Chapter 4

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Ground Subsidence

by A C Waltham

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4 Subsidence and collapse on chalk

Chalk is a fine-grained, soft, pure, white and porous variety of limestone. It has an extensive outcrop across northern Europe, including nearly 15% of the solid geology of England. Chalks also occur elsewhere in the world, including the Caribbean, the Middle East and Australia, and though some of these are not of Cretaceous age, they are all geologically young. The distinctive feature of chalk is that, like other limestones, it is slowly dissolved in natural water and can therefore contain cavities, and yet it has a much lower mechanical strength, especially when weathered. Chalk forms its own characteristic style of karst landscape, with rolling hills, dry valleys and underground drainage, but with a noticeable lack of bare rock crags (except in undercut sea cliffs).

Over 75% of chalk typically consists of shell structures, known as coccoliths, which are less than 5 μm in diameter. The high porosity of the chalk, ranging from 20 to 50%, is due to the open packing of the coccoliths and also to cavities within them. Chalk's variable physical properties relate to its local history of preconsolidation loading and burial; the weaker beds, notably the Upper Chalk which dominates the outcrop in England, have never had a cover of Tertiary rocks. Joints and fissures in the chalk are irregular, and are widely spaced at depth, but their density increases significantly up through the surface-weathered zones.

Unconfined compressive strength of dry unweathered chalk ranges from 5 to 27 MPa. However, saturated strength is reduced to between 1.7 and 12 MPa, with the most conspicuous loss exhibited by the very porous Upper Chalk; with its fine grain size and high water retention, most chalk is saturated. The high porosity of chalk also accounts for its spectacular susceptibility to frost shattering. Natural weathering vastly increases the fracturing and disintegration of the chalk, and creates a surface layer of structureless 'putty' chalk of very low strength. Ground subsidence over chalk may therefore be related to either the formation of solution cavities or the failure of putty chalk.

Caves, pipes and sinkholes

Chalk does not warrant the general description of 'cavernous', because its high fracture density, high porosity and also low strength enable it to act largely as a diffuse-flow aquifer. However, solution caves do exist in chalk, as at the Water End sinkholes which swallow a major stream draining part of north London; excavation of the main sink has revealed tubular passages a metre across and partly filled with clay, and the stream cascades down and along a series of fissures too narrow to enter. Isolated caves are known elsewhere, and the stronger chalks of France contain accessible stream caves over 2 km long. Shallow solutional voids do create a hazard to bored piles bearing on buried surfaces of unweathered chalk, and so warrant site investigation practices applicable to cavernous limestone. This does not apply to driven piles in weathered chalk.

Based on the concept of concentrated drainage flow and solution, it has been suggested that significant voids may form in chalk within a time span of a few years (De Bruijn, 1983). However, this hazard appears to be negligible in comparison with the threat of collapse of either overburden soil or putty chalk, as the solutional effort is very unlikely to achieve its theoretical maximum.

Some areas of chalk contain numerous pipes, with loose fills of clay, sand and flint debris containing small voids. The pipes are conical or cylindrical, are normally a few metres across, and may reach depths of 30 m. They are essentially filled caves, and have formed where concentrated drainage has flowed into the chalk, normally near or just beneath outcrops of cover sediment and in areas of higher fracture density. Ground disturbance, by construction activity and drainage modification, caused a number of small collapses in a housing development on heavily piped chalk at Henley-on-Thames, and the housing units were mostly placed on raft foundations as a justifiable precaution (Edmonds, 1987). Most pipes have no surface expression, but their subsidence hazard is generally low, unless they are active; their main influence on civil engineering is often over quality control on cut-and-fill operations and the instability they create in cut slopes.

A high density of small conical pipes is comparable to pinnacled rockhead, and this is also common in the chalk beneath the feather-edge of overlying Tertiary sediments. As on limestone pinnacles, the uneven ground conditions make construction difficult, but the weaker chalk pinnacles are more easily removed. A pinnacled rockhead below sand, revealed along part of a motorway in Kent, was excavated until over 50% of the exposed material was firm chalk, and sites for bridge piles were probed 4 m below their bases to test for buried cavities (Higginbottom, 1966).

