

Mechanisms of Subsidence Due to Underground Openings

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Subsidence from underground defects is an increasing problem, and effective preventive or corrective measures depend on knowing the mechanism causing the failure. Too often, however, the mechanism is ignored or diagnosed from the appearance of the ground surface, leading to routine indiscriminate treatment such as filling the depression or draining any water, which can be successful, ineffective, or harmful, depending on the mechanism involved. A number of types of openings are involved: open excavations, leaking sewers and culverts, solution channels in limestones, enlarged joints, faults, mines, tunnels, porous lava, erosion caves, voids between boulders, and voids between large debris. The mechanisms responsible include stratum thinning (including consolidation, collapse, or plastic flow), chemical and biochemical action (including burning), lateral strain, loss of lateral support, collapse of an opening, and raveling or erosion. Various combinations of openings and mechanisms can produce similar effects, but the necessary corrective measures are often different. Moreover, subsidences due to other mechanisms often resemble those from openings. This paper briefly discusses these to show their similarities and differences.

On June 22, 1975, both the eastbound and westbound lanes of Interstate 4 northeast of Lakeland, Florida, suddenly collapsed. Fortunately, no one was hurt and it was possible to fill the openings, repave the surface, and put the highway back in operation with little inconvenience to the public.

Aerial reconnaissance of the area disclosed a saucer-like circular depression that was centered in the median with its perimeter extending beyond the right-of-way, and an elongated system of similar depressions leading toward the area on both sides of the highway. The cause of the subsidence had been the collapse of underground cavities in the sandy soil that had developed by roofing and doming action above solution channels in the porous limestone 16 m (50 ft) below.

Unfortunately, this is not an isolated case. Failures due to sinkhole action in areas underlain by limestone are well known. In such areas, their frequency of occurrence is such that they are almost ignored as engineering problems. Sinks also occasionally occur in

areas underlain by volcanic rocks, and are common in iron and coal mining regions. While the locations, mechanisms, the rates of failure, and warnings of trouble available to the public vary greatly, there is one thing in common among many of these failures—nearby openings in the soil or rock. These openings may be natural or man-made; they may be large or small. They take many forms: pores between solid particles, covered openings such as tunnels and caves, and open cuts.

Failure occurs through numerous independent and interdependent mechanisms. The surface effects of many of these mechanisms are so similar that the cause of a subsidence is sometimes misdiagnosed and the remedial action is then ineffective. This paper summarizes the forms of openings that have been the focal points for surface subsidences, describes the various mechanisms by which failure eventually develops, and points out places where confusion in diagnosing the type of opening and the mechanism of failure has led to continuing trouble.

TYPES OF OPENINGS

There are numerous types of openings beneath the ground surface that have been the focal point of ground surface subsidence. These are illustrated by diagrams in Figure 1.

