Quarterly Journal of Engineering Geology, **26**, 243–251. 0481-2085/93 $03.50

Crown hole development in the sandstone caves of Nottingham

A. C. Waltham

Civil Engineering Department, Nottingham Trent University, Nottingham, NG1 4BU, UK

Abstract

The Nottingham caves have been artificially excavated in the Triassic sandstone. Some of their unsupported roofs, spanning up to 5 m, exhibit progressive collapse which can develop into crown holes. Nearly all recorded roof failures have occurred where and when the rock has become saturated by water from rainfall or pipe leakages. Saturation causes the sandstone to lose rapidly about half its strength as a consequence of the breakdown of clay bridges between the sand grains.

Introduction

The city centre of Nottingham stands on an outcrop of Triassic Sherwood Sandstone. This rock is easily excavated with hand implements, and consequently many hundreds of artifical caverns have been cut into it. The caves originally had many purposes, including dwellings, storage rooms, beer cellars, malt kilns, factories, passageways, sand mines and air raid shelters (Owen & Walsby 1989; Waltham 1992). Most are between 200 and 800 years old; the few in use today are mainly beer cellars beneath public houses.

Most of the caves are individual rooms 3–5 m wide and generally less than 10 m long (Fig. 1). Many of the roofs are flat although some are arched to varying degrees and spring from walls which are flared to varying extents. In some of the wider rooms central rock columns have been left for roof support and many caves are interconnected into small groups beneath individual properties. Figure 2 shows the

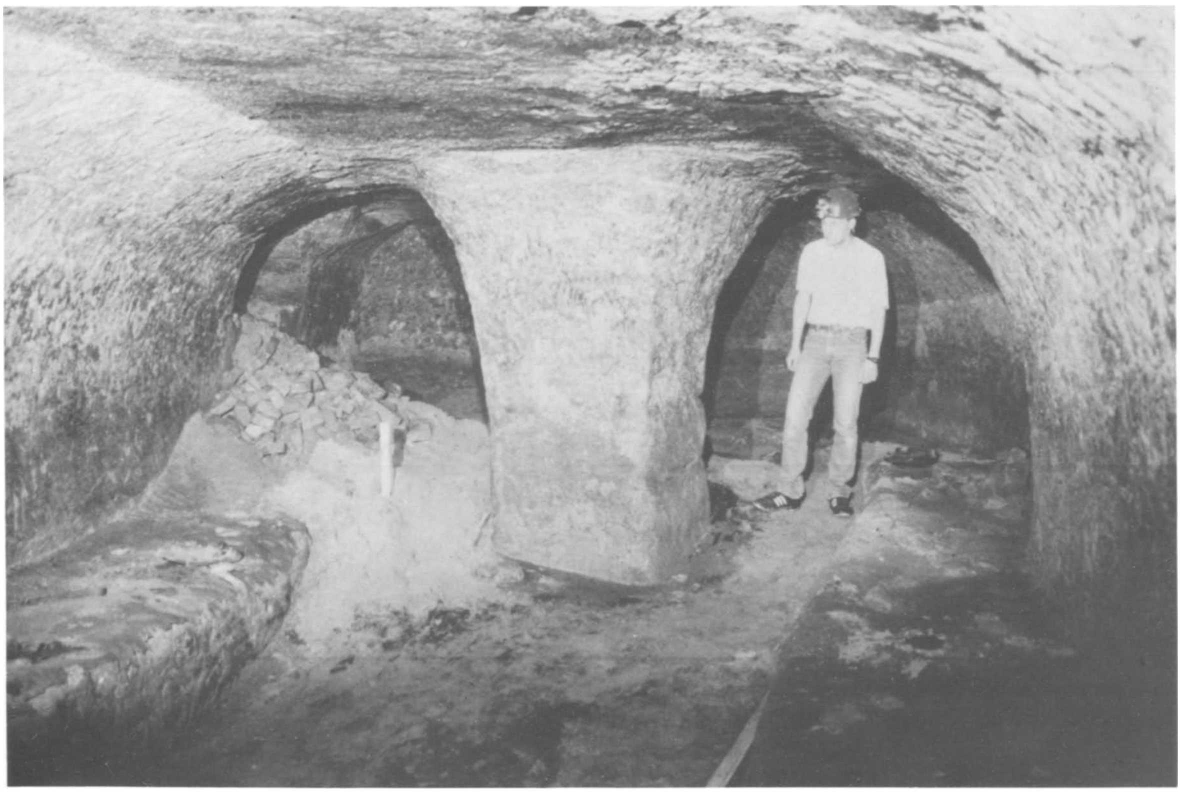


FIG. 1. A typical Nottingham cave—one of the old beer cellars beneath the Corner Pin public house. The flat roof section in front of the rock pillar subsequently failed (see Fig. 7).

