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EARTHWORK

Earthwork involves movement of a portion of the earth's surface from one location to another and, in its new position, creation of a desired shape and physical condition. Occasionally, the material moved is disposed of as spoil. Because of the wide variety of soils encountered and jobs to be done on them, much equipment and many methods have been developed for the purpose. This section describes and analyzes the equipment and methods.

13.1 Types of Excavation

A common method of classifying excavation is by type of excavated material: topsoil, earth, rock, muck, and unclassified.

Topsoil excavation is removal of the exposed layer of the earth's surface, including vegetation. Since the topsoil, or mantle soil, supports growth of trees and other vegetation, this layer contains more moisture than that underneath. So that the lower layer will lose moisture and become easier to handle, it is advantageous to remove the topsoil as soon as possible. When removed, topsoil usually is stockpiled. Later, it is restored on the site for landscaping or to support growth of vegetation to control erosion.

Earth excavation is removal of the layer of soil immediately under the topsoil and on top of rock. Used to construct embankments and foundations, earth usually is easy to move with scrapers or other types of earthmoving equipment.

Rock excavation is removal of a formation that cannot be excavated without drilling and blasting. Any boulder larger than ½ yd^3 generally is classified as rock. In contrast, earth is a formation that when plowed and ripped breaks down into small enough pieces to be easily moved, loaded in hauling units, and readily incorporated into an embankment or foundation in relatively thin layers. Rock, when deposited in an embankment, is placed in thick layers, usually exceeding 18 in.

Muck excavation is removal of material that contains an excessive amount of water and undesirable soil. Its consistency is determined by the percentage of water contained. Because of lack of stability under load, muck seldom can be used in an embankment. Removal of water can be accomplished by spreading muck over a large area and letting it dry, by changing soil characteristics, or by stabilizing muck with some other material, thereby reducing the water content.

Unclassified excavation is removal of any combination of topsoil, earth, rock, and muck. Contracting agencies frequently use this classification. It means that earthmoving must be done without regard to the materials encountered. Much excavation is performed on an unclassified basis because of the difficulty of distinguishing, legally or practically, between earth, muck, and rock. Unclassified excavation must be carried out to the lines and grades shown on the plans without regard to percentage of moisture and type of material found between the surface and final depth.

Excavation also may be classified in accordance with the purpose of the work, such as stripping, roadway, drainage, bridge, channel, footing, borrow. In this case, contracting agencies indicate the nature of the excavation for which materials are to be removed. Excavation designations differ with agencies and locality. Often, the only reason a certain type of excavation has a particular designation is local custom.

Stripping usually includes removal of all material between the original surface and the top of any material that is acceptable for permanent embankment.

Roadway excavation is that portion of a highway cut that begins where stripping was completed and terminates at the line of finished subgrade or bottom of base course. Often, however, stripping is made part of roadway excavation.

Drainage excavation or structure excavation is removal of material encountered during installation of drainage structures other than bridges. Those structures are sometimes referred to as minor drainage structures and include roadway pipe and culverts. A culvert is usually defined as any structure under a roadway with a clear span less than 20 ft, whereas a bridge is a structure spanning more than 20 ft. After a pipe or culvert has been installed, backfilling must be done with acceptable material. This material usually is obtained from some source other than drainage excavation, which generally is not acceptable or workable. Often, culvert excavation does not include material beyond a specified distance from the end of a culvert.

Bridge excavation is removal of material encountered in digging for footing and abutments. Often, bridge excavation is subdivided into wet, dry, and rock excavation. The dividing line between wet and dry excavation usually is denoted by specification of a ground elevation, above which material is classified as dry and below which as wet. A different elevation may be specified for each foundation.

Channel excavation is relocation of a creek or stream, usually because it flows through a right-of-way. A contracting agency will pay for any inlet or outlet ditch needed to route water through a pipe as channel excavation, to the line where culvert excavation starts.

Footing excavation is the digging of a column or wall foundation for a building. This work usually is done to as neat a line and grade as possible, so that concrete may be cast without forms. Although elimination of forms saves money, special equipment and more-than-normal handwork are usually required for this type of excavation.

Borrow excavation is the work done in obtaining material for embankments or fills from a source other than required excavation. In most instances, obtaining material behind slope lines is classified as borrow, although it commonly is considered as getting material from a source off the site. Most specifications prohibit borrow until all required excavation has been completed or the need for borrow has been established beyond a reasonable doubt. In some cases, need for a material not available in required excavation makes borrow necessary. A borrow pit usually has to be cleared of timber and debris and then stripped of topsoil before desired material can be excavated.

Dredge excavation is the removal of material from under water.

13.2 Basic Excavating Equipment

A tractor is the most widely used excavating tool. Essentially, it is a power source on wheels or tracks (crawler). Equipped on the front with a **bulldozer**, a steel blade that can be raised and lowered, a tractor can push earth from place to place and shape the ground. If a scraper is hooked to the drawbar and means of raising, lowering, and dumping are provided, a tractor-drawn scraper results. Addition of other attachments creates tools suitable for different applications (see also Art. 13.7).

Another basic machine is one that by attachment of different fronts may be converted into a shovel, dragline, clamshell, backhoe, crane, or pile driver. The basic machine made for a shovel, however, has shorter and narrower tracks than one made for a dragline or clamshell, and more counterweight has to be added to the back. A shovel attachment will fit the basic machine made for a dragline or clamshell, but the longer tracks will interfere with the shovel (see also Art. 13.4).

Scrapers may be tractor-drawn or self-propelled. More excavation is moved with self-propelled or rubber-tired scrapers than with scrapers towed and controlled by crawler tractors (see also Art. 13.8).

Trenchers, used for opening trenches and ditches, may be ladder or wheel type. They do most of the pipeline excavation in earth. The ladder type has chains to which are attached buckets that scoop up earth as the chains move. It is adaptable to deep excavation. The wheel type has digging buckets on the circumference of a rotating wheel. The buckets dump excavated material into a conveyor mounted in the center of the wheel. This type of trencher is used mainly for shallow trenches. Neither type is used to any great extent when rock is encountered in trench excavation.

Wheel excavators, used in constructing earth dams or in strip mining, excavate soft or granular materials at very high rates. For example, one excavator with a 28-ft wheel moves 1500 tons of iron ore per hour. A typical wheel excavator resembles a wheel-type trencher. Buckets mounted on a wheel 12 or more ft in diameter scoop up the earth. They may be 2 ft or more wide, with a capacity of ⅓ yd^3 or more, and equipped with a straight cutting edge or teeth. The buckets dump into a hopper, which feeds the earth onto a conveyor belt. The belt moves along a boom, which may be 200 ft or more long, to dump the earth into another hopper. This hopper in turn feeds the earth to a stockpile or to earthmoving equipment.

13.3 Selecting Basic Equipment

Type of material to be excavated may determine the basic equipment to be used. But length and type of haul road must also be considered. For example, suppose excavation is in earth and best results could be obtained with rubber-tired scrapers, but the haul is over city streets. In this case, this type of equipment probably could not be used because of heavy wheel loads and interference with traffic.

For rock, a front-end loader, backhoe, or shovel would be the basic rig. For earth, when a haul road can be built, scrapers would be chosen. But if the earth has to be moved several miles over existing streets or highways, the choice would be a front-end loader, shovel, or backhoe that would load dump trucks. Whether a shovel or backhoe would be used depends on whether the excavation bottom can support a front-end loader or shovel and hauling units. If the bottom is too soft, a dragline or backhoe would be required. A dragline can sit outside the excavation and load a hauling unit at the same level (loading on top). But when a backhoe can be used, it is preferred to a dragline because of greater production.

Therefore, in selecting basic equipment, consider:

Types of material to be excavated

Types and size of hauling equipment to be used

Load-supporting ability of original ground

Load-supporting ability of material to be excavated

Volume of excavation to be moved

Volume to be moved per unit of time

Length of haul

Type of haul road

13.4 General Equipment for Excavation and Compaction

Clearing or Grubbing

Use *tractor* with bulldozer or root rake.
Bulldozer can fell trees, uproot stumps.
Root rake piles for burning, makes cleaner pile.
Brush hog may be required for light brush.

Grubbing

Use low-strength *explosives*, slow detonation speed.

Clearing

Drag *chain* or *chain and heavy ball* between two tractors. Useful for trees that break easily. Tractors equipped with cutter blades can operate on any footing and cut any tree at ground level.

Stripping

Bulldozers are limited by length of push or haul but are useful for swampy conditions.

Scrapers are limited by terrain and support ability of ground; they may be tractor-drawn for short hauls.

Draglines are limited by depth of stripping, ability to service with hauling units, and space for casting the bucket. They are used where swampy conditions prevent other equipment from being used.

Graders are limited to use where stripping can be windrowed on final position. Material can be loaded from a windrow by a front-end loader.

Pipe Installation

Backhoes are used on firm soil where depth of trench is not excessive; they are good in rock.

Draglines are used for deep trenches if the sides can be flattened; they have difficulty digging vertical walls.

Clamshells are used where sheeting of sides is required and it is necessary to dig between braces and to great depths. They are inefficient in rock.

Bulldozers are limited to shallow excavation.

Trenching machines produce vertical or near-vertical walls and can maintain line and earth grade.

Earth Excavation

Tractor-drawn scrapers are limited by length of haul and supporting ability of the soil. Cost gets excessive if haul distance greatly exceeds 1000 ft.

Two-axle, rubber-tired, self-propelled scrapers are limited by length of haul, terrain, and supporting ability of the soil; they bounce on long hauls at top speed.

Three-axle, rubber-tired, self-propelled scrapers need maneuvering or working space and are limited by terrain and supporting ability of soil. They are most efficient on long hauls.

