The classification, recording, databasing and use of information about building damage caused by subsidence and landslides

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Abstract

Building damage as a result of subsidence and lateral movement can be caused by numerous mechanisms including mining, dissolution of soluble rocks, shrink–swell of clays and landslides. In many instances, the distribution and severity of the damage caused can be diagnostic of the underlying geological condition and can be used as an aid to geological and geomorphological mapping. Many rigid buildings are sensitive to movement, meaning that careful surveys can delineate fine details that can be compiled to identify broader patterns of mass-movement. This paper discusses how damage has been recorded in the past and presents a unified scheme that is based mainly on UK and Italian practice and that can be applied to most situations. It broadens the existing schemes to include the assessment of damage to infrastructure (such as roads and pavements), which are also sensitive to movements; it also extends the existing schemes to include more serious building damage. In this way it unifies the current, disparate approaches and extends the usage of the semi-quantified approach to damage assessment. The damage assessment lends itself to storage in a database that can be interrogated, displayed and interpreted using a geographical information system (GIS).

In the UK, figures from the Association of British Insurers (ABI) posted on the Internet indicate that building damage as a result of subsidence cost about £500 million over the dry summers of 1975–1976, and £400 million in 2003 (Professional Broking 2007). Other figures from the ABI (Dlugolecki 2004) suggest that with the effects of climate change, by 2050 the costs could be as much as £600 million in a normal year and £1.2 billion in a bad year (at 2004 prices). This damage is caused by a range of geological problems, including natural subsidence, mining-induced subsidence, shrink–swell clays, collapsible soils and landslides. In many cases, the style and severity of damage can be directly related to the nature of the geological event and the distribution of the geological unit responsible. Many man-made structures, especially old buildings with very inadequate foundations, are prone to damage by such movements and, as such, they form sensitive recording devices for small amounts of movement. By mapping the degree and spatial extent of damage, it is often possible to gain a better understanding of the mechanisms and magnitudes of movements causing the subsidence. By repeating the monitoring after an interval of time, it may be possible to understand the evolution of the spatial and temporal aspects of the subsidence and gain a measure both of how the area is evolving and of its long-term stability.

This paper presents a review of several building damage schemes currently in use, and proposes an amalgamated scheme that can be applied more universally to varied situations. Compared with the numerous reviewed schemes, this amalgamated scheme is both broadened and extended with respect to subsidence recording. First, it is broadened to give a rating to damage that occurs on land without buildings, but with some infrastructure such as roads and pavements. Second, for subsidence damage, it is extended to include partial and total collapse, something that many of the existing building subsidence damage schemes do not include, but that landslip schemes do include. The unified scheme presented here has been kept as close as possible to existing well-established schemes that are widely used for assessing damage in landslide, shrink–swell and mining subsidence affected areas. This is the first time that they have all been compared and combined into a unified recording scheme. The rationale for this was to allow the recording of building damage in Britain (and Western countries with similar building types) and to include the UK information in the British Geological Survey database of building damage. This database was set up initially, but not exclusively, for the recording of damage caused by karst collapse (Cooper *et al.* 2001). By utilizing data that are already recorded or published, historical data can also be incorporated into the database. Examples of damage recording are presented along with some indications of how the data can be analysed using modern techniques such as a geographical information system (GIS).

Typical subsidence damage effects

Subsidence affects different structures in different ways. The severity of the damage is, to a great extent, controlled by construction method, including the type of foundation that has been employed. For instance, a property with shallow or inadequate foundations could

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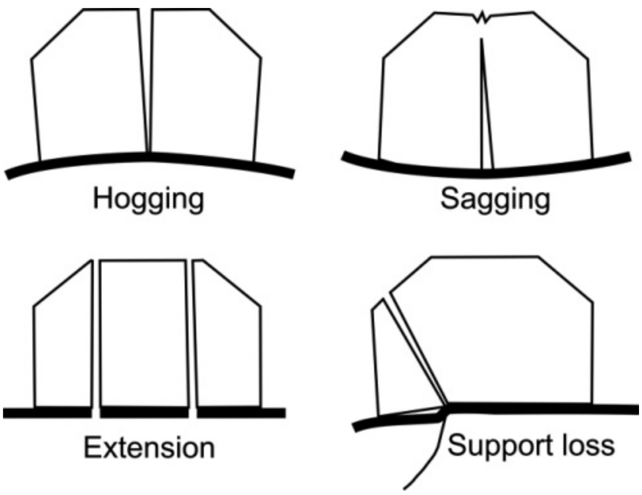


Fig. 1. Schematic illustration of building damage associated with various types of subsidence movement, some of which may occur together. In practice, these movements are concentrated in areas such as windows and doors, and may occur in many places throughout the building.

be affected more by ground movement than a building on a reinforced concrete raft foundation. However, even a building designed to withstand movement may fail if the amount of subsidence or lateral movement exceeds design parameters. Damage to surrounding infrastructure (paths and roads) can also provide an indication of movement and possible problems, which is especially useful if the building itself is reinforced.

Subsidence, by its very nature, involves the removal of a supporting volume from beneath an area. This can be a result of various mechanisms, which include shrinkage (shrink–swell clays), compression (often involving peat, clay or artificial deposits), collapsible soils, undermining, dissolution (karst) and landslides. In some situations the movement is essentially vertical; in others there is a component of lateral movement, or a combination of these, that effectively results in concave-upward bending (hogging) or convex bending (sagging) (Fig. 1). Each movement type imposes a different combination of stresses upon a building, although damage is often concentrated upon corners or stress concentrators such as door or window areas (National Coal Board 1975; Institution of Structural Engineers 1994; Audell 1996).