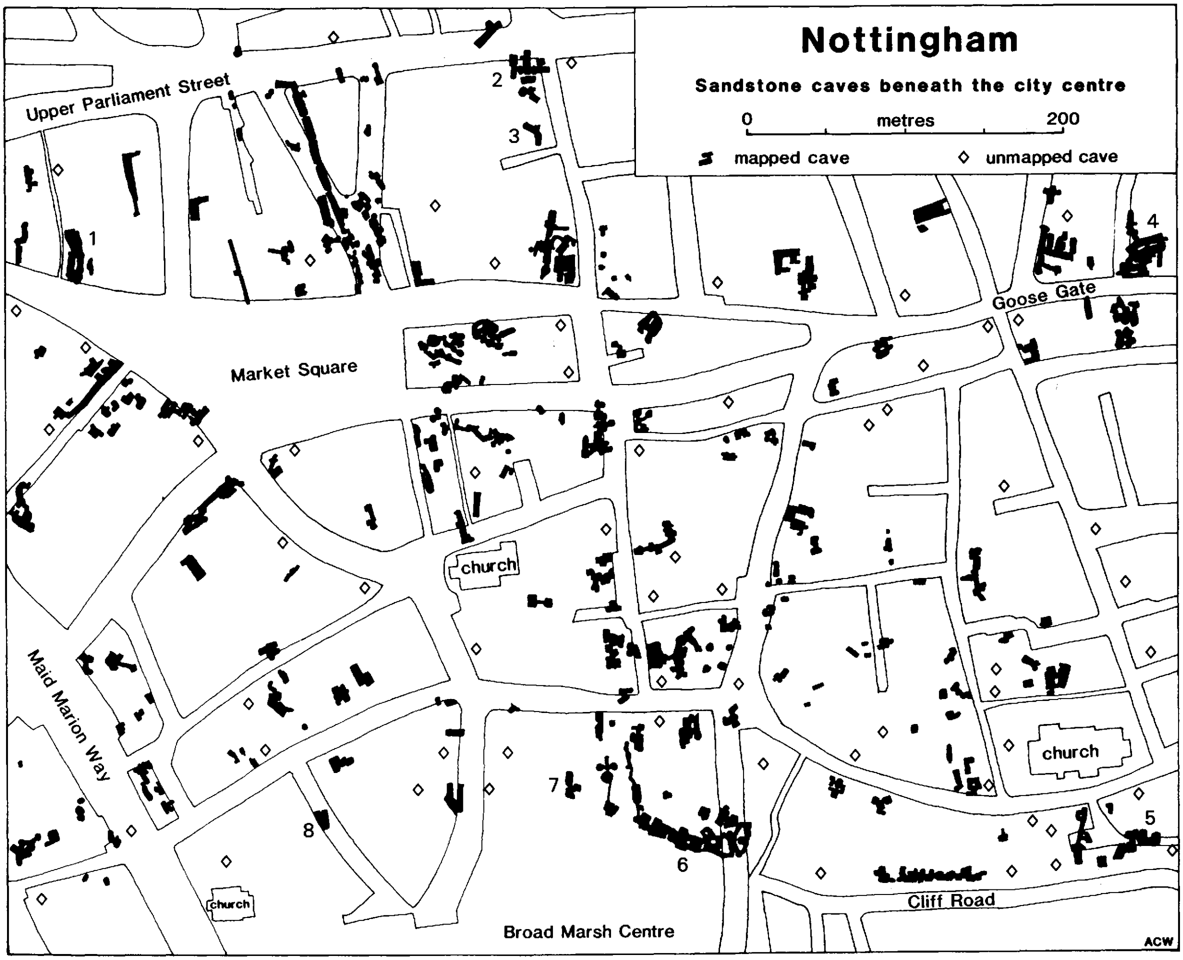


FIG. 2. Distribution of the known 'caves' beneath the city centre of Nottingham. Numbered sites are referred to in the text. 1: Pearsons; 2: Corner Pin; 3: Crystal Palace; 4: Adams Brewery; 5: Commerce Square; 6: Broad Marsh; 7: Black's Head; 8: Stanford Street.

distribution and extent of the caves as currently known, but there are many more unrecorded; new ones are revealed frequently during site clearance and excavation for building redevelopment. Indeed it is now known that most buildings in the modern city centre (covering the site of the medieval town) have caves beneath them.

The existence of such large cavities at shallow depths within the bedrock sandstone is an obvious concern and a potential hazard for ground engineering works (Walsby, Lowe & Forster 1993; Waltham 1992). There are three types of failure. Firstly, building foundations may suffer loss of integrity if less than 3 m of sound rock separates them from underlying caves (Waltham & Chorlton 1993) but codes of practice applied to site investigation and foundation design within the city have prevented any significant failures within the last hundred years. Secondly, unloaded roofs may exhibit progressive failure; development through to crown holes is not common and the failure of Stanford Street (see below) was the first for many years. Thirdly, the sandstone walls and roofs may weather and deteriorate rapidly where there are open entrances in cliff faces. However, weathering is not a problem in the majority of caves reached only through doors from building basements.

