nite orientation of discontinuities, or is composed of weathered material, will fail in the same way as a soil slope.

10.6.1 Failure on a planar surface

In rock, this failure mode corresponds to Section 10.4.1 for soil slopes, and again, the plane may be intersected by a fissure, which should be taken as filled with water (see Figure 10-5). Analysis is by statics, and worked examples for various slope profiles are found in Hoek and Bray (1981). Note that triangular distributions of groundwater pressure are assumed to be acting in the fissure and the surface of rupture.

10.6.2 Wedge failure

This is a three-dimensional failure mode, with failure on two intersecting weak planes as shown in Figure 10-6. The direction of movement is along the line of intersection, which must dip toward the slope face if failure is to occur. Analysis is again by statics, with worked examples presented in Hoek and Bray (1981).

10.6.3 Toppling failure

This failure mode consists primarily of rotation of rock blocks, with any shearing as a secondary effect. It occurs when joints or discontinuities dip steeply into the slope face (see Figure 10-7).

10.7 Choosing an Analysis Method

Several papers have been written comparing the various analysis methods for failures in *soil*, with the aim of determining which is the most reliable

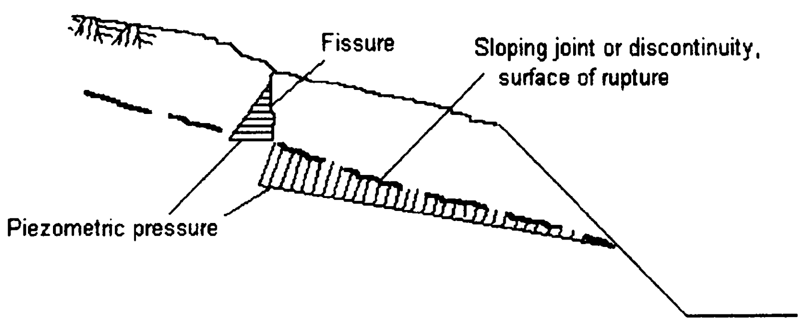

FIGURE 10-5 Failure on a planar surface—rock.

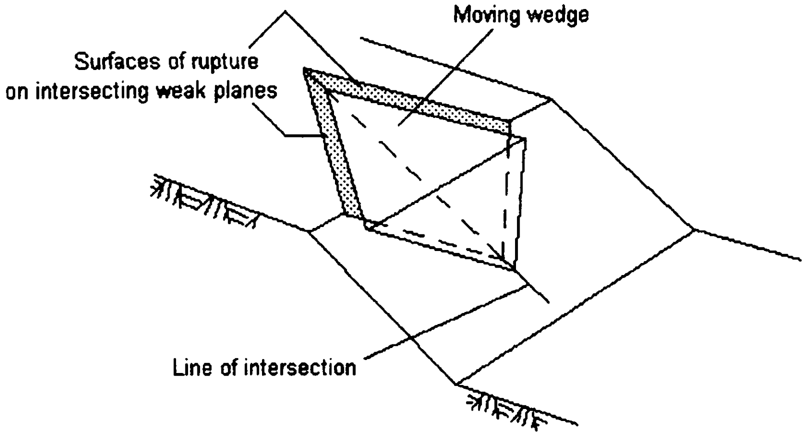

FIGURE 10-6 Wedge failure.

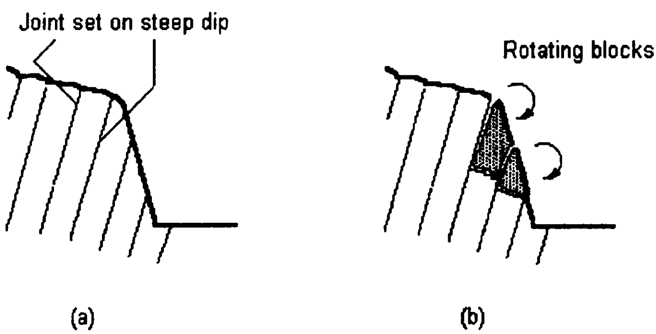

FIGURE 10-7 Toppling failure. (a) Initial condition. (b) Rotational failure.