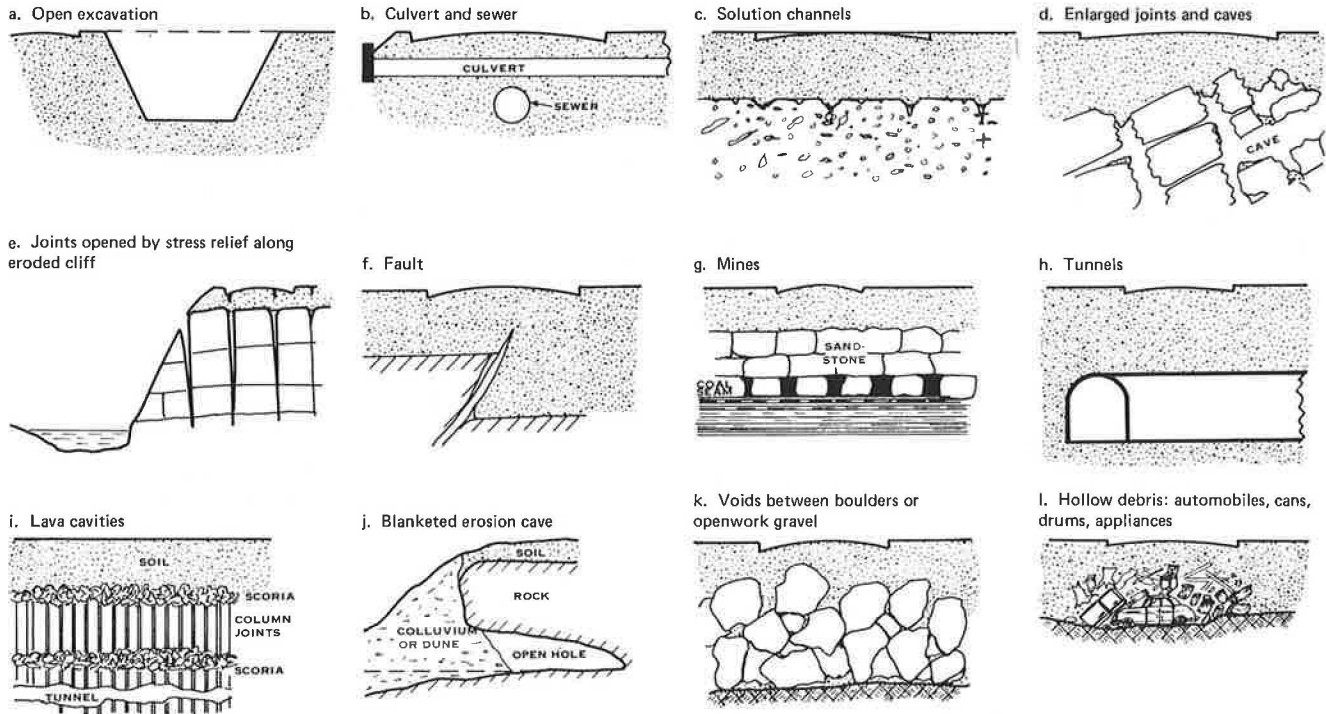
Cuts and Open Excavations

The simplest underground opening is a nearby excavation or cut (Figure 1a). There is no general relation between the depth and size of the excavation, the material, and the distance to the point of subsidence, although there is generally little trouble if the distance from the excavation is several times the excavation depth. However, quarries less than 60 m (200 ft) deep near Birmingham, Alabama, have been related to sinkhole development as far as 1.6 km (1 mile) away.

Sewers and Culverts

Leaking sewers and culverts (Figure 1b) are common and underrated sources of trouble. Most city sewers are beneath the streets; culverts are necessary for

Figure 1. Types of underground openings.



drainage under railroads, highways, and airport runways. There appears to be no relation between the size of the sewer or culvert and the size of a related subsidence. For example, a dropout 2.5 m (8 ft) in diameter and 6 m (20 ft) deep occurred directly over a 15-cm (6-in) sewer below a poorly consolidated fill. The only requirement for trouble is a leak or opening into the sewer through which soil can be eroded.

Solution Channels

Solution channels in soluble formations, in particular limestones and dolomites, and also to some extent calcareous sands and gypsum, are the most familiar form of underground opening leading to serious subsidences. These channels can arise in two ways: from primary porosity between mineral grains (Figure 1c) and from solution-enlarged joints and bedding planes that form slots and underground caves (Figure 1d). The softer, poorly consolidated limestones of the southeastern coastal plain and the margins of the Caribbean Sea exhibit primary porosity: They have voids between spherical oolitic particles, irregular channels between coral fragments, and lens-like openings between fragments of shells, and water can circulate through the pores to enlarge them and give the rock the texture of petrified sponge. This creates numerous interlaced solution channels, ranging from 1 mm (a small fraction of an inch) to as much as 1 m (3 ft) in diameter. When the rock is highly soluble and there is some concentration of flow, as near Ocala, Florida, the solution channels may become caves 10 m (33 ft) or more in diameter.

The more indurated limestones, as well as the porous limestones, can become cracked or jointed from differential consolidation, flexure, folding, and faulting. The rock mass then consists of a series of discrete blocks, the size of which depends on the joint and bedding plane spacing. Water circulating around these blocks will then enlarge the openings to form vertical slots and horizontal lenticular cavities, and vertical chimneylike channels will

develop where the slots intersect. The rapid circulation of water may enlarge the channels to form caves as wide as 10 m (33 ft). Some of these caves, such as the Luray Caverns in Virginia, Mammoth Cave in Kentucky, and Carlsbad Caverns in New Mexico, are well known. However, these cave systems are but a fraction of the solution openings that are found throughout limestones (7, 8).

