CHAPTER 3 – ROCK EXCAVATION METHODS

This section reviews standard excavation practices used to construct and modify rock slopes and provides current design and construction guidelines for their use in context sensitive areas. Several of these practices have been used for many years, while others are new techniques or recent modifications of established methods. The most common are blasting (which includes drilling the holes to be filled with explosives), ripping, and breaking. Table 1 provides a brief description of these procedures, along with the advantages and limitations of each. Each procedure is discussed in detail below.

BLASTING

Blasting—the controlled use of explosives to excavate rock—has been part of construction engineering for hundreds of years.

In any blasting situation, the geologic structure of the rock mass will be the most important consideration. Other considerations include the degree of scarring that would be acceptable (some areas can tolerate more blasting scars than others), cost, and safety (blasting cannot be performed in close proximity to populated areas).

Effect of Geologic Structure on Blasting Procedure

The first consideration when designing a blasting operation should be the local geologic conditions. Rock competency and fracture patterns can have a significant impact on the success of a blasting operation.

Discontinuity Sets

When discussing blasting, the single most important geologic factor is fracture: the spacing and orientation of any breaks, or *discontinuity sets,* in the rock. In particular, the orientation of the discontinuity sets with respect to the cut slope angle will influence any slope failures that may occur along the slope face. The modes of failure can be grouped into four primary mechanisms, shown left to right in Figure 6.

- planar failure (a),
- wedge failure (b),
- circular failure (c), and
- toppling failure (d).

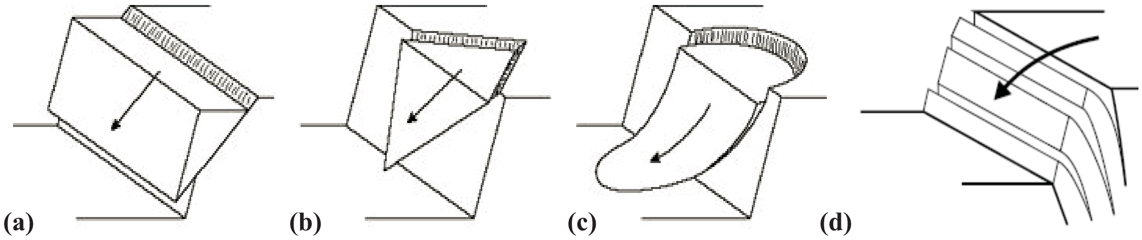

Figure 6. Illustration. The four primary mechanisms of slope failure.

Table 1. Description, advantages, and limitations of common excavation practices.

PROCEDURE	DESCRIPTION	ADVANTAGES	LIMITATIONS
Presplit Blasting	Presplit holes are blasted before production blasts. Procedure uses small diameter holes at close spacing and lightly loaded with distributed charges.	Protects the final cut by producing a fracture plane along the final slope face that fractures from production blasts cannot pass. Can produce steeper cuts with less maintenance issues. Performs well in hard competent rock.	The small diameter borings limit the blasting depth to 15 m (50 ft). Borehole traces are present for entire length of boring. Does not perform well in highly fractured, weak rock.
Smooth Blasting	Smooth blast holes are blasted after production blasts. Procedure uses small diameter holes at close spacing and lightly loaded with distributed charges.	Produces a cosmetically appealing, stable perimeter. Can be done on slopes years after initial construction. Drill hole traces are less apparent than presplitting. Performs best is hard, competent rock.	The small boring diameter limits blasting depth to 15 m (50 ft). Borehole traces are present for much of the boring length. Does not protect the slope from damage caused by production blasting. Does not perform well in highly fractured, weak rock.
Cushion Blasting	Cushion blasting is done after production blasts. Larger drill holes are used with small diameter, lightly loaded distributed loads. Space around the explosive is filled with crushed rock to cushion the explosive force.	Reduces the amount of radial fracturing around the borehole and also reduces borehole traces. The large diameter holes allow blasting depths up to 30 m (100 ft). Produces a ragged final slope face. Performs well in all rock types.	Radial fractures are more abundant than presplit and smooth blasting. Slope face is more prone to raveling. A catchment area is recommended at slope base. More demanding on the driller. Borehole traces still apparent in hard, competent rock.
Step Drilling	Larger diameter drill holes, drilled vertically and used as production blasting (although spaced closer and loaded lighter to minimize radial fractures). Slope face is formed along base of blast holes.	If properly designed the final slope face shows minimal signs of blasting. Can be used when sloped controlled blasting cannot. Best used in moderately to highly fractured rock.	Can produce extensive damage to slope or inadequate base fracturing if not designed properly. Should only be used with experienced driller and blasting engineer. Only applicable for slopes between 0.7:1 and 1:1 (H:V). Does not perform well in hard competent rock.
Horizontal Drilling	Larger diameter, closely spaced, lightly loaded horizontal borings are used for production style blasting. Used in massive rock to eliminate drill holes or in areas of poor access.	Eliminates bore hole traces when drilled perpendicular to the slope face. Good in massive rock where traces are not acceptable.	Demanding on the driller and explosives engineer. Can produce extensive radial fractures or inadequate base fracturing if not loaded properly. Requires complicated loading and timing procedures, and special stemming procedures.
Ripping	Uses a tractor with an attached tooth or teeth that is lowered into the rock and dragged to break up material for excavation.	Much cheaper and safer than blasting. Can be done in close proximity to development without disturbance. Is effective on a variety of angled cuts and an excavator can be used after ripping to slope sculpting.	The tooth of the ripper can leave scars on the rock surface. The tractor cannot be used on steep slopes because of risk of overturning. Ripping is limited to relatively low density rocks.

In order to avoid long-term slope instability and increased maintenance costs, designers should measure and evaluate prominent discontinuities on the rock face using a scan line survey and computer-based kinematic analysis, also known as a equal area net (or stereonet) analysis. Regardless of the number of joints in a slope, one set will usually be the dominant (or weakest) and therefore will dictate the rock slope design. Generally speaking, the direction of this dominant joint will have the greatest influence on blasting results and potential failure modes. For example, if this joint set is parallel to the final slope face as illustrated in Figure 7, the borehole can prematurely link to the joint, which will create coarse or blocky burden fragmentation and severe end break (breakage at the end of the row of blastholes). In this case, increasing the borehole spacing will reduce fragmentation size (if the end result of the blast will be rip-rap, the explosive load can also be reduced).

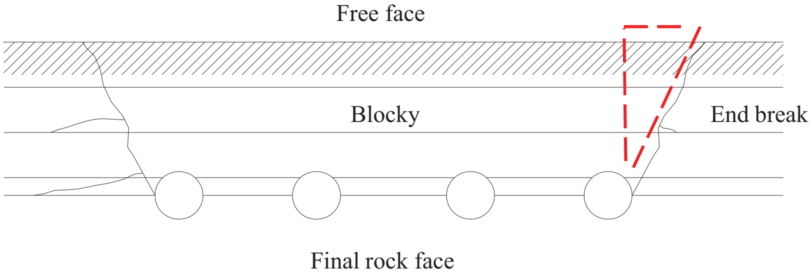

Figure 7. Illustration. Excessive end break caused by blasting parallel to jointing (modified from Konya and Walter 2003).

However, there can be problems blasting perpendicular to the final slope face, as well illustrated in Figure 8. While end break is not typically a problem in this case, backbreak (or overbreak)—fractures that extend from the blastholes back into the final slope face—can be significant (backbreak can cause slope instability and possible raveling of large blocks during excavation and thereafter). In addition, creating blastholes in an area with a significant number of joints can create blocky breakage. Reducing the spacing between blastholes can prevent this, but it might make backbreak worse. In this case, using smaller blastholes with a better distribution of powder may be the best solution (Konya and Walter 2003).