method. (See for example Fredlund 1984.) The intrinsic flaw in all limit equilibrium methods is described in Section 10.1. In addition, the following points provide guidance:

- The method should always be appropriate to the problem. It is unwise, for example, to apply a circular failure method, such as one of Bishop's, when the surface of rupture clearly has a composite shape.
- Some relationship should exist between the accuracy of the method used and the complexity and/or importance of the problem. A job of low priority would only call for Bishop's simplified or Janbu's simplified, or an equivalent. A job where lives and/or property are threatened would require one of the rigorous methods.

- Readers may already be familiar with certain methods, prefer certain methods, or have access to software to apply them.

Unless readers are using finite element methods, there is no choice when the analysis of ***rock*** slopes is required. Given the shape of the surface of rupture, solutions are obtained from statics computations.

10.8 Mode of Failure of an Intact Slope

Consideration so far has applied to slopes that have failed and their surface of rupture can be located. For an intact slope (see Sections 6.1(1), 6.1(2)), a prediction must be made regarding how the slope may fail and whether or not it actually will fail. In a ***soil*** slope, this is done by looking for zones of soft material in the geotechnical model and computing for various surfaces of rupture through them. Computer programs often include a search facility, which can give a rapid indication of the worst failure mode. Alternatively, a finite element computation will identify the most likely shearing zone directly as part of the computing process (see Griffiths and Lane 1999).

The influence of the orientation of definite joints and discontinuities on the failure mode of a slope of sound ***rock*** is described in Section 10.6. Information gathered from the rock joint survey (see Section 6.5) may be used to predict one or more possible modes of failure. For a detailed treatment of the procedure, readers are referred to John (1968) and Hoek and Bray (1981), but a brief description of the principles is given here. Two separate geometrical plots are involved:

1. Dip and dip direction information on rock joints, gathered as part of the terrain evaluation, is plotted on a ***polar equal-area stereonet***. The plotting system used represents the two parameters of each surveyed joint as a single point on the net. Ideally, the points should appear in three clusters—one cluster for each joint set—but some scatter is inevitable. Inspection may reveal predominant groupings, but otherwise, they may be identified by statistical computer methods.
2. Planes representing selected joint set orientations are then plotted as great circles on an ***equatorial equal-area stereonet***, together with a great circle corresponding to the plane of the slope face. Possible failure in one of the three modes described in Section 10.6 may then be predicted using the methods of interpretation described in John (1968) and Hoek and Bray (1981).

The references also show how plots on the equatorial net may be used to check whether failure will actually occur, but any groundwater pressure complicates this. Knowing a possible failure mode, then, readers are advised to use statics methods to determine the corresponding FS.

10.9 Seismic Effects

In a location subject to earthquakes, seismic effects are most simply dealt with, as part of the stability analysis computation, by applying additional forces to the moving material in the horizontal direction through the center of gravity of the block or of each slice (see Figure 10-8). Values of k_H appropriate to the location should be taken from local design codes.

10.10 Back-analysis of a Failed Slope

If it is accepted that FS = 1 at failure, a failed slope may in theory be analyzed to evaluate the strength parameters of the sheared material. Assuming the location of the surface of rupture is known, the main unknown quantities are the cohesion, the friction angle, and the piezometric levels at the time of failure. If movement previous to failure has been significant, then cohesion may be taken as zero, but piezometric levels must be estimated, unless the slope was being monitored before failure. This leaves only the friction angle to be determined. In the case of a failed slope, a back-analysis is advisable, even if only approximate piezometric levels are known. Attention may then be drawn to any gross disagreement with laboratory test results. Readers are referred to Sauer and Fredlund (1988) for a discussion of back-analysis procedure.