The Nottingham Castle Sandstone

Almost all the caves were excavated in the upper unit of the Sherwood Sandstone, which is locally known as the Nottingham Castle Sandstone (Charsley, Rathbone & Lowe 1990). This poorly sorted coarse- to medium-

TABLE 1. *Strength of the Nottingham sandstone related to degree of saturation and the depth below rockhead*

Location	Depth below rockhead (m)	Unconfined compressive strength (MPa) dry	Unconfined compressive strength (MPa) saturated	Saturated strength / Dry strength %	No of samples	Source
Mansfield Road mines	2	1.0	0.2	20	8	1991 tests
Adams Brewery caves	3	3.5	1.2	34	17	1991 tests
Castle Boulevard	3	10.2	6.1	60	6	Storm 1988
Nottingham mean	—	14.0	6.8	49	28	Forster 1989
Chaucer Street	4	14.8	6.6	45	6	1992 tests
Broad Marsh caves	7	26.5	15.8	60	4	Storm 1988
Commerce Square caves	10	31.3	17.3	55	6	Froggatt 1992

grained, buff coloured sandstone, originated as flood deposits and contains scatttered lenses and horizons with quartzite pebbles and mud flakes. It is extensively cross bedded, although the bedding planes, generally more than 100 mm apart, are neither conspicuous nor developed as fractures in most exposures. However, roof failures of wet rock commonly reveal bedding planes as close as 10 mm apart. Joints, which are generally sub-vertical, are spaced more than 10 m apart in nearly all exposures.

The strength of the Nottingham Castle Sandstone varies considerably. Unconfined compressive strengths range between about 3 and 30 MPa for air-dry unweathered rock, but many of the caves appear to be cut in Class II weathered material which produces strengths as low as 1 MPa (Table 1). The sandstone is very porous and highly permeable with a mean dry density of 1.7 $Mg\,m^{-3}$ and a saturated moisture content of 17% (Forster 1989). These values indicate a low degree of grain contact, accounting for the generally low strength (Dobereiner & de Freitas 1986). The high porosity is probably due to the leaching of calcite, dolomite and/or anhydrite, which is characteristic of much of the Sherwood Sandstone close to outcrop (Strong & Milodowski 1987). The strength of the sandstone is related to the clay cement, which forms up to 15% of the rock and accounts for the considerable loss of strength when saturated (Table 1).

Cave roof failures

The Stanford Street crown hole

A typical crown hole failure occurred in the road surface of Stanford Street (Fig. 2) in June 1990 (Fig. 3). As the cave had been blocked many years previously, the early stages were not observed but progressive roof failure, at an unknown rate, eventually caused the 1.3 m thick sandstone bedrock to fall away, exposing rockhead within the cavity (Fig. 4) adjacent to a deep drain trench. Subsequent ravelling of the soil and trench fill would have been more rapid, the road surface finally breaking under the wheel of a slowly moving lorry.

FIG. 3. Crown hole above the failed roof of the Stanford Street cave in June 1990.

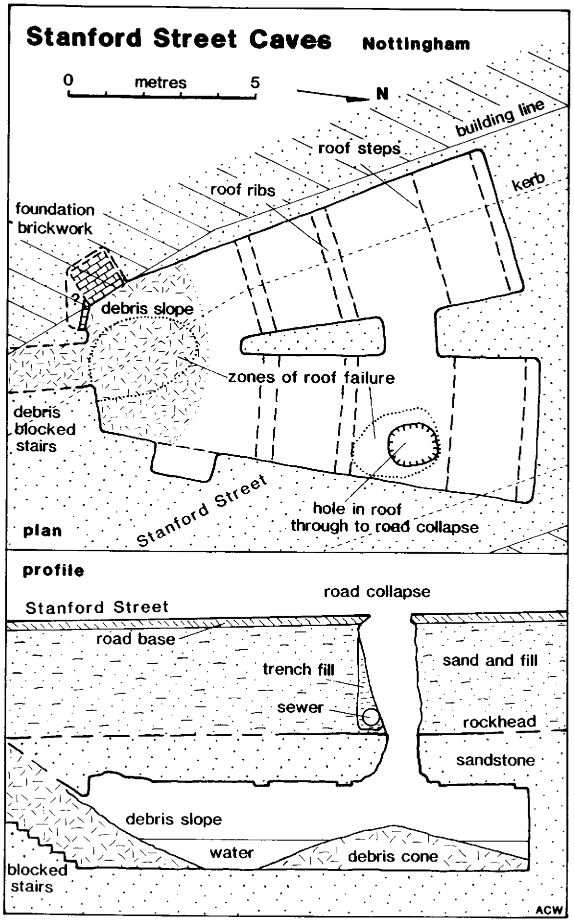


FIG. 4. Plan and profile of the Stanford Street 'caves'.

The cave at the bottom of the crown hole had a roof with an unusually high arch, almost semi-circular in profile. The failure was close to its axis and left an almost cylindrical shaft with little flare at its base (Fig. 5); the fallen plug of rock was buried beneath debris and fill. Water from a nearby leaking main was still emerging from the soil at rockhead level and trickling down the side of the hole. The entire cavity was subsequently filled with concrete to rockhead level.