Twin-engine, rubber-tired scrapers have few limitations. They are useful in rough terrain and where traction is needed on all wheels.

Front-end loaders generally discharge into hauling units if the haul greatly exceeds 100 ft and they also are limited by digging and dumping ease of excavated material.

Shovels are also used to load into hauling units. Working room must be ample and distance to cast short. Shovels also have to dig from a face.

Draglines may be used where excavation is deep and the material has no supporting ability. Material should be easy to dig. Draglines usually load into hauling units.

Wheel excavators offer high excavation rate and loading into hauling units with soft or granular soils.

Mobile belt loaders (Fig. 13.1) give high-production loading into hauling units but are limited by working room and supporting capacity of excavation bottom. Belt loaders are limited to short, infrequent moves. A wide belt handles some rock excavation.

Dredges usually are used where transportation and digging costs are prohibitive if other than water-borne equipment is used. Water must be available for mixing with the excavated material for pumping through pipes. Distance to spoil area should not be too great.

Clamshells are low producers but are useful in small or deep spaces, where there is no overhead interference with swinging of the boom.

Gradall, not a high-production tool, is suitable for dressing or finishing where tolerances are close.

Scoopers, hydraulically operated, are high-production equipment, limited by dumping height and to easily dug material. Production is not so greatly influenced by height of face as for a shovel.

Rock Excavation

Shovels can dig any type of rock broken into pieces that can be easily dug. Limited to digging from a

Fig. 13.1 Mobile belt loader. (*Barber-Greene Co.*)

face, shovels are used for high-production loading into hauling units.

Bulldozers are limited to short movements and easily dug rock. Sometimes, they are used to dispose of boulders when drilling and blasting are not economical.

Front-end loaders are used instead of shovels because of their high production, lower cost of operation, and ease of moving from job to job.

Backhoes are used for foundation excavation, trenches, and high production in rough terrain. They must dig below their tracks.

Scrapers are suitable for short movements and rock broken down to small sizes, such as blasted shale, but tire wear may be greater than in other applications.

Scoopers may be used instead of shovels where working space is tight. They are limited by the height of hauling units and to easily dug rock.

Gradalls are used for trench and foundation excavation, but material must be well blasted.

Clamshells are most suitable for deep foundations or where the reach from machine position to excavation prohibits other equipment from being used. Rock must be well broken for maximum production.

Compaction

Sheepsfoot rollers, made with feet of various shapes, offer high-speed production. Compaction depends on unit pressure and speed of roller. They are not suitable for compacting sand. They also are limited by depth of layer to be compacted.

Rubber-tired rollers are used for granular soils, including shales and rock. Ranging from very light weight to 200 tons, they may be self-propelled or towed. Depth of lift compacted depends on weight.

Vibratory compactors, towed, self-propelled, or hand-held, are also used for granular soils. Compaction ability depends on frequency and energy of vibrations. Depth of lift is not so much a factor as for other types of compactors.

Grid rollers, useful in breaking down oversize particles, are limited to shallow lifts of nonsticky material. They can be towed at any safe, economical speed.

Air tamps are used to backfill pipe and foundations and for work in areas not accessible to power equipment. Usually hand-held, they are powered by compressed air imparting reciprocating blows. They are limited to low production and shallow lifts.

Paddlefoot rollers, usually self-propelled, compact from the top of lift down. They are limited to an average depth (up to 8 in) of lift in all soils.

A *rubber-tired front-end loader* can be converted to this type of roller by a change of wheels.

Steel-wheel rollers, self-propelled, are used where a smooth, sealed surface is desired. They are limited to shallow depth of lift.

13.5 Power Shovels, Draglines, Clamshells, and Backhoes

These four machines are made by installing an attachment on a basic machine, which may be mounted on crawler tracks or a trucklike chassis (Art. 13.2). (See Figs. 13.2 to 13.5.) When mounted on a trucklike chassis, the machine usually is designed for use as a truck crane, but it also can be used as a shovel or backhoe if mobility is desired and low production is acceptable. Most backhoes, however, are hydraulic and cannot be converted.

There is not much difference between equipment used as a clamshell and that used as a dragline or crane. A boom used with a clamshell has two-point sheaves, so that two cables can attach to the bucket. One cable is used to open and close the bucket and the other to hoist or lift the bucket. Since the two cables should travel at the same

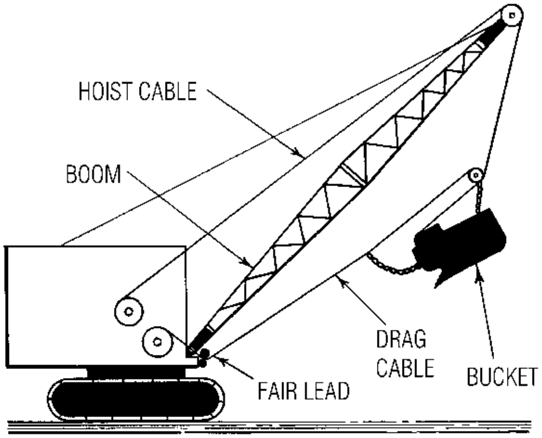

Fig. 13.2 Dragline.

Fig. 13.3 Hydraulic excavator (backhoe). (*Caterpillar Tractor Co.*)

speed, the drums on a clamshell are the same size. To keep the bucket from spinning and twisting the hoist and closing lines, a tagline extends between the bucket and a spring-loaded reel on the side of the boom (Fig. 13.4).

A dragline has a hoist cable that goes through a point sheave atop the boom and attaches to the bucket. Another line, the drag cable, goes through the fairlead and attaches to the bucket (Fig. 13.2). The drum that exerts pull on the drag cable is smaller than the hoist drum because more force is required on the drag cable than on the hoist lines. Typical performance factors for a dragline are given in Tables 13.1 and 13.6.

Power shovels are used primarily to load rock into hauling units. Production depends on type of material to be loaded, overall job efficiency, angle of swing, height of bank or face the shovel digs against, ability of operator, swell of material, slope of ground machine is working on, and whether hauling units are of optimum size and adequate in number. For highest efficiency, the degree of swing should be held to a minimum. (Typical performance factors are given in Table 13.2.) Working the shovel so that a hauling unit can be loaded on each side is desirable so there is no lost time waiting for a hauling unit to get into position.

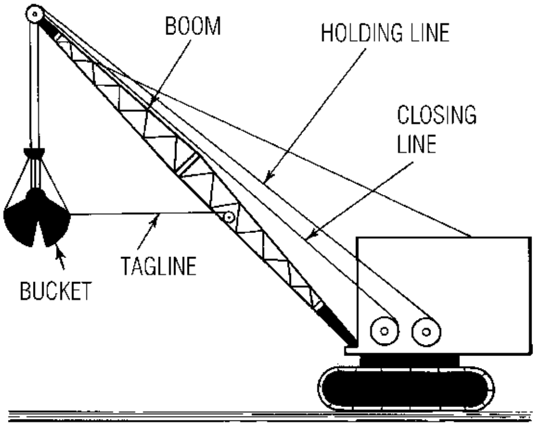

Fig. 13.4 Clamshell.

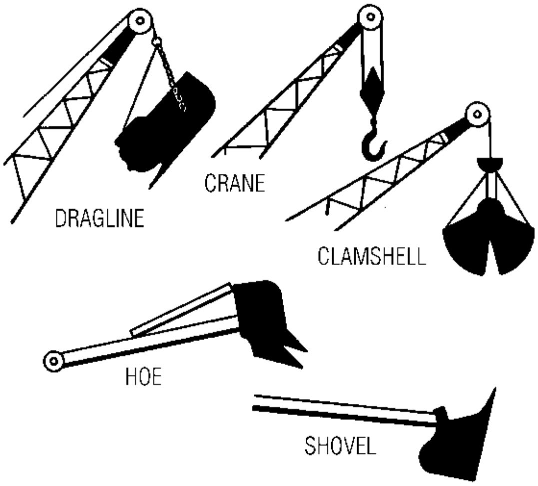

Fig. 13.5 Excavating and crane attachments.

Table 13.3 gives estimated hourly production of power shovels. It is based on bank cubic yards measure, 90° swing, optimum digging depth, grade-level loading, 100% efficiency, 60-min hour, and bucket-fill factor of 1.00 (see Table 13.5).

Table 13.1 Typical Dragline Calculating Factors: Average Swing Cycle with 110° Swing

Bucket capacity, yd^3	½	1½	2
Time, s	24	30	33

Bucket Factors

Type of digging	% of rated capacity (approx)
Easy	95–100
Medium	80–90
Medium hard	65–75
Hard	40–65

Table 13.2 Typical Shovel Calculating Factors: Average Swing Cycle with 90° Swing

Bucket capacity, yd^3	½	1	1½	2	2½
Time, s	20	21	22	23	24

Dipper Factors

Type of digging	% of rated capacity (approx)
Easy	95–100
Medium	85–90
Medium hard	70–80
Hard	50–70

Table 13.4 indicates the effect on production of depth of cut and angle of swing.

Optimum digging depth is the shortest distance a bucket must travel up a face or bank to obtain its load. This depth usually is the vertical distance from shipper shaft (dipper-stick pivot shaft) to ground level. Optimum depth varies with type of material to be excavated since a lower boom is needed for hard materials than for soft.