10.11 Additional Comments on Stability Analysis

10.11.1 Probabilistic methods

Recently, some interest has been shown in applying statistical methods to assess safety in terms of probability of failure (see Chowdhury 1984). The

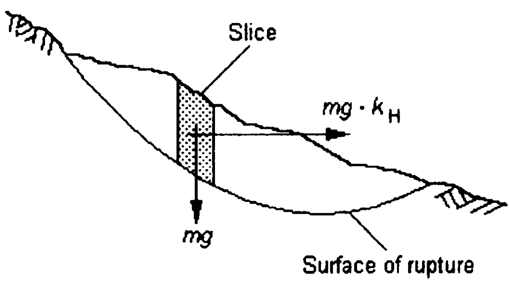

FIGURE 10-8 Allowance for seismic effects.

main difficulty with this concept on many projects is that the number of test results obtained is too small for reliable statistical treatment. Another related approach has been to use partial safety coefficients, applying different coefficient values to loads and strengths, depending on the confidence with which they are known (see Janbu 1996). This method is already common in structural work. Applying these methods to stability is logical, but geotechnical engineers have become familiar over many years with the concept of a single FS value, and its simplicity will probably ensure that its use persists for years to come.

10.11.2 Sensitivity assessment

Given the intrinsic flaw in any limit equilibrium method, described in Section 10.1, any calculated FS should be thought of only as an approximation. These methods are quite reliable, however, for testing the sensitivity of the FS to variations in parameters. In drainage work, pore pressure is the parameter of most interest. A drainage solution that can cause a substantial increase in the FS of an undrained slope—such as 50 percent—is worth considering, while an increase of only 5 percent would indicate that drainage should be used only as an auxiliary control measure, or even omitted completely. Sensitivity analyses are also useful for cost comparisons. For example, the gain in FS and the cost associated with placing horizontal drains may be compared with similar figures for prestressed ground anchors.

10.11.3 Creep deformation

The analysis methods cited in Sections 10.4 and 10.6 follow the conventional practice of using limit equilibrium theory, in which failure is taken as being ***rigid-plastic***: the material is assumed to remain intact and undeformed up to its maximum shearing strength. This strength is the one appropriate to site conditions, as indicated in Table 10-1 or Section 10.5. The theory does not consider plastic deformation, either before or after failure. However, readers should be aware of plastic creep movements that may occur in the long term under stresses that are less than those that can cause the abrupt failure predicted by limit equilibrium computation. These movements were described briefly in Section 1.7, and may be examined by finite element analysis (see for example Desai et al 1995).

11

Drain Construction Materials

Reference is made in previous chapters to the various materials and components used for building subsurface drains. These materials and components are described here in more detail.

11.1 Natural Aggregates

Natural aggregates are derived either from crushed quarried rock or from deposits of rock material, and most civil engineers first encountered them as a component of concrete. Many of the properties looked for in concrete aggregates are also required in aggregates used in drainage work. Particle material should be hard and able to withstand secondary breakage into smaller particles during handling. From this it follows that the rock material should be fresh, i.e., not significantly weathered. The material should also be stable in water. Aggregates with rounded particles are preferred over crushed rock in concrete work because they produce a more workable mix. In drainage, rounded and sharp particles are equally acceptable, although rounded particles have better hydraulic properties (see Section 2.2.3).

The most important property of an aggregate, whatever its application, is its grading. Most national standards list a large number of sieve sizes for concrete aggregates; those commonly used in American, British, and Australian laboratory practice are shown in Table 11-1. Coarse aggregate for concrete is arbitrarily classified as all material retained on a 5 mm sieve, or the sieve nearest to that size. Fine aggregate, i.e., sand, is similarly material passing about 5 mm, but retained on 150 µm. In soil work, the lower size limit

TABLE 11-1 Sieve sizes most commonly used for concrete aggregates.

