Geohazards


Collapse of old mine shaft forgotten beneath restored site, Walsall.


Vaiont landslide, Italy, with rock scar above tree-covered debris.


Moving houses threatened by erosion and beach loss, Alabama.


Sinkhole collapse in soil and rock over buried gypsum, Ripon.


Road across scree and debris of large landslide, Indian Himalaya.


Ground anchors supporting landslide at Hoar Edge, Pennines.


Rotational landslide in thick soil on deforested hillside, China.


Flooding in Venice due to subsidence on deltaic sands and clays.


Old pillar-and-stall mine with thin pillars of strong limestone, Dorset.


Earthquake-proof in San Francisco.


Driven piles in alluvial sand, England.


Fly rock from blast of unsafe buttress, Cheddar Gorge.


Anchored panel wall retaining poor rock at tunnel portal, Wales.


Rock fall from glacially over-steepened valley side, Switzerland.


Earthquake damage to temple built on alluvial sand, Burma.


Failure of steep hillside after unusually heavy rain, Jordan.


Subsidence sinkhole near deep limestone quarry, Pennsylvania.


Lined tunnel, too close to hillside, destroyed by landslide, Taiwan.

27 Ground Subsidence

Subsidence is only possible where the ground material can be displaced into some sort of underground voids, which can only occur in certain rock types.

Macrovoids, large cavities: solution caves in limestones (*section 29*); much rarer natural cavities in other rocks, including salt and basalt; mined cavities in any rocks of economic value (*sections 30, 31*).

Microvoids in very porous, deformable rocks: most important in clay (*section 28*); in peat, some silts and some sands; in made ground and backfill (*section 30*).

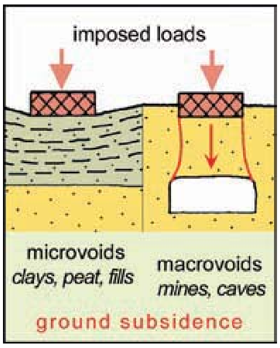
Subsidence cannot occur on solid, unmined rock, except by shear failure and rotation to the surface under excess load, or by landslides within slopes (*section 32*).

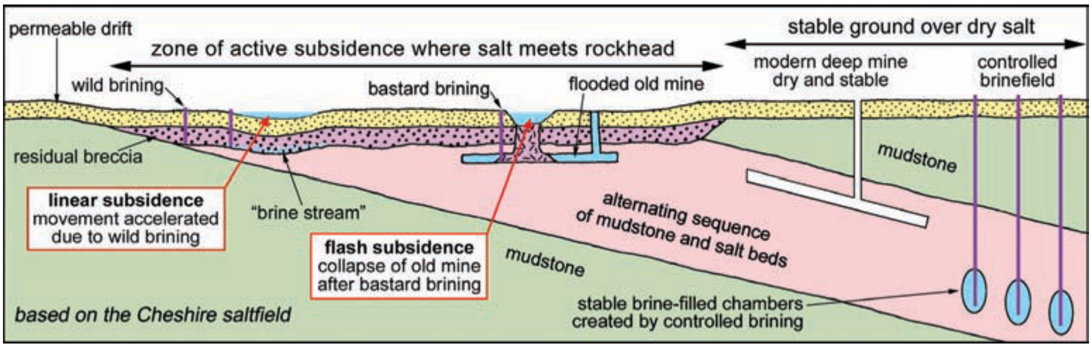
SALT SUBSIDENCE

Rock salt may occur as extensive beds in sedimentary sequences. It dissolves in circulating groundwater rapidly enough to cause slow natural subsidence.

Most solution takes place at the rockhead beneath permeable drift; thus creates a residual breccia of the collapsed mudstone that was originally interbedded with the salt; cavities collapse before they become large.

Linear subsidences are localized over ‘brine streams’ – zones of concentrated groundwater flow along rockhead, many along buried outcrops of the salt bands; typical subsidences are 5 m deep, 100 m wide, 5 km long.





Geohazard of potential subsidence can therefore be recognized largely by rock type on geological maps.

All rocks do compact under load. Weak mudstone or sandstone can compact enough to cause settlement of structures, but normally well inside acceptable limits.

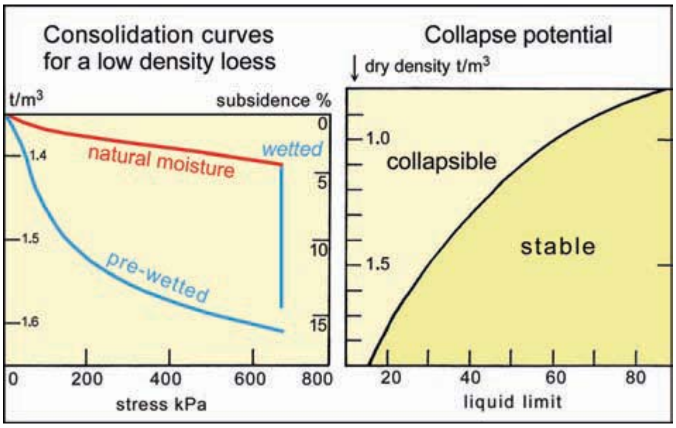
COLLAPSIBLE SOIL HYDROCOMPACTION

Some fine soils collapse due to restructuring when saturated for the first time; this hydrocompaction may cause subsidence by 15% of the soil thickness. The collapse is due to total loss of cohesion, after disruption of fragile clay bonds or solution of a soluble cement.

Loess collapses most easily where it contains about 20% clay; with more or less clay, it is less unstable.

Alluvial silts deposited by flood events in semi-arid basins (notably in California), some tropical soils and some artificial fills may all exhibit collapse on saturation.

Collapse potential is highest in soils with dry density of <1.5 t/m^3, liquid limit <30, and moisture content $<15\%$ in dry climate zones. Recognize potential by consolidation test with saturation part way through the loading cycle.



Some collapsing soils only hydrocompact with loading.

Subsidence hazard is highest in irrigated arid areas.

Soil collapse may be induced prior to construction by pre-wetting through flooding; thin soils respond to dynamic consolidation or vibro-flotation.

Wild brining is uncontrolled pumping from the brine streams; it greatly accelerates formation of the linear subsidences, which may then form in tens of years.

Deep solution mining (controlled brining) and modern deep mines in dry salt are both stable: no subsidence.

Pumping brine from old shallow mines (bastard brining) causes serious collapses; now illegal in Britain.

Cheshire has the worst salt subsidence in Britain; houses and structures in Northwich all have timber or steel frames or concrete rafts that can be jacked up. Now that wild brining has almost ended, subsidence due to natural solution is very slow – but does continue.

Surface movements are small and slow; engineering precautions are as for longwall mining (*section 31*).

GYPSUM SOLUTION

Gypsum may be dissolved and removed naturally. Solution is slower than of salt, faster than of limestone – rock can dissolve within the lifetime of a built structure.

Rockhead pinnacles may be dissolved by groundwater, so may not be safe for foundations in the long term.

Caves are smaller and less common than in the strong limestones, but may create a significant hazard where weak roof rock collapses easily to create sinkholes.

Plugging or filling cavities in gypsum requires care, as diverted groundwater may rapidly create new caves.

NATURAL CAVES

Common in limestone (*section 29*) and gypsum; basalt has lava tubes on shield volcanoes; rare in other rocks.

Open fissures beneath soil cover may develop around heads of landslides and as gulls on camber folds.

Soil pipes, sea caves and rock arches are all of limited extent; latter are conspicuous as surface features.

TECTONIC SUBSIDENCE

Crustal sag can cause very slow subsidence;
combines with sea level rise to cause coastal flooding;
London subsides 1–2 mm/year; hence Thames Barrier.
Large deltas have crustal sag and sediment compaction,
causing subsidence up to 8 mm/year in Mississippi delta.

SUBSIDENCE ON PEAT

Peat may contain ten times its own weight of water; it can shrink by 10–75% under load.
When loaded to exceed its very low shear strength, peat also creeps and spreads; so very high settlements are normal; coefficient of compressibility, $m_V > 1{\cdot}5$ m^2/MN.

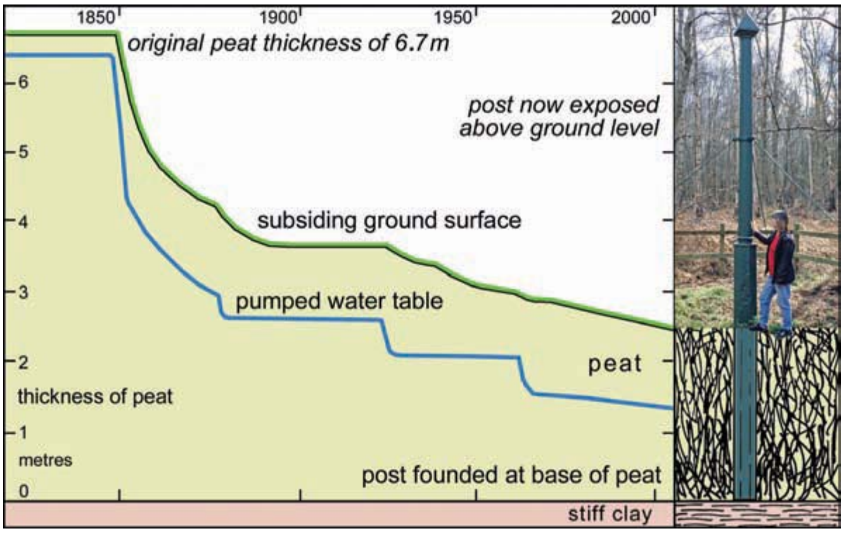
Drainage of peat causes subsidence of up to 60% of the groundwater head decline; less on later redrainage.
Was major cause of New Orleans suburbs lying below sea level, and therefore flooded so widely in 2005.

Wastage, by oxidation of biomass above watertable, continues at low rate dependant on climate; causes surface lowering, and major loss of agricultural land; reduced by maintaining high water table.