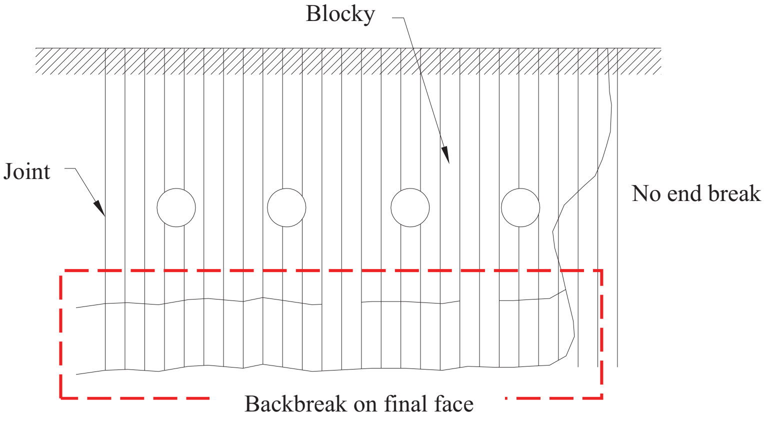

Figure 8. Illustration. Excessive backbreak caused by blasting perpendicular to jointing (modified from Konya and Walter 2003).

When blasting perpendicular to the final slope face, discontinuities occurring at sharp angles from the excavation plane tend to have the biggest effect. For example, discontinuities between 30° and 80° don't have much impact, but discontinuities from 20° to 25° can create some backbreak. Discontinuity angles less than 15° can allow the blast energy to travel into the discontinuity plane, which can cause it to form the final slope face as shown in Figure 9.

However, if these discontinuity planes are favorably orientated with respect to the road (orientations that parallel the road alignment or road bed), they can be used for the final face of the cut slope, resulting in a more natural-looking rock cut. The use of favorable joint orientation and/or bedding planes for controlling the blast is the most common and accepted method for developing rock slopes that fit within the geologic context of the surrounding area.

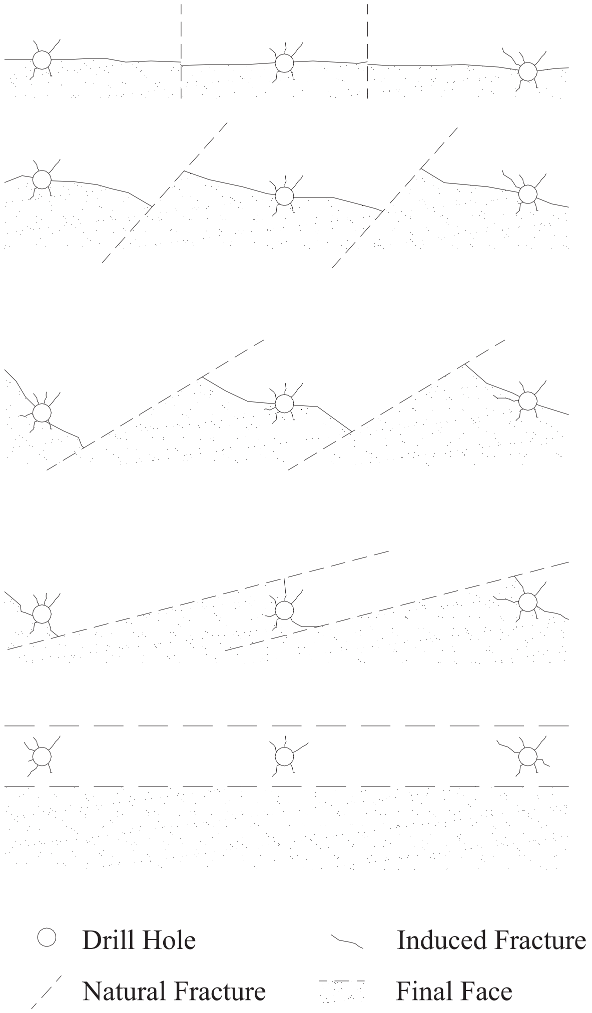

Figure 9. Illustration. The effect of joint orientation on the quality of the final wall face (modified from Matheson 1986).

Slope Dip

A slope's dip—its fall, illustrated as an imaginary line running down the steepest part of the slope—is another important factor to be considered in blasting. Blasting with the dip carries a greater risk of backbreak than blasting against the dip because the discontinuities (joints, bedding, etc.) channel the energy along the planes. However, this type of blasting allows engineers to use smaller explosive charges (or blast larger burdens) because the blasted rock moves more readily down the slope than it would if the blast were oriented against the dip. Blasting with the dip also creates a better-looking slope toe.

On the other hand, blasting against the dip typically creates less backbreak but can create more overhangs. It also can leave more material at the slope toe, resulting in a rough surface. Blasting against the dip also removes a smaller burden, meaning it will require more explosives.

Figure 10 illustrates the effect of dip on blasting. In this cut, blasting on the left side was performed against the dip, while blasting on the right side was done with the dip.

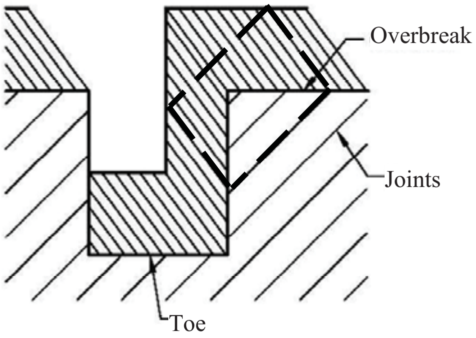

Figure 10. Illustration. Example of an excavation that blasts against the dip on the left side and with the dip on the right side (modified from Konya and Walter 2003).

Slope Strike

The strike of a slope—the direction the crest of the slope travels (i.e., the "across slope" direction), also plays a role in blasting design. Blasting parallel to strike in bedded rock can produce unpredictable results. The blast pattern intersects many different rock layers, and each layer will respond differently, as fragmented block size, toe conditions, and degree of backbreak all may vary slightly among them as shown in Figure 11.

Mud and Soft Seams

In addition to strike and dip, the presence of mud or soft seams in a slope also requires special consideration in the blast design. They can occur in any rock type, and are often unseen. Clay seams often respond like a liquid in that during initiation of a blast they provide an almost instantaneous attenuation of explosive energy. Therefore, it is essential to stem across soft seams to obtain good blasting results.

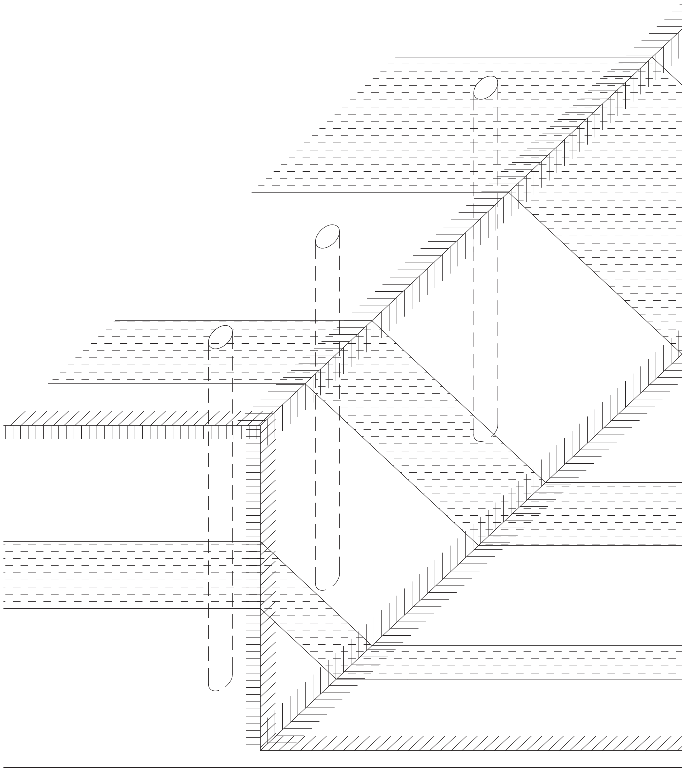

Figure 11. Illustration. Example of a blasting pattern that runs parallel to strike (modified from Konya and Walter 2003).

