Slope geomorphology and threshold slopes
at Callow Bank, Hathersage, Derbyshire

Martin Cross

Abstract: Recognition of threshold and slope classes within a region indicates slope units where specific geomorphological processes are operating, and may be used to predict slope hazard areas. Using slope profile surveys and GIS techniques, analysis of slope form in the Callow Bank catchment near Hathersage identified characteristic and threshold slope angles. Geomorphological maps that adopt recognized characteristic and threshold slope classes allow an engineer or planner to identify slopes associated with particular hazardous processes.

Slopes exist in a variety of forms that reflect variations in climate, vegetation, rock type and rock structure. Characteristic angles and slope form are produced by specific geomorphological processes. All slopes are affected, though the rate at which they are being modified is usually extremely slow. Many slopes retain aspects of their form that were caused by processes no longer operating, notably in Britain from past glacial and periglacial activity. The main processes affecting slope form include mass movement, weathering and soil formation, and the movement of water and weathered slope material (regolith). The character of the materials can affect the processes involved.

Threshold slope angles

These may be regarded as the boundaries above, or below, which particular geomorphological processes cannot operate (Chandler, 1970; Carson and Petley, 1970; Anderson *et al*., 1980; Brooks *et al.* 1993; Montgomery, 2001). The various mass movement processes, including deep and shallow slides or flows, may set limits to the angle at which a particular slope type may be maintained. The upper parts of scree slopes are commonly restricted to angles no greater than 36–38°, terracettes rarely occur below 32–33°, and first-time soil slips are more common on slopes >20° (Carson & Kirkby, 1972). Slopes above 45° undergo rapid retreat, and slopes of around 33–35° develop from these at close to the limiting angle for dry scree. This marks the upper limit for valley-side slopes, since any steeper than this are mostly free faces. Slopes of 25–29° replace the steeper slopes by retreat where rapid basal erosion is absent. This angle corresponds to the stability angle (threshold) of the weathered regolith material (Carson & Petley, 1970). Slopes of 5–9° are associated with the limiting angle for relatively rapid solifluction (Young, 1972).

Certain threshold slopes are more common, and relate to soil lithologies (Table 1). In the southern Pennines, straight segments on slopes at about 25° are considered to represent the angle of long-term stability for regolith, excluding clays (Carson & Petley, 1970). Breakdown of slope mantle during weathering determines reductions in the angle of internal friction of the soil (Cross, 2010); these affect the shear strength and cause changes in the stable slope angle (Fig. 1).

In South Wales, slopes showing clear evidence of planar failures within superficial material typically have angles of about 18° (Conway *et al.* 1980). In the same area, a survey (Table 2) related threshold slope angles to regolith, bedrock and process (Rouse & Farhan, 1976). Conclusions from the Welsh studies included:

1: processes of rapid mass movement can be used to interpret most of the valley side slopes in Britain, where the slopes are largely a relict feature of a former periglacial environment;

2: rock type, geological structure and resultant lithology of the regolith influence slope development;

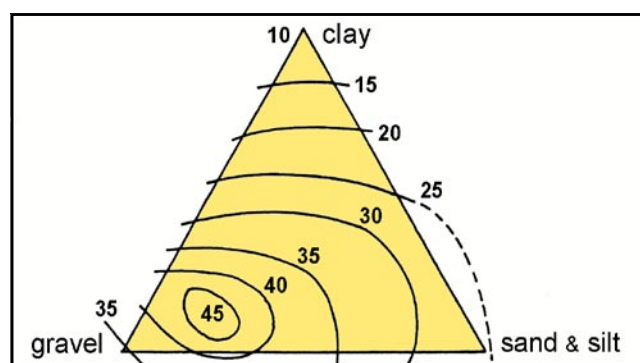3: glacial erosion created free-faces that developed large scree slopes under periglacial conditions;

***Figure 1**. Angles of internal friction (in degrees) for different soil lithologies (after Kirkby, 1973).*

43° - 45°:	slopes on fractured and jointed rock.
33° - 38°:	drained talus slopes.
25° - 28°:	slopes on talluvium.
19° - 21°:	slopes on granular soil debris.
8° - 11°:	slopes on cohesive material.