Work must be planned to load or move the maximum yardage each shift: Locate the shovel and hauling units for the shortest swing of the shovel. If it is necessary to work high, dig the upper portion first. Move up to the face while a hauling unit is getting into position. Make short moves frequently, instead of less frequent long moves. Stay close to the face; do not dig at the end of the stick. Lower the dipper only enough to get a full bucket; this cuts down on hoist time. Keep dipper teeth sharp. Have spare cables and dipper teeth readily available near the shovel. Hoist the load no more than necessary to clear the hauling-unit bed. Start the swing when the bucket is full and clear of the bank. Spot the hauling unit under the boom point so it is not necessary to crowd or retract to dump into the bed (Fig. 13.6). Break rock well for easier digging.

A dragline is more versatile than a shovel. With a dragline, load can be obtained from a greater distance from the machine (reach is greater). Excavation can be done below water and at a long distance above or below the dragline. A larger bucket than the machine's rated capacity can be used if a short boom is installed. It is not uncommon for a machine rated at 2½ yd^3 to be loading with a 4-yd^3 bucket into hauling units. But weight of bucket and load should not exceed 70% of the tipping load of the machine. (Lifting-crane capacity is based on 75% of actual tipping load. A dragline may approach this if it is on solid footing and is digging good-handling material.)

Since a dragline loads its bucket by pulling it toward the machine, the pit or face slopes from bottom to top toward the dragline. Best production is obtained by removing material in nearly horizontal layers and working from side to side of the excavation. A keyway, or slot, should be cut next to the slope. This keyway should always be slightly lower than the area being taken off in horizontal layers. A good operator fills the bucket

Table 13.3 Estimated Hourly Production of Dipper-Type Power Shovel*

Material class	Shovel dipper sizes, yd^3															
	½	¾	1	1¼	1½	2	2½	3	4	4½	5	6	7	8	9	10
Moist loam or sandy clay	115	165	205	250	285	355	405	454	580	635	685	795	895	990	1075	1160
Sand and gravel	110	155	200	230	270	330	390	450	555	600	645	740	835	925	1010	1100
Common earth	95	135	175	210	240	300	350	405	510	560	605	685	765	845	935	1025
Clay, tough hard	75	110	145	180	210	265	310	360	450	490	530	605	680	750	840	930
Rock, well blasted	60	95	125	155	180	230	275	320	410	455	500	575	650	720	785	860
Common with rock	50	80	105	130	155	200	245	290	380	420	460	540	615	685	750	820
Clay, wet and sticky	40	70	95	120	145	185	230	270	345	385	420	490	555	620	680	750
Rock, poorly blasted	25	50	75	95	115	160	195	235	305	340	375	440	505	570	630	695

* Caterpillar Tractor Co.

Table 13.4 Correction Factors for Effect of Depth of Cut and Angle of Swing on Power-Shovel Output*

Depth of cut, % of optimum	Angle of swing, deg						
	45	60	75	90	120	150	180
40	0.93	0.89	0.85	0.80	0.72	0.65	0.59
60	1.10	1.03	0.96	0.91	0.81	0.73	0.66
80	1.22	1.12	1.04	0.98	0.86	0.77	0.69
100	1.26	1.16	1.07	1.00	0.88	0.79	0.71
120	1.20	1.11	1.03	0.97	0.86	0.77	0.70
140	1.12	1.04	0.97	0.91	0.81	0.73	0.66
160	1.03	0.96	0.90	0.85	0.75	0.67	0.62

* "Earthmoving Data," Caterpillar Tractor Co.

as soon as possible, within a distance less than the bucket length. Digging on a slight incline helps fill the bucket. When the bucket is full, it should be nearly under the boom point and should be lifted as drag ceases.

As with shovels, a relatively shallow pit yields the greatest efficiency for draglines. The hauling units should be in the excavation or at the same elevation to which the dragline is digging. Thus, when the bucket is full, it will have a short lift to reach the top of the hauling units. If the pit bottom is soft or for some other reason hauling units cannot be spotted below the machine, then loading on top must be resorted to, with a loss in loading efficiency. Table 13.6 indicates dragline production in cubic yards bank measure per hour. The table is based on suitable depth of cut for maximum effect, no delays, 90° swing, and all materials loaded into hauling units (see also Table 13.1).

Production of clamshells, like that of draglines, depends on radius of operation and lifting capacity. It is general practice to limit the clamshell load, including bucket weight, to 50% of the full power-line pull at the short boom radius.

Table 13.5 Bucket-Fill Factor*

Material	Fill-factor range
Sand and gravel	0.90–1.00
Common earth	0.80–0.90
Hard clay	0.65–0.75
Wet clay	0.50–0.60
Rock, well blasted	0.60–0.75
Rock, poorly blasted	0.40–0.50

* "Earthmoving Data," Caterpillar Tractor Co.

Types of clamshell bucket are general-purpose, rehandling, and heavy excavating. The rehandling bucket is best for unloading materials from bins or railroad cars or loading materials from stockpiles. The heavy-excavation bucket is used for extreme service, such as placing riprap. It can be adjusted so that the operation is easy on components since a clamshell does not demand a tightly adjusted friction band. The general-purpose bucket is between the rehandling and excavating buckets and can be used with or without teeth.

13.6 Tractor Shovels

Also commonly known as front-end loaders, tractor shovels can be mounted on wheels (Fig. 13.7) or crawler tracks (Fig. 13.8). A crawler is desirable if moving it from one job to another is no problem, haul distance is short, and type of excavation bottom is not suitable for rubber tires. Most wheel loaders have four-wheel drive.

Capacity of a tractor shovel depends on unit weight of material to be handled, so there is a variety of buckets for each loader. These are of three basic types: hydraulically controlled, gravity dump, and overhead (overshot). Hydraulically controlled machines are preferable for most operations. The overhead is desirable where working room for turning is unavailable.

All loaders except overhead use a load, turn, dump cycle. For best efficiency and reduction of wear on tires or undercarriage, turning should be held to a minimum.

A loader should dig from a relatively low height of bank or face. Since most loaders are equipped with automatic bucket positions, the height of bank

Fig. 13.6 Hydraulic shovel loads off-highway dump truck. (*Caterpillar Tractor Co.*)

Table 13.6 Hourly Dragline Handling Capacity, yd^3

	Bucket capacity, yd^3								
Class of Material	3/8	1/2	3/4	1	1 1/4	1 1/2	1 3/4	2	2 1/2
Moist loam or sandy clay	70	95	130	160	195	220	245	265	305
Sand and gravel	65	90	125	155	185	210	235	255	295
Good, common earth	55	75	105	135	165	190	210	230	265
Clay, hard, tough	35	55	90	110	135	160	180	195	230
Clay, wet, sticky	20	30	55	75	95	110	130	145	175

should be adjusted so it is not higher than necessary to fill the bucket; this is about the same height as the push-arm hinges.

On an average construction job, a front-end loader is a versatile tool. Attachments are available so that it can be used as a bulldozer, rake, clamshell, log loader, crane, or loader.

13.7 Tractors and Tractor Accessories

Tractors are the prime movers on any construction job where earth or rock must be moved. They may be mounted on wheels or crawler tracks. Properly equipped, a tractor usually is the first item moved onto a job and one of the last to finish.

Crawlers are more widely used than wheel tractors. Crawlers will work on steep, rugged terrain; soft, marshy conditions; and solid rock. Rubber-tired tractors are suitable for specific projects or uses, such as excavation of earth or sand where track wear would be excessive. Tires and track system are the most expensive parts to maintain.

Basic components of a crawler tractor include engine, radiator, transmission, clutch, steering clutches, final drives, and undercarriage, consisting of tracks, rollers, sprockets, and idlers. Components

Fig. 13.7 Wheel loader loads off-highway dump truck. (*Caterpillar Tractor Co.*)

of a wheeled tractor include engine, radiator, transmission, clutch, tires, and rear end. A wheeled tractor may have two- or four-wheel drive. Its travel speed may range from a minimum of 3 mi/h to a maximum of over 40 mi/h. Travel speed of a crawler may range from less than 1 mi/h to not much more than 8 mi/h.

A crawler tractor can be equipped with accessories that enable it to perform a wide variety of tasks:

Rear Double-Drum Cable Control Unit ▪ This is used for pulling a scraper; or cable control for a bulldozer by using only one drum.

Bulldozer ▪ Either cable-controlled by rear or front unit, or hydraulically controlled (Fig. 13.9). Several different types of blade are available, such as angle, straight, U, root rake, rock rake, stump dozer, tree dozer, push dozer.

Fig. 13.8 Track-type loader. (*Caterpillar Tractor Co.*)

Ripper ▪ Rear-mounted and hydraulically controlled to provide pressure up or down (Fig. 13.10).

Side Boom ▪ A short, cable-operated boom mounted on one side with a counterweight on the opposite side of the tractor. The main use is laying cross-country pipelines (Fig. 13.11).

Tractor Crane ▪ A boom with limited swinging radius.

Fig. 13.9 Tractor with bulldozer attachment. (*Caterpillar Tractor Co.*)

Fig. 13.10 Tractor (bulldozer) with ripper. (*Caterpillar Tractor Co.*)

Pusher Block or Blade ▪ Used for pushing scrapers, to assist and speed up loading (Fig. 13.12). A pusher block may be attached rigidly to the frame, mounted on an angle bulldozer C frame, or mounted in the center of a bulldozer. Or it can be mounted as a short bulldozer. Although designed especially as a tool for pushing, a pusher block can be used in a limited manner as a bulldozer. One

Fig. 13.11 Pipelayers. (*Caterpillar Tractor Co.*)

Fig. 13.12 Tractor pushing a scraper. (*Caterpillar Tractor Co.*)

Fig. 13.13 Tandem-powered, elevating scraper. (*Caterpillar Tractor Co.*)

way to absorb the shock when a pusher makes contact with a scraper is with springs; another is to use a hydraulic accumulator, which eliminates the need for stopping.