Classification	*American*	*British*	*Australian*
Coarse aggregate	37.5 mm (1-1/2 in.)	37.5 mm	37.5 mm
			26.5 mm
	19.0 mm (3/4 in.)	20.0 mm	19.0 mm
			13.2 mm
	9.5 mm (3/8 in.)	10.0 mm	9.5 mm
			6.7 mm
Fine aggregate (sand)	4.75 mm (#4)	5.0 mm	4.75 mm
	2.36 mm (#8)	2.36 mm	2.36 mm
	1.18 mm (#16)	1.18 mm	1.18 mm
	600 µm (#30)	600 µm	600 µm
	300 µm (#50)	300 µm	300 µm
	150 µm (#100)	150 µm	150 µm
			75 µm

for sand is 75 µm. The preference for ***well-graded aggregate*** for concrete work, and for ***open-graded*** or ***single-size aggregate*** for subsurface drainage, is discussed in Section 2.2.1.

11.2 Artificial Aggregates

Some industrial waste products and by-products are suitable for use in drains as substitutes for natural aggregates. Typical materials are recycled crushed concrete and slag produced in the manufacture of iron. To be acceptable in drainage work, any such material must comply with the following requirements:

- Its grading must be within the required limits.
- It must be relatively hard and able to resist significant secondary breakage.
- It must be clean, with minimal fine material adhering to it.
- It must not deteriorate in the presence of water.
- It must not produce a leachate that is environmentally unacceptable.
- It must not produce a leachate that later forms a precipitate that may clog the drainage system.

Regarding the last item, if slag or recycled crushed concrete are used as a drainage aggregate, they may contain free uncombined lime (CaO), which causes precipitation of calcium carbonate ($CaCO_3$), particularly in the slots in drain pipes and in the pipes themselves. The result is loss of drain efficiency, or even complete failure. Hurd (1988) described an investigation of a number of drains that were associated with various types of slag pavement subbase material. The extent of precipitation was directly related to the proportion of free lime originally present in the slag. Blast furnace slags, which came from the manufacture of crude iron, were generally found to contain no free lime, and so produced no precipitate. However, the slags derived from the process of converting crude iron to steel contained significant quantities of lime, and so produced enough precipitate to impair drain performance.

A component that produces an undesirable leachate from an artificial aggregate in some cases may be removed, at least in part, by long-term stockpiling. Unfortunately, the time required to reduce the component to an acceptable level is in most cases not known in advance with any certainty. Local climatic conditions should also be considered. Further, the effectiveness of the treatment varies with the location of the aggregate within the stockpile. Gupta et al (1994) reported persistent calcium carbonate precipitation from steel slags, even after stockpiling. Therefore, these slags should be avoided. An aggregate that has undergone long-term stockpiling should also be checked for soundness shortly before it is used in case it has deterioration due to weathering.

11.3 Synthetic Fabrics

The principles of filtration/separation are described in Chapter 4. Most subsurface drainage systems require a fine filter material of some kind, and sand has been used for this in the past. Recently, cloths made from synthetic materials have been used to replace the sand layer, which has totally revolutionized drainage technology. Techniques that would have previously been regarded as impractical or too expensive are now routine. These new fabrics are easy to transport and place, have predictable, factory-controlled properties, and are able to withstand degradation when placed in the ground. One vital feature of any filter is the size of the openings, which may be taken as fairly constant in the case of fabrics.

At the International Conference on the Use of Fabrics in Geotechnics, held in Paris in 1977, Giroud (1977) suggested that the new materials be thenceforth called "***geotextiles***." Not only was the suggestion adopted, but the prefix "***geo-***" was used in the terminology applied to the many synthetic materials that were subsequently developed for geotechnical use, such as geocomposites, geogrids, and geonets. The present convention is to restrict the term "geotextile" to synthetic fabrics that have the general appearance of cloth and that have no attached components such as reinforcing meshes.

11.3.1 Polymers

Polyolefins (polyethylene and polypropylene) and polyesters are the synthetic materials that are commonly available as spun or extruded filaments and are suitable for geotechnical work.

Polyethylene and ***polypropylene*** have similar chemical structures, and consequently similar physical properties. Polypropylene may be regarded as an upgraded version of polyethylene. Both are cheap, chemically inert, and do not absorb water. Their strain at ultimate tensile strength and creep factor are relatively large. They burn easily, so precautions against fire should be taken during storage and placement. Since their density is less than unity, they will float on water, which may cause difficulties when placing fabrics made from these polymers on a wet site. When burning, polyolefins give off an odor of burning candle wax. This, and their ability to float on water, may be used as a means of identification.