These openings are of greatest potential danger when they are covered by a blanket of residual soil or subsequent deposits such as the old beach sands in Florida. The cavity (the source of trouble) is hidden from view, but if it is close enough to the ground surface, it can easily become the focal point for a subsidence. If the solution channels are hidden by thick deposits of reasonably competent rock, as occurs in the Appalachian ridge and Shenandoah Valley, or if some of the limestones are covered by younger shales and sandstones, the potential for future subsidence is much less severe. There appears to be no simple rule for establishing the degree of risk in each case. Experience in the area is the most reliable index.

Open Joints

Joints that have become enlarged due to local flexure or stress relief are another type of opening (Figure 1e). These are generally much smaller than the previously described openings and occur in localized belts adjacent to deep valleys or zones of severe structural distress, or adjacent to deep, steep cuts (1).

Faults

Faults (Figure 1f) may similarly produce networks of underground openings; however, the grinding and sliding action associated with faulting seldom produces large open voids. In some instances of normal faulting where the earth is subject to tension, or in irregular strike slip faulting, localized narrow openings sometimes develop. Faulting in limestone can lead to enlarged solution chan-

nels similar to those that develop along joints and bedding planes, but the weathering of the fractured materials in many fault surfaces may produce zones that are less porous than any of the surrounding formations.

Mines

Mines (Figure 1g) are a major source of both sudden and continuing subsidence (2). The risk depends on a number of factors (3): (a) the width and height of the mine openings, (b) the percentage of pillar left to support the mine roof, (c) the thickness of rock and soil above the mine compared to the size of mine opening, and (d) the engineering properties of the soils and rocks present.

Small, deep mines seldom cause ground surface subsidence, but large, shallow mines can produce major areas of subsidence. There are, however, exceptions: The gold mines near Johannesburg, South Africa, several hundred meters below the surface, have triggered disastrous subsidences, although the intervening rocks fully support the mine opening. These subsidences have been triggered by drainage from the mines and resemble the cave collapse that occurs in shallow limestones or the raveling failures that occur in residual soils.

Tunnels

Tunnels (Figure 1h) are similar to mines. However, except for urban subways and sewers, there is seldom great risk of damage above them because they are generally built beneath inaccessible areas. Thus, the collapse of a tunnel is of less consequence to the general public than it is to those who are using it. On the other hand, failures of tunnels in cities have produced large local subsidences.

Lava Cavities

Cavities of many forms occur in lavas (Figure 1i). There are blow holes from gases in the harder lavas, enlarged joints due to cooling, scoriaceous zones of high primary porosity, and tension cracks from movement of the solidifying lava, all of which create zones of localized high porosity. The larger openings are seldom more than a few meters (about 10 ft) across. The primary porosity of scoriaceous lava generally occurs in strata 1 to 2 m (3 to 6 ft) thick between more competent rock layers with well-developed joints perpendicular to the layer.

Erosion Caves

Caves produced by erosion (Figure 1j) are another type of localized underground opening and are generally formed by the action of wind, waves, or underground streams on poorly indurated formations. For example, weak sandstones along the sea coast are frequently undercut to form sea caves, and wind erosion in desert areas produces similar enlarged underground openings. These openings are seldom serious hazards to construction, although they can cause localized subsidence if they are subsequently buried by younger formations. They occur in areas of old sea and river terraces or shifting sand dunes that bury the old caves beneath younger deposits.

Concentrated seepage through enlarged joints or solution channels in limestone can cause erosion of adjacent, poorly cemented formations. For example, in a small cave system in north Alabama, water flowing under pressure through the limestone has produced narrow, tall, wedge-shaped channels in the soft sandstone above. Some of these channels lead to the surface and have

been the cause of local subsidence.

Voids Between Large Solid Bodies

The voids between large solid masses in fills are a man-made system of underground openings. One example of this is that of large boulders obtained from blasting rock having insufficient fine fragments to fill the voids between the boulders (Figure 1k). A second type is that of the irregular voids between fragments of debris, stumps, and other rubbish that make up waste fills. A third type is that of large, hollow metallic bodies (such as cans, bottles, oil drums, old refrigerators, stoves, and even railroad tank cars) that have been buried in the ground (Figure 1l).

Thus, there is a wide variety of underground openings—some are geologic, others are man-made. The mechanisms by which they cause subsidence are described in the following section. Various combinations of these mechanisms may combine with different types of openings to create complex subsidence conditions that are difficult to anticipate and just as difficult to treat. Regardless, the understanding and treatment of a subsidence must begin with knowledge of the character of the opening that is the ultimate source of the subsidence, and of the failure that created it.