Welder ▪ Mounted on the tractor for mobility, welding machines are powered by the tractor engine.

Drills ▪ Often, a tractor serves as the prime mover for a rotary drill. During the drilling, the tractor engine powers the drill-steel rotation, hydraulic pumps, and air compressors. A percussion-type drill and air compressor also can be mounted on a tractor for mobility. Instead of a separate compressor, a piston-type compressor, powered by the tractor engine, can be mounted on the front or rear. Except for very large tractors, horsepower available is sufficient to furnish the required air for only one drill at a time.

13.8 Scrapers

Commonly used for earthmoving, a scraper may be self-propelled or powered by a crawler tractor. A self-propelled scraper may have two or three axles and may be single- or twin-engine. The single engine powers the front wheels (Fig. 13.13). With twin engines, one drives the front wheels; the second, the trailer wheels. Scrapers also can be worked in tandem, that is, two scrapers behind one power unit or tractor.

Essentially, a scraper acts like a scoop. A bowl hung from the frame tilts downward to permit its cutting edge to scrape off a thin layer of earth. As the scraper moves forward, the bowl fills. When it is full, it is tilted up and an apron is dropped down over the open end to close the bowl. For discharge in thin layers, the bowl tilts down and an ejector pushes the earth out.

On most scrapers, the bowl and apron are hydraulically operated, with pressure applied to the cutting edge and the apron forceably closed to retain shale, rock, or lumpy material in the bowl. Bowl and apron also may be cable-operated, but with hydraulic pressure on the cutting edge, harder material can be loaded.

Tractor-drawn scrapers can be used for short hauls. Maximum economic haul is about 1000 ft. This type of scraper is useful for stripping topsoil and earthmoving in marshy conditions.

Twin-engine scrapers are suitable for steep grades and swampy conditions. Such a scraper can outperform a crawler tractor-scraper combination on adverse grades and marshy soil. For best performance, a twin-engine scraper should be equipped with the largest-size tires, to obtain the greatest flotation under difficult conditions. Although this machine can obtain a load without a pusher, the scraper can load faster with a pusher, tire wear will be less, and there will be other benefits to offset the higher cost of pushing.

Two-axle self-propelled scrapers are more maneuverable, adaptable to rougher terrain and more difficult conditions, and better for shorter haul distance than three-axle units. The latter are more efficient on long hauls because they move faster on a haul road. Two-axle units bounce at high speeds, even on smooth haul roads. A three-axle unit is suitable for short hauls where there are no adverse return grades and there is ample maneuvering room, such as sites for airports, railroad classification yards, or industrial buildings.

On jobs with a small amount of rock, scrapers may be competitive with a shovel and rock-type trucks. Scraper tire and cutting-edge costs may exceed normal, but properly evaluated, wear costs may not be excessive. To keep costs within economic limits, cuts must be laid out so that scrapers can load without difficulty. At least half a cut, but preferably the entire cut, should be blasted for its entire length before scrapers start excavation. Better results will be obtained if some earth remains at the end of the cut or in locations where scrapers can complete a load in earth. Broken rock and shale do not "boil" or roll into the scraper; more power is required to force them into the bowl than for earth. When loading is completed in earth, however, rock is forced into the bowl. Hydraulic scrapers can forceably close the apron, thus reducing spillage. But a heaped or full load is very difficult to obtain. So the amount of material moved per trip is less with rock than with earth.

For handling by scrapers, rock has to be broken into small particles efficiently. Blasting holes have to be spaced closer, and more explosives per cubic yard are needed than for shovel-and-truck excavation. Most shales and sandstones can be blasted so that the maximum size can be easily controlled and enough fines produced to facilitate scraper loading. But igneous and metamorphic rocks, when blasted, do not readily produce a material that can be scraper-loaded. They have cleavage planes that form oversize particles and few fines. Experience, observations of rock formation, and comparisons of unit and total cost are necessary to determine whether to use scrapers or a shovel and supporting equipment.

13.9 Formulas for Earthmoving

External forces offer *rolling resistance* to the motion of wheeled vehicles, such as tractors and scrapers. The engine has to supply power to overcome this resistance; the greater the resistance, the more power needed to move a load. Rolling resistance depends on the weight on the wheels and the tire penetration into the ground.

$$R = R_f W + R_p p W \qquad (13.1)$$

where R = rolling resistance, lb

R_f = rolling-resistance factor, lb/ton

W = weight on wheels, tons

R_p = tire-penetration factor, lb/ton · in penetration

p = tire penetration, in

R_f usually is taken as 40 lb/ton (or 2% lb/lb) and R_p as 30 lb/ton · in (1.5% lb/lb · in). Hence Eq. (13.1) can be written as

$$R = (2\% + 1.5\%p)W' = R'W' \qquad (13.2)$$

where W' = weight on wheels, lb

R' = 2% + 1.5%p (see Table 13.7)

Table 13.7 Typical Total Rolling Resistances of Wheeled Vehicles

Surface	Lb per ton	Lb per lb
Hard, smooth, stabilized, surfaced roadway without penetration under load, watered, maintained	40	0.020
Firm, smooth roadway, with earth or light surfacing, flexing slightly under load, maintained fairly regularly, watered	65	0.033
Snow:		
Packed	50	0.025
Loose	90	0.045
Earth roadway, rutted, flexing under load, little if any maintenance, no water	100	0.50
Rutted earth roadway, soft under travel, no maintenance, no stabilization	150	0.75
Loose sand or gravel	200	1.00
Soft, muddy, rutted roadway, no maintenance	300–400	1.50–2.00

Additional power is required to overcome rolling resistance on a slope. Grade resistance also is proportional to weight.

$$G = R_g s W \tag{13.3}$$

where G = grade resistance, lb

R_g = grade-resistance factor = 20 lb/ton = 1% lb/lb

s = percent grade, positive for uphill motion, negative for downhill

Thus, the total road resistance is the algebraic sum of the rolling and grade resistances, or the total pull, lb, required:

$$T = (R' + R_g s)W' = (2\% + 1.5\%p + 1\%s)W' \tag{13.4}$$

In addition, an allowance may have to be made for loss of power with altitude. If so, allow 3% pull loss for each 1000 ft above 2500 ft.

Usable pull P depends on the weight W on the drivers:

$$P = fW \tag{13.5}$$

where f = coefficient of traction (Table 13.8). (See also Art. 13.12.)

Table 13.8 Approximate Traction Factors*

Traction surface	Traction factors	
	Rubber tires	Tracks
Concrete	0.90	0.45
Clay loam, dry	0.55	0.90
Clay loam, wet	0.45	0.70
Rutted clay loam	0.40	0.70
Loose sand	0.30	0.30
Quarry pit	0.65	0.55
Gravel road (loose not hard)	0.36	0.50
Packed snow	0.20	0.25
Ice	0.12	0.12
Firm earth	0.55	0.90
Loose earth	0.45	0.60
Coal, stockpiled	0.45	0.60

* See also Art. 13.12.

Earth Quantities Hauled. When soils are excavated, they increase in volume, or swell, because of an increase in voids (Table 13.9).

$$V_b = V_L L = \frac{100}{100 + \%\ \text{swell}} V_L \tag{13.6}$$

Table 13.9 Load Factors for Earthmoving

Swell, %	Voids, %	Load factor	Swell, %	Voids, %	Load factor
5	4.8	0.952	5.3	5	0.95
10	9.1	0.909	11.1	10	0.90
15	13.0	0.870	17.6	15	0.85
20	16.7	0.833	25.0	20	0.80
25	20.0	0.800	33.3	25	0.75
30	23.1	0.769	42.9	30	0.70
35	25.9	0.741	53.8	35	0.65
40	28.6	0.714	66.7	40	0.60
45	31.0	0.690	81.8	45	0.55
50	33.3	0.667	100.0	50	0.50
55	35.5	0.645			
60	37.5	0.625			
65	39.4	0.606			
70	41.2	0.588			
75	42.9	0.571			
80	44.4	0.556			
85	45.9	0.541			
90	47.4	0.526			
95	48.7	0.513			
100	50.0	0.500			

where V_b = original volume, yd^3, or bank yards
V_L = loaded volume, yd^3, or loose yards
L = load factor (Tables 13.9 and 13.10)

When soils are compacted, they decrease in volume.

$$V_c = V_b S \tag{13.7}$$

where V_c = compacted volume, yd^3
S = shrinkage factor

Bank yards moved by a hauling unit equals weight of load, lb, divided by density of the material in place, lb per bank yard.

Table 13.10 Percentage Swell and Load Factors of Materials

Material	Swell, %	Load Factor
Cinders	45	0.69
Clay:		
Dry	40	0.72
Wet	40	0.72
Clay and gravel:		
Dry	40	0.72
Wet	40	0.72
Coal, anthracite	35	0.74
Coal, bituminous	35	0.74
Earth, loam:		
Dry	25	0.80
Wet	25	0.80
Gravel:		
Dry	12	0.89
Wet	12	0.89
Gypsum	74	0.57
Hardpan	50	0.67
Limestone	67	0.60
Rock, well blasted	65	0.60
Sand:		
Dry	12	0.89
Wet	12	0.89
Sandstone	54	0.65
Shale and soft rock	65	0.60
Slag, bank	23	0.81
Slate	65	0.60
Traprock	65	0.61

13.10 Scraper Production

Production is measured in terms of tons or bank cubic yards of material a machine excavates and discharges, under given job conditions, in 1 hour.

$$\text{Production, bank yd}^3\text{/h} \tag{13.8}$$

$$= \text{load, yd}^3 \times \text{trips per hour}$$

$$\text{Trips per hour} = \frac{\text{working min/h}}{\text{cycle time, min}} \tag{13.9}$$

The load, or amount of material a machine carries, can be determined by weighing or estimating the volume. Payload estimating involves determination of the bank cubic yards being carried, whereas the excavated material expands when loaded into the machine. For determination of bank cubic yards from loose volume, the amount of swell or the load factor must be known (Tables 13.9 and 13.10); then the conversion can be made by use of Eq. (13.6).