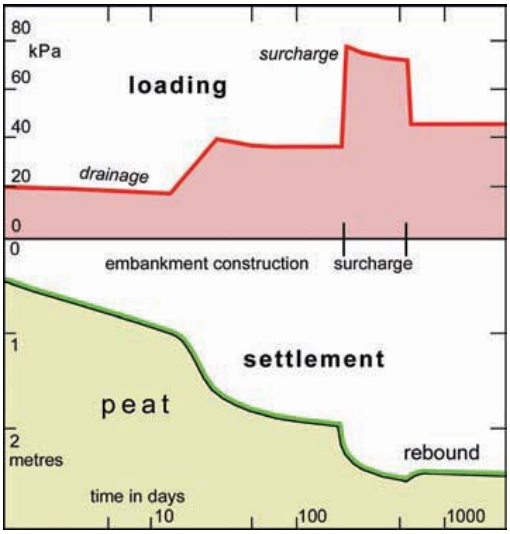
Strength of undrained peat is negligible, drained peat may be UCS = 20–30 kPa, and E = 100–140 kPa.
Peat consolidated by structural load gains strength; may reach SBP = 50–70 kPa. Primary consolidation takes place in days; secondary stage may last years.
Laboratory testing and consolidation prediction are hindered by peat's variability and difficulties of sampling; full scale field tests are often worthwhile for major projects.

CONSTRUCTION ON PEAT

Removal is economical if peat is less than about 3 m thick. Displacement of thicker peat is possible by end-tipped sand, purely by gravity, or aided by jetting to 6 m deep, or peat-blasting to 9 m deep.
Piles through peat are often economic, and are required by state law in some parts of the USA; house foundations may be left above ground if drained wastage continues.
Pre-loading is successful with surcharge of 1–3 m of sand or fill for 1–12 months; rebound is about 5%.
Sand drains are of limited use as peat permeability is already high; wick drains have been used to accelerate consolidation in English Fenlands.
Embankments on peat may cause more settlement than their height. So lightweight fill is used; polystyrene blocks are best; sawdust, brushwood and peat bales have been used in Canada and Ireland, and are stable when depressed below water table.
Rafts can be used for light, centrally loaded buildings, with under-rim to reduce peat spreading; houses on rafts in northern England settled 800 mm on 2·5 m of peat with imposed load of only 15 kPa.
Basements to give nil net loading rarely economic in houses.



Pumped drainage and ground subsidence recorded over 150 years against the Holme Post in the peat of the English Fenlands.



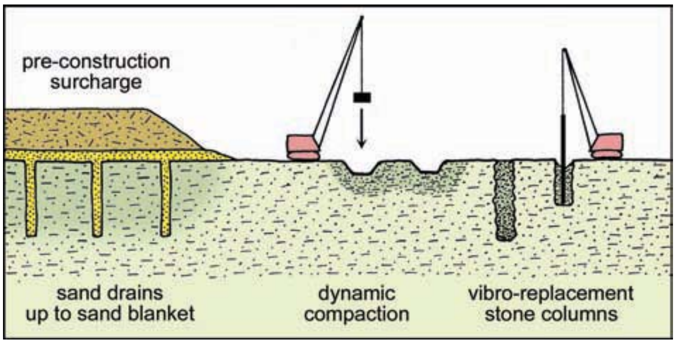
Loading and settlement of an embankment for a road over peat in Canada.

EARTHQUAKE LIQUEFACTION

Sand may liquefy due to a temporary loss of effective stress during period of earthquake vibration, if it is:

- uniformly graded, with grain size <0·7 mm;
- poorly packed with low relative density;
- below the water table at shallow depth.

Hazard zones may be defined by SPT, notably where N values < 20 at 10 m depth.
Liquefaction causes total loss of strength during the period of vibration, as in the 1964 earthquake at Niigata, Japan, when intact, earthquake-proof buildings subsided rapidly into saturated alluvial sands.
Stabilize sand and reduce the hazard by dynamic consolidation, drainage and water table decline, or by surcharge to raise internal stress.



GROUND IMPROVEMENT

Surcharge: consolidation accelerates under a few metres of placed fill, and almost stops when surcharge is removed, after 6–12 months, prior to construction.
Drainage: accelerates water expulsion, and therefore accelerates consolidation; may allow settlement beneath embankment to be completed during construction time. Sand or fibre drains spaced at 1–3 m are most effective at depths < 15 m.
Grouting: cannot penetrate clays; 10% cement mixed into clays of LL <45 increases strength.
Liming: adding 5% lime creates stronger soil; reduces plasticity and shrinkage; stabilizes montmorillonite by replacing sodium with calcium.
Vibro-compaction: densify sandy, non-cohesive soils with a crane-supported vibrating poker.
Vibro-replacement; feed crushed stone beside poker to create stable stone columns in cohesive soil or fill.
Dynamic consolidation: drop 15 t block, 3–5 times, 20 m from crane, at all points on 5–10 m grid, to densify sandy soil; this may also fissure thin clay layers, and thereby accelerate drainage consolidation.
Ground freezing: expensive temporary stabilization of excavation, mainly of tunnels.
Geotextiles: increase shear strength, notably with coarser geogrids, but can only be installed in placed soils, not in undisturbed ground.

28 Subsidence on Clays

Clays have high porosity with deformable grains of clay mineral; so they have high potential compaction.

• Compaction = volume decrease = consolidation •

This is due to water expulsion (primary consolidation), followed by restructuring (secondary consolidation).

Consolidation of clay, subsidence of surface and the settlement of structures all increase with imposed load or with drained water loss.

Subsidence is greatest on thick clay, with high smectite content, low silt content and of young age with minimal history of over-consolidation.

Bearing capacity of clays ranges 50–750 kPa, largely related to water content; generally limited by settlements that exceed acceptability long before threat of failure.

Older clay, shales and mudstones are stronger and less compressible; strong mudstone may have SBP = 2000 kPa; hard shales deteriorate by slaking.

SETTLEMENT

Clay is consolidated by imposed structural load.

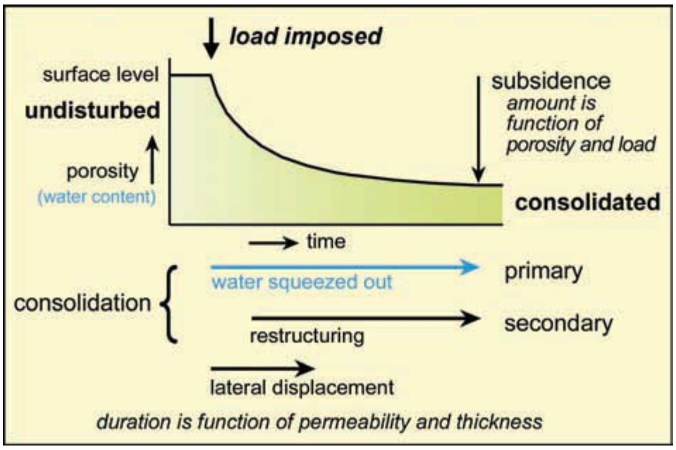
All clays cause some degree of settlement.

Water is squeezed out by applied stress.

Subsidence of ground, and settlement of structures, depend on initial water content of clay and stress applied; laboratory assessment is by consolidation test.

Remedy is to avoid loading the clay, or to wait for settlement to stop (or reduce to acceptable rate).

Modest settlement beneath buildings may fracture brittle drains; subsequent leakage may remove mineral soil in piping failure; this also causes subsidence but involves a different process (*see opposite*).



SHRINKAGE

Consolidation of clay is accelerated by water loss.

All clays exhibit some degree of shrinkage.

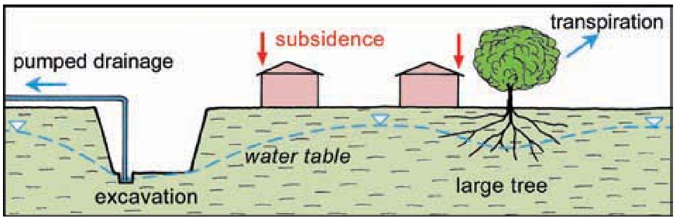
Water is drained out, causing volume decrease of drained soil; also loss of pore water pressure support.

Tree roots cause shrinkage in top 2 m of clay soil, but reached 6 m in London Clay in recent dry summers.

Britain's insurance claims for damage to houses on shrinkable clays are over £500M/year.

Pumped drainage of site may cause shrinkage nearby.

Remedy is control and stabilization of pore water pressure in clay.



DIFFERENTIAL SETTLEMENT

Settlement of a structure most serious when differential. Commonly due to uneven loading, lateral change of silt content in soil, rockhead slope or uncontrolled drainage.

Tilting of a tall structure creates differential loading, and that then accelerates differential settlement.

Transcona grain elevator, Canada, tilted 27° in a day in 1912; clays under raft base compacted unevenly over sloping rockhead, then sheared and displaced laterally.

LEANING TOWER OF PISA

Cathedral bell tower is 58 m high, 4 m out of vertical; it weighs 14,000 t, and imposed stress of 500 kPa on clay with ABP ~50 kPa.

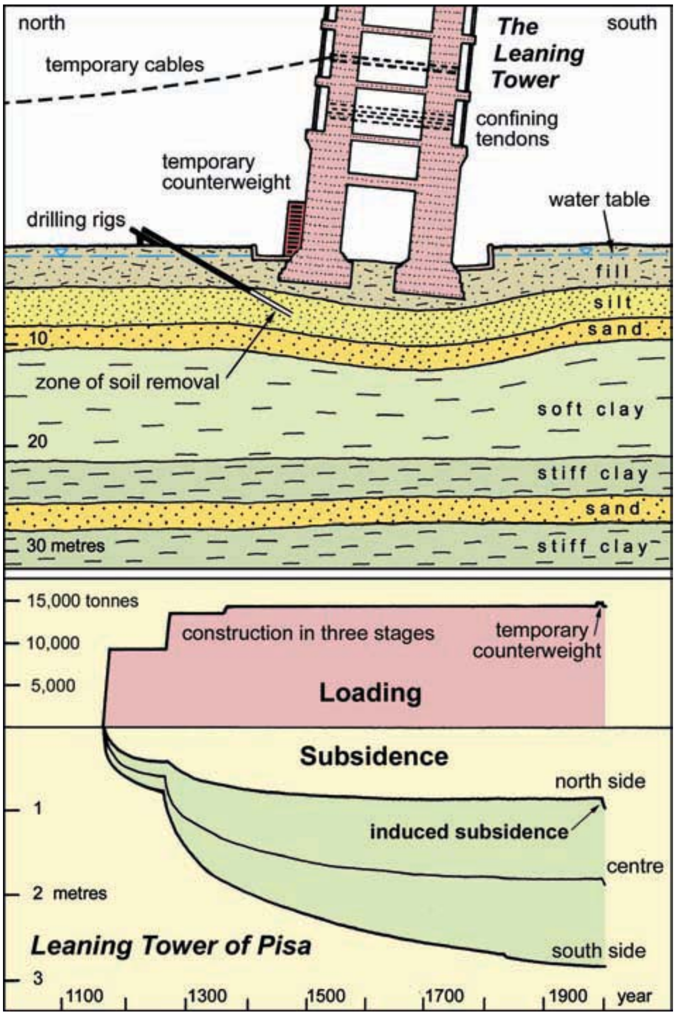
Main settlement is due to compaction and deformation of a bed of soft clay at depth of 11–22 m. Differential movement probably started due to clay variation within the overlying silt layer; subsequently, the main tilting was due to eccentric loading.