In former ancient coal mining and present karst subsidence areas, collapse of bell pits, pillar and stall workings, mine shafts and dolines (sinkholes) tends to result in a movement that is predominantly downward, causing a loss of support (Fig. 1), although lateral movement towards the openings and extension is also possible. Similarly, landslides also cause a loss of support, but it is commonly combined with extension (Fig. 1). Ground movement associated with recent and present-day long-wall coal mining tends to follow a cycle, often described as a wave passing across the area as the mined panel advances (Gray & Bruhn 1984). Where the subsidence front, which is related to the angle of draw of collapse from the workings, intersects the surface, the ground and associated structures first experience a concave-upward bending (hogging), which causes extension of the structure, followed by a convex-upward (sagging) form, which causes compression (Fig. 1; National Coal Board 1975; Shadbolt 1978). For most properties the subsidence wave passes through them and after the extension, compression and settlement, damage is repaired and the property is left fairly intact, but with the ground at a lower level (Shadbolt 1978). Depending on the depth of mining and amount of extraction, this lowering commonly varies from a few tens of centimetres to a metre or more. If the extracted area is large enough, the deformation is transmitted to the surface, where it is seen as a physical surface step around an area that is much larger than the extracted panel (which lies beneath a cone of depression). In places, subsidence cones from different seams or panels intersect, causing enhanced differential settlement. Houses left on the subsidence steps, which mark the edges of the subsidence cones, are commonly very severely damaged; affected houses may undergo compression in one direction and extension in another (Bell *et al.* 2000; Bell 2004). For example, in Old Micklefield, Yorkshire, there is a terrace of houses with a gap and downward step that marks the locations of two former houses that have been demolished because of subsidence damage. The houses in the terrace to either side have also been affected by subsidence, but they have now settled, although with a relative displacement. The houses that were demolished were left on the subsidence step and could not be repaired. Fault reactivation in mining areas is also a cause of subsidence damage or distortion of the ground, commonly resulting in the formation of a subsidence step.

Karst subsidence can occur by the physical compaction or collapse of dissolution-weakened rocks, the removal of material from infilled voids or the dissolution of soluble rocks by the movement of water (Culshaw & Waltham 1987; Gutiérrez *et al.* 2007). Movement is primarily vertical, although in cases of large dissolution collapses or events on slopes, there may be considerable lateral movement and support loss with shear failures around the doline (Waltham *et al.* 2005).

Landslide and creep movements are, by definition, a downward and outward movement of rock, soil or earth (Hunt 2005). Therefore, subsidence events related to landslides tend to involve a combination of the two directions of movement and in some instances the pattern of stresses involved is extremely complex.

Subsidence related to shrink–swell activity tends to be smaller in magnitude, measured in tens of centimetres rather than metres when compared with some of the other processes described here. By the seasonally controlled nature of shrink–swell, the movement also tends to be cyclical and can involve a complex combination of hogging, sagging, lateral extension and compression (Fig. 1; Bell 2004).

Table 1. *Ranking of damage categories used by the UK NCB (National Coal Board 1975)*

Change in length of structure (m)	Class of damage	Description of typical damage
≤0.03	1: very slight or negligible	Hairline cracks in plaster, perhaps isolated slight fracture in the building, not visible from the outside
0.03–0.06	2: slight	Several slight fractures showing inside the building. Doors and windows may stick slightly. Repairs to decoration probably necessary
0.06–0.12	3: appreciable	Slight fractures showing on outside of building (or one main fracture). Doors and windows sticking. Service pipes may fracture
0.12–0.18	4: severe	Service pipes disrupted. Open fractures requiring rebonding and allowing weather into the structure. Window and door frames distorted; floors sloping noticeably; walls leaning or bulging noticeably. Some loss of bearing in beams. If compressive damage, overlapping of roof joints and lifting of brickwork with open horizontal fractures
>0.18	5: very severe	As above, but worse and requiring partial or complete rebuilding. Roof and floor beams lose bearing and need shoring up. Windows broken with distortion. Severe slopes on floors. If compressive damage, severe buckling and bulging of the roof and walls

Building damage caused by earthquakes is not specifically included in this paper because there are well-established internationally accepted schemes that have been linked to earthquake intensity. However, as shown by correlation later in this paper, close comparisons can be made between the scheme presented here and the seismic damage recording schemes. It must be stressed that not all damage will be caused by subsidence or earthquakes, and other causes such as collapsing cellars or deterioration of material can cause downward movement; poor building can have catastrophic damage effects (Kaltakei *et al*. 2007). Heave caused by chemical or moisture changes can also cause upward movements (Hawkins & Pinches 1987; Bell 2004), which in some circumstances could look like hogging associated with subsidence. Fluid withdrawal and collapsible soils are further causes of subsidence and damage (Hunt 2005); the proposed scheme can be used to record all these forms of damage.

Comparison of damage assessment schemes

For a building damage assessment to be useful for the task of hazard mapping, on a town or village scale, the method needs to be quick, easy to apply and preferably without the need for access to buildings. This philosophy is fundamentally different from that used by structural or civil engineering surveys and reflects the very different aim of the recording. It is also important that it can be universally applied to damage whatever the cause, and be carried out by staff who most probably will not be qualified structural engineers. The measurement and classification of building damage has been attempted by numerous workers. Many of the schemes have common features, but vary slightly in the parameters and categories. The way in which damage has been assessed falls into four main types: (1) quantitative structural deformation schemes that measure in detail the amount of distortion of structures and accompanying damage; (2) detailed recording schemes that utilize measurements of damage patterns in buildings and relate them to a pattern of stress that has affected the structure; (3) established earthquake recording schemes used to assess both earthquake damage and earthquake intensity; (4) visual building damage schemes used to record building damage in various geological situations including mining, landslide and shrink–swell clays, and general building damage generated by other causes. This last group of schemes are the most useful for damage recording on a mapping scale. However, the other types of schemes also contribute useful information and are briefly reviewed below.

Quantitative structural deformation schemes

The National Coal Board (1975) scheme One the first, widely used schemes for recording building damage in Britain was that of the UK National Coal Board (NCB) (Table 1) based on the NCB approach detailed in the *Subsidence Engineers Handbook* (National Coal Board 1975). The scheme is based on the change in the length of the structure related to the length of the actual structure. As such, it required reference to a second table to relate the actual strain to the length of the building. This table could be interpreted to give an indication of the amount of extension and cracking a building of any category had undergone. Because the table is based on change of length rather than crack width, it was also applicable to compressional stresses in the sagging mode. However, it requires detailed measurements and does not lend itself to quick surveys based on crack widths, though these are included in the categories. It is

Table 2. *The damage scheme of Bhattacharya & Singh (1985)*

Building category (this is not a damage scale)	Damage level	Angular distortion ($mm\ m^{-1}$) range	Angular distortion ($mm\ m^{-1}$) recommended value	Horizontal strain ($mm\ m^{-1}$) range	Horizontal strain ($mm\ m^{-1}$) recommended value	Deflection value ($mm\ m^{-1}$) range	Deflection value ($mm\ m^{-1}$) recommended value	Radius of curvature (km) range	Radius of curvature (km) recommended value
1: brick or masonry low-rise	Architectural	0.5–2.0	1.0	0.25–1.5	0.5	0.3–1.0	0.3	–	–
	Functional	2.0–6.0	2.5–3.0	1.0–4.0	1.5–2.0	0.14–0.6	0.5	3–20	20
	Structural	7.0–8.0	7.0	2.75–3.5	3.0	–	–	–	–
2: steel reinforced concrete frame	Architectural	1.0–2.5	1.3	–	–	–	–	–	–
	Functional	2.5–5.5	3.3	–	–	–	–	–	–
	Structural	–	–	–	–	–	–	–	–
3: timber frame structures	Architectural	2.0	1.5	1.0	1.0				–
	Functional	3.3–10	3.3–5.0	–	–				–
	Structural		–	–					–

Damage levels are as follows. Architectural: onset of architectural damage is characterized by small-scale cracking of plaster and sticking doors and windows. Functional: onset of functional damage is characterized by instability of some structural elements, jammed doors and windows, broken window panes, building services restricted. Structural: onset of structural damage is characterized by impairment of primary structural members, possibility of collapse of members, complete or large-scale rebuilding necessary, may be unsafe for habitation.