Four recent roof failures

A beer cellar of the old Crystal Palace public house (Fig. 2) now lies disused beneath shop basements. Part of its sandstone roof has fallen away, to a maximum thickness of 350 mm (Fig. 5). The timing of the failure is not known, but the fallen debris rests on top of recent floor material. This area has been monitored since December 1990 and no new falls have occurred. The stepped profile of the break reveals bedding planes only 20 mm apart. A fracture cuts across one edge of the failed area and water drips from this on some occasions. It would appear that the roof has now developed an arched profile which is more stable than the original almost flat cut roof, although some of the exposed cantilevered beds are continuing to sag as the beds dilate.

When the Stanford Street cave was entered through its crown hole in 1990, a second zone of roof failure was found at the southern end (Fig. 4). The roof was breaking away in thin beds over an area nearly 3 m × 2 m. Thin slabs of sandstone lay where they had fallen onto a bank of debris blocking the original

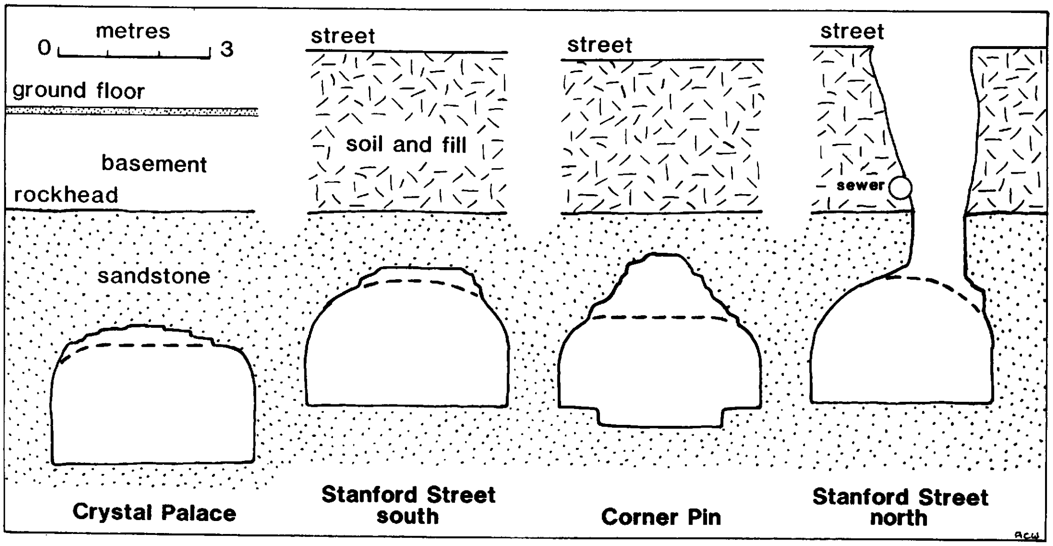


FIG. 5. Cross sections through four 'caves', demonstrating progressive stages of roof failure, including the ultimate crown hole development at the north end of the Stanford Street caves.

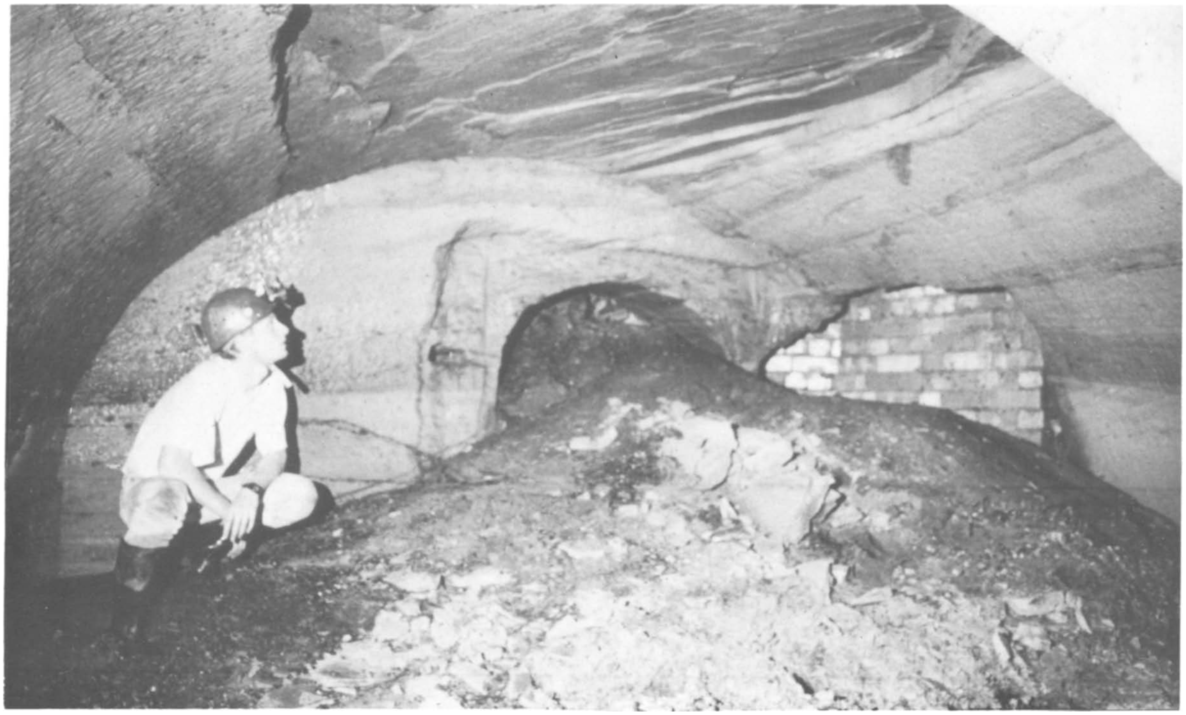
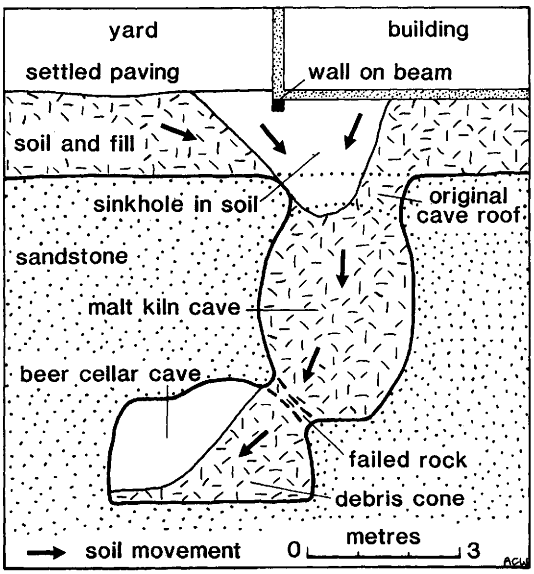