Compared with the polyolefins, ***polyester*** has a high strength and elastic modulus and much smaller creep factor. Polyester shows little variation in physical properties with temperatures rising up to about 100 °C. It absorbs only a small amount of water, and does not burn easily. Its density is greater than unity. When burning, polyester gives off an odor like coal gas. This, and the fact that it sinks in water, may be used as a means of identification.

Polyester and the polyolefins are resistant to attack by a wide range of agents, but of those normally encountered, one that should always be considered seriously is the ultra violet (UV) component of sunlight. The polyolefins are particularly vulnerable to UV degradation. Most manufacturers attempt to deal with this problem in various ways, the most usual of which is to include a dark pigment in the plastic. These preventive measures are successful to varying degrees, but the prudent user should assume that all synthetic fabrics are subject to UV degradation if they are left exposed to sunlight for any significant amount of time.

11.3.2 Types of thread

The most common spun threads are produced in the form of single filaments, or ***monofilaments***, of circular cross section or approximately so. The threads are composed of only one polymer, although one of the heat-bonded fabrics, which are mentioned in Section 11.3.3, uses filaments with a polypropylene core and polyethylene cover. The intention is to maintain the strength properties of the core unaffected during the heat bonding process.

Before being processed into fabric, monofilaments may be combined to form threads of ***multiple parallel filaments*** or ***multiple twisted filaments***. As an alternative to spinning or extrusion, threads may also be formed by slitting sheet plastic to obtain filaments of flat cross section known as ***tapes*** or *slit film*. These variations on monofilaments are used in some woven fabrics (see Section 11.3.3).

11.3.3 Types of geotextiles

Fabrics are often anisotropic with regard to some of their properties. The ***machine direction*** is the direction in which the fabric has been manufactured; the ***cross machine direction*** is at right angles to the direction of manufacture.

To obtain a finished fabric requires that the threads be linked together in some way. Fabrics are classified by the process by which this is done, namely wovens, knitteds, and non-wovens.

Wovens are produced by conventional weaving methods, i.e., the interlacing of threads in the machine and cross machine directions. Plain weave, or one-to-one interlacing, is the most common. The textile industry has variants of this, such as twill, satin, and basket weaves, but it is unusual to find any of these in geotextiles. The tensile strength of woven fabrics is fairly independent of direction of stress, but it is slightly greater at 45° to the machine and cross-machine directions. Elongation, on the other hand, is low in the two main directions, but substantially higher at 45° to them. Opening sizes are uniform, at least in the undistorted state. However, distortion in a soil structure causes some openings to close up, and others to become larger, thus increasing the range of opening sizes. This is particularly true when contact with large sharp aggregate particles is involved. A further disadvantage of woven fabrics is that once a tear begins, it propagates more easily than in non-woven fabrics of comparable mass per unit area.

Knitted geotextiles are not usually available in sheet rolls, but are produced in tubular form, typically more than 100 m long. They are used as a sleeve over corrugated perforated plastic pipe to act as a filter/separator when the pipe is placed in a sand that would otherwise pass through the pipe slots (see Section 11.5.2.1 and Figure 11-4). In the machine direction, a knitted fabric is relatively strong and has low elongation, but is quite extensible in the cross machine direction. With an ordinary knit stitch, the fabric ladders if the thread is severed in only one place, leading possibly to the total unravelling of the fabric. Knit stitches are available, however, that can resist laddering.

Non-wovens. The most obvious feature of non-woven fabrics is the random orientation of the filaments. A fabric is formed by spreading filaments onto a conveyor belt. They are then linked by one of the bonding processes. Filaments may be in the form of either ***continuous filaments*** or ***staple fibers***, which are continuous filaments cut into lengths of 50 to 200 mm long. When continuous filaments are used, filaments are spun, spread on a conveyor belt, and bonded into a complete fabric in one continuous process