Weighing is the most accurate method of determining the actual load. This is normally done by weighing one wheel or axle at a time with portable scales, adding the wheel or axle weights, and subtracting the weight empty. To reduce error, the machine should be relatively level. Enough loads should be weighed to provide a good average.

$$\text{Bank yd}^3 = \frac{\text{weight of load, lb}}{\text{density of material, lb/bank yd}^3} \tag{13.10}$$

For Eq. (13.9), cycle time, the time to complete one round trip, may be measured with a stopwatch. Usually, an average of several complete cycles is taken. Sometimes, additional information is desired, such as load time and wait time, which indicate loading ability and job efficiency, so the watch is kept running continuously and the times for beginning and ending certain phases are recorded. Table 13.11 is an example of a simple time-study form. It can easily be modified to include other segments of the cycle, such as haul time and dump time, if desired. Similar forms can be made for pushers, bulldozers, and other equipment.

Wait time is the time a unit must wait for another machine so that the two can work together, for example, a scraper waiting for a pusher. Delay time is any time other than wait time when a

Table 13.11 Cycle-Time Observations

Total cycle times (less delays), min	Arrive cut	Wait time	Begin load	Load time	End load	Begin delay	Delay time	End delay
	0.00	0.30	0.30	0.60	0.90			
3.50	3.50	0.30	3.80	0.65	4.45			
4.00	7.50	0.35	7.85	0.70	8.55	9.95	1.00	10.95
4.00	12.50	0.42	12.92	0.68	13.60			

machine is not working, for example, a scraper waiting to cross a road.

Since cycle time is involved in computation of production [Eq. (13.8)], different types of production may be measured, depending on whether cycle time includes wait or delay time. Measured production includes all waits and delays. Production without delays includes normal wait time but no delay time. For maximum production, wait time is minimized or eliminated and delay time is eliminated. Cycle time may be further altered by using an optimum load time, as determined from a load-growth study. (See also Art. 13.13.)

Example 13.1: A job study of wheeled scrapers yields the following data:

Weight of haul unit empty, 44,800 lb. Average of three weighings of haul unit loaded, 81,970 lb. Density of material to be excavated, 3140 lb/bank yd^3.

Average wait time, 0.28 min; average delay time, 0.25 min; average load time, 0.65 min; average total cycle time, less delays, 7.50 min.

What will be the production of the haul unit?

Average load will be $81{,}970 - 44{,}800 \text{ lb} = 37{,}170$ lb. This load is equivalent to $37{,}170/3140 = 11.8$ bank yd^3. In 60 working min/h, the scraper will make $60/7.50 = 8.0$ trips per hour. Hence, production (less delays) will be $11.8 \times 8.0 = 94$ bank yd^3/h.

Equipment Required ▪ To determine the number of scrapers needed on a job, required production must first be computed.

Production required,

$$\frac{\text{yd}^3}{\text{h}} = \frac{\text{quantity, bank yd}^3}{\text{working time, h}} \tag{13.11}$$

No. of scrapers needed

$$= \frac{\text{production required, yd}^3\text{/h}}{\text{production per unit, yd}^3\text{/h}} \tag{13.12}$$

No. of scrapers a pusher will load

$$= \frac{\text{scraper cycle time, min}}{\text{pusher cycle time, min}} \tag{13.13}$$

For computation of rolling resistance, see Art. 13.9; for traction, see Art. 13.12.

("Earthmoving Data," Caterpillar Tractor Co.)

13.11 Bulldozer Production

Production normally is measured by bank cubic yards dozed per hour. Because of the number of variables involved, determination of bulldozer production is difficult. A simplified method can provide a satisfactory estimate:

Two workers, using a 50-ft tape measure, can determine bulldozer payloads on the job. The bulldozer pushes its load onto a level area, stops, raises the blade while moving slightly forward, then reverses to clear the pile. The workers measure height, width, and length of the pile. To determine the average height, one worker holds the tape vertically at the inside edge of each grouser mark. The second worker, on the other side of the pile, aligns the tape with the top of the pile. To measure average width and length, the two hold the tape horizontally and sight on each end of the pile. Sighting to the nearest tenth of a foot is sufficiently accurate. Multiplication of the dimensions yields the loose volume in cubic feet; division by 27, in cubic yards. Application of a load factor [Eq. (13.6) and Tables 13.9 and 13.10] gives the loads in bank cubic yards.

13.12 Traction

This normally is measured by the maximum drawbar pull or rim pull, lb, a tractor exerts before the tracks or driving wheels slip and spin. When computing pull requirements for track-type tractors, rolling resistance does not apply to the tractor, only to the trailed unit. Since track-type tractors move on steel wheels rolling on steel "roads," rolling resistance is relatively constant and accounted for in the drawbar-pull rating.

Traction depends on the weight on driving tracks or wheels, gripping action with the ground, and condition of the ground. The coefficient of traction (Table 13.8) is the ratio of the maximum pull, lb, a tractor exerts when on a specific surface to the total weight on the drivers.

Example 13.2: What usable drawbar pull can a 59,100-lb tractor exert while working on firm earth? On loose earth?

The solution can be obtained with Eq. (13.5) and Table 13.8:

$$\text{Firm earth: } P = 0.90 \times 59{,}100 = 53{,}200\text{ lb}$$

$$\text{Loose earth: } P = 0.60 \times 59{,}100 = 35{,}500\text{ lb}$$

If 48,000 lb were required to move a load, then this tractor could move it on firm earth, but on loose earth the tracks would spin.

Example 13.3: What usable rim pull can a wheeled tractor-scraper exert while working on firm earth? On loose earth? Assume the weight distribution for the loaded unit as 49,670 lb on the drive wheels and 40,630 lb on the scraper wheels.

The solution can be obtained with Eq. (13.5) and Table 13.8. Use the weight on the drivers only.

$$\text{Firm earth: } P = 0.55 \times 49{,}670 = 27{,}320\text{ lb}$$

$$\text{Loose earth: } P = 0.45 \times 49{,}670 = 22{,}350\text{ lb}$$

If 25,000 lb were required to move a load and the engine were sufficiently powerful, the tractor-scraper could move the load on firm earth, but the drivers would slip on loose earth.

Equipment specification sheets show how many pounds pull a machine can exert in a given gear at a given speed. But if the engine works at high altitudes, it cannot produce as much power as it is rated for at sea level because of the decrease in air density. Up to 2500 ft above sea level, the reduction is insignificant. For each 1000 ft above 2500 ft an engine loses about 3% of its horsepower. But some machines with turbocharged engines operate at altitudes above 2500 ft without loss of power, so consult service literature on a machine before derating for altitude.

("Earthmoving Data," Caterpillar Tractor Co.)

13.13 How to Estimate Cycle Time and Job Efficiency

Before production on an earthmoving job can be estimated, cycle time for the equipment must be known [Eqs. (13.8) and (13.9)]. Cycle time is the time required to complete one round trip in moving material. Different approaches are used in estimating cycle time for each type of machine.

Track-Type Tractor-Scrapers ▪ Cycle time is the sum of fixed times and variable times. Fixed times in scraper work are the number of minutes for loading, turning, dumping, and in bulldozing, for gear shifting. Variable times comprise haul and return times. Experience shows that the fixed times in Table 13.12 are satisfactory for estimating purposes.

Since speeds and distances may vary on haul and return, haul and return times are estimated separately.

$$\text{Variable time, min} \tag{13.14}$$

$$= \frac{\text{haul distance, ft}}{88 \times \text{speed, mi/h}} + \frac{\text{return distance, ft}}{88 \times \text{speed, min/h}}$$

Haul speed may be obtained from the equipment specification sheet when the drawbar pull required is known.

Wheel-Type Tractor-Scrapers ▪ The procedure for estimating cycle time for wheel- and track-type tractors is about the same. But for wheel-type tractors, time consumed in acceleration and deceleration must be included in the estimate of fixed time. The values given in Table 13.12 may be used for estimating.

To determine the haul speed of a wheel-type tractor-scraper, it is necessary to match the rim pull required (total road resistance) against rim pull available (obtained from equipment specifications) and select a reasonable operating gear (from the specifications). Equation (13.14) may be used to

Table 13.12 Fixed Times for Estimating Cycle Time, min

Track-type Tractor and Scraper	Self-loaded 15 yd^3 or more	Self-loaded 14 yd^3 or less	Push loaded 15 yd^3 or more
Loading	1.5	1.0	1.0
Dumping, turning	1.0	1.0	1.0
Total fixed time	2.5	2.0	2.0
Track-type Tractor and Bulldozer			
Shuttle bulldozing using same gear and shifting only forward-reverse lever			0.1
Shuttle bulldozing shifting to higher reverse gear			0.2
Power-shift tractors			0
Track-type Tractor-Shovels (Fixed time for loading, turning, dumping)		Manual Shift	Power Shift
Bank or stockpile loading		0.35	0.25
Excavation		0.61	0.43
Wheel-type Tractor-Shovels			
Stockpile loading, power shift			0.20
Wheel-type Tractor-Scrapers with Pushers	5th-gear hauls	4th-gear hauls	3d-gear hauls
Loading	1.0	1.0	1.0
Maneuver and spread	0.5	0.5	0.5
Acceleration and deceleration	1.5	0.8	0.4
Total fixed time	3.0	2.3	1.9

figure variable time. The sum of fixed and variable times gives the estimated cycle time.