FIG. 6. (above) Saturated sandstone breaking into thin beds and falling away from the roof arch at the southern end of the Stanford Street caves. The light material on the debris pile is fallen roof, some remaining in thin slabs, other broken to sand on impact.

FIG. 7. (left) The roof failure in the Corner Pin cave, with temporary timbering to prevent any immediate further collapse.

FIG. 8. (below) Cross section of the failure at the Black's Head caves, showing the debris pile and the sinkhole into the upper malt kiln cave, revealed beneath the building floor and yard paving.



entrance (Fig. 6) while more could be dislodged from the roof at only a finger's touch. The roof now steps up to a wide, flat bedding plane, with a profile less stable than the original cut arch (Fig. 5). With water seeping through the roof sandstone, this appears to be an 'active' zone of roof failure, in the early stages of developing into a crown hole, perhaps larger than its neighbour. As this site also lay under the road the cavity was completely infilled with concrete.

Redevelopment of the site of the Corner Pin public house (Fig. 2) revealed a large group of caverns which were entered for the first time in many years in 1990 (Waltham 1992). One 4 m wide room extended out under Parliament Street, its roof having a central flat section 2 m wide beneath a cover of 5 m, consisting of 2 m of rock and 3 m of soil. There was no sign of any previous failure, although water had entered the cave at various points at some time in the past. The roof had been bored through from above at four points so that rock anchors could be placed in the floor in order to prevent rotation of temporary works on the site above. Probably during the drilling operation, a prism of rock nearly 3 m across and 1.2 m high fell away from the roof, approximately 2 m away from the nearest borehole. This created a high arch stepped roof profile (Fig. 5). As access to the cave was still required, temporary support was immediately provided using timber and Acrow props (Fig. 7). No further failure occurred and a few weeks later the whole cavity was filled with concrete.

In 1991, settlement of paving slabs behind some offices was found to be related to a debris cone from a hole in the roof of the old Black's Head cellar cave (Fig. 2). Excavation revealed a previously unknown malt kiln cavern and intimated a more protracted failure mechanism. The medieval malt kiln cave had been abandoned and filled with soil and rubble by about 1600. Probably a hundred years later, the cellar cave was excavated from an adjacent cliff, by chance leaving about 200 mm of rock between the two cavities (Fig. 8). Some time later the malt kiln was unroofed and backfilled to the surface; the building above being placed on beams and columns to span the cave fill. Seeping water and leaking drains later saturated the fill and the rock beneath, causing its failure into the lower cellar hollow. Subsequent ravelling of the fill created the sinkhole which was revealed when the paving slabs were removed.

Older roof failures

In addition to those cited above there is incomplete data on nearly twenty roof failures. Some failure of the roof beds has been seen in about 20% of the caves recently inspected, but most is on a small scale. In some, however, part of the roof arch has failed in a manner very similar to that shown at the Crystal Palace (Fig. 5). Hence some now appear to be stable, while others have floor debris from recent falls.

Apart from those referred to above, only one roof failure has extended to a height of more than 300 mm. The old wine cellar cave at Wollaton Hall (4 km west of the city) partially failed around 1985. At one point its roof has broken obliquely by over a metre and exposes brick foundations only 600 mm from the edge of the cavity. Examination, however, indicates no sign of distress in the brickwork.

One group of caves either side of Mansfield Road (1 km north of the city centre) originated as small, hand-worked, pillar-and-stall sand mines which date back about 200 years. With only 2–3 m of rock over them and no protective cover of buildings or roads, rainwater infiltrates freely into the sandstone. It is recorded that a roof collapse killed a miner in 1809 and hence that section of mine was broken and demolished by the council a few years later. Although a surviving section of the old mines was used as an air raid shelter in 1941 it suffered three roof falls around 1980, when slabs of sandstone fell away between the rock pillars.

