GEOLOGY AND CONSTRUCTION

Bell F.G.
Blyth, Nottinghamshire, United Kingdom

Keywords: open excavation, drilling and blasting, ripping, digging, slope stability, groundwater control, tunneling, geological conditions, tunneling methods, stand-up time, tunnel support, highway construction, embankments, reinforced earth, ground improvement, footings, rafts, piles, ground movements, ground treatment

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Summary

Geology is of fundamental importance in construction since construction operations take place either on or in the ground. Open excavation involves removal of material at the surface within certain specified limits. The method of excavation depends on the ground conditions. Rock, especially strong rock, is removed by drilling and blasting. Rock can also be ripped if it is suitably discontinuous. Soils and weak rocks are excavated by digging. Slope stability is of critical importance in excavation, although in certain areas some amount of failure has to be tolerated because of cost. This applies especially to rock fall. Various measures can be used for stabilizing slopes. Excess groundwater presents another problem and can be handled by dewatering techniques or the placement of impermeable barriers around the site.

Geology has a large influence on the cost of a tunnel. Because geology is so important, it is frequently necessary to obtain data ahead of tunneling by constructing a pilot tunnel or by probing ahead with drills. The stability of a tunnel opening in rock during its excavation depends primarily on the strength of the rock masses concerned; the nature of the discontinuities they contain, including faults; the stresses on them; and the groundwater conditions. Usually however, the worst conditions are met with in soft ground, which may ravel, flow, squeeze, or swell. Tunnels are excavated by conventional drilling and blasting, by tunnel-boring machines, or in soils, by shield cutters. Various means have been used in rock masses to provide support prior to the placement of the permanent lining. In some weak rocks and soils the permanent lining may have to be placed almost immediately.

Because highways are linear structures, they are likely to encounter different ground conditions along their length. Obviously, they require stable foundations and they may involve the excavation of cuttings and/or tunnels, the construction of embankments and/or bridges, and construction materials. Suitable drainage measures need to be installed and the ground may need some form of stabilization before road construction can begin.

Building foundation structures are of three main types, that is, footings, rafts, and piles. The type used depends primarily on the ground conditions. The foundation structure supports the building and should ensure that the building does not suffer damaging ground movements. Ground movements may be caused by the load imposed by the building, that is, settlement, by subsidence, or by earth tremors. Ideally, the design of a building should ensure that ground movements are accommodated without consequential damaged occurring. Differential ground movements cause the worst damage. There are a number of methods by which the ground conditions can be improved.

1. Introduction

Geology is obviously one of the most important factors in construction since construction takes place either at the surface or below the surface. Hence, geology has an important influence on most construction operations since it helps determine their nature, form, and cost. For example, route design and tunnel construction are largely dependent on geological considerations. Indeed, a tunnel can be an uncertain and sometimes hazardous undertaking because information on ground conditions along the alignment is never complete, no matter how good the site investigation.

A site investigation is required for a construction operation. Just how extensive the site investigation is depends on the type of operation and the complexity of the geological conditions. Generally, subsurface excavations are more extensive than those for construction at the surface, except where very sensitive structures such as nuclear power stations are concerned. The initial stage of a site investigation involves a literature survey making use of maps and aerial photographs to obtain an overall impression of the geological conditions, and to plan subsequent investigations to assess the feasibility of the particular location. Once the location has been decided, a more detailed investigation involving ground exploration follows. The information gathered from this stage of the investigation is used to assist in the design and estimation of the cost of the project.

2. Open Excavation

Open excavation refers to the removal of material at the surface, within certain specified limits, for construction purposes. In order to accomplish this economically and without hazard the character of the rocks and soils involved, and their geological setting, must be investigated. Indeed, the method of excavation and the rate of progress are very much influenced by the geology on site. Furthermore, the position of the water table in relation to the base level of the excavation is of prime importance, as are any possible effects of construction operations on the surrounding ground and/or buildings.