Stabilization in 1993–2001 was by inducing controlled subsidence of the north side. Temporary counterweight, of 600 t of lead blocks, tilted the tower back 15 mm, to remove immediate threat of instability. This was followed by creep closure of 41 uncased boreholes, each 225 mm in diameter, with repeat drilling to remove a total of 35 m^3 of soil. This tilted the tower back by another 425 mm; so it is now in no danger of collapse.

With the differential loading, subsidence and tilting will continue, and drilling will be repeated in the future.

Cable bracing was just for security during drilling.

Temporary tendons confined masonry to reduce risk of bursting failure until load was reduced by tilt reduction.



SEVERE SETTLEMENT: MEXICO CITY

City is built on drained lake bed in basin ringed by mountains of volcanic rock.

Young, porous, highly compressible clays are largely montmorillonite (smectite); water content around 300%.

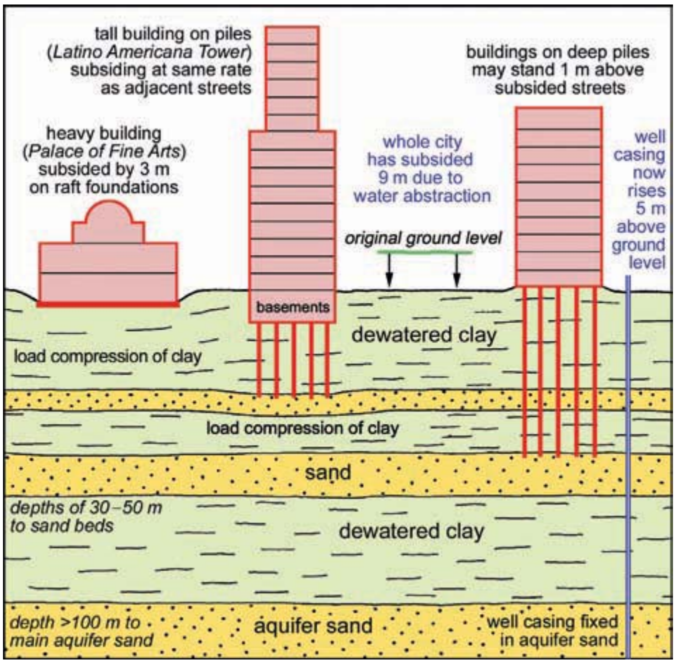
All buildings on shallow foundations settle severely.

Palace of Fine Arts was built on a massive concrete raft; imposed load of 110 kPa caused 3 m settlement.

Heavy rafts create their own subsidence bowls and damage adjacent buildings.

Stable foundations are piled to sand.

Latino Americana Tower has buoyant foundations with basements to reduce imposed load, and piles to upper sand. Designed so that settlement (of 0·25 m) due to compaction of lower clay equals the ground subsidence due to pumped head decline in the upper clay.



REGIONAL SUBSIDENCE

Groundwater abstraction which exceeds natural recharge causes decline of water table.

Loss of pore water pressure within clays causes widespread subsidence; significant where overpumping is from sand aquifers interbedded with clay aquitards.

Pumping from sand causes small, instantaneous, elastic, recoverable compaction of the sand.

Repressuring of aquifers has caused elastic rebound of sand – but < 10% of original subsidence.

Compaction of clay is greater and inelastic, and is non-recoverable; it occurs as groundwater pressures equalize between sand and clay, with a time delay due to the low permeability of clay.

Ratio of subsidence to head loss varies with clay type:
- 1 : 6 on young Mexico City montmorillonite,
- 1 : 250 on old consolidated London Clay illite.

Subsidence stops if water tables recover.

Venice has subsided on clay; large areas flood on a very high tide (known as an *aqua alta*), while St Mark's Square now floods on about 100 tides per year. Induced subsidence has stopped since pumping of groundwater was controlled, but continuing natural subsidence, along with rising sea levels, demand tidal barriers (now under construction) on the three entrances to the lagoon.

Mexico City has 9 m of subsidence on montmorillonite clays interbedded with overpumped sands; well casings, founded in the sands, now protrude in the streets.

Bangkok is now fastest subsiding city, at >10 cm/year.

Santa Clara Valley, California, was the first site where it was recognized that water table decline correlated with ground subsidence, which reached 4 m, before it was stopped by restrictions on groundwater abstraction.

EXPANSIVE SOILS

Clay soils that exhibit major free swelling on hydration and similar contraction on desiccation.

Montmorillonite is the cause – unstable clay mineral that associates with water, causing crystal expansion with force of 600 kPa, then loses water by drainage or desiccation. Sodium variety is most unstable, with liquid limit up to 500, and activity >5; calcium variety is more stable.

Smectite = unstable clay mineral group
Montmorillonite = main member of smectite group
Bentonite = clay soil with high smectite content

Montmorillonite clays form primarily by weathering of volcanic rocks in warm climates, so minor in Britain; annual costs of uplift damage on expansive soils in USA exceed combined costs of earthquakes and flooding.

Highest swelling is in any soils which are rich in montmorillonite, fine grained, dense and consolidated, dry, remoulded, lightly loaded, with high plasticity index.

Field recognition of expansive soils: sticky when wet; polished glaze on cut dry surfaces; dry lump dropped in water expands so fast that it breaks up explosively.

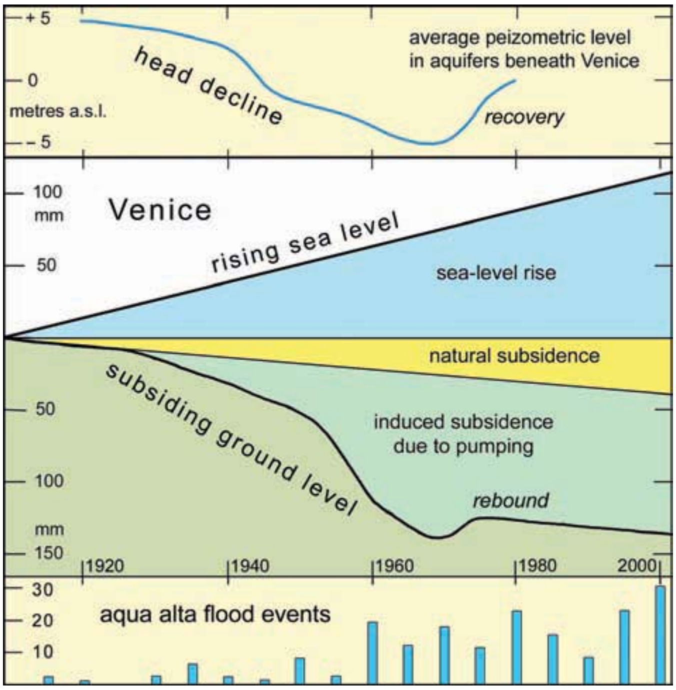
Remedies for expansive soils: liming to form stable calcium variety; control of groundwater, as soils are stable if they stay wet, or are kept dry under buildings.

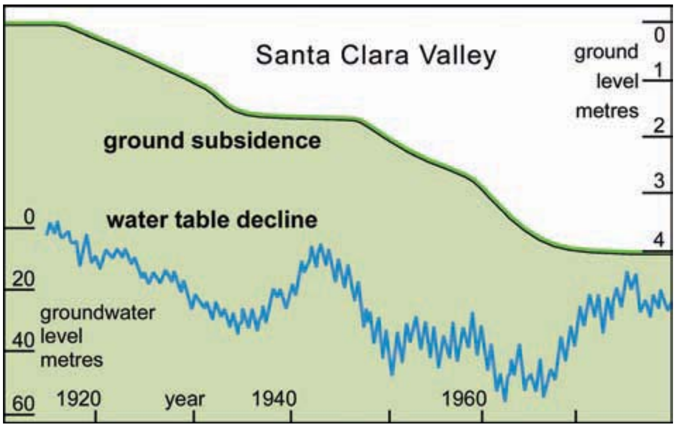
SOIL PIPING

A through-flow of water washes out the finest soil particles, thereby increases the porosity, then washes out progressively larger particles to create a pipe.

Cavity may reach metres in diameter before collapse.

Commonly form where seepage water carries soil into broken drain; or naturally through terraces in silty soils.





29 Subsidence on Limestone

Limestone is the only common rock that is soluble in water. It dissolves in rainwater enriched by carbon dioxide derived from organic soils, so the processes and results are on a larger scale in areas of warm, wet climate.

Karst features are erosional forms produced by solution on bare rock surfaces, beneath the soil at rockhead, and within the rock.

Dissolution is highly selective, so that most joints are etched out to create fissures, gullies and caves; they may be full of air, water or soil, between remnant blades of strong, unweathered rock. This creates the highly variable ground conditions that typify limestone areas.

Pinnacled rockhead is a highly fissured limestone surface beneath a soil cover. Tall, narrow, unstable or loose pinnacles may be supported only by the soil, and fissures may extend far below into caves. Rockhead relief in tropical areas may be $>$ 20 m.