The involvement of water in the roof failures, and the role of buildings in preventing the ingress of rainwater, is demonstrated by the Pearsons cave (Fig. 2). This spectacular medieval storage cave lay beneath the Pearsons department store in the city centre until the building was demolished in 1990. This left the rock over the cave exposed to rainfall and within six months a section of the roof 1.5 m across and 150 mm deep had fallen away. The ground above has subsequently been sealed in order to prevent further failure.

Processes and causes of failure

Surviving documentation on roof failures in the Nottingham caves is by no means complete, but does provide enough data to recognize the role of certain factors, notably the presence of water.

There is no complete record of the rate of roof failure and evidence from different caves suggests that there is considerable variation. The failures in the Stanford Street (south end) and Crystal Palace caves (Fig. 5), together with others where the height of break is less than 300 mm, indicate slow progressive failure as the sandstone falls away in thin beds. By contrast, the failures at the Corner Pin (Fig. 5) and Wollaton Hall caves were larger and more than a metre of rock fell in a single event.

The effect of water

The strength of the dry sandstone varies considerably

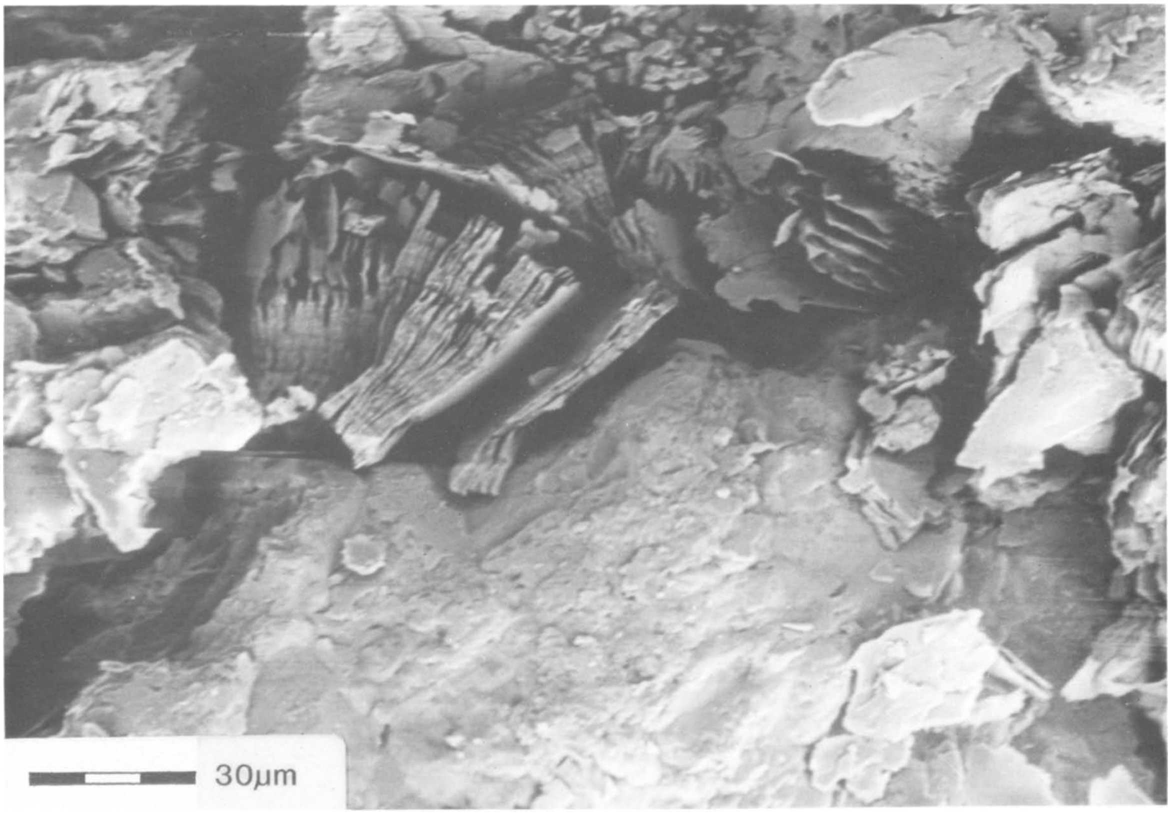


FIG. 9. Scanning electron microscope image (at magnification ×900) of sandstone from the Mansfield Road sand mines. Books of authigenic kaolinite have grown in the pore space between quartz grains and now constitute the only cementing material.

and it is difficult to distinguish between the effects of weathering and lithological contrast. Clearly, weathering is an important factor and the rock can be seen disintegrating to sand on the walls of some exposed caves.

All available data show a major loss in the sandstone strength when it is saturated, Table 1 indicating losses of 40–80%. The same table shows the loss of strength of the sandstone upon weathering, seen as a function of the depth below rockhead; this is especially significant as most cavities are less than 5 m down, in the zone of reduced rock strength. Furthermore, the strength loss on saturation is greatest in the weathered sandstone; rock from the failing roof of the Mansfield Road mine can be crushed by hand.