Power loss due to altitude is taken into account by dividing the total road-resistance factor [Eq. (13.4)] by a correction factor k. The resulting effective resistance factor then is used to compute travel time.

Table 13.13 Efficiency Factors for Average Job Conditions*

	Min per working h	Efficiency factor
Day Operation		
Track-type tractor	50	0.83
Wheel-type tractor	45	0.75
Night Operation		
Track-type tractor	45	0.75
Wheel-type tractor	40	0.67

* These take into consideration only minor delays. No time is included for major overhauls and repairs. Machine availability and weather also should be taken into account.

$$k = 1 - 0.03\frac{H - 2500}{1000} \tag{13.15}$$

where H = altitude above sea level, ft. Travel time can be determined from data supplied by the scraper manufacturer.

Job efficiency depends on many variables, including operator skill, minor repairs and adjustments, delays caused by personnel, and delays caused by job layout. Table 13.13 lists approximate efficiency factors for estimating when job data are unavailable. Production, cubic yards per working hour, then equals production, yd^3/h, times the efficiency factor.

13.14 Mass Diagram

This is a graph showing the accumulation of cut and fill with distance from a starting point, or origin. Cut usually is considered positive and fill negative. The volume of each is plotted in cubic yards. Distance normally is measured, along the center line of the construction, in stations 100 ft apart, starting with the origin as $0 + 00$. Swell factors are applied to the cuts and shrinkage factors to the embankments [Eqs. (13.6) and (13.7)] to obtain bank cubic yards excavated and compacted fill, respectively.

Figure 13.14*b* shows a mass diagram for the profile in Fig. 13.14*a* (shrinkage factor of 10% and

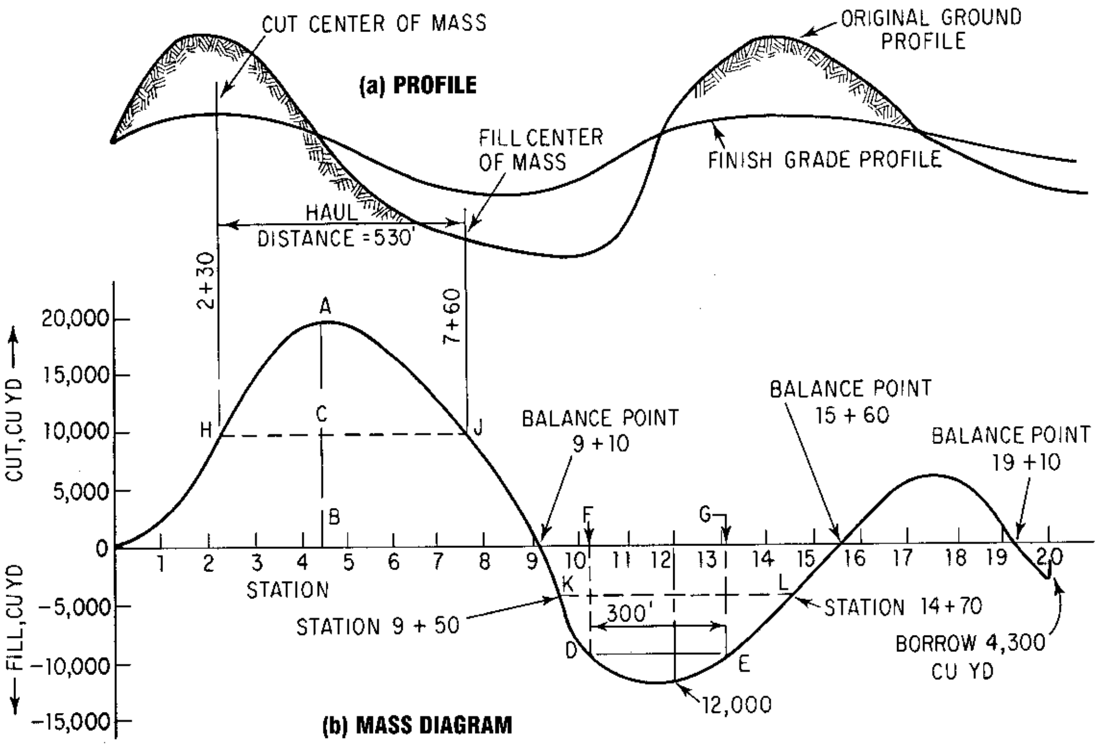

Fig. 13.14 Profile and mass diagram for cut and fill for grading a highway.

swell factor of 20% included). Between 0 + 00 and 1 + 00, there is a cut of 2000 yd^3. This is plotted at 1 + 00. Between 1 + 00 and 2 + 00, there is a cut of 5000 yd^3, making a total of 7000 yd^3 between 0 + 00 and 2 + 00; 7000 is plotted at 2 + 00. At 4 + 00, there is a total accumulation of 18,000 yd^3 of cut. Between 4 + 00 and 5 + 00, there are 1000 yd^3 of cut and 550 yd^3 of embankment (corrected for shrinkage), making a net accumulation of

$$18{,}000 + 1000 - 550 = 18{,}450\,\text{yd}^3$$

From 6 + 00 to 12 + 00, there is mostly embankment, and the accumulation decreases to −12,000 yd^3. Cut follows, then some more embankment. At the end of the construction, 20 + 00, there is a net of −4300 yd^3 embankment that must be obtained from borrow.

If a mass curve is horizontal between stations, the implication is that no material has to be moved in that stretch. Actually, there may be cuts and fills but they balance. If work consists of side-hill cuts and fills, the mass diagram tends to flatten because the cuts can be moved into the fills and not moved from one station to another. Moving excavation from one side of the center line to the other is called **cross haul**.

The slope of the mass curve increases with volume between stations. An ascending mass curve indicates cut; a descending diagram, fill. The curve reaches a maximum where cut ends and fill begins, and a minimum where fill ends and cut begins.

If a mass diagram is intersected by a horizontal line, cuts balance fills between the points of intersection. If the mass curve loops above the line, cuts will have to be hauled forward (in the direction of increasing stations) for the embankments; if the diagram lies below the horizontal line, the haul will have to be backward.

Haul, station-yards, for a section of earthwork is the product of the amount of excavation, cubic yards, and the distance it is moved, stations. Total haul is the product of total amount of excavation hauled and average haul distance. The area between the mass diagram and a balancing (horizontal) line equals the haul, station-yards, between the two points cut by that line. Average haul distance equals the area between the mass diagram and the balancing line divided by the total cut (maximum ordinate) between the points of intersection.

Center of mass of cut and fill can be determined from the mass diagram. Draw the maximum ordinate between a balancing line and the curve (for example, *BA* in Fig. 13.14*b*). Then, draw a horizontal line (*HJ*) through the midpoint of that ordinate, and note the stations at the points of intersection with the curve. The station (*H*) on the increasing portion of the diagram is the center of mass of cut; the station (*J*) on the decreasing portion, the center of fill. The distance between the stations is the haul distance.

If the mass curve terminates below the horizontal axis, borrow is required. If the curve ends above the axis, excavation must be wasted.

Free haul is the distance excavation may be moved without an increase in contract price; that is, the unit bid price for excavation applies only to haul distances less than free haul. Overhaul is haul distance exceeding free haul. The bid price for overhaul usually is given in terms of dollars per station-yard.

Example 13.4: For Fig. 13.14, if free haul is 300 ft. determine the overhaul between 9 + 10 and 15 + 60.

Draw horizontal line *DE* with length 300 ft between two points on the mass curve. Draw ordinates *FD* at *D* and *GE* at *E*. These vertical lines set the limits of free haul. Next, the center of mass of cut and fill outside these limits must be found. To do this, draw a horizontal line through the midpoints of *FD* and *GE* intersecting the mass curve at *K* and *L*. The center of mass of cut is at *L*, 14 + 70, and of fill, at *K*, 9 + 50. *KL* = 5.2 stations represents the average haul distance. Hence, the overhaul equals the product of $DF = 9500 \text{ yd}^3$ and *KL* less the free-haul distance (5.2 − 3.0), or 20,900 station-yards.

(C. F. Allen, "Railroad Curves and Earthwork," McGraw-Hill Book Company, New York.)

13.15 Drilling for Rock Excavation

Usually, before rock can be excavated, it must be blasted into pieces small enough for efficient handling by available equipment. To place explosive charges for this purpose, holes have to be drilled into the rock. This is done with percussion or rotary drills. Percussion generally is used for hard rock and small-diameter holes. Maximum size of bit for percussion drills is about 6 in. Larger bits may be used on rotary drills (Fig. 13.15), but they rarely exceed 9 in in diameter.

Normally, percussion drills are mounted on self-propelled crawlers (Fig. 13.16). Drilling commonly is done with sectional drill steel and carbide-insert bits, both of which have to be rugged. A bit has first to crush its way into the rock. Next, the hole must be reamed. Finally, the cuttings are mixed and

Fig. 13.15 Track-mounted rotary drill with air compressor. (*Caterpillar Tractor Co.*)

Fig. 13.16 Percussion drill powered by an air compressor and mounted on a tractor. (*Caterpillar Tractor Co.*)

blown from the hole by compressed air fed through a hole in the center of the drill steel and discharged through holes in the bit. Hard rock requires a bit with good crushing or penetrating and reaming ability. Shales, usually soft, require a bit that mixes material fast. The bit does not need to have good crushing ability. For sandstone, the gage will usually be destroyed first or the bit will lose its reaming ability. A bit used in sandstone must have exceptional reaming ability plus good mixing features.