Table 3. *The building damage scheme of Chiocchio et al. (1997) applied to landslide damage*

Grade	Damage level	Load-bearing structure	Damage: Rigid settlement (cm)	Damage: Rigid rotation (cm)	Damage: Distortion (%) and differential settlement (cm)	Damage: Cracking	Damage: Thrusting
0	None	Masonry	0	0	0	None	None
		Reinforced concrete frame	0	0	0	None	None
1	Negligible	Masonry	0	0	0	Hairline cracks of the plaster	None
		Reinforced concrete frame	0	0	0	Hairline cracks of the plaster	None
2	Light	Masonry	2–3	2.5‰*h	3‰*1	Small cracks through walls and partitions	None
		Reinforced concrete frame		2.5‰*h	3‰*1	Small cracks through perimetric and partition walls	None
3	Moderate	Masonry	10–15	4‰*h	4–5‰*1	Open cracks in walls; wall disjunction; lintel deformation; badly working casings	Only in significant sites
		Reinforced concrete frame	10–15	4‰*h	4–5‰*1	Significant cracking in the beams; partition walls deformed and crumbling; badly working casings	Not spread
4	Serious	Masonry	15–20	8‰*h	7‰*1	Considerable disjunction of walls; space deformation; partition walls collapsed; unusable casings	Spread and remarkable
		Reinforced concrete frame	15–20	8‰*h	7‰*1	Perimetric and partition walls partly collapsed; deformed structures; spread cracking	Spread and remarkable
5	Very serious	Masonry	>25	10‰*h	10‰*1	Open cracks in floor; partition walls totally collapsed; seriously ruined lintels	Very spread
		Reinforced concrete frame		10‰*h	10‰*1	Partition and perimetric walls collapsed; heavy deformation in the structures; cracking in floor and slab	Very spread
6	Partial collapse	Masonry	u.d.	u.d.	u.d.	u.d.	u.d.
		Reinforced concrete frame	u.d.	u.d.	u.d.	u.d.	u.d.
7	Total collapse	Masonry	u.d.	u.d.	u.d.	u.d.	u.d.
		Reinforced concrete frame	u.d.	u.d.	u.d.	u.d.	u.d.

*h, ...; *l,...; u.d., undetermined.

Table 4. *Modified Mercalli scale of earthquake damage by Wood & Neumann (1931) as applied to earthquake severity and damage*

Degree	Description	Acceleration (mm s^{-2})
I	Not felt. Detected only on seismographs	<2.5
II	Feeble. Felt by persons at rest, on upper floors, or favourably placed	2.5–5.0
III	Slightly felt indoors. Hanging object swing. Vibration like passing of light trucks. Duration estimated. May not be recognized as an earthquake	5.0–10
IV	Slightly felt indoors. Hanging object swing. Vibration like passing of light trucks, or sensation of jolt like a heavy ball striking the walls. Standing motor cars rock. Windows, dishes and doors rattle. Glasses clink. Crockery clashes. In the upper range of IV wooden walls and frames creak	10–25
V	Rather strong. Felt outdoors. Sleepers wakened. Liquids disturbed, some spilled. Small unstable objects displaced or upset. Doors swing, close, open. Shutters and pictures move. Pendulum clocks stop, start, change rate	25–50
VI	Strong. Felt by all. Many frightened and run outdoors. Persons walk unsteadily. Windows, dishes, glassware broken. Ornaments, books, etc., fall off shelves. Pictures fall off walls. Furniture moved or overturned. Weak plaster or masonry cracked. Small bells ring (church, school). Trees shaken visibly or heard to rustle	50–100
VII	Very strong. Difficult to stand. Noticed by drivers of motor cars. Hanging objects quiver. Furniture broken. Damage to masonry D, including cracks. Weak chimneys broken at roof line. Fall of plaster, loose bricks, stones, tiles, cornices also unbraced parapets and architectural ornaments. Some cracks in masonry C. Waves on ponds, water turbid with mud. Small slides and caving-in along sand or gravel banks. Large bell rings. Concrete irrigation ditches damaged	100–250
VIII	Destructive. Steering of motor cars affected. Damage to masonry C, partial collapse. Some damage to masonry B, not to masonry A. Fall of stucco and some masonry walls. Twisting, fall of chimneys, factory stacks, monuments, towers, elevated tanks. Frame houses moved on foundations if not bolted down; loose panel walls thrown out. Decayed piling broken off. Branches broken from trees. Changes in flow or temperature of springs and wells. Cracks in wet ground and on steep slopes	250–500
IX	Ruinous. General panic. Masonry D destroyed, masonry C heavily damaged, sometimes with complete collapse, masonry B seriously damaged. General damage to foundations. Frame structures, if not bolted down, shifted on foundations. Frames cracked. Serious damage to reservoirs. Underground pipes broken. Conspicuous cracks in ground. In alluviated areas sand and mud ejected, earthquake fountains and sand craters	500–1000
X	Disastrous. Most masonry and frame structures destroyed with their foundations. Some well-built wooden structures and bridges destroyed. Serious damage to dams, dykes, embankments. Large landslides. Water thrown on banks of canals, rivers, lakes, etc. Sand and mud shifted horizontally on beaches and flat land. Rail tracks bent slightly	1000–2500
XI	Very disastrous. Rail tracks bent greatly. Underground pipelines completely out of service	2500–5000
XII	Catastrophic. Damage nearly total. Large rock masses displaced. Lines of sight and level distorted. Objects thrown in the air	>5000

A, reinforced masonry designed to resist lateral forces; B, reinforce masonry; C, normal masonry; D, weak masonry.

from this scheme that the subsequent crack width recording schemes have been derived, based on the measured parameters and the damage description.