***Table 1**. Threshold slope angles related to soil lithologies (after Carson & Kirkby, 1972).*

36°	Upper limit for valley side slopes
36° - 34°	Dry scree at the foot of free faces
30° - 28°	Fossil scree on sandstone
22° - 18°	Fossil scree on shale
10° - 8°	Solifluction slopes
6° - 2°	Flat areas of valley floors

***Table 2**. Characteristic threshold slopes angles (after Rouse & Farhan, 1976).*
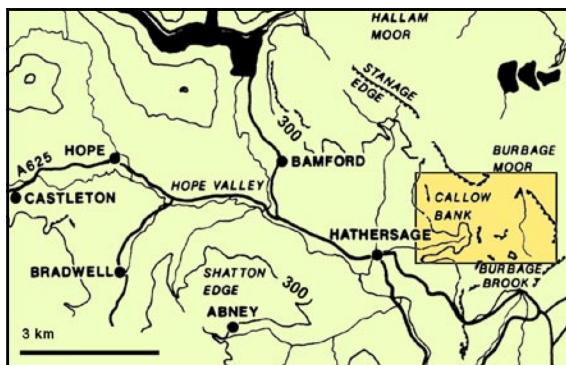
Figure 2. The Hathersage region, with the area on Figure 4 shaded brown.

Figure 3. View up the length of the Callow Bank landslide, with the abandoned farm of Callow Bank on the right.

4: weathering and down-washing of soil fines create an increase in fines downslope, so that the footslopes possess different groundwater regimes and slope angle thresholds differ from those of the drained upper scree slopes; and

5: rapid mass movements, particularly small-scale planar slides, continue to affect these slopes.

Callow Bank

The region east of Hathersage comprises high hill moors and plateau dissected by steep-sided valleys eroded through a succession of Carboniferous sandstones, mudstones and shales (Fig. 2). Locally the high plateaux reach altitudes of about 450m, and at their margins the well known gritstone edges formed by massive beds of sandstone overlook gentler valley sides. Callow Bank

is the head scar of a landslide formed at the plateau edge in the lower leaf of the Chatsworth Grit, which is coarse grit and finer sandstone interbedded with about 20% of shale and mudstone (Fig. 3). Alternations of sandstones and sandy siltstones make up the lowest 18m of the lower leaf, and are exposed in the upper part of the slip face of the landslide. The thicker upper leaf of the Chatsworth Grit is the coarse-grained rock that forms Stanage Edge and the outliers of Higger Tor and Carl Wark to the south.

Solifluction deposits, 1.2 – 3.0m thick, overlie most of the shale and mudstone outcrops on the lower slopes below Callow Bank. The solifluction deposits are a matrix of sandy clay with lenses of rubbly sand, and containing cobbles, boulders and blocks of flaggy sandstone. Their material was derived from
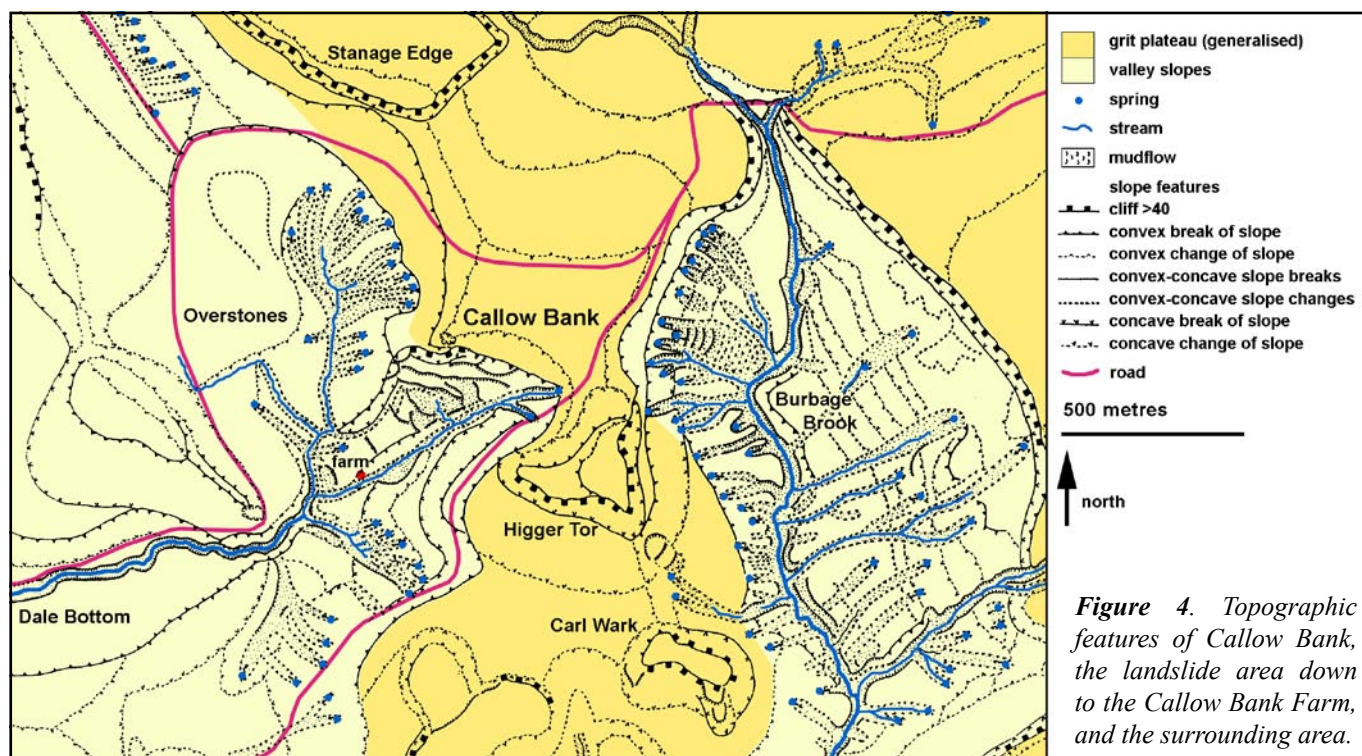