Drillability in rock masses is influenced by their hardness, abrasiveness, and grain size, and the discontinuities present. The harder the rock, the stronger the bit that is required for drilling, since higher pressures need to be exerted. Abrasiveness refers to the ability of a rock to wear away drill bits. Bit wear is a more significant problem in rotary than percussive drilling. The size of the fragments produced during drilling operations also influence abrasiveness. For example, large fragments may cause scratching but comparatively little wear, whereas the production of dust causes polishing. Even diamonds lose their cutting ability on polishing. Generally, coarse-grained rocks can be drilled more quickly than can fine-grained varieties or those in which the grain size is variable. The ease of drilling in rocks in which there are many discontinuities is influenced by their orientation in relation to the drillhole. Drilling across the dip is generally less difficult than drilling with it. If a drillhole crosses discontinuities at a low angle, the bit may stick or the hole may go off line. Drilling over an open discontinuity means that part of the energy controlling drill penetration is lost. Where discontinuities are filled with clay this may penetrate the flush holes in the bit, causing it to bind or deviate from alignment. The drillhole may require casing if the ground is badly broken.

Spacing of the blastholes is determined by the strength, density, and fracture pattern within the rock mass, as well as the size of the charge. As a rule, spacing will vary between 0.75 and 1.25 times the burden (i.e., the width of the strip blown from the face). Generally, 1 kg of high explosive will bring down about 8–12 tonnes of rock. Good fragmentation reduces or eliminates the amount of secondary blasting, while minimizing wear and tear on loading machinery. Rocks characterized by high specific gravity and high intergranular cohesion with no preferred orientation of mineral grains resist crack initiation and propagation on blasting. Blasting in rocks that are relatively brittle with a low resistance to dynamic stresses, may give rise to extensive pulverization immediately around the blastholes, leaving the area between largely unfractured. Those rocks that possess marked preferred orientation present difficulties on blasting because of their mechanical anistropy: they split easily along the lineation, but crack propagation across it is limited.

In many excavations it is important to keep overbreak to a minimum, as damage to the walls or floor of the excavation may lower its strength and necessitate further excavation. What is more, smooth faces are more stable. Line drilling is the method most commonly used to improve the peripheral shaping of excavations. It consists of drilling alternate holes between the pattern blastholes forming the edge of the excavation. The quantity of explosive placed in each line hole is significantly smaller, and if the holes are closely spaced, from 150 to 250 mm, then explosive may be placed only in every second or third hole. These holes are timed to fire ahead, with or after the nearest normally charged holes of the blasting pattern. In pre-splitting, a line of trimming holes is charged and fired to produce a shear plane. This acts as a limiting plane for the blast proper, and is carried out prior to drilling and blasting of the main round inside the proposed break lines. Once pre-split, the rock excavation can be blasted with a normal pattern of holes.

The major objective of ripping is to break the rock just enough to enable economic loading to take place. Rippability depends on intact strength, fracture index, and abrasiveness: that is, strong, massive, and abrasive rocks do not lend themselves to ripping. By contrast, if sedimentary rocks are well bedded and jointed, or if strong and weak rocks are thinly interbedded, then they can be excavated by ripping rather than by blasting. The run direction during ripping should be normal to any vertical joint planes, down-dip to any inclined strata, and on sloping ground, downhill. Ripping runs of 70–90 m usually give the best results. Where possible the ripping depth should be adjusted so that a forward speed of 3 km h^{-1} can be maintained, since this is generally found to be the most productive. Adequate breakage depends on the spacing between ripper runs, which is governed by the fracture pattern in the rock mass.

Diggability depends principally on the intact strength of the ground, its bulk density, bulking factor, and natural water content. When material is excavated it increases in bulk, this being brought about by the decrease that occurs in density per unit volume. Some examples of typical bulking in soils are given in Table 1. The bulking factor is important in relation to the loading and removal of material from the working face. The natural moisture content influences the adhesion or stickiness of soils, especially clay soils.

Density	**Bulking factor ($Mg\ m^{-1}$)**	**Diggability**
1.8	1.25	E
1.7	1.15	E
1.95	1.15	E
1.65	1.3	M
2.1	1.35	M-H
1.6	1.3	M

Notes: E = easy digging, loose, free-running material such as sand and small gravel; M = medium digging, partially consolidated materials such as clay and clayey soil; M–H = medium-hard digging, materials such as heavy wet clay, gravels, and large boulders.

Table 1. Density, bulking factor, and diggability of some common soils

The stability of slopes is a critical factor in open excavation. This is particularly the case in cuttings, as for instance for roads, canals, and railways, where slopes should be designed to resist disturbing forces over long periods. Instability in a soil or rock mass occurs when slip surfaces develop and movements are initiated within the mass. Undesirable properties in a soil, such as low shearing strength, development of fissures, and high pore water pressures, aid instability and are likely to lead to deterioration of slopes. Generally, the most important factors relating to the stability of a rock mass are the incidence, geometry, and nature of discontinuities. In the case of open excavation, removal of material can give rise to the dissipation of residual stress, which can further add to instability.