Blasting Methods

Blasting is used for rock excavation on both small- and large-scale projects. There are two general types: *production blasting* and *controlled blasting*.

Production Blasting

Production blasting uses large explosive charges, widely spaced, that are designed to fragment a large amount of *burden* (the rock that lies between the existing slope face and the blasthole). Production blasting is the most efficient way to remove large rock burdens, but it typically creates radial fractures around the blasthole and backbreak (fractures that extend into the final slope face), which reduce the strength of the remaining rock mass and increase its susceptibility to slope raveling and rockfall.

Controlled Blasting

Controlled blasting is used for removing material along the final slope face. In some cases, it's also used before production blasting to create an artificial fracture along the final cut slope, which will prevent the radial cracks caused by production blasting from penetrating back into the finished face.

Controlled blasting can also be used alone, without production blasting. Controlled blasting creates less backbreak than production blasting because it removes less burden and uses more tightly spaced drill holes with lighter charges.

There are several types of controlled blasting; they vary most importantly in the amount of burden they remove and the type of powder they use. The discussion below will focus on controlled blasting techniques that best minimize the visual impacts of the blasting process, thus meeting the objectives of CSS design. These techniques are *presplit blasting*, *smooth blasting*, and *cushion blasting*.

Presplit Blasting:

Presplit blasting, or presplitting, is used before production blasting to protect the final rock face from damage caused by the production blasting. Presplitting creates a fracture plane along the final slope face, which prevents the radial cracks created by production blasting from penetrating into the finished face; without presplitting, production blasting damage can extend up to 15 m (50 ft) into the final slope face. Presplitting also allows for steeper and more stable cuts than any other blasting procedure. In massively bedded, competent rock, a properly charged presplit blast will contain drill hole half cast (the hole trace is split in half, axially) for almost the entire length of the blast line and will have no backbreak because the energy from the blast will travel uniformly, thus creating a continuous fracture between holes.

However, presplitting creates abundant visible drill traces, which makes it unsuitable in some areas (such as national parks). In some cases, these half casts can be chipped away with a pneumatic hammer, but it’s very difficult to eliminate them without completely removing the outer layer of rock. In areas where such scars are not acceptable, presplit blasting will not be a suitable option. Figure 12 shows an example of a cut slope that used presplit basting methods which left visible half casts in the slope face.

Presplit blasting requires relatively small drill holes, between 5 to 10 cm (2 to 4 in) in diameter because its goal is to create discrete fractures, not massive breaking. However, because the small hole diameters allow the drill bit to deviate from the anticipated line more readily than larger drill diameters; the maximum depth of presplitting is usually about 15 m (50 ft). For this reason presplitting is used only for relatively small blasting operations.

Because of these limitations, presplitting is most often used on slopes steeper than 1H:1V (45°), which helps the drillers to maintain adequate hole alignment at depth. Presplitting performs best in competent, hard to extremely hard rock; it is the best method for minimizing backbreak, as the induced fracture plane prevents the shockwave from the main blast from being effectively propagated behind the final face of the rock mass. Presplitting is most difficult in highly fractured, weathered, and/or soft rock, where it requires the use of closely spaced drill holes and/or uncharged guide holes (see below).

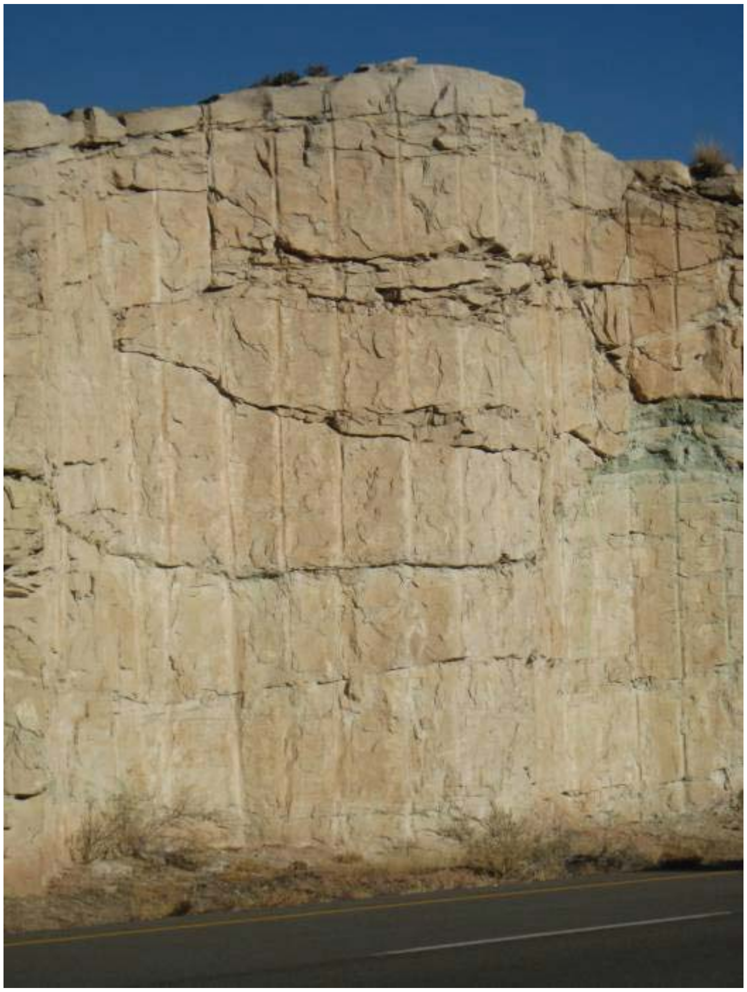

Figure 12. Photo. Example of a presplit slope in massive sandstone. Note the abundant drill hole traces (half casts).

Smooth Blasting:

Smooth blasting, also called contour blasting or perimeter blasting, can be used before production blasting as an alternative to presplitting. It's also used after production blasting, either as an entirely different event or as the last delay of the production blast. Smooth blasting uses drill holes with roughly the same diameter and depth as those used in presplitting, spaced slightly further apart and loaded with a slightly larger charge density. If the burden is adequately reduced, smooth blasting produces a more ragged slope face with minimal backbreak.

Smooth-blasted slopes may require more maintenance than presplit slopes due to increased radial fractures from the controlled blasting and overall fracturing from production blasting. Although smooth blasting creates abundant drill hole traces, they're generally less noticeable than the half casts left by presplitting. If drill hole traces are not acceptable, smooth blasting may be suitable only if the cut slope height is small and the drill traces can be easily removed with a pneumatic hammer or other device (see below).

Smooth blasting is best preformed in hard, competent rock, although it can be used in soft or highly fractured rock by increasing the spacing of the drill holes and/or adding uncharged guide holes to the pattern. Smooth slope blasting can be used on a variety of cut slope angles and is effective in developing contoured slopes with benches or other slope variations.

Cushion Blasting:

Cushion blasting, sometimes referred to as trim blasting, uses a row of lightly loaded "buffer" holes filled with crushed stone over the entire depth of the hole, which reduce the impact on the blasting holes and protect the surrounding rock mass from the shock caused by the blast, thus minimizing the stress and fractures in the finished slope face as shown in Figure 13.

Figure 13 also illustrates other blast hole drilling techniques (breaker, production, and looker drill holes), which can be used in conjunction with cushion blasting to fragment and mobilize the rock mass in the production zone. The application of these drilling methods is contingent on the structural characteristics of the rock, the existing and final slope geometry, and access via pioneering to the production zone.