Laboratory tests on sandstone from some of the caves revealed four features.

(1) The loss of strength is instantaneous on saturation, with no further measured strength decline over a period of up to 16 months.
(2) There is no measurable difference in strength loss between samples saturated by immersion in standing water or by through-flow of percolation.
(3) Sandstone from one locality loses about 15% of its oven-dry strength when it is damp (stored over water in saturated air and therefore comparable to how it occurs in unsaturated ground) but suffers a 45% loss when saturated.
(4) The sandstone strength recovers completely when dried after a period of saturation.

In three caves, roof beds of saturated sandstone can be seen to sag away from the undisturbed rock above, under their own weight, and ultimately fail by tensile rupture. These sagged beds are so weak that they can be moved by hand and when they do fall, they disintegrate to sand on impact with the cave floor. The response time between saturation and failure is unknown. A leaking water pipe on a construction site saturated the sandstone and caused a roof fall in the Pillar Cave (now beneath the Broad Marsh Centre; Fig. 2) within a period of a few weeks. Since the water percolation was prevented there has been no further failure of the sandstone, which now lies beneath a watertight shopping centre.

These failure characteristics are typical of sandstones cemented only by clay, which responds rapidly to saturation. Clay forms up to 15% of the bulk rock and the electron microscope reveals its role as an interstitial binding material. Authigenic clay minerals can be seen bridging between the sand grains (Fig. 9). Most of the clay minerals are kaolinite, with some occurring in small books, but flaky and cellular smectite are also seen. No soluble cementing material which can be lost to percolation water can be detected. Such a loss of strength on saturation is characteristic of locked sands (Dusseault & Morgenstern 1979) and some of the sandstones have pitted grains and high relative density indicative of partial locking.

Documentation of past cave roof failures is not always precise with reference to the presence of water but it appears to have been a factor in the great majority of cave roof failures (Table 2). The water originated from two main sources: leaking pipes or drains locally wetting previously dry zones of rock, and prompting new failures; and infiltration of direct rainfall where there is no cover of buildings or road. Where flowing water has been observed with no associated rock failure, in two examples the water emerged from well-defined bedding places in the walls, and in only one case did it seep through the roof rock.

TABLE 2. *The role of water in the various cases of roof collapse recorded in the sandstone caves of Nottingham*

	Number of cave collapses
Water present at collapse?	
Certainly (observed or documented)	6
Probably (incomplete data)	6
Possibly (no building cover)	5
Possibly (beneath building)	1
Failure of dry rock	2
Water present, but no roof collapse	3

Other factors associated with roof failures

Weathering, including frost action, ultimately causes disintegration of the sandstone and may have been a contributory factor behind small roof failures in two caves soon after they had been exposed to weathering via newly opened entrances. However, some others which have been very heavily weathered show no sign of roof failure. In contrast to the deeper mines not far to the south which exhibit no roof breakdown, the very weathered rock forming the shallow cover to the Mansfield Road sand mines may have contributed to their roof falls. There is a tendency for collapses to be more common where the cave roof is near the surface (Fig. 10), due to the lower strength of the weathered sandstone close to rockhead rather than the structural disadvantage of a thin roof.

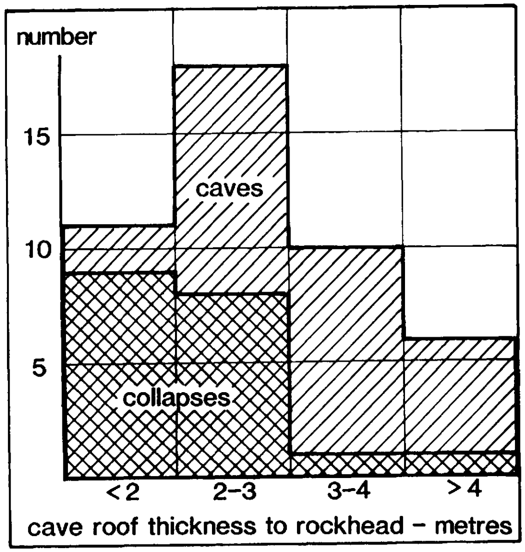


FIG. 10. Distribution of rock roof thicknesses over caves and without collapse.

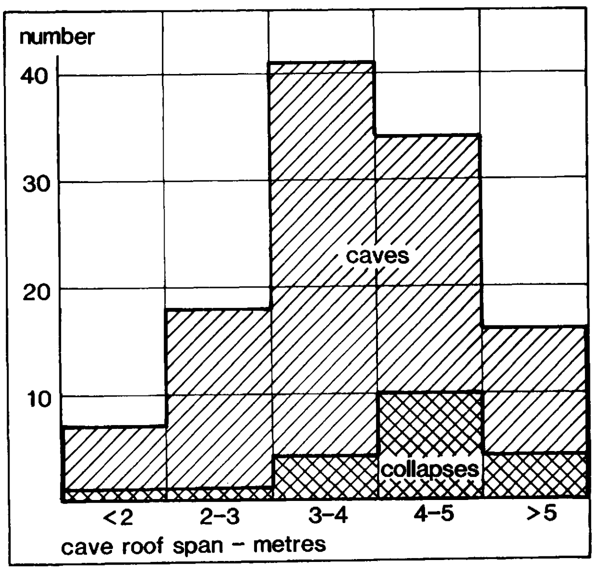


FIG. 11. Distribution of roof span widths in caves with and without collapse.