There are several methods available for analysis of the stability of slopes in soils. Most of these may be classed as limit equilibrium methods, in which the basic assumption is that the failure criterion is satisfied along the assumed path of failure. A free mass is taken from the slope, and starting from known or assumed values of the forces acting on the mass, calculation is made of the shear resistance required for equilibrium of the soil.

This shearing resistance then is compared with the estimated or available shear strength of the soil to give an indication of the factor of safety, assessed in two dimensions. The analysis gives a conservative result.

The design of a slope excavated in a rock mass requires as much information as possible on the discontinuities present. Information relating to their spatial relationships affords some indication of the modes of failure that may occur, and information relating to the shear strength of the rock mass, or more particularly the shear strength along discontinuities, is required for use in stability analysis. The joint inclination is always the most important parameter for slopes of medium and large height, whereas density is more important for small slopes than friction. Cohesion becomes less significant with increasing slope height, while the converse is true as far as the effects of pore water pressure are concerned.

The principal types of failure that occur in rock slopes are rotational, translational, and toppling failures. Rotational failures normally only occur in structureless overburden, highly weathered material, or very high slopes in closely jointed rock. Relict jointing may persist in highly weathered materials, along which sliding may take place. These failure surfaces are often intermediate in geometry between planar and circular slides. Translational or planar failures take place in inclined layered sequences of rock, the movement occurring along a planar surface such as a bedding plane. Wedge failure is a type of translational failure in which two planar discontinuities intersect, the wedge so formed daylighting into the face; that is, failure may occur if the line of intersection of both planes dips into the slope at an angle less than that of the slope. Toppling failure is generally associated with steep slopes in which the discontinuities are near vertical. It involves the overturning of individual blocks, and is therefore governed by discontinuity spacing as well as orientation. The likelihood of toppling increases with increasing inclination of the discontinuities.

Excavation in fresh, massive, plutonic igneous rocks, such as granite and gabbro, can be left more or less vertical after removal of loose fragments. On the other hand, volcanic rocks such as basalts and andesites are generally bedded and jointed, and may contain layers of ash or tuff, which are usually softer and weather more rapidly. Thus, slope angles have to be reduced accordingly.

Gneiss, quartzite, and hornfels are highly weather resistant, and slopes in them may be left almost vertical. Schists vary in character, and some of the softer schists may be weathered and tend to slide along their planes of schistosity. Slate generally resists weathering, although slips may occur where the cleavage dips into a cut face.

If strata are horizontal, then excavation is relatively straightforward and slopes can be determined with some degree of certainty. Vertical slopes can be excavated in massive limestones and sandstones that are horizontally bedded. In brittle, cemented shales, slopes of 60^o and 75^o are usually safe, but increasing fissility and decreasing strength necessitate flatter slopes. Even in weak shales, slopes are seldom flatter than 45º. However, excavated slopes may have to be modified in accordance with the dip and strike directions in inclined strata. The most stable excavation in dipping strata is one in which the face is oriented normal to the strike, since in such situations there is a low tendency for rocks to slide along their bedding planes. Conversely, if the strike is parallel to the face, then the strata dip into one slope. This is most critical where the rocks dip at angles varying between 30^o and 70^o. If the dip exceeds 70º and there is no alternative to working against the dip, then the face should be developed parallel to the bedding planes for safety reasons.

Sedimentary sequences in which thin layers of shale or clay are present may have to be treated with caution, especially if the bedding planes are dipping at a critical angle. Weathering may reduce such material to an unstable state within a short period of time and this, in turn, can lead to slope failure.

A slope of 1:1.5 is generally used when excavating dry sand; this more or less corresponds to the angle of repose of 30º to 40º. This means that a cutting in a noncohesive soil will be stable, irrespective of its height, as long as the slope is equal to the lower limit of the angle of internal friction, and provided that the slope is suitably drained. Slope failure in frictional soils is a surface phenomenon that is caused by the particles rolling over each other down the slope. As far as sands are concerned their packing density is important. For example, densely packed sands that are very slightly cemented may have excavated faces with high angles that are stable. The moisture content is of paramount importance in loosely packed sands, for if these are saturated they are likely to flow on excavation.