Sinkholes and depression may be common in the chalk surface, and Edmonds (1983) found densities in England ranging from less than 1/100 km^2 (mostly north of the Wash) to over 100/km^2 in some small unit areas. They are very numerous in parts of Dorset, where they are mostly up to 50 m across and 10 m deep, with steep collapse profiles, all formed in the sands and clays which overlie the chalk (Sperling *et al.*, 1977); in the main, these are typical subsidence sinkholes (see Chapter 3).

Isolated sinkhole collapses are reported from various parts of the chalk

Figure 4.1 A group of clay-filled pipes in the chalk, exposed in a quarry near Water End on the southern slope of the Chiltern Hills. Some almost cylindrical pipes are intersected obliquely by the quarry face, while the clay behind the person on the right fills a larger buried sinkhole. The top of the face is close to the original surface.

outcrop, including the well-known subsidence of the policeman's garden at Mickleham, south of London, in 1947 (Fagg, 1958). An unusual concentration of events was the 41 subsidences that occurred in the chalklands around Liège, Belgium, in the winter of 1966 (De Bruijn, 1983), all of which were due to loessic soils collapsing into chalk cavities at depths of 15–25 m. The Liège events may have been triggered by a small earthquake, or could have been due to a wet year and the temporarily high water table. As with limestone sinkholes, heavy rain is the commonest promoter of failures over chalk, though West and Dumbleton (1972) also note the effect of disturbance by construction traffic. A sinkhole into chalk undermined railway tracks behind a bridge abutment at Rainham, Kent (Toms, 1966); this occurred shortly after the bridge had been widened when site investigation boreholes had revealed no bad ground, though previously a cavity in the chalk had been found and filled. The placing of soakaway drains is also commonly responsible for subsidence activity, especially where the drains are in a thick cover of sand over the chalk.

Regardless of influence by construction traffic or by implanted drains, the greatest densities of chalk subsidences occur close to the boundary of overlying sands and clays, where a history of natural drainage input has created the most solutional cavities in the chalk (Figure 4.2). Most chalk sinkholes have formed beneath the feather-edge of, or very close to, outcrops of permeable cover deposits (Edmonds, 1983). They are virtually absent beneath impermeable clays, either Tertiary or glacial, or remote from impermeable boundaries, but are widespread beneath Tertiary, glacial or alluvial sands and

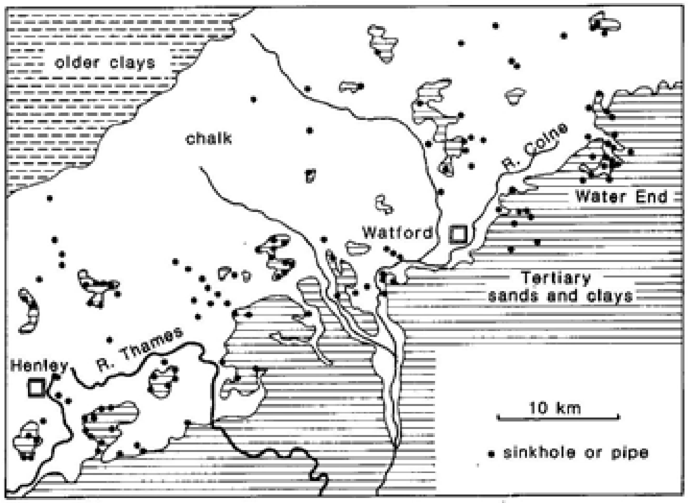

Figure 4.2 Distribution of known pipes and sinkholes in the chalk outcrop of part of the Chiltern Hills, northwest of London. Each dot represents either a single or a close group of sinkholes or clay-filled pipes, and there is a clear spatial relationship with the outcrop edge of the overlying Tertiary sands and clays (after Edmonds, 1983).

also along valley floors and in fold belts of fractured chalk (Edmonds *et al.*, 1987). A semi-quantitative hazard rating scheme has been devised by Edmonds *et al.* (1987) to facilitate land zoning and planning on chalk. Their main parameter is topography, whereby defined drainage channels and steep slopes create hazardous concentration of drainage compared with conditions on flat ground. Other parameters recognize increased sinkhole hazard due to adjacent cover rocks, a water table below rockhead, certain beds of weaker chalk, and past drainage routes.