The Bhattacharya & Singh (1985) scheme Bhattacharya & Singh (1985) collated information from a large number of sources to define recommended maximum values for subsidence effects in coal mining areas (Table 2). Their values give parameters for engineers to design foundations and structures, but do not function as a method of surveying and recording damage. They considered factors such as curvature of bending, angle of rotation and differential movement amounts. They also gave values for different types of structures ranging from sensitive brick buildings to reinforced concrete structures. The blanks in the table represent insufficient data, which Bhattacharya & Singh hoped to be able to complete in due course. Their scheme was based on a review of the literature with the aim of producing a universally workable scheme that could be applied by people other than qualified mining subsidence specialists.

The Chiocchio et al. (1997) landslide damage recording scheme The scheme developed for landslide damage by Chiocchio *et al*. (1997) has similarities to the NCB scheme in that it presents measurements (Table 3), but it also has descriptions of crack, deformation and damage development that make it resemble the damage recording schemes. Much of it is comparable with the National Coal Board (1975) scheme, but with the addition of two

Table 5. *Medvedev et al. (1965) building damage classification to complement their seismic intensity scale*

Grade	Damage
1: slight damage	Fine cracks in plaster; fall of small pieces of plaster
2: moderate damage	Small cracks in walls; fall of fairly large pieces of plaster; pantiles slip off; cracks in chimney; parts of chimney fall down
3: heavy damage	Large and deep cracks in walls; fall of chimneys
4: destruction	Gaps in walls; parts or buildings may collapse; separate parts of the buildings lose their cohesion; inner walls and filled in walls of the frame collapse
5: total damage	Total collapse of buildings

Table 6. *European Macroseismic Intensity Scale (Grünthal 1998)*

Grade	Damage to masonry structures	Damage to reinforced concrete buildings
1: negligible to slight damage (no structural damage to slight non-structural damage)	Hairline cracks in a few walls. Fall of small pieces of plaster only. Fall of loose stones from upper parts of buildings in very few cases	Fine cracks in plaster over frame members or in walls at the base. Fine cracks in partitions and infills
2: moderate damage (slight structural damage, moderate non-structural damage)	Cracks in many walls. Fall of fairly large pieces of plaster. Partial collapse of chimneys	Cracks in columns and beams of frames and in structural walls. Cracks in partition and infill walls; fall of brittle cladding and plaster. Falling mortar from the joints of wall panels
3: substantial to heavy damage (moderate structural damage, heavy non-structural damage)	Large and extensive cracks in most walls. Roof tiles detach. Chimneys fracture at the roof line; failure of non-structural elements (partitions, gable walls)	Cracks in columns and beam column joints of frames at the base and at joints of coupled walls. Spalling of concrete cover; buckling of reinforced rods
4: very heavy damage (heavy structural damage, very heavy structural damage)	Serious failure of walls; partial structural failure of roofs and floors	Large cracks in structural elements with compression failure of concrete and fracture of rebars; bond failure of beam reinforced bars; tilting of columns. Collapse of a few columns or of a single upper floor
5: destruction (very heavy structural damage)	Total or near-total collapse	Collapse of ground floor or parts (e.g. wings) of buildings

more categories to encompass more severe damage. It also has details for masonry structures and reinforced concrete structures in the same settings.

Detailed crack recording schemes

A detailed scheme of building crack classification and analysis was presented by Audell (1996). This thorough, but fairly complicated scheme requires a full internal survey of the property and is best carried out by a qualified structural engineer. The work provides useful insight into the way that different movements affect a structure and how lateral movements can cause very different crack patterns from vertical subsidence movements and bending. The scheme is useful for detailed inspection of properties to determine the sort of stresses that would cause the damage; as such, it is also a suitable training document worth reading before any damage surveying is undertaken. Although the various styles and orientations of crack development are related by Audell (1996) to different mechanisms of formation, no assessment of crack size or intensity of movement is given. Because buildings are sensitive to movements the actual amount of ground deformation between minor damage and complete collapse can be small. For the assessment of damage to single properties, detailed internal and external surveys of cracks using tell-tales (Building Research Establishment 1990; Johnson 2005) is standard engineering practice. Information gathered in this way can be incorporated in the wider recording scheme presented in the present paper.

Earthquake intensity or impact recording schemes

Earthquakes have, on many occasions, caused severe damage to buildings worldwide; consequently, there are

Table 7. *Ranking of damage categories used by the Institution of Civil Engineers, Institution of Structural Engineers and Building Research Establishment Scheme (Freeman et al. 1994)*

Category of damage	Description of typical damage (nature of repair in italic type)
0	Hairline cracking that is normally indistinguishable from other causes such as shrinkage and thermal movement. Typical crack widths 0.1 mm. *No action required*
1	Fine cracks that *can easily be treated using normal decoration*. Damage generally restricted to internal wall finishes: cracks rarely visible in external brickwork. Typical crack widths up to 1 mm
2	*Cracks easily filled. Recurrent cracks can be masked by suitable linings*. Cracks not necessarily visible externally: *some external repointing may be required to ensure weather-tightness*. Doors and windows may stick slightly and *require easing and adjusting*. Typical crack widths up to 5 mm
3	Cracks that *require some opening up and can be patched by a mason. Repointing of external brickwork and possibly a small amount of brickwork to be replaced*. Doors and windows sticking, service pipes may fracture. Weather-tightness often impaired. Typical crack widths are 5–15 mm, or several of, say 3 mm
4	Extensive damage that *requires breaking-out and replacing sections of walls*, especially over doors and windows. Windows and door frames distorted, floor sloping noticeably. [a] Walls leaning or bulging noticeably; some loss of bearing in beams. Service pipes disrupted. Typical cracks widths are 15–25 mm, but also depends on number of cracks
5	Structural damage that *requires a major repair job, involving partial or complete rebuilding*. Beams lose bearing; walls lean badly and require shoring. Windows broken with distortion. Danger of instability. Typical crack widths are >25 mm, but depends on the number of cracks

The same scheme is used by the Institution of Structural Engineers (1994) with minor word changes.
[a]Crack width is one factor in assessing category of damage and should not be used on its own as a direct measure of it. Local deviation of slope, from the horizontal or vertical, of more than 1/100 will normally be clearly visible. Overall deviations in excess of 1/150 are undesirable.