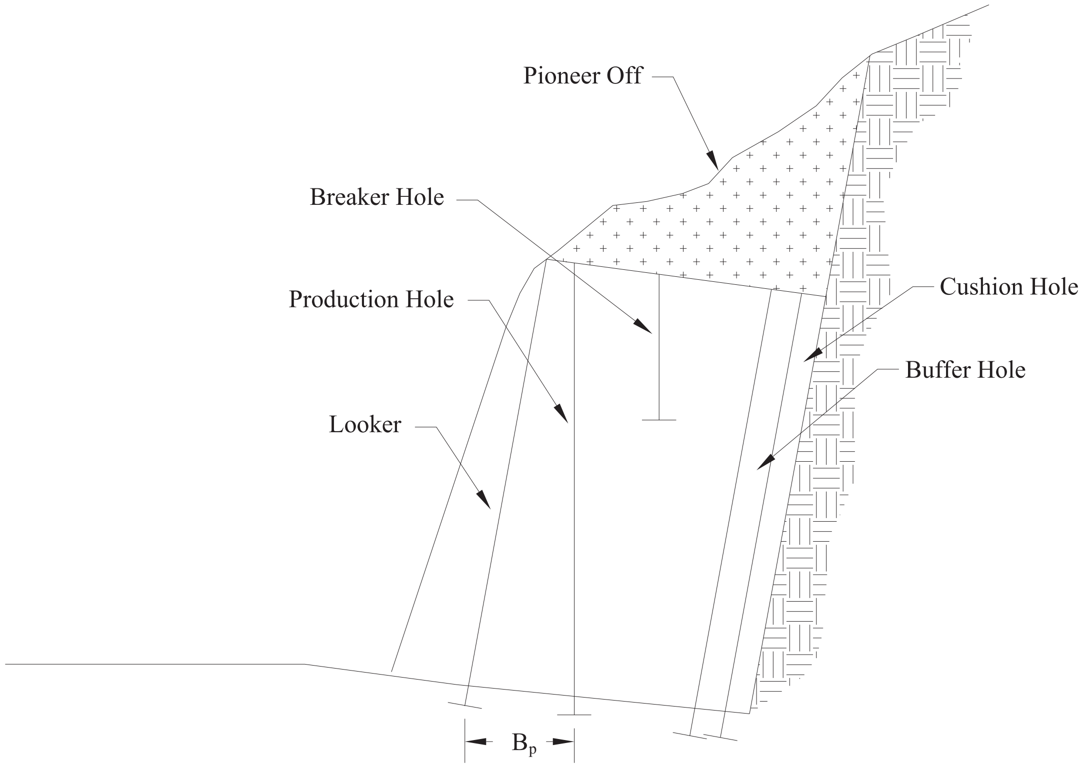

Figure 13. Illustration. Cross section of a cushion blasting design using buffer holes to control the burden on the cushion holes (modified from Cummings 2002).

The maximum diameter for cushion holes used in transportation is typically 75 mm (3 in). The drill steel used to advance these smaller holes tends to drift at depth, meaning the maximum depth is usually held to 12 m (40 ft). Cushion blasting creates some backbreak, which can make a slope more prone to raveling. Because cushion blasting can increase the danger of rockfall, the catchment area may need to be enlarged.

Figure 14 shows a recently constructed slope created using cushion blasting in fractured granitic rock. Note the wider ditch width in relation to the cut height.

Cushion blasting is more demanding than presplit or smooth blasting for the explosives engineer because hole spacing, burden, and charge density must be carefully chosen and continually reassessed in order to minimize backbreak. It also can be more time consuming because more drilling is required and charges take more time to load.

In poorly lithified, moderately to highly fractured and weathered formations, cushion blasting produces better results than smooth or presplit slope blasting. However, even cushion blasting may can leave drill hole traces in massive, homogeneous formations with few fractures.

Figure 14. Photo. Final configuration of a cushion-blasted slope in granitic rock.

Explosives

The type of explosive used in any project depends on the hardness and structural characteristics of the rock and the overall geometry of the cut (burden, depth, and width). There are numerous types of explosives, and for each type there are several different concentrations and mixtures. Properties to be considered when selecting an explosive include its sensitivity, density, strength, water resistance, fumes, price, and availability. Table 2 provides a general overview of explosives commonly used in the transportation industry.

Dynamite

Dynamite is the best known and most widely used explosive. It is classified according to its percentage by weight of nitroglycerin (percentages range from 15 to 60%). Strength does not increase linearly with proportion, however. For example, 60% dynamite is about 1.5 times stronger than 20% dynamite.

There are several variations in dynamite composition:

- Straight dynamite consists of nitroglycerine, sodium nitrate, and a combustible absorbent (such as wood pulp) wrapped in strong paper to make a cylindrical cartridge.

- Gelatin dynamite consists of a nitrocellulose-nitroglycerine gel. It is available in very high strengths (up to 90% nitroglycerin), making it useful for excavating extremely hard rock.

- Ammonia dynamite has similar composition to straight dynamite, but a portion of the nitroglycerine content is replaced with ammonium nitrate to create more stable and less costly dynamite. It has a strength of approximately 85% of straight dynamite.

Ammonium Nitrate and Fuel Oil (ANFO)

This combination of a nitrogen fertilizer and fuel oil has largely replaced dynamite in medium and large borehole blasting. The explosiveness of ANFO greatly increases with the concentration of fuel oil (the maximum is 6%). Mixing can be done on-site or in the factory, although premixed compounds present concerns regarding handling and storage (premixed ANFO has been known to spontaneously combust when kept in storage for long periods of time). Straight ammonium nitrate can be shipped and stored the same way as any other blasting agent. ANFO does not combust well in water, but it can be sealed in bags to prevent water seepage.

Slurry (Water Gel)

Also known as a dense blasting agent (DBS), slurry is a mixture of a sensitizer, an oxidizer, water, and a thickener. The sensitizer can be any number of reducing chemicals, but is usually TNT (trinitrotoluene). The oxidizer is ammonium nitrate. The thickener is guar gum or starch. High-density slurry can remove a greater burden than ANFO, which allows for the use of smaller diameter boreholes (or wider borehole spacing) to obtain the same explosive power and fragmentation. However, the higher price of the slurry may offset the cost savings of drilling fewer holes. Slurries are reasonably insensitive, but temperature and density have large effects

Table 2. Explosives commonly used in transportation projects.

TYPE OF EXPLOSIVE	DYNAMITE	AMMONIUM NITRATE AND FUEL OIL (ANFO)	SLURRY (WATER GEL)	EMULSION EXPLOSIVES
Most Common Application(S)	Most often used in smaller boreholes. Gelatin dynamites are useful for blasting extremely hard rock.	Medium and large borehole blasting and cushion blasting. The most common general-purpose explosive in use today.	Often used in place of dynamite because of safety and convenience.	Has begun to replace dynamite, particularly in wet or submerged conditions.
Composition	Straight dynamite contains nitroglycerine, sodium nitrate, and a combustible absorbent (e.g., wood pulp). Ammonia dynamites contain ammonium nitrate. Gelatin dynamites contain nitrocellulose to create the gelatinous consistency.	Ammonium nitrate (a nitrogen fertilizer) mixed with up to 6% fuel oil.	A sensitizer (typically TNT), an oxidizer (ammonium nitrate), water, and a thickener (such as guar gum or starch).	An oxidizer solution (typically ammonium nitrate) and oil.
Strength	Straight dynamite is the benchmark for explosive weight/strength comparisons. It is generally available in 15% to 60% concentrations of nitroglycerin (gelatin dynamite contains up to 90% nitroglycerin).	Similar strength to straight dynamite.	Stronger than ANFO, less strong than gelatin dynamite.	Similar in strength to slurry explosives.
Impact Sensitivity	Ammonia and gelatin dynamites are less volatile and sensitive to shock and friction than straight dynamite.	Premixed compounds can be sensitive. If not pre-mixed, they are quite stable and insensitive.	A lot less sensitive than dynamite but more sensitive than emulsion. More sensitive at higher temperatures.	Emulsions are the least sensitive type of explosives. Cartridges are fairly resistant to rupturing during normal handling.
Water Resistance	Straight dynamite has good water resistance. Gelatin dynamite is nearly waterproof. Ammonia dynamite has poor water resistance.	Poor water resistance	Good to excellent water resistance.	Excellent water resistance.
Fumes	Straight dynamite has some toxic fumes. Ammonia and gelatin dynamite fumes are less toxic.	ANFO produces less toxic fumes than dynamite but more than slurry or emulsion explosives.	Slurries and emulsions have a similar fume class.	Slurries and emulsions have a similar fume class.
Price/ Availability	Dynamite is easy to obtain and relatively inexpensive.	The least expensive and most available explosive.	Widely available. Less expensive than dynamite, more expensive than ANFO.	Similar in both cost and availability to slurries.