MECHANISMS OF SUBSIDENCE

There are many mechanisms of subsidence. In most cases, water is involved in some way. It weakens many soils and some poorly cemented rocks and serves as an agent of internal erosion; conversely, loss of moisture destroys the apparent cohesion that holds some fine-grained cohesionless soils together.

In each situation, the combination of mechanisms that might be involved must be carefully evaluated. Blaming a subsidence on a single factor may be an oversimplification and lead to misdirected corrective action.

Local Thinning of Formation

Settlement, as a process (in contrast with a sudden event), is sometimes caused by a local thinning of a formation that has been overstressed adjacent to one of the types of openings described in the previous section (4). In some cases, these openings are of primary or enlarged primary porosity; in others, large openings are involved. This process is often confused with subsidence due to large openings.

Of course, the classic consolidation produced by that reduction of the primary voids of soils and similar materials is the most frequent cause of thinning. This process is not related to large openings.

One of the more mysterious of the thinning phenomena is the crushing of highly porous rock. For example, in south Florida and the humid tropical areas surrounding the Caribbean, the poorly consolidated limestones have been reduced to a skeleton of their former mass by continued solution. This has been aggravated by water drainage, groundwater use, and changing sea levels. If the effective stress on these limestones is increased, as by a highway embankment, their porous skeleton locally fractures, which produces a phenomenon analogous to the consolidation of clean sand (Figure 2a). This mechanism has been responsible for the settlement of several structures in the Miami area and could be responsible for some of the solution depressions found in central and south Florida (5, 6). Similar crushing consolidation is observed in scoriaceous lava and shale-sandstone fills.

The collapse of a loose cemented soil due to deterioration of interparticle bonding is a major mechanism of

thinning subsidence in loess soils and the valley fill deposits of arid regions. This is not related to openings although it has sometimes been blamed on caves.

The plastic flow of soft rocks such as shale and mudstones under high stress can similarly cause a local thinning of formations and subsidence above. Concentrations of stress adjacent to excavations, as shown in Figure 2b, are responsible for the subsidence of steep cliffs of sandstone underlain by shale. If the shale deteriorates and weakens upon exposure, the subsidence can become a landslide with shear failure across the shale and through the sandstone joints. Again, openings are sometimes blamed.

In mines in which the roof support is provided by coal pillars resting on soft underclays, the pillars may punch downward and extrude the clay into the mine opening. This results in a reduction of the mine opening and continuing subsidence of the ground surface. The mine pillars themselves may also bulge plastically. This is seen in coal and salt formations.

Plastic flow can also occur at the heading of a tunnel that is inadequately supported in soft clays. If the rate of excavation at the tunnel face exceeds the rate of forward progress of the tunnel lining and bracing, there will be a trough above the tunnel at the ground surface. Similarly, the upward squeezing of soft clay on the bottom of an open excavation, even if the sides are supported by bracing, can cause subsidence outside the excavation. This is frequently unseen because the soil movement occurs while excavation is taking place. Local squeezing also occurs at the trailing edge of a tunnel shield. It is impossible to measure the volume of soil excavated accurately enough to compare it with the theoretical volume of an excavation unless the discrepancy exceeds 10 percent. These forms of subsidence are sometimes termed lost ground.

Chemical and biochemical action, including decay, chemical attack of groundwater on soil and rock minerals, and the burning of coal, bituminous shale, and certain waste fills, is a third mechanism of local thinning of formations (Figure 2c). For example, either as the result of spontaneous combustion or lightning, certain soft coals of Ohio, Pennsylvania, and the Dakotas have burned for years, and from time to time both slow surface settlement and sudden collapse occur.

Mine wastes consisting of carboniferous shale and coal frequently ignite by spontaneous combustion and burn slowly, converting the shale to bricklike fragments of soft rock, and producing large voids. Eventually, those voids collapse, causing localized subsidence. The burning of waste materials in fills, either by spontaneous combustion or by fires intentionally set to reduce the waste volume, has been responsible for localized settlement of roadways and light structures. Similarly, chemical interaction between minerals within waste fills has caused subsidence. For example, the acids from cinders have produced galvanic reactions, accelerating the corrosion and collapse of open metallic bodies such as refrigerators and automobile bodies.