Table 8. *Building damage classification scheme of Alexander (1986) devised for landslide damage assessment*

Category of damage	Building damage
0: none	Building is intact
1: negligible	Hairline cracks in walls or structural members; no distortion of structure or detachment of external architectural details
2: light	Building continues to be habitable; repair not urgent. Settlement of foundations, distortion of structure and inclination of walls are not sufficient to compromise overall stability
3: moderate	Walls out of perpendicular by 1–2°, or substantial cracking has occurred to structural members, or foundations have settled during differential subsidence of at least 15 cm; building requires evacuation and rapid attention to ensure its continued life
4: serious	Walls out of perpendicular by several degrees; open cracks in walls; fracture of structural members; fragmentation of masonry; differential settlement of at least 25 cm compromises foundations; floors inclined by up to 1–2°, or ruined by soil heave; internal partition walls will need to be replaced; door and window frames too distorted to use; occupants must be evacuated and major repairs carried out
5: very serious	Walls out of plumb by 5–6°; structure grossly distorted and differential settlement will have seriously cracked floors and walls or caused major rotation or slewing of the building (wooden buildings may have detached completely from their foundations). Partition walls and brick infill walls will have at least partly collapsed; occupants will need to be rehoused on a long-term basis and rehabilitation of the building will probably not be feasible
6: partial collapse	Requires immediate evacuation of the occupants and cordoning of the site to prevent accidents from falling masonry
7: total collapse	Requires clearance of the site

several schemes that have been applied to the description of their damage. The modified Mercalli scale of Wood & Neumann (1931) included some details of building damage (Table 4). A similar, but more detailed scheme by Medvedev *et al*. (1965) (the Medvedev–Sponheuer–Kárnik scheme) included a sub-table of building damage characteristics (Table 5) that is comparable with some of the recording schemes applied to damage by other causes. The more recent European Macroseismic Scale (Grünthal 1998) presented damage classification information relevant to different construction types and linked that to the intensity scale (Table 6). The

Table 9. *The damage recording scheme used by Howard Humphreys & Partners (1993) for the Department of the Environment Norwich study*

Category	Typical damage to buildings	Effect on open ground and highways
0: negligible	Hairline cracks in walls and between floor and skirtings	Not noticeable
1: very slight	Perhaps isolated slight cracking in walls, but not visible in external brickwork. Cracks below skirting	Not noticeable
2: slight	Hair cracks in plaster, possibly isolated slight fracture showing inside the building, not generally visible on outside. Cracks open up below skirting. Doors and windows may stick slightly. Cracks can be filled or masked. Repairs to decoration probably necessary	Generally not noticeable
3: moderate	Slight fracturing apparent on the outside of the building (cracks up to 3 mm wide); or one main fracture open 5–15 mm. Doors and windows may stick. Service pipes may fracture. Foundation improvement or treatment may have been carried out under part of the building. Repointing of external brickwork may be required, and possibly a small amount of brickwork to be replaced	Slight depression in open ground or highway, noticeable to vehicle users, but may not be obvious to casual observers. Repairs generally superficial, but may involve limited local pavement reconstruction
4: severe	Open fractures (15–25 mm) develop that require breaking-out and replacing section of walls. Bays may drop. Window and door frames distorted, causing openers to stick badly. Floors slope noticeably; walls lean or bulge noticeably. Service pipes disrupted. Foundation improvement or treatment may be required to part or all of the building. Rebuilding of part of the structure may be required	Significant depression, often accompanied by cracking, in open ground or highway. Obvious to the casual observer. Small open hole may form. Repairs to the highway generally require excavation and reconstruction of the road pavement
5: very severe	Severely cracked walls with open fractures, usually >25 mm. Windows and doors broken with distortion. Severely sloping floors and sagging ceilings. Service pipes dislocated. Foundation improvement probably required. Partial to complete rebuilding may be necessary	Significant depression, often accompanied by cracking, in open ground or highway; open crater formed, often with large void. Generally, disruption of services in highways. Significant works may be required to repair road pavement
6: extremely severe	Very severe distress to buildings with dislocation of walls; partial or complete collapse may occur, and this may be sudden. Open void may develop, which often extends to depth. Services severed. Infilling or capping of voids required. Foundation treatment or improvement required. Structure requires demolition or major rebuilding	Collapse of ground or highway, which may be sudden. Significant open void forms, which requires partial or total closure of the highway. Services severed or severely disrupted. Infilling or capping of void followed by significant works to backfill and reinstate road pavement
?Not known	Damage not recorded	Details not recorded

Medvedev–Sponheuer–Kárnik scheme is similar in many respects to the modified Mercalli scale, but has sub-tables defining types of structures, definition of quality, classification of building damage, and arrangement of the scale. The classification of the building damage (Table 4) is the scale that is the most important for comparison with the other damage scales.

Table 10. *The damage scheme of Van Rooy (1989)*

Crack width (mm)	Degree of damage	Risk
0	No damage	Very low
0–2.5	Slightly damaged	Low
2.5–5.0	Visibly damaged	Medium
5–10	Moderately damaged	High
>10	Badly damaged	Very high

Building damage recording schemes

Schemes that describe building damage have proven to be popular. They tend to be simple to use and can easily be constructed to deal with local or process-specific needs. Some building damage schemes are subdivided by the type of building or structure that is affected; a logical step, as different building designs will be expected to perform differently under stress. However, from a practical point of view, it is often difficult to recognize

Table 11. *Correlation between various building damage assessment schemes*

Proposed scheme with classes (and descriptors for building damage)	National Coal Board (1975), coal mining subsidence	Freeman *et al.* (1994), Institution of Structural Engineers (1994), shrink–swell clays and general damage	Howard Humphreys & Partners (1993), Norwich chalk mining subsidence	Alexander (1986), landslide damage	Geomorphological Services Ltd (1991), Ventnor landslide damage	Chiocchio *et al.* (1997), landslide damage	Grünthal (1998), European Macroseismic Scale	Medvedev *et al.* (1965), earthquake damage	Wood & Neumann (1931), modified Mercalli scale
0: none		0	0: negligible	0: none		0: none			I, II, III, IV, V; no significant damage
1: very slight	1: very slight or negligible	1	1: very slight	1: negligible	Negligible	1: negligible			
2: slight	2: slight	2	2: slight	2: light	Slight	2: light	1: negligible to slight	1: slight damage	VI
3: moderate	3: appreciable	3	3: moderate	3: moderate	Moderate	3: moderate	2: moderate damage	2: moderate damage	VII
4: severe	4: severe	4	4: severe	4: serious	Serious	4: serious			
5: very severe	5: very severe	5	5: very severe	5: very serious	Severe	5: very serious	3: substantial to heavy damage	3: heavy damage	
6: partial collapse			6: extremely severe	6: partial collapse		6: partial collapse	4: very heavy damage	4: destruction	VIII
7: total collapse				7: total collapse		7: total collapse	5: destruction	5: total damage	IX
									X
									XI
									XII: total devastation