The most frequently used gradients in many clays vary between 30º and 45º. In some clay, however, in order to achieve stability the slope angle may have to be less than 20º. The stability of slopes in clay depends not only on its strength and the angle of the slope, but also on the depth to which the excavation is taken, and on the depth of any firm stratum—if one exists—not far below the base level of the excavation. Slope failure in uniform clay takes place along a near circular surface of slippage. In stiff fissured clays, the fissures appreciably reduce the strength below that of intact samples. Thus, reliable estimation of slope stability in stiff fissured clays is difficult. Generally, steep slopes can be excavated in such clays initially, but their excavation means that fissures open because of the relief of residual stress, and there is a change from negative to positive pore water pressures along the fissures, the former tending to hold the fissures together. This change can occur within a matter of days or hours. Not only does this weaken the clay, it also permits a more significant ingress of water, which means that the clay is softened. Irregular shaped blocks may begin to fall from the face, and slippage may occur along well-defined fissure surfaces, which are by no means circular. If there are no risks to property above the crests of slopes in stiff-fissured clays, then they can be excavated at about 35º. Although this will not prevent slips, those that occur are likely to be small.

The stability of the floor of large excavations may be influenced by ground heave. The amount of heave and the rate at which it occurs depend on the degree of reduction in vertical stress during construction operations, on the type and succession of underlying strata, and on the surface and groundwater conditions. It is generally greater in the center of a level excavation in relatively homogeneous ground, as for example clays and shales. Long-term swelling involves absorption of water from the ground surface, or is due to water migrating from below. Where the excavation is in overconsolidated clays or shales, swelling and softening are quite rapid. In the case of clays with a low degree of saturation, swelling and softening take place very rapidly if surface water gains access to the excavation area.

It is rarely economical to design a rock slope so that no subsequent rock falls occur; indeed many roads in rough terrain could not be constructed with the finance available without accepting some degree of risk. Therefore, except where absolute security is essential, slopes should be designed to allow small falls of rock under controlled conditions.

Rock traps in the form of a ditch and/or barrier can be installed at the foot of a slope. Benches may also act as traps to retain rock fall, especially if a barrier is placed at their edge. Wire mesh fixed to the face provides yet another method for controlling rock fall.

Excavation involving the removal of material from the head of an unstable slope, flattening of the slope, benching of the slope, or complete removal of the unstable material helps stabilize a slope. If some form of reinforcement is required to provide support for a rock slope, then it is advisable to install it as quickly as possible after excavation. Dentition refers to masonry or concrete infill placed in fissures or cavities in a rock slope. Thin-to-medium bedded rocks dipping parallel to the slope can be held in place by steel dowels grouted into drilled holes, which are up to 2 m in length. Rock bolts may be up to 8 m in length, with a tensile working load of up to 100 kN. They are put in tension so that the compression induced in the rock mass improves shearing resistance on potential failure plans. Bearing plates, light steel sections, or steel mesh may be used between bolts to support the rock face. Rock anchors are used for major stabilization works, especially in conjunction with retaining structures. They may exceed 30 m in length. Gunite or shotcrete is frequently used to preserve the integrity of a rock face by sealing the surface and inhibiting the action of weathering. These are pneumatically applied mortar or concrete respectively. Coatings may be reinforced with wire mesh or used in combination with rock bolts. It is generally considered that such surface treatment offers negligible support to the overall slope structure. Heavily fractured rocks may be grouted in order to stabilize them.

Restraining structures control sliding by increasing the resistance to movement. They include retaining walls, cribs, gabions, and buttresses. The ability of a retaining wall to resist shearing action, overturning and sliding on or below its base, must be considered before a retaining wall is used for slope control. They are often used where there is a lack of space for the full development of a slope, such as along many roads and railways. As retaining walls are subjected to unfavorable loading, a large wall width is necessary to increase slope stability. Reinforced earth can be used for retaining earth slopes. Such a structure is flexible and so can accommodate some settlement. Thus, reinforced earth can be used on poor ground. Reinforced earth walls are constructed by erecting a thin front skin at the face of the wall at the same time the earth is placed. Strips of steel are fixed to the facing skin at regular intervals. Cribs may be constructed of precast reinforced concrete or steel units, set up in cells that are filled with gravel or stone. Gabions consist of strong wire mesh surrounding placed stones. Concrete buttresses have occasionally been used to support large blocks of rock, usually where they overhang.

Drainage is the most generally applicable method for improving the stability of slopes or for the corrective treatment of slides, regardless of type, since it reduces the effectiveness of one of the principal causes of instability, namely excess pore water pressure. The most likely zone of failure must be determined so that the extent of the slope mass that requires drainage treatment can be defined. Surface run-off should not be allowed to flow unrestrained over a slope.