In Nottingham, the roof spans vary between 1 and 7 m with most averaging 4 m. Figure 11 shows the wider spans to fail more frequently. Roof profile varies considerably and their structural competence is not easily assessed. Two similar caves at the Corner Pin site were drilled through and it was noted that the one with a flatter roof remained intact, while the one with the arched shoulders failed (Fig. 5). Many flat cave roofs appear to be sound, while the unusually deep arch of the Stanford Street cave experienced two failures (Fig. 5). Local stress concentration has also caused some small falls from roofs adjacent to shafts.

Natural fissures in the sandstone have played a subsidiary role in three roof failures, but also occur in other situations with no sign of roof breakdown. Though roots and deep fissures are well known as a cause of breakdown in and over the adits cut into the exposed cliff faces, neither appears to be of notable significance with respect to crown hole development.

Roof failures and cliff erosion both commonly break back to bedding planes rich in quartzite pebbles and mud flakes within the sandstone. Many of these planes appear to have no intrinsic weakness, but may be broken more easily because water concentrates along them due to their poorer grain sorting and reduced permeability.

Vibration has also to be considered as a potential cause of rock failure. There is some association of roof failure with the rock drilling at the Corner Pin site and with mining in the old sand mines as well as with traffic along the lightly used Stanford Street. While vibration may have triggered these failures, the large number of caves which remain intact beneath construction sites and busy roads indicates that it cannot be a dominant factor in roof collapse.

Conclusion

Roof failue in the sandstone caves of Nottingham may develop progressively or instantaneously and may evolve into a stable arch or continue and form a crown hole. The major factor behind cave roof failure is the ingress of water which saturates the ground and reduces the strength of the sandstone. Rockfalls are slightly more common from the wider cave roofs in the weathered sandstone close to rockhead. Engineering and construction work over and around shallow workings in Nottingham need to be designed to prevent any ingress of water to the sandstone, especially where bedrock over the cavity is less than 3 m thick.

ACKNOWLEDGEMENTS. The author is grateful to R. Storm, I. Froggatt and P. Walker for data obtained on their student projects at Nottingham Trent University, to A. Milodowski of the British Geological Survey for assistance in interpreting the electron microscope images, to the Civil Engineering and Mechanical Engineering Departments of Nottingham Trent University for laboratory facilities and support, and to A. MacCormick, J. Walsby and A. Forster for generous assistance and cooperation.

References

CHARSLEY, T. J., RATHBONE, P. A. & LOWE, D. J. 1990. Nottingham: a geological background for plannning and development. *British Geological Survey Technical Report* **WA790/1**.

DOBEREINER, L. & DE FREITAS, M. H. 1986. Geotechnical properties of weak sandstones. *Géotechnique*, **36**, 79–94.

DUSSEAULT, M. B. & MORGENSTERN, N. R. 1979. Locked sands. *Quarterly Journal of Engineering Geology*, **12**, 117–132.

FORSTER, A. 1989. The engineering geology of the Nottingham area. *British Geological Survey Technical Report* **WN/89/4**.

FROGGATT, I. J. 1992. *Rock Stability over the Sandstone Caves of Nottingham*. B.Eng. Thesis, Civil Engineeering Department, Nottingham Polytechnic.

OWEN, J. F. & WALSBY, J. C. 1989. A register of Nottingham's caves. *British Geological Survey Technical Report* **WA/89/27**.

STORM, R. H. 1988. *The Sherwood Sandstone and Caves of Nottingham*. B.Eng. Thesis, Civil Engineering Department, Nottingham Polytechnic.

STRONG, G. E. & MILODOWSKI, A. E. 1987. Aspects of the diagenesis of the Sherwood Sandstones of the Wessex Basin and their influence on reservoir characteristics. *In*: MARSHALL, J. D. (ed.) *Diagenesis of Sedimentary Sequences*. Geological Society, London, Special Publication, **36**, 325–337.

WALSBY, J. C., LOWE, D. J. & FORSTER, A. 1993. The caves of the city of Nottingham; their extent, geology, origin and implications for engineers and planners. *In*: CRIPPS, J. C., COULTHARD, J. M., CULSHAW, M. G., FORSTER, A., HENCHER, S. R. & MOON, C. F. (eds) *The Engineering Geology of Weak Rock*, Balkema, Rotterdam, 479–487.

WALTHAM, A. C. 1992. The sandstone caves of Nottingham. *Mercian Geologist*, **13**, 5–36.

—— & CHORLTON, I. E. 1993. Rock roof stability in the sandstone caves of Nottingham. *In*: CRIPPS, J. C., COULTHARD, J. M., CULSHAW, M. G., FORSTER, A., HENCHER, S. R. & MOON, C. F. (eds) *The Engineering Geology of Weak Rock*, Balkema, Rotterdam, 489–492.

Received 12 June 1992; revised typescript accepted 31 August 1993