Table 12. *The damage recording scheme used by Geomorphological Services Ltd (1991) for landslips at Ventnor, Isle of Wight*

Class	Description
Negligible	Hairline cracks to roads, pavements and structures with no appreciable lipping or separation
Slight	Occasional cracks. Distortion, separation or relative settlement apparent. Small fragments of debris may occasionally fall onto roads and structures, causing only slight damage. Repair not urgent
Moderate	Widespread cracks. Settlement may cause slight tilt to walls and fractures to structural members and service pipes
Serious	Extensive cracking. Settlement may cause open cracks and considerable distortion to structures. Walls out of plumb and the road surface may be affected by subsidence. Parts of roads and structures may be covered with landslide debris from above. Repairs urgent to safeguard future use of roads and structures
Severe	Extensive cracking. Settlement may cause rotation or slewing of ground. Gross distortion to roads and structures. Repairs will require partial or complete rebuilding and may not be feasible. Severe movements leading to the abandonment of the site or area

foundation types or record damage to foundations or other subsurface amenities. Consequently, schemes that describe the above-ground damage, rather than the causes and underlying physical distortion parameters, are more practical for field recording.

Building Research Establishment, Institution of Civil Engineers and Institution of Structural Engineers schemes (1981 and 1994) In Britain, the National Coal Board (1975) scheme was the first to be widely used, but it partly based on quantitative measurements. It was followed by those of other organizations that recorded subsidence caused by different mechanisms and deposits. The UK Building Research Establishment (1981, 1990) published a scheme similar to that of the NCB, but translated the movements mainly into crack widths (adding that they were not the only factors to consider). However, the categories and the nature of the damage recorded are remarkably similar to those of the National Coal Board (1975) scheme. Later, the Institution of Civil Engineers and Building Research Establishment published a similar scheme (Freeman *et al.* 1994), which allowed the assessment and classification of subsidence and heave caused by shrink–swell clay. Similarly, the Institution of Structural Engineers (1994) used almost the same scheme as a general tool to assess damage to walls in low-rise buildings. The later schemes use slightly different wording and also emphasize that crack width alone is not the only factor to be taken into account when assigning a damage rating (Table 7).

Alexander (1986) landslide damage recording scheme Alexander (1986) devised a landslide building damage classification scheme from work carried out on the 1982 Ancona landslide in central Italy, which involved 3.41 km^2 of land and about 475 buildings. The scheme proposed has strong similarities to the National Coal Board (1975) scheme, which was not referenced. Alexander (1986) included more severe categories of damage in the scheme, including a category 6 (partial collapse) and category 7 (total collapse) (Table 8).

Howard Humphreys & Partners (1993) subsidence damage scheme Much of the town of Norwich is undermined by largely uncharted chalk and flint mines. These commonly collapse, causing subsidence and structural damage. In addition, there may be subsidence caused by natural dissolution of the Chalk and the settlement or piping of fill in dolines. The subsidence damage classification proposed by Howard Humphreys & Partners (1993) was used to rank historical records of subsidence in the town. It is based on the National Coal Board (1975) and Institute of Civil Engineers/Building Research Establishment (Freeman *et al.* 1994) schemes with the addition of extra fields to allow the incorporation of historically based details and indications on open ground and highways (Table 9). The scheme is also extended to category 6 (extremely severe).

Van Rooy (1989) karst subsidence damage scheme In South Africa, Van Rooy (1989) studied karst sinkhole formation on dolomitic areas. The investigation looked at methods of mapping the karst areas and classifying them to zone the risk of karstic subsidence. One of the datasets included was building damage resulting in a scheme that works in a similar way to the National Coal Board (1975) and subsequent schemes, but with different intervals (Tables 10 and 11).

Geomorphological Services Ltd (1991) landslide damage scheme Landslides have also been the subject of several building damage classification schemes and the Geomorphological Services Ltd (1991) scheme parallels that of the NCB and BRE classifications (Table 12). This scheme does not record crack widths, but the descriptions of damage allow a reasonable comparison with the other schemes; this is discussed below.

Correlation between damage assessment schemes

The range of schemes presented above is far from exhaustive, but it does usefully demonstrate that there

Table 13. *Ranking scheme of building damage categories based on the schemes of: the National Coal Board (1975), Alexander (1986), Geomorphological Services Ltd (1991), Freeman et al. (1994) and the Institution of Structural Engineers (1994)*

Class	Typical building damage	Subsidence ground damage	Landslide ground damage
0	Hairline cracking, widths to 0.1 mm. Not visible from outside	Not visible	Not visible
1	Fine cracks, generally restricted to internal wall finishes: rarely visible in external brickwork. Typical crack widths up to 1 mm. Generally not visible from outside	Not visible	Not visible
2	Cracks not necessarily visible externally, some external repointing may be required. Doors and windows may stick slightly. Typical crack widths up to 5 mm. Difficult to record from outside	Not visible	Not visible
3	Cracks that can be patched by a builder. Repointing of external brickwork and possibly a small amount of brickwork to be replaced. Doors and windows sticking, slight tilt to walls, service pipes may fracture. Typical crack widths are 5–15 mm, or several of say 3 mm. Visible from outside	Slight depression in open ground or highway, noticeable to vehicle users, but may not be obvious to casual observers. Repairs generally superficial, but may involve local pavement reconstruction	No damage likely to be noticed in vegetated ground. Tight cracks in hard surfaces, paths, roads, pavements and structures with no appreciable lipping or separation
4	Extensive damage that requires breaking-out and replacing sections of walls, especially over doors and windows. Windows and door frames distorted, floors sloping noticeably; some loss of bearing in beams, distortion of structure. Service pipes disrupted. Typical crack widths are 15–25 mm, but also depends on number of cracks. Noticeable from outside	Significant depression, often accompanied by cracking, in open ground or highway. Obvious to the casual observer. Small hole may form. Repairs to the highway generally require excavation and reconstruction of the road pavement	Slight stretching of roots, tension changes on wires and fences. Open cracks, distortion, separation or relative settlement. Small fragment falls cause slight damage to roads and structures. Remedial works not urgent
5	Structural damage, which requires a major repair job, involving partial or complete rebuilding. Beams lose bearing capacity, walls lean badly and require shoring. Windows broken with distortion. Danger of instability. Typical crack widths are >25 mm, but depend on the number of cracks. Very obvious from outside	Rotation or slewing of the ground or significant depression, often accompanied by cracking, in open ground or highway. General disruption of services in highways. Significant repair required	Widespread tension cracks in soil and turf. Ground surface bulged and/or depressed. Settlement may tilt walls, fracture of structures, service pipes and cables. Remedial work necessary
6	Partial collapse. Very obvious from outside	Collapse of ground or highway, significant open void, services severed or severely disrupted	Extensive ground cracking with minor scarps, ground bulging and soil rolls. Minor flows, falls and slides may affect roads and structures. Settlement causes cracks and distortion to structures and roads. Remedial works urgent
7	Total collapse. Very obvious from outside	Large open void	Extensive ground cracking, major scarps and grabens. Major debris, earth or mud flows, and slides and falls. Settlement causes rotation or slewing of ground, gross distortion and destruction of structures. Major remedial works may not be feasible