Extrusion of soft soils (Figure 2d) is a fourth possible mechanism. It does not appear to occur often.

Lateral Strain

A certain amount of strain (Figure 3a) accompanies any excavation, whether it is man-made or is a natural development of an underground opening. The increase in stress caused by the reduction in the amount of solid material present produces a readjustment of the solid mass involved. Frequently, the extent of the mass involved is far greater than might be suspected from simple theories of earth pressure involving shear of the soil. For ex-

ample, the lateral strain and vertical subsidence adjacent to an excavation sometimes extend from the face of the excavation as much as five times the excavation depth. This strain occurs even though the structural supports for the excavation are capable of resisting shear failure within the soil mass. In fact, excavation support designed on the basis of active earth pressure inherently requires sufficient strain to mobilize a significant part of the shear strength of the soil supported. Thus, movement within the mass is inherent in most excavation bracing designs.

Loss of Support

Still larger subsidences are produced when the excavation supports in mines, tunnels, or open excavations are not adequate to prevent continuing shear failure (Figure 3b). The soil or rock moves downward and inward, producing large lateral and vertical strains, and sharp discontinuities along surfaces of shear. This occurs because the load is greater than had been anticipated or because the supports are inadequate.

There are three major factors in the support loading. First, the rigidity and strength of the soil and rock determine what part of the ambient stress field must be provided by the support system. Any structural defects in the soil and rock, such as joints and faults, play a major part in reducing the mass rigidity and strength compared to that of intact rock. Design loads based on tests of small intact laboratory specimens can be misleading.

Second, the design and installation of the support determine the degree of load transfer as well as the ability of the support to carry the load safely. A rigid (as compared to the soil or rock) support may receive more load than one that deforms readily. On the other hand, a support that permits excessive deformation can allow disruption of the mass that will be followed by even greater loads on the support.

Third, the excavation produces reductions of the effective confining stress on the soil or rock and of its strength. The design of supports should initially be based on the undrained strength, which represents the strength as it exists under ambient conditions—generally the maximum. After excavation and reduction of the effective stresses, the effective strength is necessarily lower. Many an excavation failure, mine collapse, or tunnel blow-in has been caused by neglect of the drained strength of the material.

Two factors may be responsible for a decrease in support strength. An unforeseen load from localized movements in the mass can produce overstress and excessive bending or buckling, and damage from impact or deterioration of the material can reduce its ability to carry the load for which it was designed. For example, coal pillars in mines (Figure 3c) deteriorate from the exposure of shale seams or pyrite inclusions.

The failure of a man-made support or a portion of the intact soil or rock produces a transfer of load to the remainder of the support system. If this is already stressed to levels approaching its strength, adjoining supports may also fail, and failure propagates outward, generating extensive subsidence. On the other hand, if the initial support stresses are low, the failure of one part of the system may not cause subsidence.

Overexcavation in advance of support is also a major cause of subsidence (Figure 3d). As with bracing, designers and builders are often lulled into a false sense of security by the undrained strength of intact samples of material, but an unsupported excavation face in soil or soft rock that is stable one day may become unstable the next, due to reduction in the effective stress or to

Figure 2. Mechanisms of stratum thinning.

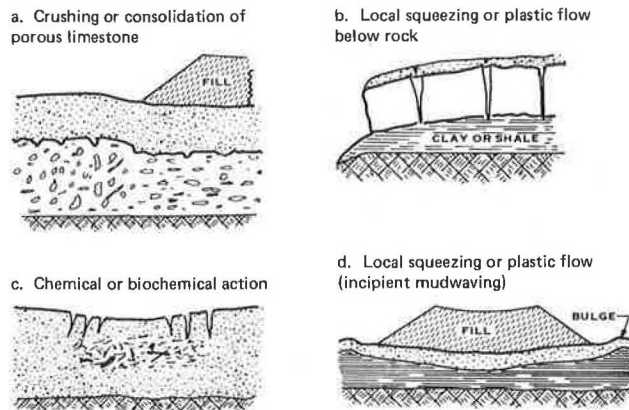
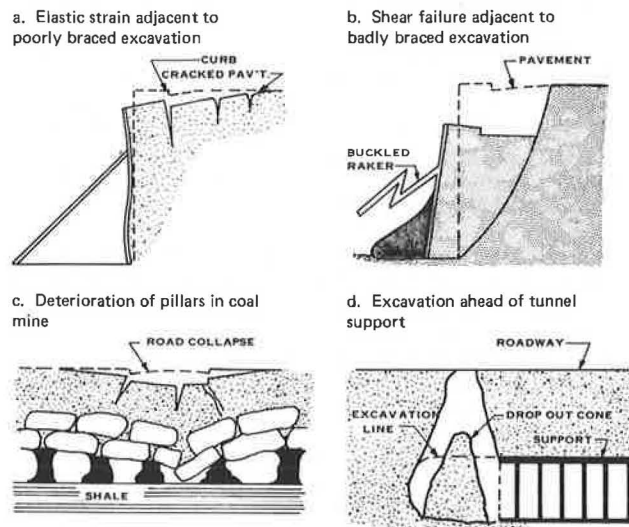