on this (i.e., slurries become less sensitive and less fluid as temperature decreases). Sensitivity can be increased by adding sensitizers to the composition. Slurries load about three times faster than conventional dynamite, making them more convenient and faster to use.

Emulsion Explosives

Emulsions are a water-in-oil type of explosive consisting of microdroplets of super-saturated oxidizer solution within an oil matrix. The oxidizer is usually ammonium nitrate. Packaged in a thin, tough plastic film, emulsion cartridges have a good degree of rigidity and resistance to rupturing during normal handling but maintain the ability to rupture and spread when tamped.

Drilling Methods

Blast holes are drilled at various orientations, from vertical through horizontal. To create vertical holes, which are used almost exclusively in production blasting, rock slope excavation uses two types of drilling: *downhole* and *step drilling*. *Horizontal drilling* is used for both production and controlled blasting because of limited drill rig access or geometry requirements. Angled drilling can be performed as determined by slope face angle requirements.

Downhole Drilling

Also known as vertical or production drilling, this technique is used in production blasting using a conventional rotary tri-cone blast hole rig or a rotary percussion rig if smaller blast holes are adequate.

Step Drilling

Step drilling is another type of vertical drilling that’s also used in production blasting, most often to produce relatively flat and benched slopes (usually shallower than 1:1 H:V). It’s similar to downhole drilling, but creates holes that gradually increase or decrease in depth to allow for a stepped slope "break" line shown earlier in Figure 14. (This method is technically not part of a controlled blasting operation because it relies on backbreak to form the slope face.) If done properly, step drilling can produce a slope face that shows minimal signs of blasting—just drill holes entering the slope face, which are noticeable only by someone looking directly at the face. On projects involving step drilling, drillers have been awarded a pay item for tightening the drill hole pattern and using lighter, distributed loading to avoid performing excessive blasting charges along the slope later.

Step drilling is limited to ideal geologic conditions, such as blocky volcanic rock, where breakage at the bottom of each blasthole is reasonably well controlled, but it can provide good results with minimal backbreak. It has proven popular with contractors who favor the vertical drilling setup.

In step drilling, the blast holes are loaded with more explosives (about 25% greater charge density) at the bottom of the hole, which helps to ensure proper fracturing along the base of the excavation. However, this heavier loading will also increase the amount of radial fracturing and backbreak along the final slope face and create the need for a widened catchment area. Step drilling should be used only when the driller and blast designer are experienced in the practice because of the potential for excessive backbreak and a ragged slope face. In most instances, the vertical drill holes are extended beyond the final cut line (a practice known as sub-drilling) to ensure proper fragmentation and achieve a more natural final cut face as illustrated in Figure 15.

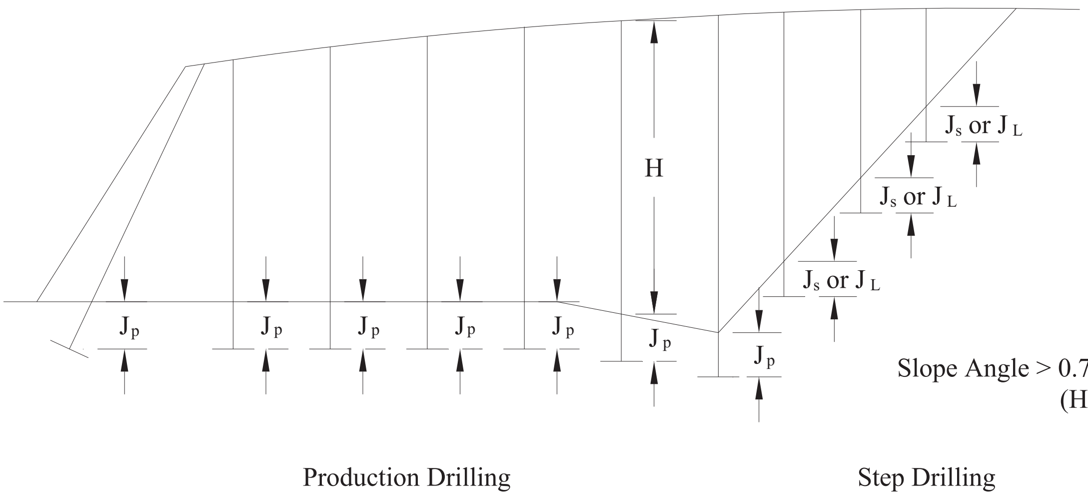

Figure 15. Illustration. Cross section of downhole and step drilling with sub-drilling techniques (modified from Cummings 2002).

Horizontal Drilling

Horizontal drilling is an effective technique for starting new excavations and for small excavations with poor access at the top of the slope. There are two basic techniques used for horizontal drilling. The first uses blastholes drilled perpendicular to the final rock face as shown in Figure 16, while the second uses holes drilled parallel to the rock face. When drilling perpendicular to the face, angled holes are typically required to mobilize and fragment the rock at the toe (these holes are called toe lifters) and the ditch (ditch lifters) to achieve the proper final slope configuration.

The second method sometimes uses a fan configuration, which can leave a distinctive pattern is shown in Figure 17.