Collapses in putty chalk

Chalk is especially susceptible to frost shattering, and heavily fractured rock may be described as rubble chalk, while the totally disintegrated, structureless material is known as putty chalk. Patches of putty chalk have been induced in test samples of highly porous Upper Chalk after fewer than ten cycles of freeze and thaw (Bell, 1977). Prolonged periglacial activity, notably in the extensive chalk outcrops just beyond the Devensian ice limits, has therefore produced putty chalk, typically to depths of 5 m and locally to depths of 30 m, in most natural chalk exposures, and also beneath thin drift deposits. The shattered chalk has then been prone to solifluction; chalk head is the widespread soliflucted putty chalk, and coombe rock is the same, with a variable degree of partial recementing by secondary calcite.

Putty chalk is structureless mélange, with irregular fragments in a remoulded matrix; Ward *et al.* (1968) outlined a chalk grading scheme,

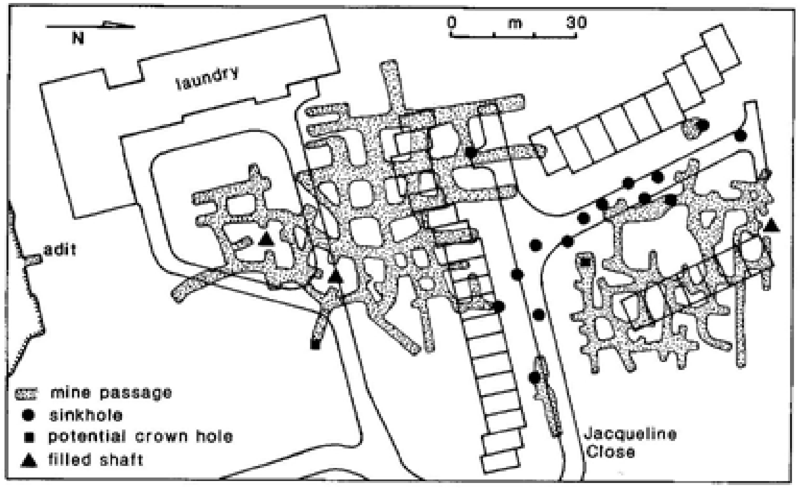

Figure 4.3 The collapse sinkholes and the underlying mines in the chalk at Jacqueline Close, Bury St Edmunds, Suffolk. The sinkholes are as recorded in 1977. Near the laundry building, the adit is a blocked mine entry in a small old quarry face. Many of the blind ends of the mine workings are blocked by fallen or stacked debris, so the mines are certainly more extensive than those that could be mapped (mine plans after Young, 1970).

comparable with the engineering grades of weathering, and their grade V material yields at bearing pressures below 200 kPa, exhibits significant creep, and has a standard penetration test *N*-value of less than 15. Putty chalk is usually sensitive, losing much of its strength when disturbed without drainage (Burland *et al.*, 1983). The liquid limit of the remoulded material is commonly close to the water content of many chalks. All putty chalk is mechanically disturbed, either by frost, solifluction or engineering works; the failure of excavated wet chalk, and its moderate thixotropy, are well known, as are cases of piles which can be driven almost endlessly unless given time to stabilize.

Sudden failures of putty chalk, creating significant sinkhole collapses, exhibit the properties of total liquefaction of the material. Small sinkholes are often recorded on construction sites, and many do not involve overburden soil failure. These can occur with no warning, but are related to disturbance by construction traffic, are often after periods of heavy rain, and depend on the presence of some buried cavity into which the liquefied debris can flow. Some of the natural chalk sinkholes, as described above, may involve putty chalk liquefaction in addition to surface soil failure.

A fine example of chalk liquefaction sinkholes is the suite that formed in a housing area at Bury St Edmunds in the late 1960s. Abandoned chalk mines underlie the site at depths of 10–12 m (Figure 4.3), and were not identified by an inadequate site investigation before the houses were built; stormwater was diverted into soakaway drains 6 m deep. Beneath only a thin soil, the chalk is weathered and frost-shattered; an adjacent hospital laundry was founded on

Figure 4.4 One of the collapses in Jacqueline Close, Bury St Edmunds, with the abandoned houses behind. The profile in the collapse reveals the tarmac on 30 cm of roadbase, with a broken drain on the right, on almost structureless putty chalk.