The best way to determine how well a bit is performing is to inspect the chips. They should be firm pieces of rock, not dust. When cuttings are dust, usually the chips are not being blown from the hole until they have been reground several times. This causes more than normal bit wear. Low air pressure also may produce excessive dust. Pressure at the drill should be at least 90 psi. When computing the pressure, take into account the drop in pressure due to friction in the hose.

Rotary drilling is more suitable for large holes. With low-cost ammonium nitrate and fuel oil as the explosive, economical production results. With large holes, spacing can be greater and more cubic yards can be produced per foot of hole. When determining whether to use large or small holes, the engineer should bear in mind that the amount of explosives is directly proportional to the area of the hole.

In rotary drilling, it is essential to maintain sufficient down pressure, rotation speed, and volume and pressure of air used to blow cuttings out of the hole or excessive bit wear and low production results. Down pressure should be at least 5000 psi/in of bit diameter. Rotation speed should be the largest possible without regrinding chips before they are blown out of the hole. Therefore, rotation speed depends on air volume. Air is blown through the center of the drill steel and discharged through passages in the bit. Except in extremely deep holes, 40 psi usually is enough pressure to clean holes.

13.16 Explosives for Rock Excavation

Explosives are used to blast rock into pieces small enough to be handled efficiently by available equipment. The charges usually are set in holes drilled into the rock (Art. 13.15) and detonated.

If the reaction is instantaneous or extremely rapid over the entire mass of the explosive, detonation has occurred. Deflagration, however, takes place when the reaction particles move away from the unreacted particles or the material burns. The basic difference between these two reactions is that detonation produces a high-pressure shock wave that is self-propagating throughout the charge.

Several factors contribute to the effectiveness of an explosive charge: confinement, density, most efficient uniform propagation diameter, and critical mass.

Confinement helps the reacted products contribute to detonation of the unreacted products. If the reacted portions can escape, the reactions will cease. An air space can be very effective in dampening a reaction.

The denser the mass of the charge, the more effective it will be, up to a point. For every explosive, there is an optimum density. Since drilling costs more than explosives per cubic yard of excavation, it is desirable to use as many pounds of explosive per foot of borehole as possible.

The most efficient uniform propagation diameter is the width or length over which the explosive mass will be self-propagating after detonation starts. This length ranges from very small to about 9 in for ammonium nitrate.

The self-propagating diameter can be lowered by the overdrive method. Overdrive is the ability of an explosive to detonate at a rate greater than the self-propagating detonating rate. Suppose, for example, an explosive that detonates at 21,000 ft/s is set off in contact with another type of explosive that detonates at 12,000 ft/s. Then, the slower explosive will detonate at more than 12,000 ft/s but less than 21,000 ft/s for a given distance, usually less than 2 ft.

Sensitivity of an explosive is very important from a safety standpoint. An explosive should be easy to detonate by specific methods, but hard or impossible to set off with normal or careful handling during manufacture, shipment, storage, and preparation for detonation.

Critical mass is that amount of an explosive that must be present for the reaction to change from deflagration to detonation. This mass is very small for high-order explosives but about 123 tons for ammonium nitrate.

Explosive manufacturers generally balance the ingredients of their products to get maximum gas volume. This usually depends on the amount of oxygen available from an unstable oxidizer in the explosive. A combination of gas ratio and brisance (shattering effect) is called power factor. Explosive ingredients can be combined many ways to provide almost any power factor.

Rate of detonation is a rough measure of the shattering ability of an explosive. Mass formations of rock require a rate of at least 12,000 ft/s. Maximum detonating rate for commercial explosives is 26,000 ft/s.

Explosive strength generally is rated by the percent of nitroglycerin or equivalent in explosive power contained in an explosive. Straight dynamites contain only nitroglycerin and an inert ingredient. In an ammonia dynamite, some of the nitroglycerin is replaced by other ingredients, such as ammonium nitrate. Explosive power may be denoted by weight strength or bulk or cartridge strength. When weight strength is given, an ammonia dynamite will have the same explosive power as a straight dynamite of the same strength. Following are important features of explosives commonly used in construction:

Gelatin Dynamites ▪ Weight strength from 100 to 60%. Detonation rate from 26,200 to 19,700 ft/s, respectively. Suitable for submarine blasting or for use where considerable water pressure will be encountered. Inflammable. Has high shattering action.

Gelatin Extras ▪ Weight strength from 80 to 30%. Detonation rate from 24,000 to 15,000 ft/s, respectively. Ammonium nitrate replaces part of nitroglycerin. Gelatin extras have less water resistance than gelatins but can be used satisfactorily except under the most severe conditions.

Extra Dynamites ▪ Weight strength from 60 to 20%. Detonation rate from 12,450 to 8200 ft/s. Ammonium nitrate replaces part of nitroglycerin. Extra dynamites can be used in average water conditions if properly wrapped with waterproofing. They usually are called original ammonia dynamites.

Semigelatins ▪ Weight strength from 65 to 40%; bulk strength from 65 to 30%. Detonation speed from 17,700 to 9850 ft/s. Higher detonation speeds for larger-diameter cartridges. Can be used instead of gelatins in most blasting uses. Water resistance is adequate for average conditions.

High-Ammonium-Nitrate-Content Dynamites ▪ Weight strength from 68 to 46%; bulk strength from 50 to 20%. Detonation speed from 10,500 to 5250 ft/s. Has low water resistance but can be used if fired within a relatively short time of exposure.

Boosters or Primers ▪ Have high density. Detonation speed of 25,000 ft/s. Used to detonate ammonium nitrates and fuel oil or any non-cap-sensitive explosive because boosters and primers have a very high detonation pressure.

Detonating Cord ▪ Used as a fuse. Has high-explosive core that detonates at 21,000 ft/s with sufficient energy to detonate another, less sensitive explosive alongside in a borehole. When strung from top to bottom of a hole, detonating cord will act as a detonating agent throughout the length of the hole.

Ammonium nitrate, for best results, should be mixed with at least 6% fuel oil, by weight. The oil is added for oxygen balancing and to lower the self-propagating diameter. Quantities of fuel oil greatly in excess of 6% have a dampening effect on the explosion. By use of the overdrive method, the rate of detonation for ammonium nitrate and fuel oil will be sufficient to shatter any rock formation encountered. Ammonium nitrate plus 10% booster has a rate of 4500 to 10,000 ft/s; when fuel oil is added, the rate increases to 10,000 to 16,500 ft/s. For overdrive, best results are obtained with at least 5% of a primer with a high detonation rate. The primers should be properly spaced to ensure that critical propagation length will not be exceeded and detonation will occur throughout.

Special precautions should be observed when overdrive is used. If free fuel oil is available in the mixture, an ammonia dynamite should not be used as a primer. Fuel oil will desensitize ammonia dynamite, and a partial or complete failure will result. Fuel oil also has an adverse effect on the explosive contained in detonating cord. This, however, can be avoided by using a plastic coating on the cord.

Table 13.14 gives the approximate amount of ammonium nitrate to use per foot of borehole. The table assumes a density of 47 lb/ft^3 for ammonium nitrate and fuel oil.

Ammonium nitrate is soluble in water. It develops some water resistance when mixed with fuel oil. But exposure to water results in loss of efficiency, and detonation becomes difficult.

Table 13.14 Amount of Ammonium Nitrate per Foot of Borehole

Hole dia., in	Approx. weight, lb per ft	Approx. volume, ft^3 per ft
2	1.02	0.0218
2¼	1.29	0.0275
2½	1.59	0.034
3	2.30	0.049
3¼	2.67	0.057
3½	3.00	0.064
4	4.09	0.087
4½	5.17	0.110
5	6.39	0.136
5½	7.75	0.165
6	9.21	0.196
6¼	10.01	0.213
6½	10.81	0.230
6⅞	12.03	0.256
7	12.54	0.267
7¼	13.44	0.286
7⅞	15.79	0.336
8	16.40	0.349
8½	18.51	0.394
9	20.72	0.441
9½	23.12	0.492
10	25.61	0.545
10½	28.24	0.601
11	30.97	0.659
11½	33.88	0.721
12	36.89	0.785

13.17 Rock Excavation by Blasting

To secure the desired shape of rock surface after blasting, explosive charges must be placed in boreholes laid out in the proper pattern and of sufficient depth. (See also Arts. 13.15 and 13.16.) Before the pattern is chosen, an explosive factor must be selected (Table 13.15).

Next, drill size, burden, and spacing can be selected. Then, the amount of stemming can be determined. **Stemming** is the top portion of a borehole that contains a tightly tamped backfill, not explosive. Since an explosive exerts equal pressure in all directions, depth of stemming should not exceed the width of burden. **Burden** is the distance from the borehole to the rock face. Burden distance should be less than the hole spacing so that the blasted rock will be thrown in the direction of the burden.

Holes should be placed in lines parallel to the rock face because a rectangular pattern gives better breakage and vibration control. Depth of drill holes is determined by height of face desired and the distance it is necessary to drill below grade so that the bottom can be controlled.

A mathematical check should be made to determine that the explosive factor is correct for the burden and spacing selected. If properly blasted rock is not produced when a drill pattern is tried, a new spacing or burden width should be tried. It is best to vary only one dimension at a time until desired fragmentation is obtained.

Delay caps may be used on the explosive charges for better fragmentation and vibration control. Delay caps permit detonation of explosive charges in different holes at intervals of a few milliseconds. The result is better fragmentation,

Table 13.15 Explosive Factors

Types of rock	Explosive factor, lb/yd^3
Shales	0.25–0.75
Sandstone	0.30–0.60
Limestone	0.40–1.00
Granite	1.00–1.50

controlled throw, and less back break since better displacement is obtained. Table 13.16 gives characteristics of short-period delay caps. Use of regular delays is not recommended because of "hole robbing" and uncontrolled throw.