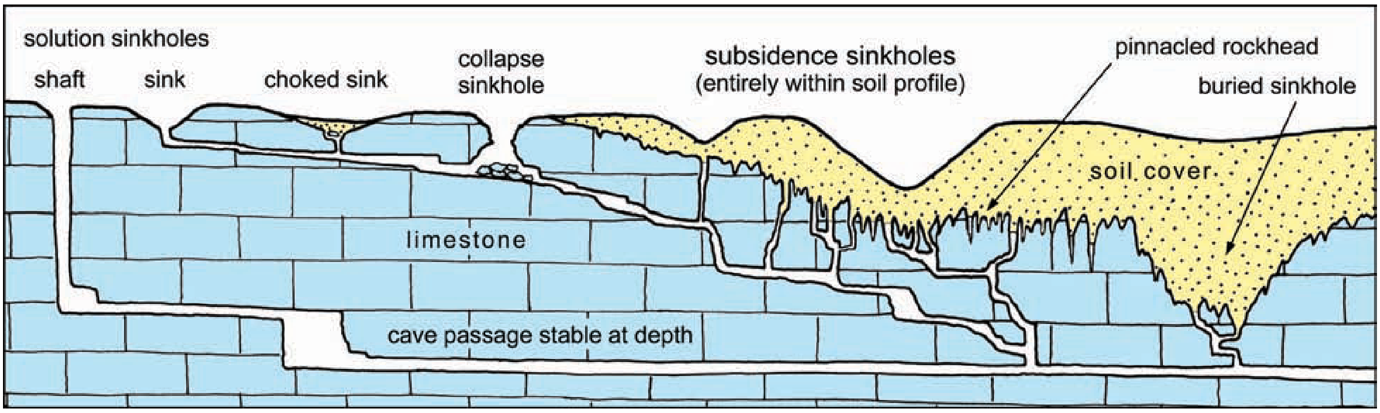
SINKHOLES

These are all forms of closed surface depression with drainage sinking underground; also known as dolines, and ubiquitous in karst terrains. Different types have different implications for engineering activity.

Solution sinkholes develop slowly like blind valleys; slow rates of formation create no subsidence threat.

Collapse sinkholes are not common, and events of rock failure are rare. Collapse processes contribute to forming many sinkholes; over geological time, they can create zones of broken unstable ground in limestone.

Buried sinkholes provide potential differential settlement over compacting fill. Conical, cylindrical or irregular; isolated or clustered; 1–50 m deep, 1–200 m wide. Effectively represent an extreme form of rockhead relief with short buried valleys.

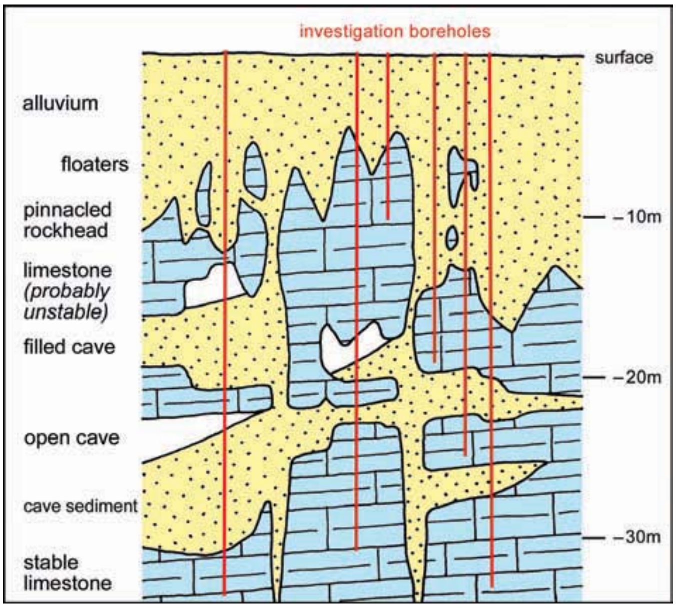


GROUND INVESTIGATION ON LIMESTONE

Many boreholes are needed to map pinnacled rockhead and buried sinkholes, and many rock probes are required to prove solid rock without caves, as at Remouchamps Viaduct (*section 23*).

Local and site history is the best guide to cave and sinkhole hazard. Shale boundaries and fault lines may have concentrations of sinkholes and caves.

Deep probes should prove bedrock to depths at least 0·7 times likely cave width; may need splayed borings to prove that pinnacles are sound.

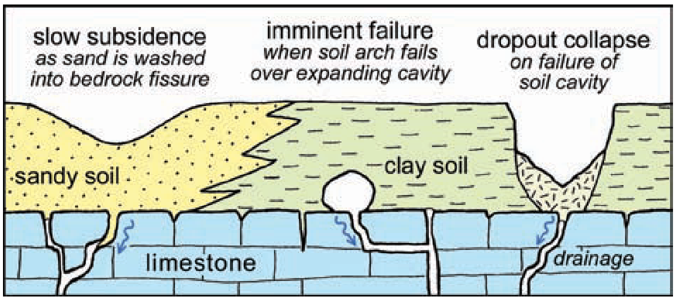


Boreholes on a site in Kuala Lumpur, Malaysia, with an interpreted geological profile reflecting a complex pattern of dissolution along fissures in the massive limestone.

Subsidence sinkholes account for 99% of ground collapses on limestone. They form in soil cover, above cavernous rock, due to down-washing of soil (also known as suffosion or ravelling) into bedrock fissures. Sinkholes may be 1–100 m across. Locations are totally unpredictable; most common in soils 2–15 m thick.

In non-cohesive **sandy soils** surface slowly subsides.

In cohesive **clay soils** cavity forms first at rockhead, then grows in size until the soil arch fails, to cause sudden dropout collapse of surface.



Induced subsidence sinkholes are much more common than natural failures; caused when and where drainage through rockhead increases, so washing away more soil; most events are triggered by rainfall.

Water table decline effectively induces sinkholes, mostly when it declines past rockhead; large areas are affected by over-pumping for supply, as in Florida, and smaller areas by quarry, mine or site de-watering.

Uncontrolled drainage diversions on construction projects cause many new sinkholes; also structural loading, excavation, de-vegetation, irrigation and leaking pipelines. Unlined drainage ditches and soakaway drains (unless sealed down to rockhead) must be avoided on limestone, especially in alluviated valley floors.

FOUNDATIONS ON LIMESTONE

Driven piles may lose integrity where they bear on rock over a cave, are bent due to meeting a pinnacled rockhead, or are founded on loose blocks ('floaters') or unstable pinnacles within the soil.

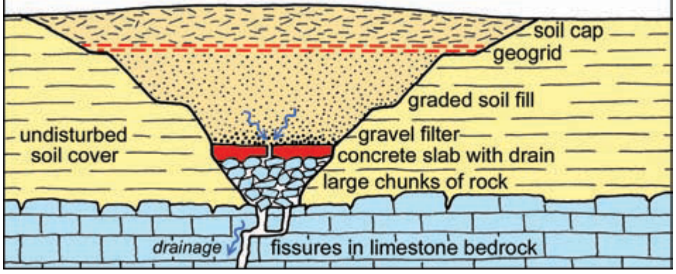
Concrete ground beams may be aligned or extended to bear on rock pinnacles that have been proven as sound; aggregate pad, stiffened with geogrid, may act in same way and avoid loading the intervening soil.

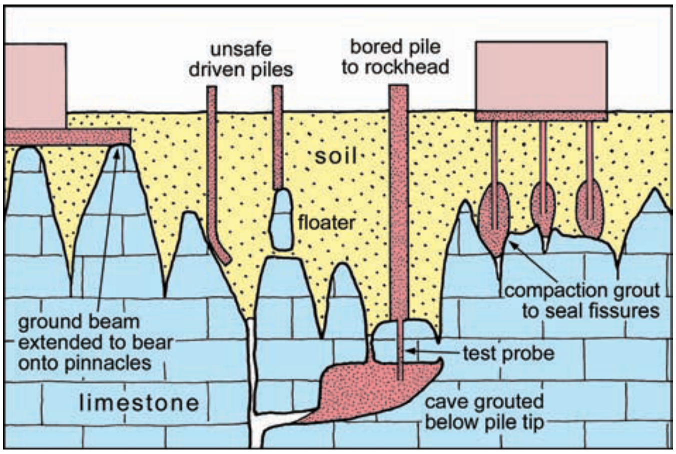
Can inject stiff compaction grout to stiffen soil over limestone and prevent its suffosion into fissures (and lift a structure), but injection of a fluid grout can incur large losses into adjacent caves before sealing karstic fissures.

Strip or raft foundations can be designed to span any small failures that may develop subsequently.

Most important single measure is to control drainage, over or into soils above limestone, during and after construction, to stop new subsidence sinkholes forming.

Sinkhole repair must prevent soil entering the bedrock fissure, while allowing drainage without diversion of water into another unprotected fissure. Coarse rock fill with filters and reinforced soil above is generally effective. Uncontrolled filling always leads to subsequent renewed failure.





CAVES IN LIMESTONE

Fissures are opened by dissolution, until they take all available drainage underground; they evolve into an infinite diversity of cave passages and chambers. In many limestones, most caves are <10 m across, but some tropical areas have cave chambers >100 m wide. Bedding planes and fractures influence the shape of most cave passages.

Cave locations within limestone are unpredictable; they commonly have no surface indication; though isolated cavities cannot exist, entrances may lie hidden beneath soil or may be only small tortuous fissures.

Cave roof collapse is only likely under structural loading where the solid cover thickness is less than 0·7 times the cave width. But small individual cavities can permit punching failure and can threaten the integrity of individual piles or column bases.

Statistically, most caves are deep enough to have no direct influence on surface engineering.

FOUNDATIONS ON CHALK

Chalk is weak, friable, pure limestone; when fresh, UCS = 5–27 MPa; but porosity is 30–50%, so UCS reduces to 50–70% when saturated.

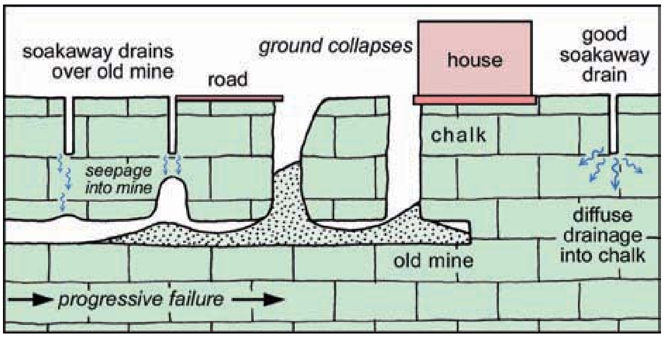
It may have solution features, caves and sinkholes, but these are generally on a smaller scale than in strong limestones.

Weathering of chalk by frost action is severe, to produce weak rubbly debris. This commonly reaches depth of 10 m in Britain due to periglacial weathering during the Ice Ages.

Putty chalk and fine-grained rubble chalk are thixotropic when saturated, and turn into slurry when disturbed. Should not be excavated or handled in wet winter months, but can be used as fill when dry.

Pile driving in chalk creates slurry at tip; this stabilizes when left undisturbed, so piles may carry higher working load if left for a time after driving. Settlements in chalk are often lower than expected, as rock strength increases under steady load.