This scheme is applicable to subsidence damage resulting from numerous causes including, shrink–swell, landslip, karst and mining.

are many similarities between them. This is partly a result of the common aim of describing building damage and relating it to an external influence. Similarities have also arisen from the tendency (repeated here) to use, revise and refine existing schemes to suit different requirements. Table 11 shows how the different damage

Fig. 2. Category 7 building damage at Ure Bank Terrace, Ripon. The damage here has been caused by gypsum dissolution and collapse with loss of support under most of the building (Cooper 1998).

categories of the selected schemes can be correlated. It can be seen from this table that some schemes are markedly different, but in general the similarities are stronger than the differences.

The unified building damage scheme and its application

As a result of the similarities between the existing landslide and subsidence recording schemes it has been feasible to extend the subsidence schemes and generate a common building damage recording scheme that can be used independent of the cause (Table 13). However, the existing earthquake recording schemes, which are either partly or totally related to seismic intensity, are internationally accepted and strongly entrenched in the literature (especially the European Macroseismic Scale of Grünthal 1998); consequently, the present study restricts itself to subsidence, landslip and similar damage.

Fig. 3. Sagging building damage category 5 caused by gypsum dissolution and associated settlement on peat deposits, Princess Road, Ripon (Cooper 1998).

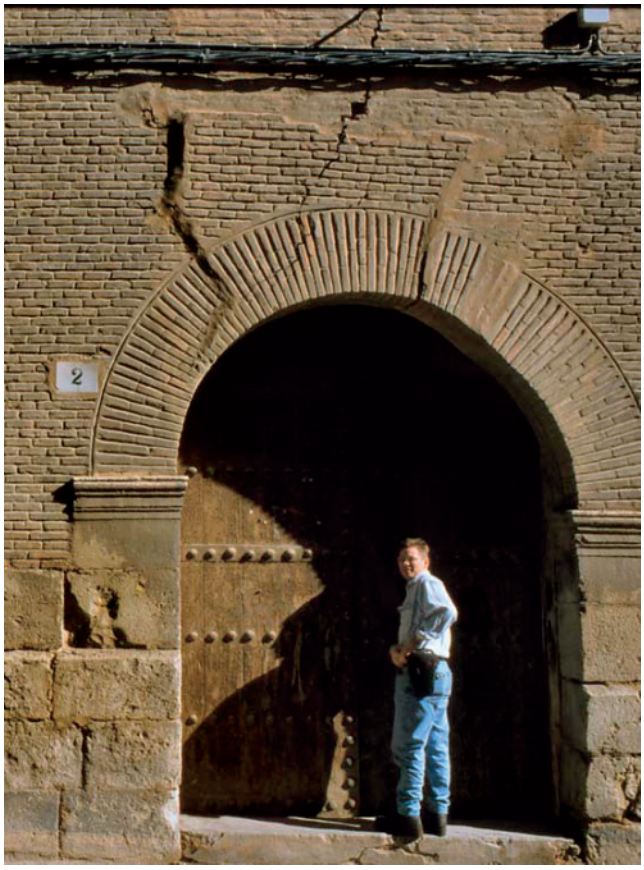


Fig. 4. Category 5 damage to a historic building in Calatayud, Spain (note the concentration of the damage in the arch). This is a hogging mode of failure with loss of support to the right of the picture.

The details of the unified building damage classification scheme are presented in Table 13. The scheme has seven categories ranging from very slight to total collapse. For compatibility and consistency, the lowest five of the categories are the same as those in the schemes applied to subsidence caused by the numerous mechanisms detailed by the National Coal Board (1975), the Institution of Civil Engineers and Building Research Establishment (Freeman *et al.* 1994) and the Institution of Structural Engineers (1994). All seven categories have previously been applied to landslide damage by Alexander (1986) and Chiocchio *et al.* (1997). In the proposed unified scheme (Table 13) the two highest categories are also applied to subsidence, making one recording scheme for subsidence caused by karst, shrink–swell, deep and shallow mining, compressible ground and landslips.

The lowest 1–5 categories of the damage scheme have previously been successfully used to record building damage in Ripon, North Yorkshire (Figs. 2 and 3; Griffin 1986; McNerney 2000). The same approach has also been applied to the historical city of Calatayud in Spain (Figs. 4 and 5; Gutiérrez *et al.* 2000; Gutiérrez & Cooper 2002). After these studies and in the light of more recent work, it became apparent that the National

Fig. 5. Cracks in historic building of Colegiata Sta. María La Mayor in Calatayud, Spain. Here the cracks are up to 30 mm wide; others on the building are larger and the degree of damage merits a category 5 classification (Gutiérrez & Cooper 2002).

Coal Board (1975) scheme required additional classes to allow more severe damage to be recorded. Extension of the recording to more open land was also possible. The extended scheme with classes 1–7 was instigated for use in the British Geological Survey karst geohazards database (Cooper *et al.* 2001).

Of necessity, the surveys in Ripon and Calatayud could be undertaken only from outside the properties (Fig. 6) and usually remotely from roads or public land. Consequently, only the more severe levels of damage (above category 2) could be surveyed. The surveying techniques involved walking around the towns noting the damage ratings on topographical maps and making additional notes in notebooks. Since then, the British Geological Survey karst geohazards database has been established, with direct input of data to a database using a GIS interface (Cooper *et al.* 2001). Initially, proformas were developed to duplicate the database fields and allow information to be collected in loose-leaf notebooks (Fig. 7). Other loose-leaf sheets were also printed for recording springs, dolines, stream sinks and natural cavities (Cooper *et al.* 2001). Recent developments of rugged waterproof mobile tablet personal computers and the development of the British Geological Survey digital field mapping system allow the gathering this type of data directly into a GIS in the field in the form and structure that the centralized database requires.