This is usually prevented by the installation of a drainage ditch at the top of an excavated slope to collect drainage from above. The ditch, especially in soils, should be lined to prevent erosion, otherwise it will act as a tension crack. It may be filled with cobble aggregate. Herringbone ditch drainage is normally employed to convey water from the surfaces of the slopes. These drainage ditches lead into an interceptor drain at the foot of the slope. Infiltration can be lowered by sealing the cracks in a slope by regrading or filling with cement, bitumen, or clay.

A surface covering such as geotextile has a similar purpose and function. Successful use of subsurface drainage depends on tapping the source of water; the presence of permeable material that aids free drainage; the location of the drain on relatively unyielding material to ensure continuous operation (flexible, perforated PVC drains are now frequently used); and the installation of a filter to minimize silting in the drainage channel. Drainage galleries are costly to construct, and in slipping areas may experience caving. They should be backfilled with stone to ensure their drainage capacity if they are partially deformed by subsequent movements.

Galleries are indispensable in the case of large slipped masses where drainage has to be carried out over lengths of 200 m or more. Drillholes may be made about the perimeter of a gallery to enhance drainage.

Groundwater frequently provides one of the most difficult problems during excavation, and its removal can prove costly. Not only does water make working conditions difficult, but piping, uplift pressures, and flow of water into an excavation can lead to erosion and failure of the sides. Collapsed material has to be removed and the damage made good. Subsurface water is normally under pressure, which increases with increasing depth below the water table. Under high pressure gradients, weakly cemented rock can disintegrate. High piezometric pressures may cause the floor of an excavation to heave, or worse still, cause a blowout. Hence, data relating to the groundwater conditions should be obtained prior to the commencement of operations.

Some of the worst conditions are met in excavations that have to be taken below the water table. In such cases the water level must be lowered by some method of dewatering. The method adopted depends on the permeability of the ground and its variation within the stratal sequence, the depth of base level below the water table, and the piezometric conditions in underlying horizons. Pumping from sumps within an excavation, bored wells, or wellpoints are the dewatering methods most frequently used. Impermeable barriers such as steel sheet piles, secant piles, diaphragm walls, frozen walls, and grouted walls can be used to keep water out of excavations. Ideally, these structures should be keyed into an impermeable horizon beneath the excavation.

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* More advanced text

Biographical Sketch

Fred Bell graduated with a B.Sc. and M.Sc. from the University of Durham, UK, and received his Ph.D. from the University of Sheffield, UK, in 1974. More recently, he received a D.Sc. from the University of Natal, Durban, South Africa. He is a fellow of the Royal Society of South Africa, a fellow of the Institution of Civil Engineers and the Institution of Mining and Metallurgy, and a fellow of the Geological Society, being both a chartered engineer and a chartered geologist. He is the recipient of several awards.

Professor Bell is currently a Visiting Research Associate at the British Geological Survey. Previously, he was Professor and Head of the Department of Geology and Applied Geology at the University of Natal, during which time he was also a Distinguished Visiting Professor, Department of Geological Engineering, University of Missouri-Rolla, USA.

Professor Bell's research subjects have included ground stability; subsidence; ground treatment; engineering behavior of soils (clays, expansive clays, saprolites, tills, laminated clays, dispersive and collapsible soils, sands); engineering behavior of rocks (sandstones, carbonates, evaporites, shales, basalts, dolerites, granites); cement, lime, and PFA stabilization of clay soils; acid mine drainage; mining impacts; landfills; derelict and contaminated ground; rock durability in relation to tunneling; slope stability; aggregates; building stone; and geohazards.

In his professional activity Professor Bell has been involved in a variety of work in the UK, southern Africa, and Malaysia concerning site investigations; foundations; settlement problems on clays, fills, and sands; old mine workings and subsidence; longwall mining and subsidence; ground treatment; groundwater resource assessment; slope stability; use of mudrocks for brickmaking; assessment of various rock types for aggregates; contaminated ground; acid mine drainage; landfills; and dam sites.

Professor Bell is the author/editor of 17 books, several reprinted, one in its fourth edition, one translated into French, two into Italian, and yet another into Malay, as well as an Indian edition (in English). He is also the author of over 200 papers on geotechnical subjects. He has served on the editorial boards of five international journals and has been a series editor for three publishers.