Driven concrete piles have ultimate end resistance of N/4 MPa, where N = SPT. Risk of solution cavities below pile tip means that load is best attained by skin resistance, with ultimate values of about 30 kPa on displacement piles and 150 kPa on cast-in-place piles.



Failures beneath roads in Bury St Edmunds, due to chalk liquefaction between soakaway drains and old mines.

Liquefaction failure of putty chalk occurs where it is saturated along route of concentrated drainage flow and can then fail into a cavity beneath, which is usually a mine, gull or cave.

Ground collapses at Norwich and Bury St Edmunds (in East Anglia) and at Reading are mostly related to old mines below soakaways or drain failures; some are collapses of clay-filled pipes within the chalk.

Good surface drainage and ban on soakaways are necessary in chalk areas, especially where voids may exist, in areas with a history of mining or with known caves, or along cambered escarpments with gulls.

Chalk properties *relate to the grade of weathering. Tabulated values are typical of those for the Middle Chalk. Most of the Upper Chalk within Britain is more porous, so is weaker.*

Weathering grade	*Description*	*Creep at 400 kPa*	*SPT N*	*SBP kPa*
V	structureless putty	significant	<15	50–125
IV	friable rubble	significant	15–20	125–250
III	blocky rubble	small	20–25	250–500
II	medium hard	negligible	25–35	500–1000
I	hard and brittle	negligible	>35	>1000

30 Subsidence over Old Mines

Ground stability ultimately depends on the style of mining utilized, which is generally dictated by the shape, size, depth and value of the ore or extractable rock.

STOPING. Conventional deep mining, of mineral vein or any shape of orebody, creates large open underground voids known as stopes. Subsidence threat is localized, but may totally sterilize narrow strips of ground directly over the mines; a wider potential hazard is failure of hanging walls left above inclined stopes.

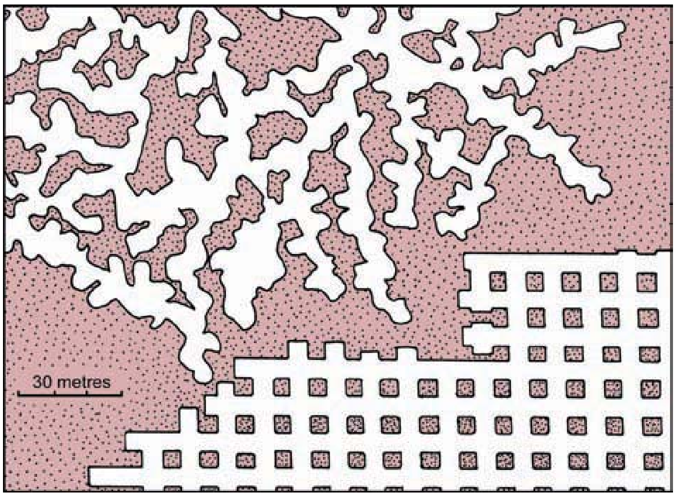
PILLAR AND STALL. Deep mining of thin low-dip beds by partial extraction; utilized for most coal working before 1940. Between 10% and 40% of the mineral ore (or the coal) is left in place to form pillars that support the roof; these are in random plan or in systematic rooms, stalls or bords in old hand-worked mines, or in regular grid in modern machine-operated mines. Many of the older mines were over-extracted, and therefore create a long-term subsidence threat, but modern mines with better control have no surface effect.

LONGWALL. Total extraction of coal in modern mines, causing surface subsidence that is normally automatic, immediate and unstoppable (*section 31*).

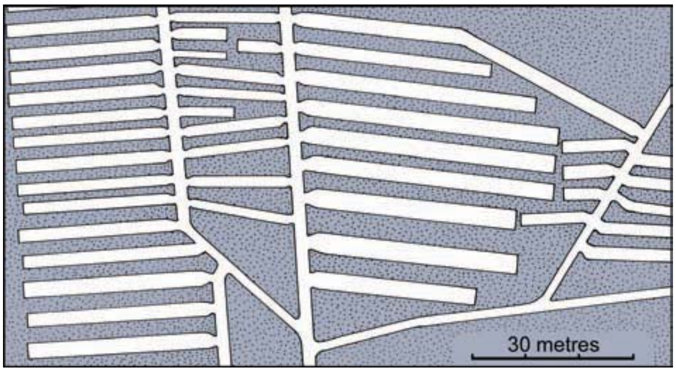
SOLUTION. Wild brining pumps natural brines from salt beds at shallow depth, and greatly accelerates linear subsidences above natural brine flows (*section 27*). Controlled brining pumps fresh water into, and brine out of, salt at depth, and should be totally stable.

OPEN PIT or **QUARRY.** Total extraction of bulk rock (quarry) or mineral ore (open pit) together with any waste rock needed to ensure pit wall stability. Backfill is rarely possible or economic in large workings, except for some waste rock fill in worked out areas. Small old quarries are far more numerous; many of these contain unstable and compressible fills of domestic refuse, where both settlement and methane hinder redevelopment.

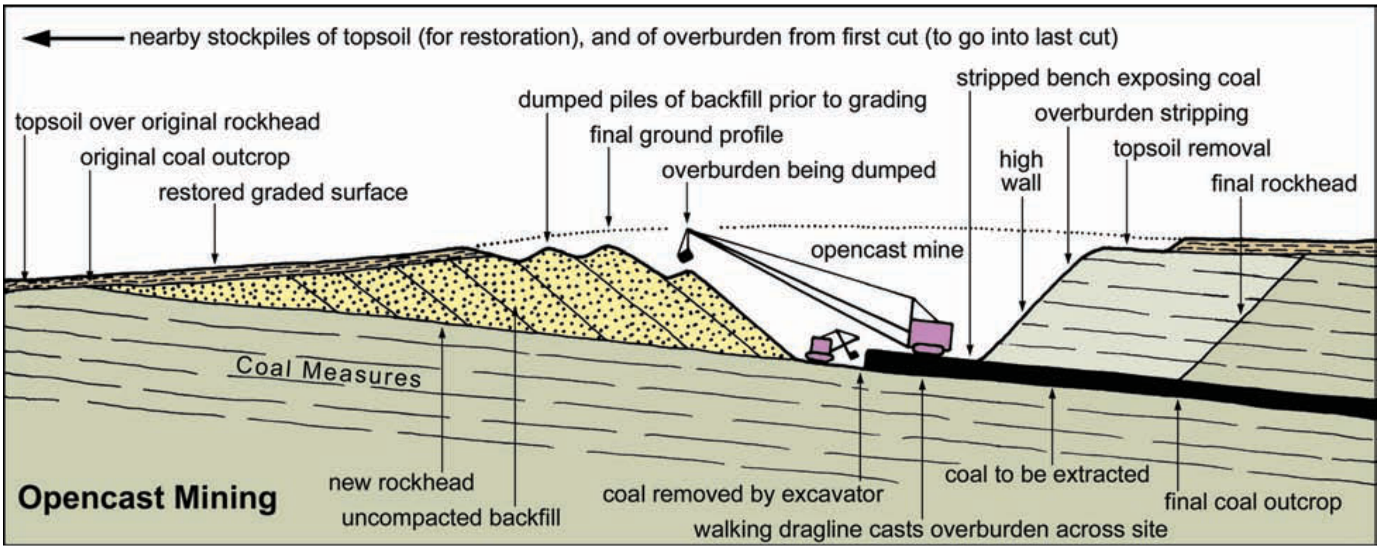
OPENCAST or **STRIP MINE.** Continuous operation of surface excavation, ore removal and backfilling with displaced overburden. Dragline may cast overburden over the site of ore removal, but earthscrapers are now used more commonly to take the overburden around the extraction site. Approximate ground level is restored with uncompacted fill, which is graded to desired profile and re-covered with topsoil; bulking of broken fill roughly compensates for removal of ore or coal. Commonly used for modern coal working; multiple seam extraction may leave benched rockhead profile beneath fill.



Pillar and stall mining of gypsum bed 2 m thick.
Above: plan of old irregular and modern regular workings.
Below: stable mudstone roof in the modern workings.



Bord and pillar working of a coal seam 1 m thick.



MINE PILLAR FAILURE

Mine pillars fail where they are left too slim, are subsequently overloaded or are subject to weathering and erosion. Multiple failures, domino-style, may affect large areas and were common in the past due to over-extraction and pillar-robbing. Pillars can sink into soft clay floor in flooded mines, to cause slow subsidence.

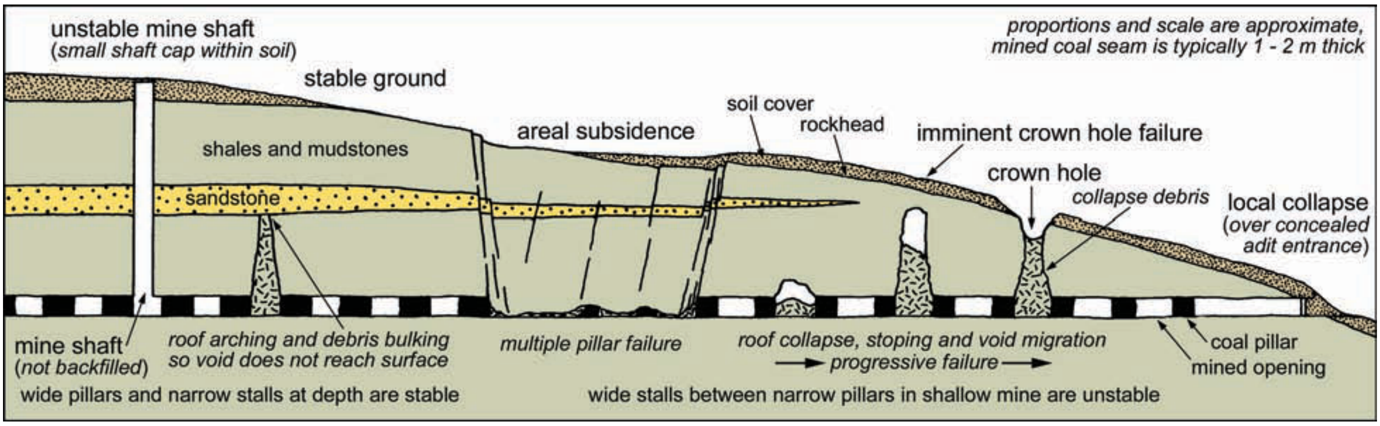
Collapse of old mines may be delayed 100 years or more. Modern threat of ground failure is minimal in mines >50 m deep, where any imposed load is small compared to overburden load and pillar weathering is slight.