piles driven to 12 m, in some cases through small cavities. Starting before the last houses were completed, a series of collapses effectively destroyed the site. The failures were not true crown holes (see Chapter 5); the mines had been stable for over 50 years when only diffuse percolation drainage reached them, and the chalk appears to have failed rapidly over the whole depth (there are also separate incipient crown holes and infilled shafts which did not fail). Also, they were not normal subsidence sinkholes, as the failures involved clearly-defined cylindrical columns of chalk, and not just a soil cover. Concentrated drainage flow, between the soakaways and mines, had induced liquefaction of the already disintegrated putty chalk (Figure 4.5). It is possible that a pinnacled boundary may have existed between the putty chalk and the underlying chalk rock; pipes of putty chalk may then have localized zones prone to liquefaction at depth, but this control is speculative. Thirty years earlier some collapses over old mines in Norwich had in some cases involved clay-filled pipes which the mines had intersected (Edmonds, 1987); the pipe

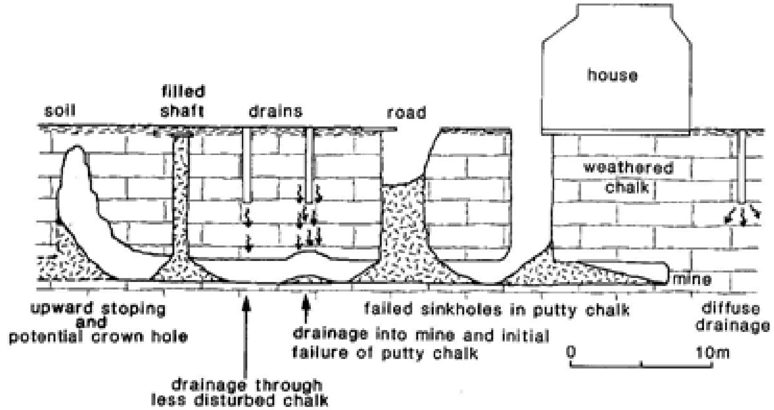

Figure 4.5 Cross-section to show the different features and stages of collapse at the chalk mines at Jacqueline Close, Bury St Edmunds.

sediments then failed, so this was a different mechanism from the failure of the weathered chalk at Bury St Edmunds. Some more recent collapses in Norwich include the one with the upended double-decker bus which achieved brief national fame on the television news programmes (Figure 1.1); again in this case there was an underlying mine, but there were no soakaway drains.

Circular sinkhole collapses have developed in cambered chalk slopes in Kent, and are probably due to liquefaction flow into underlying gulls (see Chapter 2). Near Troyes, in the chalklands of France, a sudden collapse breached a featureless cultivated hillside in the early 1970s. Over 16 m deep and 10 m across, its vertical walls of putty and rubble chalk are very similar to those in the Bury St Edmunds collapses. The role of drainage was demonstrated in Norfolk when a sinkhole destroyed a house as the water table was falling during a well pump test; the valley floor site had 10 m of sand overlying putty chalk, and failure appears to have originated in the latter. This collapse, the one at Troyes, and some other recent collapses near Norwich, have all occurred in areas with no known mines. It appears that these involve saturated putty chalk dropping into either solutional caves or networks of microcavities within the deeper chalk. As natural chalk cavities are likely to be small and with limited capability for underground sediment movement, the failures may have developed as periodic collapses with upward stoping, over longer periods than the apparently rapid failures at Bury St Edmunds.

Fortunately, putty chalk is largely a surface feature, and foundation piles for heavy structures will find stronger chalk, with *N* values greater than 40, normally at depths of 10–15 m. Furthermore, weathered chalk that is left undisturbed beneath a slab foundation may cause less settlement than indicated by SPT or laboratory tests (Burland *et al.*, 1983). Strengths of excavated chalks are greatly increased by admixed cement or bentonite (Lewis and Craney, 1966), but grouting is generally uneconomic for stabilization of in-situ putty chalk except where open cavities are identified and must be filled.

The major subsidence hazard is provided by the potential for liquefied putty chalk to flow into buried cavities, which may be old mines, solution caves or gulls. Chalk and flint mines are widespread and appear in a great variety of local styles (Edmonds *et al.*, 1987), but are always in hills above the water table. Solution cavities are more common under valley floors, and gulls occur in cambered hillsides, where clay underlying the chalk is exposed at the slope foot. Locating and sealing all cavities is commonly an unrealistic target, and any remaining hazard is always compounded by concentrated drainage from soakaways. A basic precaution is therefore to avoid the use of soakaway drains in chalk where site investigation reveals any possibility of old mines, sinkholes or cambering.