Figure 4. Topographic features of Callow Bank, the landslide area down to the Callow Bank Farm, and the surrounding area.

the alternating sandstone and shale sequences by the action of periglacial freeze/thaw processes, and was then modified by solifluction flow and multiple sliding. They are notably heterogeneous, poorly sorted and broken by numerous discontinuous slip surfaces.

Heavy caprocks of sandstone resting upon less competent mudstone and shale have developed unstable slopes throughout the south Pennines (Johnson, 1980; Johnson & Walthall, 1979; Donnelly et al. 1998; Waltham & Dixon, 2000; Donnelly, 2008). The many forms of mass movement range from superficial solifluction lobes, terracettes and soil creep, through to deep-seated mudslides, debris slides and rockfalls.

Callow Bank is dominated by its multiple retrogressive landslide within a series of mudstones,

Figure 5. Weathered shales in a rotated block within the upper landslde mass.

siltstones, shales, sandy shales and thin sandstones (Fig. 4). The main landslide back scar is about 25m high, and rotational movements are deep-seated with moderate backward rotation of separate blocks (Fig. 5). The cause of failure was glacial erosion and valley over-steepening leaving the massive competent beds of sandstone exposed over weak shales. Rotational slides occur when maximum stress at the foot of the slope is transmitted by creep in the rocks within the slip zone (Petley and Allison, 1997; Rutter et al. 2003). The first slip movement probably developed from outward bulging and deformation at the slope foot, with retrogression taking place where tensional stresses caused movement outwards and downwards from the original slope (Petley, 2004). At least four major successive rotational movements have taken place. The deepest, and dominant, failure probably occurred on the black shale and seatearth that immediately overlie the Kinderscout Grit (which outcrops in the stream bed near the toe of the slide). Chemical and mechanical weathering of these shales may have induced deep-seated creep in the failure zone. At the foot of the landslide's back scar the main slide mass is characterised by topographic benches and depressions (Fig. 6). The lower section of the landslide, 300m below the back scar, has debris slide and mudslide components. This debris was more mobile, and moved by sliding outwards from the rotated units to create a low but uneven terrain as far as the tributary stream from Overstones, 500m from and 110m below the back scar (Fig. 4). Callow Bank Farm was built in 1720, and stands on the landslide debris slide. Ground movement, inevitable at its location, has distorted the buildings, which are now abandoned (Fig. 7).
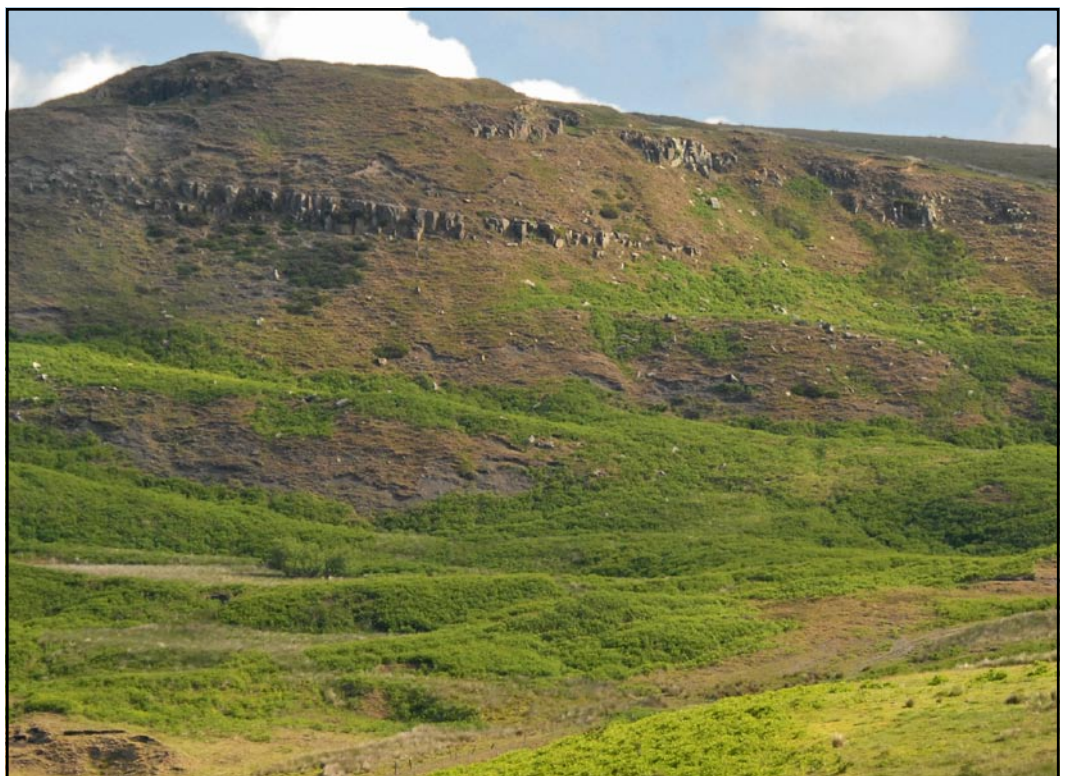