ROOF FAILURE AND CROWN HOLES

Roof span failure and progressive breakdown of beds causes upward stoping (migration of cavities), especially in thinly bedded Coal Measure rocks.

This may reach the surface to create a crown hole by sudden collapse; or the stoping may be stopped by beam action of a strong bed, by formation of a stable arch in thinner beds, or by bulked breakdown debris meeting and supporting the roof.

Crown holes are rare from mines at depths greater than about 30 m or 10 times extracted seam thickness.

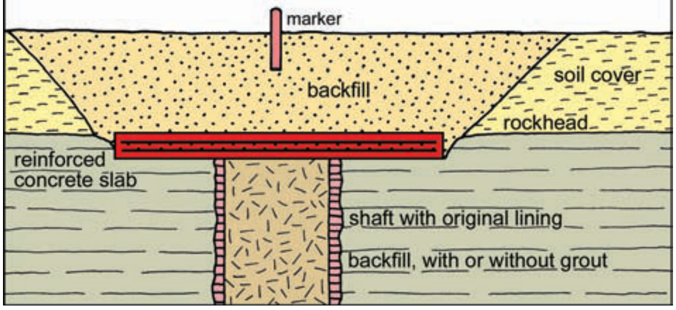


FAILURE OF OLD SHAFTS

Thousands of old mine shafts are a widespread hazard. Small old mines had more shafts than large modern mines; shaft records are incomplete, so ground investigation must pursue any documented or physical indication.

Shafts are mostly 1–5 m diameter, 10–300 m deep; may be lined with brick, concrete or dry stone or may be unlined in rock; may have loose or compacted fill to bottom of shaft or above unstable stopping, or may be empty; may be covered with timber, vegetation, steel or concrete, or may be well sealed and capped.

Shaft cap should be reinforced concrete slab of diameter 2·6 times that of shaft, founded on sound rock. Coal measure shafts usually require filling, or grout injection of old fill, for development within 20 m; remedial costs may exceed £20,000.



SAFE COVER FOR OLD MINES

Guideline figure is 30 m for old coal mines, so this is also the minimum depth for borehole investigation.

At >30 m depth, the broader pillars designed to carry higher overburden load rarely collapse, and roof stoping cannot normally reach the surface to form crown hole.

Even within Coal Measures, local conditions may vary, with strong sandstone roof or old weak pillars eroded by water; some mines 10 m down are stable for houses; others have needed filling at 50 m depth.

Safe depths are different for rocks other than Coal Measures; buildings are safe 3–5 m above old mines in Nottingham sandstone; pillar failure in limestone mines 145 m down near Walsall caused surface subsidence after stoping collapse of mainly shale cover.

TREATMENT OF OLD MINES

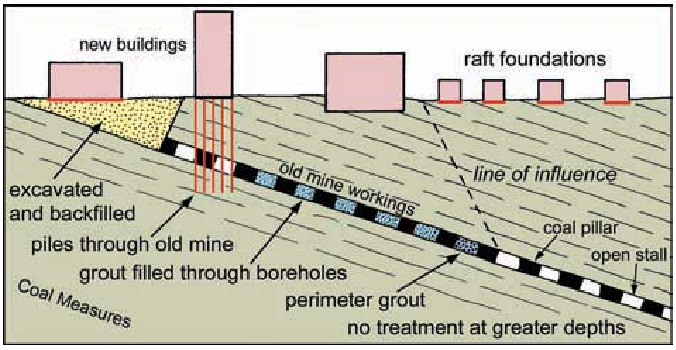
Excavation and backfill is normally only feasible and economic to <5 m depth.

Piling is normally limited to 30 m depth, and only through drift or shale, as boring through sandstone is uneconomic; cannot be used where dip is steep, where there is any risk of sliding, or where subsidence deformation due to deep mining is active or anticipated.

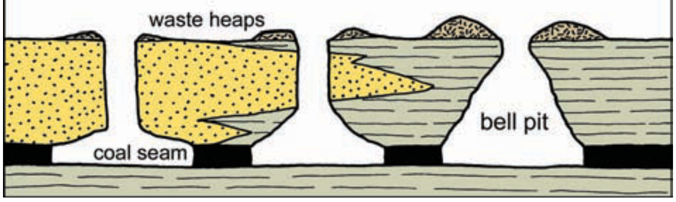
Grouting may need 100 mm bored holes on 3–6 m grid to ensure complete filling. Must include marginal zone of width that is 0·7 times depth to encompass zone of influence. Perimeter is sealed first; grout stiffened with pea gravel forms cones around holes bored on 1·5 m centres, which coalesce to create a wall within the mine. Can fill with low-strength foamed concrete or lean rock paste to prevent roof collapse between sound pillars.

Founding on rafts or reinforced strip footings may be good for low-rise buildings over mines of marginal depth.

Remedial costs may reach £100,000 per hectare, but should not exceed 5% of project costs to be realistic.



Bell pits are shafts generally <10 m deep to old coal workings that reach only a few metres from the shaft and are not interconnected. Most are in dense groups, and must be filled or excavated prior to development.



31 Mining Subsidence

Total extraction mining removes all of the mineral from a bed, allowing the unsupported roof to fail and cause inevitable and predictable surface subsidence. It is used world-wide in most modern underground coal mines.
Longwall mining is the method used in Britain. Extraction is by a machine coal cutter moving back and forth along a single migrating coal face up to 400 m long. After a slice of coal about 1 m thick has been cut from the whole length of the face, the hydraulic roof supports are advanced, the roof behind is allowed to fail, and the process is repeated. A panel of coal is removed, about 300 m wide and maybe over 2000 m long, with no support beyond the working face and access roadways.
Alternative method is a version of pillar and stall mining followed by pillar removal on the retreat. Surface subsidence effect is same as for longwall.

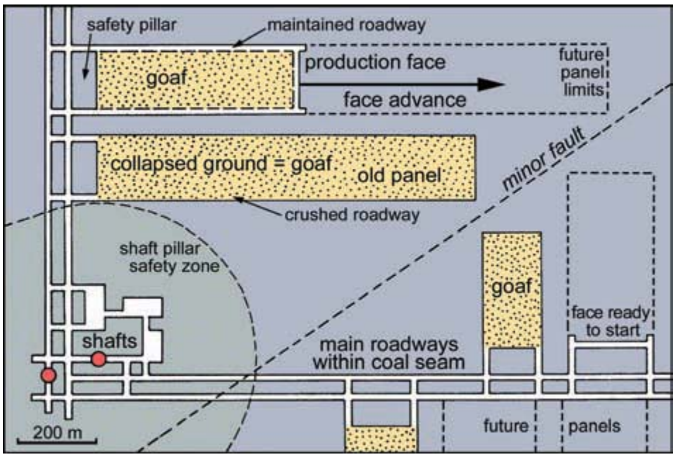
SURFACE SUBSIDENCE

The ground surface is deformed above a working coal face by a subsidence wave that migrates at the same rate as the face advance – usually 10–20 m per week. This subsidence wave has a number of effects.
Subsidence must be less than seam thickness, so usually about 1 m; may accumulate to $>$15 m by multiple seam working over time; causes little structural damage but has impact on drainage and piped services.
Ground strain develops first as extension (on convex part of the wave), then a return to neutral, followed by compression (on concave part of the wave). This causes most of the structural damage in mining subsidence.
Total strain is the sum of extension and compression, and is typically 1–10 mm/m or 0·001–0·01.
Angular movement is tilt on the subsidence wave; mainly significant to tall chimneys and sensitive machines.
Micro-earthquakes may occur due to movements in strong, massively jointed rocks under stress.

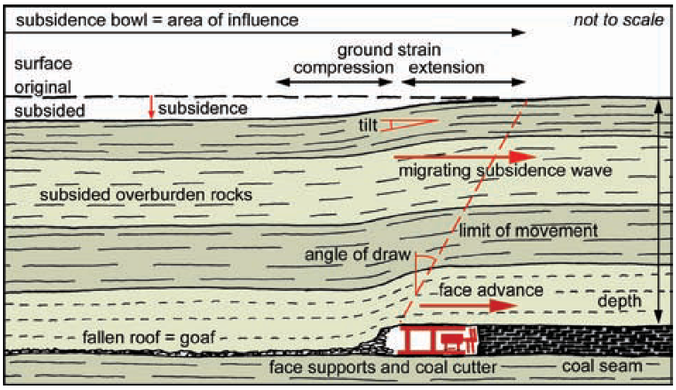
PATTERNS OF SUBSIDENCE

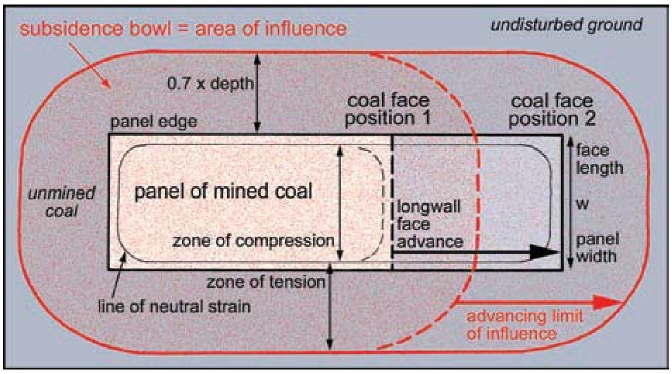
Mining subsidence follows well defined pattern.
Depth and lateral extents of the subsidence bowls and strain profiles, can be predicted on the basis of many past measurements (*section 40*), and the empirical data conforms closely to theoretical calculations.
Critical parameters that determine subsidence movements are the depth of working (h), the panel width (w), and the extracted thickness of coal (t).
Above an extracted panel, the ground moves downwards and also inwards, so that an area of ground larger than the panel is affected. The angle of draw is normally 30–35°, increasing slightly in weaker rocks.
Area of influence extends 0·7h outside the panel; edge is not clearly defined as it tapers to nothing.
Subsidence wave has a length of about 1·4h, with a midpoint of maximum tilt and neutral strain almost over the coal face. Surface wave migrates with the advancing face and develops similar profiles over the panel sides.
At any one point on the surface, movement occurs over time taken for wave to pass, 38 weeks for wave 560 m long over a 400 m deep face advancing at 15 m/week; so surface movement completed within a year.
Urban areas, where compensation costs may exceed 20% of coal's value, are not now undermined in Britain.