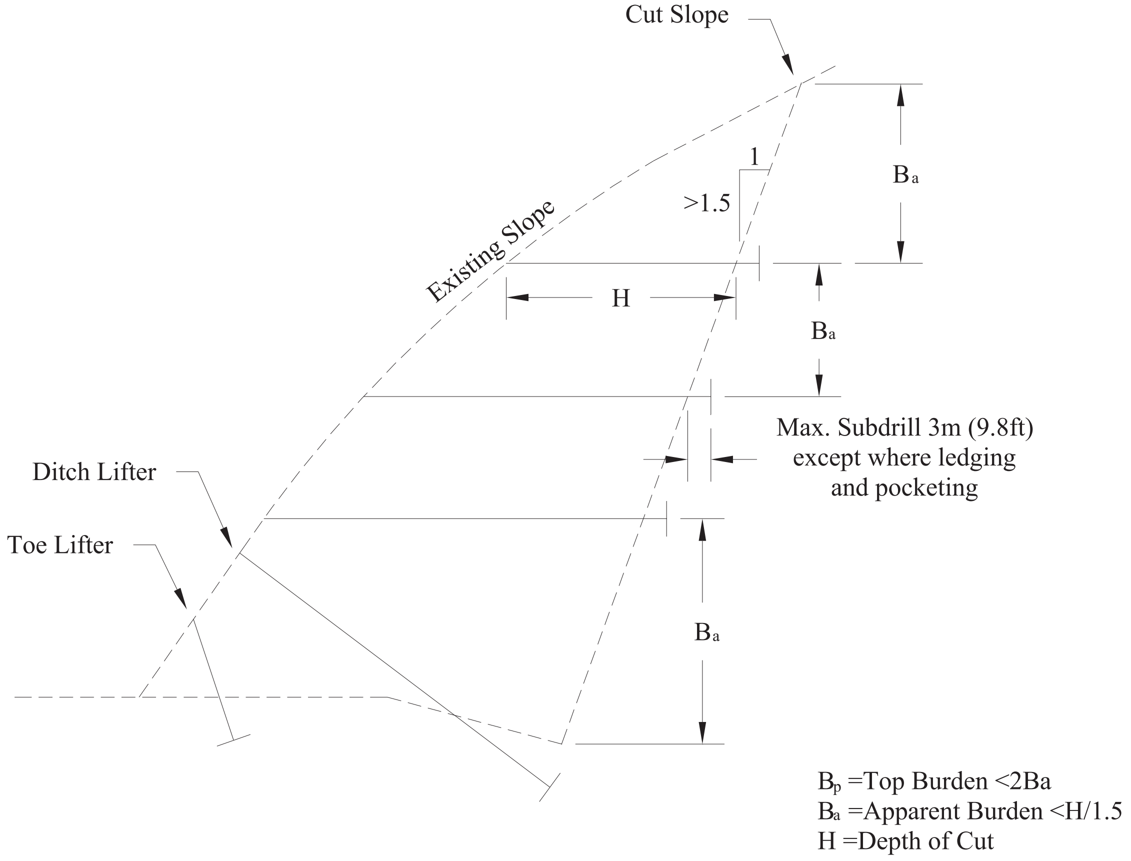

Figure 16. Illustration. Horizontal drilling design concept (modified from Cummings 2002).

In horizontal drilling, it can be difficult to maintain drill hole orientation, location, and depth. However, this is critical to avoid excessive fracturing in the final cut slope. In some cases, special drilling equipment (such as drills suspended from a crane) may be required to access the upper portions of the rock face. Special loading and timing allowances also may be required, and the drilling pattern must be adjusted to keep the drill steel from drifting downward.

The loading of explosives is also more complicated in horizontal drilling. It typically requires either packaged product or pneumatically loaded bulk product and stemming (filling, such as drilling cuttings, that's used to fill the blast hole above or between charges to "stem," or retain the explosive force within the hole).

Figure 17. Photo. Drill hole traces left by horizontal drilling parallel to the rock face (fan drilling).

In addition, horizontal drilling and blasting can produce badly fractured slope faces, as the production blastholes typically extend all the way to the final rock face. For this reason, a widened catchment area is recommended for slopes excavated this way.

Figure 18 depicts blast damage to a rock face that was excavated using horizontal blasting methods. Note the draped wire mesh in the upper portion of the photo, which was installed to control rockfall that was caused, in part, by blast damage.

Figure 18. Photo. Blast damage caused by horizontal drilling perpendicular to the rock face.

Drilling Equipment

Drilling horizontal holes is accomplished using a rig with a boom-mounted drill guide (generally a track rig) that has the ability to rotate the drill guide into a horizontal position and drill. Vertical and angled holes are bored using a downhole drilling rig or a track drilling rig as compared in Table 3.

Downhole Drilling Rig

Drilling with a downhole rig is best suited for vertical or near-vertical boreholes, deep drilling, and hard rock. Bit diameters range from 75 to 230 mm (3 to 9 in), allowing for precise borings at significant depths (although downhole drilling is engineered for a maximum depth of about 60 m or 200 ft, greater depths have routinely been achieved). Most of these drills are mounted on trucks or large tracks and therefore require wider, moderately graded benches to access the site.

Track Drilling Rig (Percussion Drill Head)

Track drills, also known as drifter drills, are the most commonly used drills in civil applications and can be used to advance vertical, angled or horizontal boreholes up to 12 m (40 ft) in depth. Bit size ranges between 40 and 150 mm (1.7 and 6.0 in.). The holes are advanced through percussion, either through a drill at the head or with tooling such as a downhole pneumatic hammer. They feature a boom that allows for borings along a slope face at a height determined by the boom length as seen in Figure 19. Track drilling rigs are generally smaller than downhole rigs and have better maneuverability, and consequently can access more difficult terrain.

Table 3. Comparison of vertical drilling rigs (modified from Konya and Walter 2003).

	DOWNHOLE DRILLING RIG	PERCUSSION/TRACK DRILLING RIG
Most Common Application(s)	Hard rock drilling of relatively deep holes. Can drill straighter holes and holes of different sizes with same rig.	Rock drilling of relatively shallow holes (vertical, angled and horizontal).
Depth and Penetration	Maintains a virtually constant penetration rate at all depths. Has higher average drilling speed for deep holes.	Higher initial penetration rates, but drilling speed falls off with each steel added.
Air Requirements	Can require less air because drill exhaust helps clean holes. Can use high-pressure air to increase drilling speeds.	Requires air for both hole cleaning and drilling. High-pressure air can cause drift and shorten steel life.
Noise Impacts	Comparatively low impact makes downhole drilling quieter, as exhaust noise is muffled in the hole.	Requires drill exhaust muffler to reduce noise. Impact noise difficult to control.
Shanks and Coupling	No shank pieces or coupling required. Uses standard API rod threads.	Shank piece and coupling threads subject to higher wear rates and more frequent replacement.
Impact and Vibration	Fewer moving parts. Almost all energy goes into rock instead of into mounting, meaning less wear on rig.	Rig must withstand much of the drilling impact and vibration.

Figure 19. Photo. Common track drill used to advance vertical blastholes.

Portable Crane-Mounted or Hand-Held Drills

Drilling on slopes with limited access will require *horizontal* drilling (see above) and/or the use of portable crane-mounted or hand-held drills, which can drill both vertical and angled borings. When drilling blastholes deeper than 5 m (15 ft), the drill will be mounted to a rigid frame or platform, typically suspended from a crane, to ensure proper alignment. Maximum drilling depth for portable rigs is around 12 m (40 ft) and bit sizes range from 40 to 100 mm (1.7 to 4 in). For borings less than 5 m (10 ft) deep, a hand-held sinker drill or jackleg-mounted drill (a drill supported on a single leg) can be used. However, drilling with a hand-held drill is slow because its downward pressure is limited by the weight of the drill and the physical strength of the operator.

Blasting Design

Blasting projects must be designed with several factors in mind, including the type of explosives used, borehole diameter, and loading levels. Each type of blasting—presplit, smooth, and cushion blasting—has its own formula.

Presplit Blasting

As discussed above, presplit blasting (or presplitting) is most often done before production blasting to create a secondary fracture plane that will protect the final slope face from damage in the main production blast. Table 4 lists recommended borehole diameters, burden, spacing, and explosive charges for presplit blasting.

Table 4. Parameters for drilling in a presplit blasting operation (modified from U.S. Department of the Interior 2001).

Hole Diameter		Spacing		Explosive Charge	
(mm)	(in)	(m)	(ft)	(kg/m)	(lb/ft)
38-44	1.50-1.75	0.3-0.46	1.00-1.50	0.03-0.1	0.08-0.25
50-64	2.00-2.50	0.46-0.6	1.50-2.00	0.03-0.1	0.08-0.25
75-90	3.00-3.50	0.6-1.0	1.50-3.00	0.05-0.23	0.13-0.50
100	4.00	0.6-1.2	2.00-4.00	0.23-0.34	0.25-0.75

In order to reduce fracturing, presplit blasting holes are drilled with smaller diameters than production holes. Presplit-hole diameter will also be influenced by many other factors, as well. For example, large-diameter holes can hold more explosives and can be spaced further apart than small-diameter holes, but can cause more backbreak if the burden-to-spacing ratios are not properly designed. Large-diameter holes yield lower drilling and blasting costs because they are less expensive per unit volume to drill. Large-diameter holes are better suited for relatively homogeneous, easily fractured rock with few planes of weakness (discontinuities) and for deep rock cuts. Small-diameter holes use less explosives and require smaller spacing between holes, which allow for better distribution of explosives, more uniform rock breakage, less backbreak, and reduced ground vibrations. Although more holes must be drilled, small-diameter holes can be drilled quickly, resulting in a relatively low unit cost. However, this may be offset by higher explosives costs, as more explosives are required to fill the extra holes. In addition, drilling depths on small-diameter holes are limited because the small-diameter drill bits are more likely to wander at depth than larger bits.