Figure 3. Loss of support.



deterioration of cementing agents. Localized zones of weakness, such as faults, can also aggravate the problem.

Failures due to lack of lateral support ordinarily can be evaluated in advance by a thorough understanding of the stress-strain and shear strength properties of the materials. Both must be considered: (a) as they exist at the time of excavation, and (b) as altered by the excavation. In most instances, environmental changes brought on by excavation, such as biochemical deterioration, altered seepage patterns, or loss of strength due to loss of effective confining stress, are responsible for ultimate failure. Finite element analyses of elastic strain and limited analyses of shear failure can provide some indication of the possibility of subsidence due to loss of support.

Collapse of Unsupported Openings

The sudden collapse of an unsupported opening is the most dramatic of the subsidence mechanisms. Regardless of the chain of events leading to collapse, such failures are the result of the enlargement of the opening beyond the ability of the materials above to bridge it. A truncated cone or trapezoid of material above drops into the opening below, as shown in Figure 4. Immediately after the failure, it is possible to see the intact mass of

Figure 4. Collapse of opening.

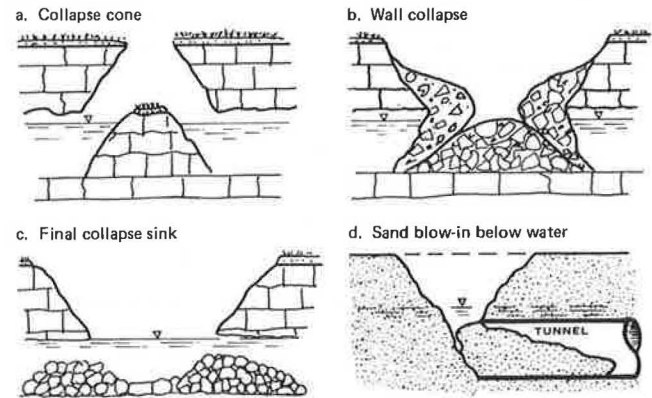
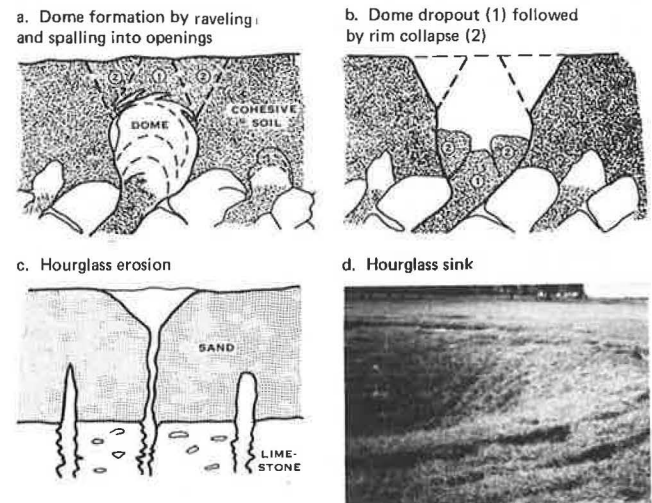


Figure 5. Raveling or soil erosion into openings.



soil or rock below, with trees and grass continuing to grow. (This is dangerous; the face of the opening slopes inward so that viewing the collapse from its rim involves standing on an overhang.) Eventually, the overhanging face sloughs or subsides, and the final opening is a truncated cone with its side slopes reversed from the initial direction (Figure 4b). If there is then erosion of the dropout cone due to surface water entering the hole from above or seepage from below, an open hole will eventually develop, sometimes with water at the bottom as shown in Figure 4c.