After mining in a region ceases, drainage pumps are switched off; groundwater rebound then raises joint water pressures and reactivates over-stressed faults; may cause new phase of localized ground movement.

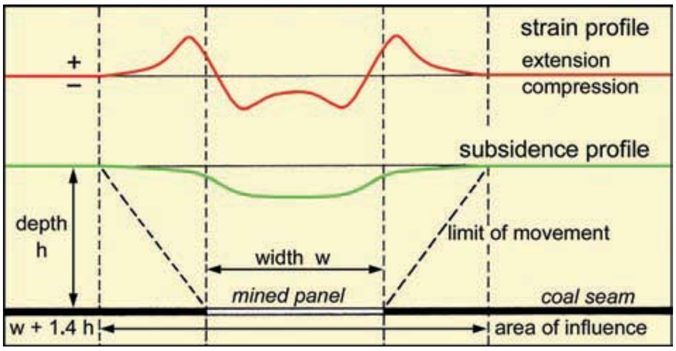


Layout of panels in a typical modern coal mine.





Strain profiles show outer zone of extension and inner zone of compression. Maximum strains are close to panel edge. Residual compression falls to zero over centre of panel where w/h $>$ 1·4.
Subsidence and strain are most severe over shallow, wide panels in thick seams; they are also complicated by multiple workings and areas of complex geology.
Geological factors (faults, strong rocks) account for 25% of movements with damage being more or less than predictions. Steep dips displace the subsidence bowl in downdip direction and significantly distort strain profiles.



CONSTRUCTION IN SUBSIDENCE AREAS

Concrete rafts are simplest and cheapest foundations for buildings; smooth based, formed on polythene over a bed of 150 mm granular sand to absorb horizontal strain; reinforced both top and base, maximum 20 m long or with stiffening beams on top.

Structural units should be small or articulated to tolerate strain. Deformable structures with sliding panels and spring bracing can be designed. Most structural damage is by tensile strain, so tie-bars can protect old buildings.

Piles need care as tilting can diminish integrity.

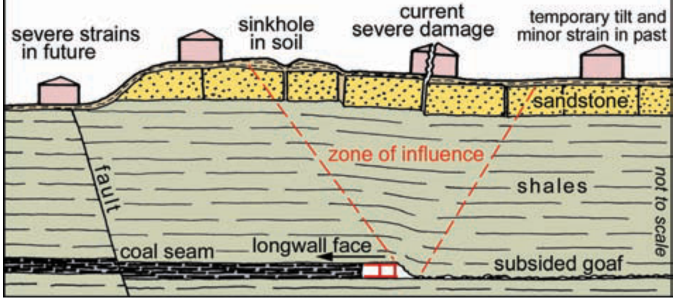
Pipelines need flexible joints, and gravity-flow drains need slope greater than predicted tilt. Can be exposed and placed on sliding chocks during undermining.

Bridge decks may be on three-point roller or spherical bearings, with bitumen or comb expansion joints; may need temporary support, or deck removal, while being undermined. Jacking points for bridges, machines or buildings are cheaper built-in than added later.

Geological factors may distort subsidence patterns.

Fractures (joints and gulls), in strong, competent rock at outcrop, localize movement into zones of high strain between stable areas where rock blocks act as natural rafts. Strong sandstones, and the Magnesian Limestone of northern England, develop open fissures in tension, with subsidence sinkholes in soil cover.

Faults localize movement with zones of high strain and ground steps due to displacement.



Brownfield Sites

Increasing demand for building land, and a shortage of greenfield sites, creates a need to re-use 'brownfield' sites – derelict land, or 'made ground' that includes old opencast mines, backfilled quarries, old industrial sites and disused waste dumps.

Of these sites, about 65% are contaminated with toxic metals, chemicals, organics and/or hydrocarbons.

On clean made ground, settlement is main problem.

SITE INVESTIGATION

On brownfield sites, this is more than a normal ground investigation, as many legal, historical and environmental factors have to be considered; it is a specialist field, where the concept of a total geological model (*section 20*) may be particularly appropriate.

Staged investigation is best on an unknown site; with pits and trenches to sample solids, hollow probes to test gases, and boreholes to monitor leachate flow.

CONTAMINATED LAND

This includes any site where buried substances may become accessible and so present a health hazard.

Each site is different, and may respond differently to disturbance, notably by migration of leachates or gas; remediation is only needed where the risk is unacceptable, but limits are not easily defined.

Harmful materials may have to be removed to a safe site, may be buried on site (except oils) under clean soil cover, or may be isolated by grout cut-off and deep burial. Total clean-up may be cost-prohibitive.

Organics may be reduced by on-site bioremediation.

SETTLEMENT OF FILL

Uncontrolled fill may have high potential compaction. For loading of 100 kPa (house strip footings), Young's modulus E may vary from >10 MPa for dense rockfill to <1 MPa for domestic waste. Creep can last for years.

Easy field test of settlement is a sand-filled skip left on site for a month; most movement is very rapid.

Normal to use raft foundations for houses on soft fill.

Main hazard is long-term differential settlement (tilt) over variable fill. Buried opencast high walls and quarry faces must be traced and avoided; tilt could be excessive and could break a raft.

Inundation collapse is loss of volume when fill is first saturated, by changed drainage or rising water table after mine-pumping stops. Loss of thickness may be 1% on compacted rock debris, over 7% on non-engineered mine waste, and higher on some refuse.

TREATMENT OF MADE GROUND

Various methods of ground improvement (*section 27*) can reduce long-term settlements.

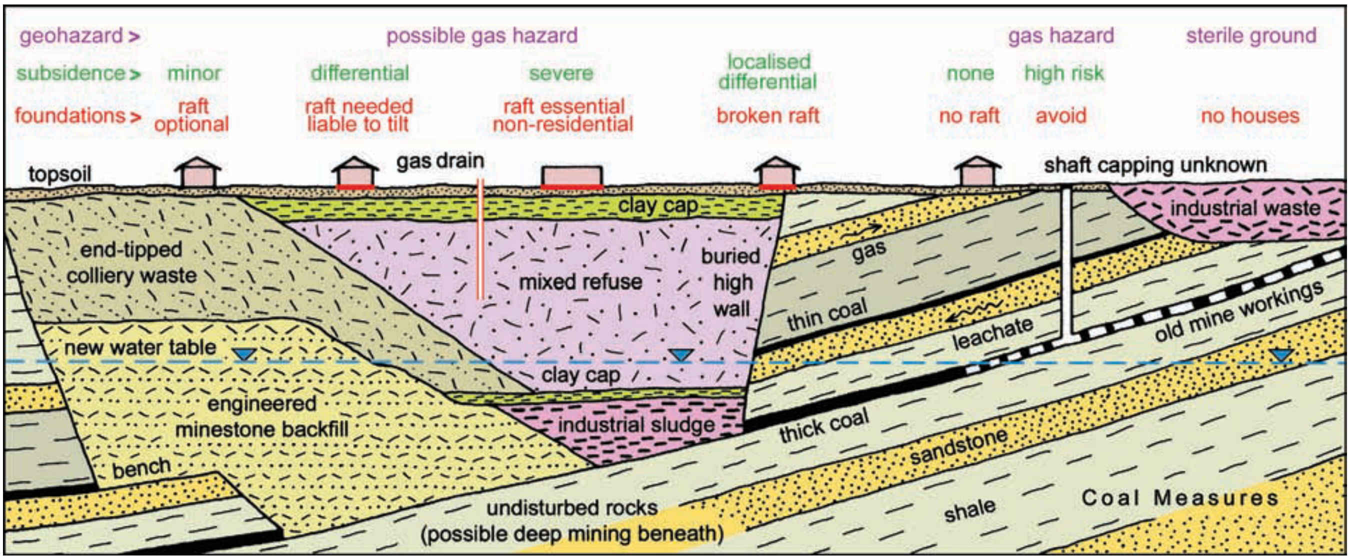
Pre-loading effectively compacts the ground to a depth that is about 1·25 times the depth of surcharge.

Dynamic consolidation is effective to depths of 9 m in sand and rockfill, or 6 m in clay or mixed refuse.

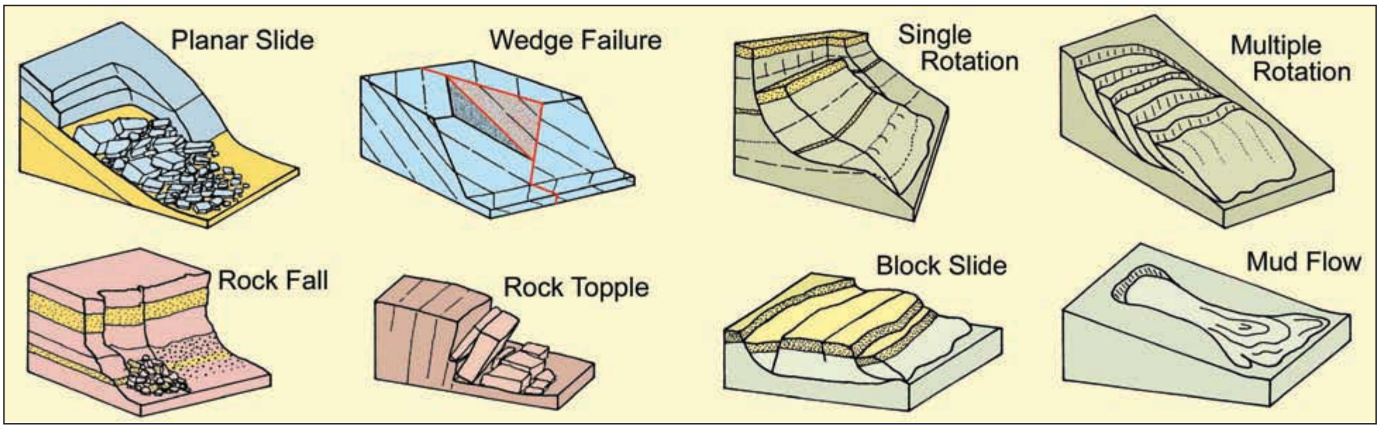
Vibro-replacement stone columns can improve any fill.

Pre-inundation may treat dry fill prone to collapse.

Methane, derived from buried domestic waste or from coal-bearing rocks, should be drained to the air, or may be tapped and burned for power production.