Theoretically, the burden for presplit blasting is unlimited. But in reality, variations in geology that are not visible on the outer face of the slope can limit that burden. Thus, the engineer must core the interior of the slope to identify the condition of the rock before determining the blasting design. In any case, a minimum of 10 m (30 ft) of burden is recommended for any presplit blasting procedure.

Hole spacing in presplit blasting is typically 10 to 12 times the borehole diameter. In very favorable geologic conditions, spacing can be increased to 14 times the borehole diameter. Wider spacing is used for hard, competent material with relatively few discontinuities; in very soft and/or weathered materials, spacing is decreased. In weak and soft formations or where corners are blasted, unloaded guide holes are recommended to direct the cracking. These guide holes are drilled between the normally spaced presplit holes (thus, using guide holes prevents the contractor from spacing the presplit holes any further apart).

Holes used for presplit blasting are lightly loaded and range from 22.5 to 25 mm (7/8 to 1 in) in diameter. A heavier charge (2 to 3 times the normal load) is used at the bottom of the borehole to ensure shearing at the floor. A common charge density is approximately 0.45 kg per square meter (0.1 lbs per square foot) of face area in the main section of the hole and 0.9 to 1.3 kg per square meter (0.2 to 0.3 lbs per square foot) at the bottom. The loads may have an air annulus (ring) surrounding them to cushion the explosive blast and reduce the radial cracking around the borehole. Figure 20 indicates three configurations.

The authors of the *DuPont Blaster's Handbook* (1978) show that slurry or water gel (in the form of "Tovex T-1") can provide excellent presplitting results while permitting increased loading rates and reduced labor costs. Konya and Walter (2003) recommend ammonium nitrate for all controlled blasting. For small-scale blasting (such as sliver cuts) in presplitting operations, 50-grain detonation cord has proven effective.

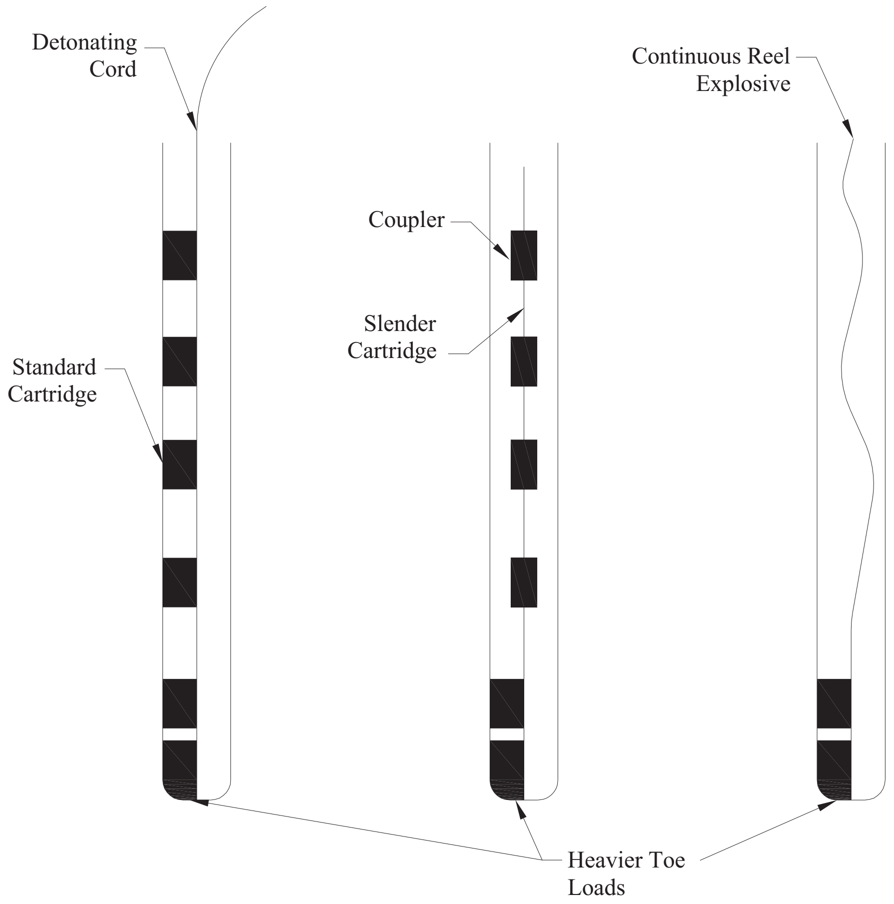

Figure 20. Illustration. Three options using lightly loaded, distributed charges in presplit blasting (modified from U.S. Department of the Interior 2001).

Smooth Blasting

Smooth blasting is a type of controlled blasting that's done either before production blasting, as an alternative to presplitting, or afterwards, either as an entirely different event or as the last delay of the production blast. Table 5 shows recommended borehole diameters, burden, spacing, and explosive charges for smooth blasting.

Table 5. Parameters for drilling in a smooth blasting operation (modified from U.S. Department of the Interior 2001).

Hole Diameter		Spacing		Burden		Explosive Charge	
(mm)	(in)	(m)	(ft)	(m)	(ft)	(kg/m)	(lb/ft)
38-44	1.50-1.75	0.6	2.00	1	3.00	0.05-0.55	0.12-0.25
50	2.0	0.75	2.50	1.06	3.50	0.05-0.55	0.12-0.25

As with presplit holes, smooth blasting holes are smaller than production holes in order to limit fracturing around the drill hole. The diameter of the hole is a function of geology, as discussed above.

The burden-to-spacing ratio for smooth blasting is approximately 1.5 to 1. Hole spacing for smooth blasting is slightly greater than presplit blasting, about 14 to 20 times the hole diameter, which means that holes are approximately 0.7 to 1.5 m (2.3 to 5 ft) apart. Wider spacing is used for hard rock and closer spacing is used for weak rock. Unloaded guide holes (drilled between the normally spaced blastholes) are recommended for weak and soft formations or for blasting corners.

The charge density, diameter, distribution, and explosive type used in smooth blasting are essentially the same as with presplit blasting. In smooth blasting, the borehole should be sealed with a tamping plug, clay plug, or other type of stemming to prevent the charge from being extruded from the hole by charges on earlier delays. Stemming also prevents excessive rifting (splitting) of the rock and permits the use of lighter charges because blast energy is better contained and therefore better distributed.

Cushion Blasting

Cushion blasting, another type of controlled blasting that's typically done after production blasting, uses a row of lightly loaded "buffer" holes filled with crushed stone (stemming), which reduces the impact on the surrounding rock as well as the finished slope face. Cushion blasting can be used with both vertical and angled holes, and good alignment is essential in both cases. The cushion holes are drilled along the final slope line and loaded with light, well-distributed charges and fired after the main production blast.

The required burden is established *either* by the last row of production boreholes *or* by a separate set of buffer holes (these buffer holes determine the burden so that the cushion blast holes produce enough backbreak to avoid borehole traces).

Table 6 shows the recommended borehole diameters, burden, spacing, and explosive charges for cushion blasting.