Figure 6. Benches and depressions on the large landslide blocks directly beneath the back scar of Callow Bank.

Figure 7. Distortion by ground movement of the old Callow Bank Farm, showing in the fracture through the stonework between the two window openings.

The slope surveys

The slopes of Callow Bank were analysed by means of field profiling using a pantometer, and by desk techniques based on digitised contour maps. This research formed part of a more detailed study of landslide susceptibility mapping in the southern Pennines (Cross, 1998). Slope profiles were measured in the field with a pantometer 1.5m long (Pitty, 1968), and 3165 angles were measured to assess their frequency distribution. As part of a regional GIS project, 23,040 slope angles were collected over an area of 932 km^2 in the southern Pennines, which included the Callow Bank site (Cross, 1998). Digital versions of 1:10,000 topographic maps were layered with a grid at 125m line spacing, and slope angles of the central points within each grid square were calculated from contour interpolations (Carrara *et al.* 1991). Slope data from the GIS method are different to those from field measurement with the pantometer, so the two data sets are not directly comparable.

For the field measurements, the slope frequency distribution at Callow Bank peaks at 20º, which is within the threshold range for sandy soil regolith (19.6–21.5º). Small peaks in the histogram also occur at 24–25º and at 34º, which may be associated with the calculated threshold values of talluvium (25.6–27.5º) and scree (33.6–35.5º). The slope frequency distribution obtained from the slope profile survey at Callow Bank was compared to the slope frequency distribution derived from a regional GIS slope database which encompassed the Callow Bank study area.

In the GIS slope angle frequency distribution for the southern Pennines project, peaks occur at 21.8º and 26.5º (Cross, 1998). These also correspond closely with the threshold values for sandy regolith and talluvium.

Another peak in this distribution occurs at 17.7º, which is similar to the predicted mean limiting angle for solifluction materials, and correlates with the slopes with identified shallow planar failures, both in South Wales (Rouse and Farhan, 1976).

The limiting angles 18.2º and 22.1º calculated for middle and upper slope sections respectively, coincide with the characteristic slope angle peak identified at 20.0–21.8º at Callow Bank and in the regional project. This represents the threshold angle for sandy soil regolith (19.6–21.5º), and appears to be related to the threshold angle for fossil scree slopes developed on mudstone and shale (18–22º). Slopes of 35.5º mark the upper limit for a valley-side slope, equal to that for dry scree), and slopes steeper than that are best described as free faces.

Engineering geomorphological mapping

Slope frequency studies reveal characteristic angles as limits for various processes of mass movement (Carson & Petley, 1970). In the southern Pennines, it has been possible to use engineering properties, process study and denudational history to interpret the genesis of present landforms, and this information can be conveniently shown on geomorphological maps (Al-Dabbagh & Cripps, 1987).

