 13 boreholes were therefore sunk into the chamber, to pour in 600,000 m^3 of rock, gravel, sand and clay fill, before the sinkhole was plugged with concrete. In contrast, a large, clay-filled cave directly beneath the Grabovica concrete gravity dam in Bosnia Herzegovina was left untouched, though the limestone around it was sealed by grout injection, and the cave exit just downstream of the dam was cleaned out and plugged with concrete to a depth of 5 m (Milanovic, 2000).

As gypsum is more readily soluble than limestone, caves and conduits can develop in gypsum much more rapidly than they can in limestone or dolomite. Under the influence of high pressure gradients, large turbulent flows created by leakage from new reservoirs can widen dissolutional fissures by 10 mm per year, and thereby cause major leakage increases after only 5 years in gypsum

(Dreybrodt *et al.*, 2002). It is therefore possible that structural integrity of dams in gypsum terrains may be lost where there is substantial ongoing leakage beneath them. The comparable rate in limestone is 1 mm per year after 25 years. Limestone dissolution rates of up to 1.02 mm/year, measured at Tennessee's Hales Bar Dam, were up to 10 times the rates in natural drainage systems (Moneymaker, 1968). Though these enhanced dissolution rates are barely significant in limestone, there remains the greater geohazard that piping and removal of sediments can induce rapid and catastrophic sinkhole development where any reservoir is impounded on any karst rock.

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