Collapse can be triggered by the blow-in of the unsupported heading of a tunnel or an unbraced cut. The unsupported soil caves, frequently impelled by unbalanced groundwater pressure. In low-cohesion soils, the sudden in-rush leaves a gaping hole in the soil mass immediately adjacent to the underground opening. This is followed by successive small collapses or raveling as described in the next section, and eventually there is a dropout at the ground surface. These successive conditions are shown in Figures 4d and 5.

Raveling or Erosion of Soil Into Openings

The most insidious form of failure is the raveling or erosion of soil into an underground opening. The opening can be as small as a joint in sandstone or as large

as a cave in limestone. The only requirement is sufficient seepage that erosion of the overburden can continue. Typically, the condition develops over a sewer or culvert with open joints, above solution-enlarged slots and chimney openings in limestone, or in porous lavas overlain by soils that are easily eroded. Continuing seepage washes the soil into the underground openings, as shown in Figure 5a. The small dome formed in the soil then acts as a focal point for further seepage. The continuing seepage toward the open surface of the dome causes small slabs to peel off its inner surface (ravel) so that the dome enlarges. The sloughed, softened material falls to the bottom of the dome and is carried by the downward seepage into the opening below. Eventually, the dome becomes far larger than the opening into which the soil is carried. There is evidence of domes as large as 15 m (50 ft) in diameter and 9 m (30 ft) high above sewer pipes 5 m (16 ft) in diameter, and similar domes in residual soils above small caves in limestones. The opening through which the soil was eroded, in most cases, was less than a meter (1 or 2 ft) wide.

Eventually, the dome becomes sufficiently wide that the soil above cannot bridge the opening. Collapse (Figure 5b) similar to that illustrated in Figure 4a, b, and c follows. In fact, in examining such collapsed domes it is difficult to determine whether failure was precipitated by doming in the soil or by collapse of the deeper original opening below.

Undersized sewers and culverts are particularly dangerous because the water is under pressure during periods of high flow. If they leak (through fractures or bad joints), water is forced into the soil, weakening it. Then when the flow recedes, the water drains back, carrying with it the softened soil. Numerous failures of this type occur below highways and railroads.

An unusual form of raveling develops in completely cohesionless sands in which the capillary tension is small. This occurs in fine sands during periods of drought or in coarse sands under conditions of downward seepage. The sand flows through relatively small openings, such as the solution chimneys in limestone or small raveling holes in clay, into larger underground openings in the same way that sand runs through the narrow throat of an hourglass. A cone-shaped zone of subsidence develops at the ground surface (Figure 5c and d). Three of these have been observed adjacent to the highway between Bartow and Lakeland, Florida, during the past 8 years (6).

Erosion and doming can also develop as a result of horizontal seepage between confining strata. Generally, its rate is lower than that in the vertical direction because the gradients are lower. Such horizontal seepage erosion is termed piping. Piping failures occur behind braced excavations that have a higher groundwater table outside and inadequate filtering at the face of the excavation. Similar failures occur through weep holes in retaining walls having inadequate filters between the backfill and the wall. Others are caused by poorly filtered subsurface drains adjacent to highways.

Raveling frequently occurs into the large voids between boulders or fragments of debris in fills. Downward seepage or traffic vibration above causes soil to filter into the voids below. The initial filtering is followed by more rapid raveling, eventually producing dome-like openings that collapse. A parking lot that had been constructed on top of 6 m (20 ft) of 9000-kg (10-ton) boulders blanketed with silty sand developed sinkholes 1 m (3 ft) in diameter and $\frac{1}{2}$ to 1 m (1.5 to 3 ft) deep within 10 years.

Raveling and seepage erosion failures take so many forms that it is difficult to fully diagnose them. However,

many of the subsidences that have been blamed on the collapse of deep caves, mines, or tunnels may have been the collapse of soil domes generated by raveling into the deep openings.

INITIATING MECHANISMS

Although there are many forms of openings, and many mechanisms leading to subsidence, the sequence of events involved is frequently initiated by some significant change in the total environment affecting the soil and rock mass. In some cases, that event is not necessarily related to the opening. This event or the environmental change is termed the triggering mechanism by engineers or the proximate cause by lawyers.