Many sites in the southern Pennines have infrastructure and buildings on slopes with evidence of former mass movement (Al-Dabbagh & Cripps, 1987). Risks of landslide re-activation may increase as a result of global climate change (Dehn and Buma, 1999; Collison *et al.*, 2000). With ground movements caused by extreme heavy rainfall events, and the greater pressure placed on development on steeper slopes, the identification of potential risk areas demands more attention by developers, planners and engineers (Doornkamp, 1994; Dietrich *et al.* 1993; Montgomery and Dietrich, 1994; Villa and McLeod, 2002). Probabilistic methods to identify potential

Figure 8. Small back scars above and behind shallow planar failures within the regolith.

2° - 6° Structurally controlled plateaux or valley floors
Upland plateaux with peat or regolith cover, localised creep mass movements and gulley erosion; lowland valley floors with alluvial floodplains or mudslide and earth flow debris from higher landslides.

12° - 14° Lower seepage slopes
Block debris from creep and solifluction, with gulleys from seepage lines; hill-wash and soil creep are active.

15° - 18° Convex creep slopes
Threshold angle for head and regolith with shallow planar movement on shallow or deep-seated translational slips.

19° - 23° Mid-level transportational slopes
Slope unit most affected by mass movements, forming the steeper valley side slopes, covered with landslide debris; threshold angle for fossil scree on mudstone and shale strata, and for sandy regolith.

24° - 28° Talluvial slopes
On talus at the threshold angle for talluvium; forming the steeper scarp slopes.

29° - 32° Fossil scree slopes
On fossil scree of sandstone, affected by deep-seated rotational slides and translational slides; slides may have lower debris flow components.

33° - 36° Dry scree slopes at the foot of free-faces
Drained scree at the foot of gritstone free-faces; at the threshold angle for dry scree.

37° - 45° Slopes on fractured or jointed rock
On fractured and drained rock; common below free-faces with rockfalls and toppling failures.

>45° Gritstone edges and free-faces
Gritstone edges and sandstone free-faces.

Table 3. *Geomorphological mapping units for the southern Pennines, based on surface morphologies, lithologies and threshold slope angles.*

Figure 9. *The lower slopes of Higger Tor, with uneven ground on a regolith disturbed by solifluction movements and shallow mudflows.*

landslide risk can fail where the historical record is not adequately reliable (Lee, 2009; Lee & Jones, 2004).

Experienced engineering geologists have traditionally used morphological mapping to isolate elements of slopes and define their characteristics (Cooke & Doornkamp, 1990; Fookes *et al*. 2003). Land elements of uniform gradient are identified in the field, their angles are measured, and the nature of the boundary between each element (concave or convex, break or inflection) is noted. It is important that the choice of these slope categories is carefully considered and reflects the characteristic and threshold angles of the mapped area.

Geomorphological mapping units based on identified characteristic and threshold slope angles have been developed for the Callow Bank and southern Pennine areas (Table 3). These can help explain the genesis of slopes and the processes active on them, and are particularly relevant to detailed maps relating slope features to shallow mass movement and poor drainage. The units are generally comparable to those identified in Longdendale (Johnson, 1981). Large areas of the southern Pennines possess slopes that are unsuitable

for building and engineering work unless ground investigation is thorough and remedial measures are designed and placed to maintain slope stability. Landslide movements are most likely to occur on slope units where weak shales form slopes over-steepened by erosion, where sandstone caprocks overlie less competent shales, and where springs have developed high pore-water pressures on the valley sides.

Deep-seated landslides appear to be located in two zones within the slopes of the southern Pennines (Johnson, 1980, 1981). One zone is at high elevation where slopes are generally concave; failures occur along bedding-plane slip surfaces with rotation in the upper parts of the slide. The second zone has deep-seated, rotational landslides on slopes at lower elevations where stream erosion at the toe of the slopes has undermined their stability.

Shallow failures tend to be more localised, and are particularly influenced by changes in the ground water regime (Fig. 9). Until drained, they may be highly susceptible to further movement if their temporary equilibrium is disturbed. The recognition of these areas is important to engineering projects on slopes. Many of the foot-slope units in the southern Pennines are covered with landslide and solifluction debris that may be up to 20m thick with numerous slip surfaces.

Much of the landscape of the south Pennines can be interpreted as a relic feature of glacial, periglacial and mass movement that is being superficially modified by current processes. Its detailed interpretation, through the application of geomorphological mapping, is important in identification of the areas of potential risk for planning and development.

Figure 10. *Broken and disturbed ground at the upper end of the Callow Bank landslide.*

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Martin Cross,
Scott Wilson Limited, Manchester.
martin.cross@scottwilson.com