Table 6. Parameters for drilling in a cushion blasting operation (modified from U.S. Department of the Interior 2001).

Hole Diameter		Spacing		Burden		Explosive Charge	
(mm)	(in)	(m)	(ft)	(m)	(ft)	(kg/m)	(lb/ft)
50-64	2.00-2.50	1.0	3.00	1.2	4.00	0.03-0.1	0.08-0.25
75-90	3.00-3.50	1.2	4.00	1.5	5.00	0.05-0.2	0.13-0.5
100-115	4.00-4.50	1.5	5.00	1.8	6.00	0.1-0.3	0.25-0.75
127-140	5.00-5.50	1.8	6.00	2.1	7.00	0.3-0.45	0.75-1.00
152-165	6.00-6.50	2.1	7.00	2.7	9.00	0.45-0.7	1.00-1.50

Diameters of buffer and cushion boreholes are smaller than those of production holes, and buffer boreholes have a slightly larger diameter than cushion boreholes. The diameter of a cushion hole depends on many factors, as discussed above.

The burden for cushion holes varies according to the rock characteristics. For example, the burden of hard, competent rock will be smaller than the burden of soft, easily fractured rock. It is important to conduct one or more test blasts and continually analyze and back-calculate results from production blasting to determine the proper burden, spacing, and charge density.

The spacing on cushion and buffer blastholes varies depending on the bedrock type and structural characteristics, but generally ranges from 15 to 24 times the borehole diameter. The burden-to-spacing relationship varies, but spacing on cushion holes should always be less than the width of the burden being removed (U.S. Department of the Interior 2005). When removing weak, heavily fractured material or when blasting corners, uncharged guide holes can be drilled between the normally spaced cushion holes to guide the blast-induced fracture.

Charge loading in cushion blasting is similar to that in smooth blasting in that lightly loaded, well-distributed charges are fired after the main production blast. Charges are typically 25 mm (1 in) in diameter and charge densities are 0.45 to 0.7 kg per square meter (0.1 to 0.15 lb per square foot) of face area for the main borehole and two to three times that for the bottom of the borehole. Historically, cushion holes are surrounded by some type of stemming (crushed rock or other loose inert material that helps cushion the blast) for the entire length of the borehole. According to the *DuPont Blaster's Handbook* (1978), an air annulus surrounding the charge produces similar results and reduces loading time.

Removing Drill Hole Traces and Blasting Scars

In weak rock, drill hole traces can be removed by chipping away at the corners of the traces or removing the outer layer of rock using a hoe ram, excavator bucket, or pneumatic hammer. For strong rock, it is nearly impossible to completely remove these traces.

In some cases, blasting is followed by other methods of excavation, which are used to get rid of remaining rock and soil to create a more aesthetically appealing final face. In cases where there is less rock to remove in the first place, these methods can be used on their own.

Ripping

Ripping is a process of breaking up rock and soil with a large tooth or teeth attached to the back of a bulldozer.

Where feasible, ripping is generally preferred over blasting because it is considerably less expensive; ripping costs are typically 50 to 65% less than blasting. Ripping is also significantly less dangerous than blasting and requires fewer permits and special precautions. Ripping can be done in close proximity to populated areas or other places where blasting noise and vibrations are restricted. However, ripping is limited to soft to moderately firm, fractured rock and construction of low-angle cut slopes and shallow, near vertical cuts. In dense rock formations, light blasting is sometimes performed before ripping.

Once the material is loosened by ripping, an excavator can be used to remove it and perform slope sculpting (see below). Ripping gives the contractor a lot of freedom to aesthetically enhance a slope by adding additional contour and allowing for revegetation in certain areas.

The teeth on rippers can leave scar marks on the rock after excavation. In most cases, these can removed using the same procedure used to remove drill hole traces. In soft and/or massive rock, the contractor may use a jet of high-pressure water or a vibratory compactor, known as a plate bucket, which is attached to an excavator or loader to remove the scars.

Ripping is usually done in one direction, but in very tough materials ripping in a grid pattern will increase excavation efficiency. The pass spacing is determined by the end use of the material (fill, aggregate, waste, etc.) and the capacity of the excavating equipment. In most cases, it is best to maximize ripping depth, but in stratified formations it may be best to rip along the natural layers.

Ripping is generally done in the same direction that loading will take place (i.e., parallel to the plane). However, when the material exhibits a foliation or bedding plane, ripping perpendicular to the plane produces much better fracturing.

Ripping Equipment

There are basically two types of rippers: the pull- (or tow-) type ripper and the integral bulldozer-mounted ripper. In rock excavation, a bulldozer-mounted ripper as shown in Figure 21 works better than a pull-type ripper because it can exert greater downward pressure.

Rippers also come in single- and multi-toothed configurations. Single-toothed rippers are used for difficult ripping work, where maximum ripping depth is required and/or the material is dense. Multi-toothed rippers, which can use up to five teeth, are used for softer ground or for secondary purposes such as breaking up already ripped ground.

Figure 21. Photo. Bulldozer with an integral ripping attachment.

Choosing the proper bulldozer-mounted ripper depends of four factors: downward pressure on tip, horsepower of the bulldozer, weight of the bulldozer, and angle of tooth penetration (Kelly 1970). The first three factors will influence the size and type of the bulldozer used, and the last is a function of the style of ripper (see below). Bulldozer style and size is not discussed in this document. Most ripper manufacturers' websites includes information on the bulldozers that are compatible with their products; ripper mounting brackets and hydraulic control mechanisms vary widely.)

Here three main styles of rippers:

Hinge-Style Ripper:

The hinge-style ripper, also known as the radial-type ripper shown in Figure 22, is fixed to the bulldozer with a pin, around which the ripper arm rotates. Because of its maneuverability, this type of ripper is best at creating sculpted and natural-appearing rock cuts.

Parallelogram-Style Ripper:

The parallelogram-style ripper features two hinged arms, which keep the shank (the tang of the tooth) vertical and hold the tooth at a constant angle as it is lowered into the material. This provides excellent penetration in many types of rock. The parallelogram-style ripper works best in easy to moderately rippable materials. In more difficult conditions, contractors prefer to have the option of selecting different tooth angles, which provides better penetration, and so would use an adjustable parallelogram-style ripper.

Figure 22. Photo. Typical hinge- or radial-style ripper (Nichols and Day 2005).

Breaking

Breaking is done with a *hydraulic hammer* (also known as a *breaker* or *hoe ram)*, a percussion hammer fitted to an excavator that is typically used for demolishing concrete structures and is shown in Figure 23. It is used to break up rock in areas where blasting is prohibited due to environmental or other constraints. Like a ripper, a hydraulic hammer can be used in most rock types, although when sculpting a slope face, it works best in soft or moderately to highly fractured rock; existing discontinuities in the rock act as presplit lines, minimizing hammer-induced scars and fractures while creating a slope face that appears to be naturally weathered.

Figure 23. Photo. Application of a hydraulic hammer attached to an excavator.

To allow for maximum downward pressure, the hammer is positioned perpendicular to the ground surface as shown in Figure 24. Hammering locations are spaced evenly in a grid-like fashion so that the end rock product is fractured into pieces that can be loaded and hauled. For slope excavations, the hammering angle should be not be parallel to the major discontinuity orientation, as this may cause fractures into the final slope face as Figure 25 shows.

Figure 24. Photo. A hydraulic hammer sculpting a rock face (the material to be removed has been outlined with common marking paint).

Figure 25. Photo. A hydraulic hammer expanding a sculpted area, creating planting areas and more natural-looking slope variation.

After breaking, the excavated slope can be configured to look like a part of the natural landscape, with the addition of boulders and topsoil and reseeding with native vegetation as Figure 26 shows.

Figure 26. Photo. Completed rock slope prior to placement of topsoil and a native seed mix.