32 Slope Failure and Landslides



Nearly all slopes ultimately degrade by the natural processes of weathering and down-slope transport.
On most slopes this is a continuous, very slow process. Landslides occur where a slope remains static for a long period and then fails in a single dramatic event.
The result in both cases is the same; landslides are one end of a spectrum of natural processes.
Landslides may occur in any rock type.
They commonly occur where some geological structure, planar weakness or local contrast interrupts the process and pattern of slow degradation.
Potential landslide sites are commonly recognizable by their geological structure.
Even at a potential site, each landslide is normally triggered by an individual event or process.
Landslides are only understood by assessment of both the initial structure and the trigger process.

UNSTABLE SLOPES

Each rock material has its own equilibrium slope angle.
Clays are generally unstable at $>10°$, roughly $\phi/2$.
Most rocks of moderate or greater strength can be stable in vertical walls 100 m high if they are massive with only vertical and horizontal fractures. Granite forms a vertical wall 700 m high on Half Dome California, and the vertical cliffs 150 m high at Beachy Head, Sussex, are formed in much weaker chalk. Minor stone fall is always a hazard on these high faces.
Planar weaknesses – bedding planes, joints, etc. – inclined towards the slope create potential slip surfaces in any rock; slopes degrade back to any major fractures with dip $> \phi$ (may be $<20°$ for clay infilling; cohesion and water pressure are also significant).
Densely fractured or thin bedded rocks weather back to slopes of 20–40°.
Potential failure can be assessed on any of the above criteria in context of local data. Rock slides are mostly related to existing planar weaknesses (bedding, joints, faults, cleavage or schistosity) that daylight within a surface slope (i.e. they have unfavourable orientations and are exposed at outcrop at their lower ends).

TYPES OF FAILURE

Large rock failures are mostly planar or wedge slides on one or more plane surfaces.
Small rock failures are commonly falls or topples.
Clay failures are mainly single or multiple rotational slides, ideally on circular slip surfaces.
Mud slides, mud flows and debris flows develop from weak clays or in failed and broken rock material after initial displacement.
Complex failures are common and involve multiple processes; block slides generally have planar slip surface except for circular head scars.

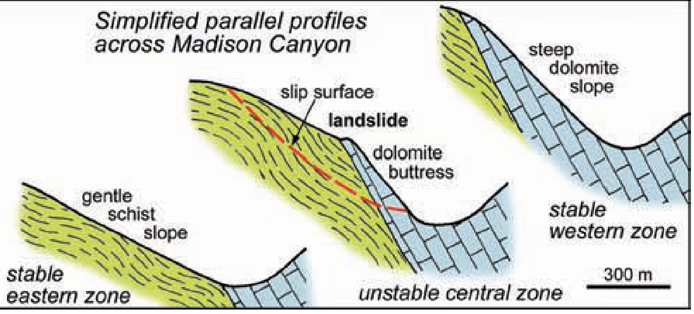
Head scar of a rotational slide breaks a road in Yorkshire.

SPEED OF FAILURE

Slow: more common in soft clays and ductile materials, notably reactivated old landslides. Thistle Slide, Utah, 1983, moved <1 m/h for two weeks.
Rapid: typical of brittle rock failures as rock is greatly weakened by initial shearing or fracturing. Velocities of >100 km/h are common, as at Madison Canyon.
Cyclic: failure creates a stable slope as the debris becomes toe weight, but erosion of the debris then permits repeat failures, as at the frequent landslides along the boulder clay cliffs of the Humberside coast. Alternatively, due to annual changes of groundwater levels; Mam Tor Slide (*section 35*) moves every winter but is stable in summer.

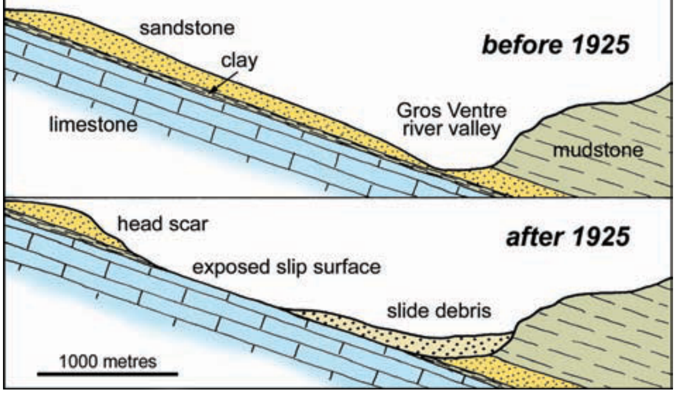
MADISON CANYON LANDSLIDE, Montana, 1959

Geology and slope angle varies along canyon wall.
West part: 45° slope in strong dolomite – stable.
East part: 30° slope in weak schist – stable.
Mid part: dolomite buttress below schist slope – unstable.
Increased stress in earthquake broke dolomite buttress; unsupported schist slope then failed: 20M m³ landslide.
Failure of this part of the slope was inevitable, whenever dolomite buttress was adequately eroded or weakened; vibration from earthquake was just the trigger process.



GROS VENTRE SLIDE, Wyoming, 1925

Strong sandstone above weak clay, dip 18° into valley. River eroded toe of slope, removing sandstone support, until 38M m^3 moved in bedding plane slide. Similar to prehistoric slides on same side of valley; opposite steeper slope is stable with dips into hillside. Slide debris blocked the valley, creating new lake; when first overtopping by the river, rapid erosion of debris dam caused destructive downstream flood.



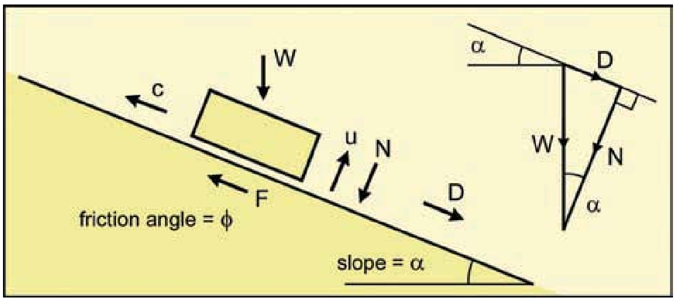
LANDSLIDE TRIGGER PROCESSES

Each landslide event can be ascribed to a process that triggered the failure of a potentially unstable rock mass.
Cause of failure is therefore a combination of unstable structure and one or more trigger events.
Water: rise in groundwater pressure (due to rainfall event or changed drainage) is by far the most important single trigger factor behind landslides (*section 33*).
Toe removal: removing toe of a slope reduces resistance to movement.
Natural toe removal: erosion by river undercutting (Gros Ventre, *above*); erosion by wave action, causing numerous coastal slides (Folkestone Warren, *section 36*); glacial erosion, leaving oversteepened hillsides (Mam Tor, *section 35*).
Artificial toe removal: by quarrying or mining (Frank), excavation for building site (Hong Kong), or road widening (Catak) (*all in section 33*).
Head loading: adding material above neutral line of a slide increases its driving force. Portugese Bend slide, Los Angeles, 1956, was activated by fill placed for a new road that added 3% to slide mass in zone above a slip surface dipping 22° in weak clays. Folkestone slide, 1915, was activated by rock falls from head scar (*section 36*).
Natural head loading causes slope instability on many active volcanoes.
Strength reduction: weathering ultimately weakens all slope materials; slow creep causes restructuring of clays that are stressed within slopes (*section 34*); slow processes eventually reach critical points.
Vibration: cyclic and temporarily increased stresses may cause soil restructuring or rock fracturing.
Artificial vibration, as from heavy road traffic (contributory at many small road failures) or from pile driving (which caused a clay slide destroying Swedish village of Surte in 1950).
Earthquake vibration has caused numerous slides, including Madison Canyon. A 1970 earthquake in Peru started a rock fall on Mt Huascaran, that developed into a giant debris flow moving fast enough to rise 150 m over ridge and bury 20,000 people in the town of Yungay.

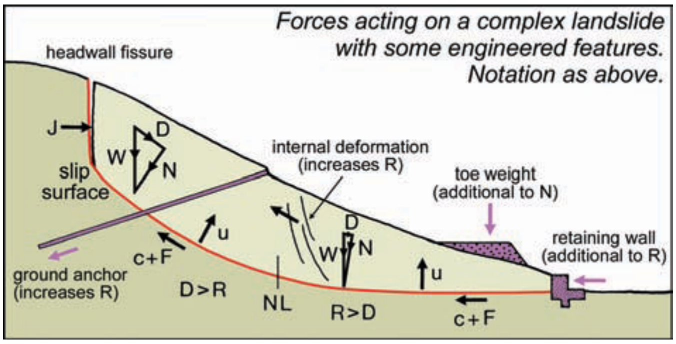
Many slides have complex origins, where and when a number of contributory factors coincide; common that rainfall is the final trigger after toe removal (natural or man-made) has destabilised the slope.

STABILITY OF A SLIDE MASS

Basic forces on a slide block are:
W = weight of block, with two components, D and N.
D = driving force = W sin α.
N = normal stress on slip plane = W cos α – u.
u = uplift force due to pore water pressure.
c and F = resistances in reaction to D.
c = cohesion across slip plane.
F = frictional resistance on slip plane = N tan ϕ.
R = resistance to shear = c + (W cos α – u) tan ϕ.
Safety factor = R/D = resistance / driving force.
c and ϕ are properties of the rock material.



Neutral line: a curved slip surface beneath a slide mass has a neutral line boundary (NL) between a steep section where D > R and a flatter section where R > D.
Tension joints and open fissures at head of slide may contain water that exerts a horizontal joint water pressure (J) additional to the driving force.
Deformation within the slide mass must occur as it moves over a slip surface which is other than plane or cylindrical; resistance to this deformation, by cohesion and friction along multiple internal slip surfaces, adds to the resisting force.


Forces acting on a complex landslide with some engineered features. Notation as above.

Stability analysis of a landslide may be by assessment of forces in two dimensions in individual slices of the mass; these vary across the slide and may include artificial constraints.

Full landslide stability analysis is more complex due to:
- breaking slide into small units;
- reaction forces between these units;
- variable water pressures;
- estimated values of c and ϕ;
- reactions in three dimensions.

Force diagrams, drawn to scale, quantitatively represent components in a two-dimensional stability analysis. Slice is stable while F+Ac > sliding force, but this is only one slice out of a larger slide mass.