Groundwater Flow

Movement of water through the ground, in one way or another, is the most significant triggering mechanism. The seepage can be vertically downward or horizontally toward the opening. Erosion induced by seepage and the gradients producing seepage form the localized stress system inducing failure.

Among the sources of underground flow are (a) increased rainfall and surface runoff that infiltrates the soil or small openings present in the ground, (b) broken water lines, (c) broken drain pipes, (d) flow of groundwater toward wells, and (e) flow of groundwater toward improperly filtered drainage systems.

Groundwater Lowering

Lowering the water table has two effects. First, although the weight of the soil mass is reduced somewhat, the effect of this is more than offset by the increase in effective stress within the soil or rock. Lowering the water table 0.3 m (1 ft) increases the effective weight by 600 to 800 kg/m³ (40 to 50 lb/ft³).

A second effect of groundwater lowering is a reduction of capillary tension and temporary cohesion in cohesionless soils. For example, in damp, fine sands, large, open raveling domes can be supported by capillary cohesion, but if the sand should become thoroughly dry, the dome will collapse because the cohesion is lost. Similarly, sewer trenches in damp, fine sand sometimes can be excavated with steep slopes because of capillary tension. If the sand dries out, the apparent cohesion is lost, and the soil slope slumps inward to its angle of repose.

Groundwater lowering can be produced by excessive use of water from wells, localized drainage for construction projects, and periods of prolonged drought.

Increased Loading

Increased loading of the mass increases the stresses in the soil and rock surrounding the underground opening and produces increased strain, plastic flow, or, eventually, shear failure. In addition, there is some evidence that increased stress produces increased solubility in carbonate rocks analogous to stress cohesion in metals.

There are a number of factors responsible for increased surface loading—embankments and fills, new structures, and reduction of lateral support by deep excavations.

Dynamic load, such as shock and vibration induced by earthquakes, vibrating machinery, and blasting, can trigger failure in two ways. First, shock and vibration directly produce strains and stress increases. Second, in loose, cohesionless soils and possibly also in ultra-sensitive clays, shock and vibration may induce struc-

tural collapse that is followed by surface settlement and sometimes a flow in the form of temporary quicksand. For example, saucer-shaped depressions in the ground surface, with small sand boils within them, frequently accompany earthquakes.

Deterioration

The deterioration of soil and rock materials, including the man-made supports for underground openings, is another form of triggering. Fire can destroy wood bracing systems or weaken steel supports. Burning of coal or waste materials produces new openings or enlarges old ones. Three mechanisms can be triggered: (a) gradual surface subsidence that keeps pace with the combustion; (b) sudden collapse of the opening, sometimes long after; or (c) raveling, doming, and a shallow collapse.

The gradual deterioration of rocks, such as coal, shale, and some poorly cemented sandstones, by physical, chemical, and biologic processes in the presence of air and water, can lead to collapse. Because such formations are often initially quite strong, engineers may be led into a false sense of security by forgetting the loss in strength from long-term exposure.

Deterioration of man-made supports in the moist environment is a cause of failure in old mines, poorly maintained tunnels, or even in braced excavations that have been left open longer than had been anticipated. The resulting subsidences can proceed as slowly as the rate of deterioration or may develop suddenly when the strength has degenerated to the point that rupture takes place.

CONCLUSIONS

Subsidences produced by underground openings, including the thinning of underground strata, are major maintenance problems for highways, railroads, airfields, and the foundations of engineered structures. There are many types of openings, any one of which can be a source of trouble that is far out of proportion to the size of the opening or even its proximity to the site. There are a number of mechanisms that produce subsidence, some unrelated but many interrelated. Ultimately, failure develops because of some change in the total environment—groundwater, stress, or a change in the materials involved.

Because of the complexity of the phenomena, many subsidences have been mistakenly diagnosed and considerable amounts of money spent for remedial measures that were of little or no benefit. Sometimes the subsidence has stopped because the movement that took place inhibits the mechanism or closes the opening. Thus, some remedial measures have been judged successful because the subsidence had already stopped itself.

The evaluation of the causes of subsidence requires a clear understanding of the geology of the soil and rock formations involved, a knowledge of the character of the openings, both natural and man-made, and an awareness of the different mechanisms that can lead to subsidence. Many subsidences could be predicted and their serious effects alleviated: Most can be temporarily or permanently stopped or their rate of movement materially reduced.

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