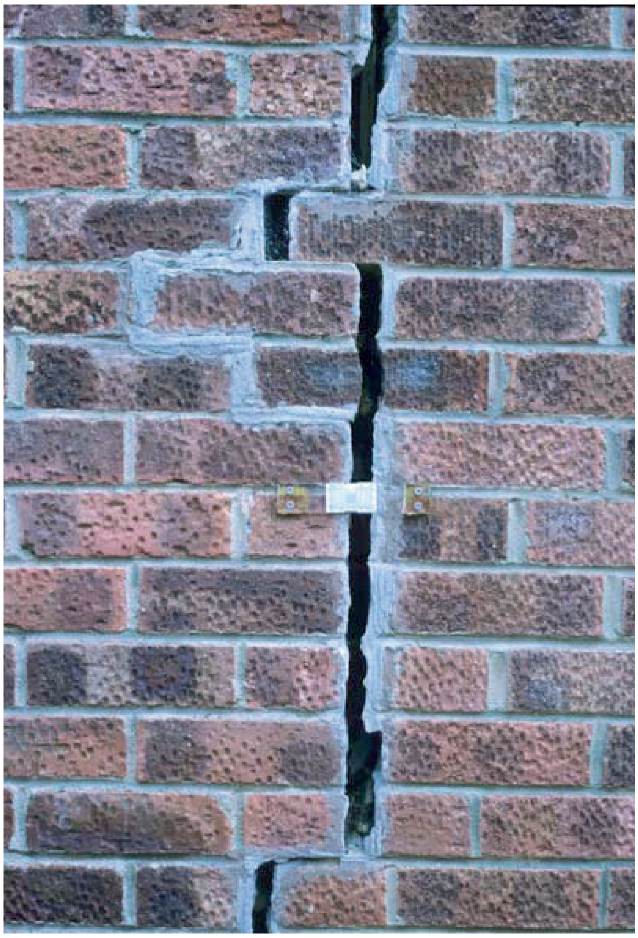
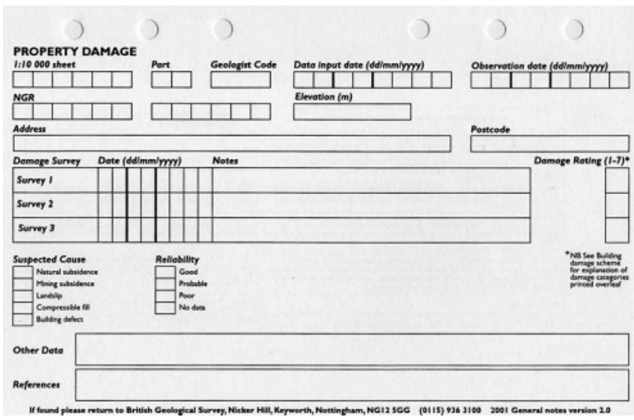


Fig. 6. An 18 mm crack in the wall of a house at Hutton Conyers near Ripon; damage caused by subsidence at the side of a large doline formed by the dissolution of gypsum. Category 4 damage formed by loss of support and rotation of the floor slab.



PROPERTY DAMAGE
1:10 000 sheet
Part
Geologist Code
Data input date (dd/mm/yyyy)
Observation date (dd/mm/yyyy)
NGR
Elevation (m)
Address
Postcode
Damage Survey
Date (dd/mm/yyyy)
Notes
Damage Rating (1-7)*
Survey 1
Survey 2
Survey 3
Suspected Cause
Natural subsidence
Mining subsidence
Landslip
Compressible fill
Building defect
Reliability
Good
Probable
Poor
No data
*NB See Building damage scheme for explanation of damage categories printed overleaf
Other Data
References
If found please return to British Geological Survey, Nicker Hill, Keyworth, Nottingham, NG12 5GG (0115) 936 3100 2001 General notes version 2.0

Fig. 7. Loose-leaf proforma sheet used to record building damage. The reverse side of the sheet includes a summary of the building damage classification scheme as detailed in Table 13.

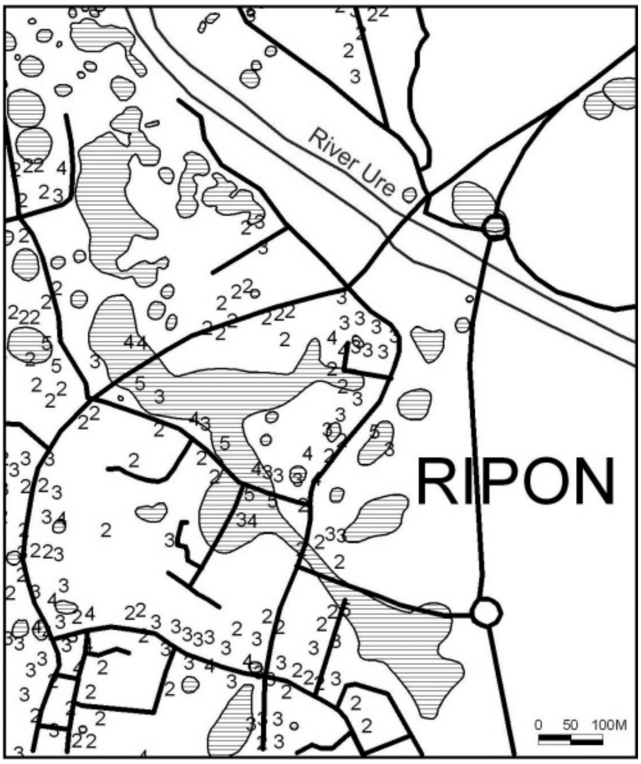


Fig. 8. Extract from the British Geological Survey karst GIS and database showing the distribution of building damage recorded by McNerney (2000) and subsidence hollows shown with a horizontal ornament, in part of Ripon.

The building damage information can be allied with records of karst features to give local information points that can be overlain on the geographical distribution of soluble rocks. These cross-correlations of datasets add real susceptibility information to the interpretation of karst-prone subsidence areas (Cooper 2007; Farrant & Cooper 2008).

Building damage information can be displayed in a GIS and zoned or gridded to give good indications of the areas most susceptible to subsidence. Where the information has also been collected for the surrounding countryside, the area can be treated as single modelling entity. Figure 8 shows an extract from the building damage table of the karst database illustrating a small area of the building damage recorded by McNerney (2000). The zoning and prediction of areas susceptible to subsidence or landslip can be a powerful tool for planning and development (Paukštys *et al.* 1999).

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