Presplitting is a technique for producing a reasonably smooth, nonshattered wall, free from loose rock. An objective is to hold maintenance of slopes and ditches to a minimum. Presplit holes are drilled in a single line in a plane that will be the final slope or wall face. Line drilling also may be used, with holes spaced about two times the bit diameter. But for presplitting, the spacing is much greater. Dynamite, evenly spaced on detonating cord, is exploded to break the web between holes. Manufacturers can furnish explosives made for presplitting. When this type of explosive is used, loading of holes is easier since no detonating cord is required. The resulting saving of labor will usually more than offset additional explosive costs.

Table 13.16 Characteristics of Millisecond Delay Caps*

Delay period	Nominal firing time, ms	Interval between delay periods, ms
0	12	
SP-1	25	13
SP-2	50	25
SP-3	75	25
SP-4	100	25
SP-5	135	35
SP-6	170	35
SP-7	205	35
SP-8	240	35
SP-9	280	40
SP-10	320	40
SP-11	360	40
SP-12	400	40
SP-13	450	50
SP-14	500	50
SP-15	550	50
SP-16	600	50
SP-17	700	100
SP-18	900	200
SP-19	1100	200
SP-20	1300	200
SP-21	1500	200
SP-22	1700	200
SP-23	1950	250
SP-24	2200	250
SP-25	2450	250
SP-26	2700	250
SP-27	2950	250

* Courtesy of Hercules Powder Co.

Percussion drills commonly are used for drilling presplitting holes. An air track with hydraulic controls is very effective in enabling the driller to move from hole to hole and reset the drill in a minimum time. Number of drills required varies with capacity of loading shovel, width of cut, and spacing of presplit holes.

For presplitting, 40% extra gelatin works satisfactorily. This explosive has a detonation speed that can break the hardest rock formations and is adequate under the most adverse conditions. Speed of detonation should not be less than 15,000 ft/s for presplitting.

Figure 13.17*a* shows a presplit hole loaded with $1\frac{1}{4} \times 8$-in cartridges spaced 18 to 24 in apart on

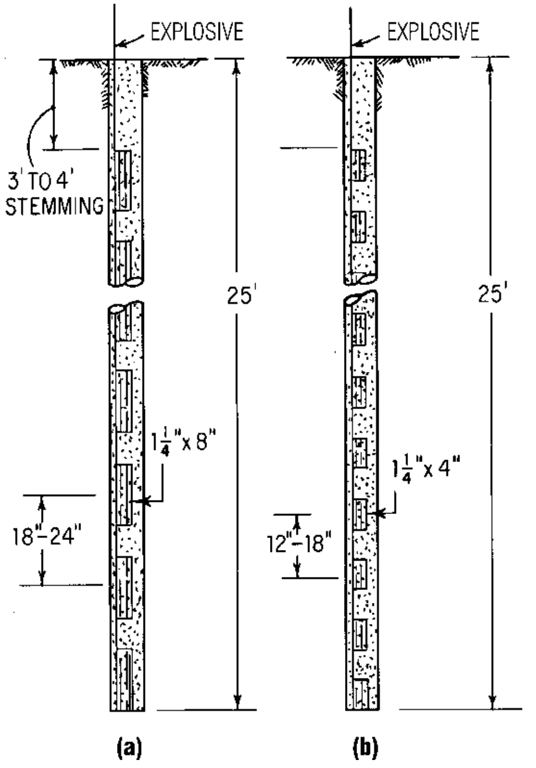

Fig. 13.17 Drill holes loaded with (*a*) $1\frac{1}{4} \times 8$-in catridges and (*b*) $1\frac{1}{4} \times 4$-in catridges on detonation cord for presplitting. Prepackaged explosives are available from explosive manufacturers.

Table 13.17 Pounds of 40% Gelatin Extra to Produce 2500 ft^2 of Wall by Presplitting

Hole Spacing	1¼ × 8-in cartridges		1¼ × 4-in cartridges	
	18 in c to c	24 in c to c	12 in c to c	18 in c to c
18	362	272	272	181
24	270	203	203	135
30	215	161	161	108
36	178	134	134	89
42	152	114	114	76
48	132	99	99	66
54	117	88	88	58
60	105	79	79	52
66	95	71	71	47
72	86	64	64	43

primacord; Fig. 13.17*b* shows 1¼ × 4-in cartridges on 12- to 18-in spacing. Table 13.17 indicates the number of pounds of 40% gelatin extra required to produce a wall 25 ft high by 100 ft long.

Presplitting should precede the primary blast. Some locations, however, preclude this; for example, a side hill where there would not be sufficient burden in front of the presplit holes. In such a case, presplitting will be accomplished, but the burden in front will be shifted, causing loss of primary blast holes or difficult drilling if the holes were not drilled previously. If a sidehill condition exists, delay caps should be used to ensure that presplitting is done before detonation of the primary blast.

Spacing of holes for presplitting varies considerably with material, location, and method of primary blasting. Spacings up to 6 ft have been found adequate where no restrictions are imposed on explosives and primary blasting can be adjusted to obtain correct balance for removal of material within the walls. Obtaining a good wall is the result of balancing primary blasting with as wide a spacing as possible for the type of rock. Use of close spacing of holes without consideration of other factors may be wasteful and not yield best overall results.

Spacing of presplit holes and charges for best results may be determined by trial. Vary only one variable at a time. For example, initially drill the holes for 25 ft of wall 18 in apart and detonate. Then, for the next 25 ft of wall, drill the holes 24 in on centers and detonate with the same loading. Continue increasing the spacing until a maximum is reached. Next, vary the charge. If too much dynamite is used, the resulting surface between

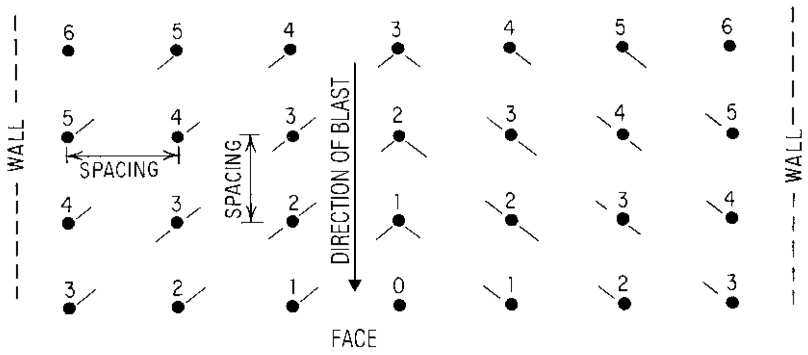

Fig. 13.18 Drill pattern for conventional blasting with holes all of the same diameter. Numbers indicate order of firing with delays.

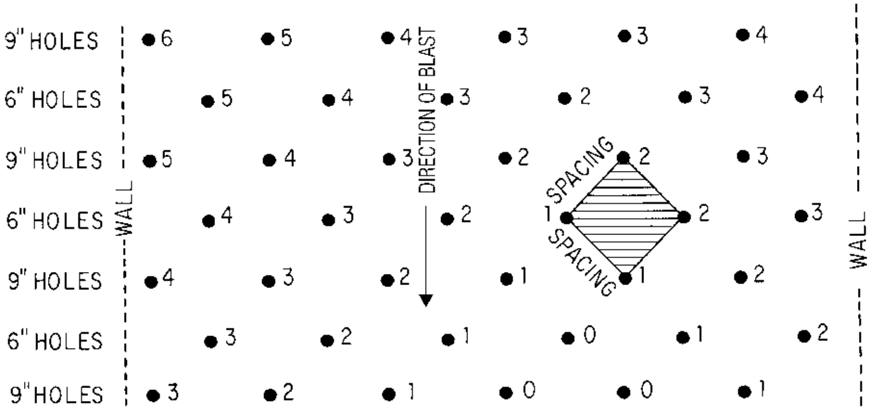

Fig. 13.19 Drill pattern for conventional blasting with two sizes of holes. Numbers indicate order of firing with delays.

holes will be concave. Conversely, with insufficient dynamite, the surface will be convex.

In **conventional blasting**, placing of delays in the primary blast is important. The more relief that can be given to holes near the wall, the less opportunity for damage to the wall (Figs. 13.18 and 13.19 and Tables 13.18 and 13.19).

The depth of each lift in presplitting is governed by the size of the shovel excavating equipment. Lifts generally average 20 to 25 ft. The last lift may be deeper, to reach grade in one setup. For efficiency, each lift should be presplit separately. Drilling speed diminishes rapidly as a 40-ft depth is approached.

When more than one lift is required, the drill has to be set up for successive lifts at least 1 ft away from the face, to provide clearance for drilling (Fig. 13.20).

Loading of deep holes, particularly if they contain water, can be very difficult. Stringing sticks of dynamite on a long detonating cord can exceed the structural strength of the cord, breaking it and causing a misfire.

After holes have been drilled, dynamite cartridges are fastened to a detonating cord, usually 50 grain, long enough to reach the bottom of the hole. Spacing of charges on the cord varies with rock formation and hole spacing. Charges may be attached with tape or rubber bands. With rubber bands, spacing is easier to maintain because the charges do not slip so easily. In a limestone formation with holes drilled at 4-ft intervals, 1¼ × 8-in charges spaced 18 in on centers have been

Table 13.18 Powder Factor for Drill Pattern of Fig. 13.18

Spacing of holes, ft	Burden, yd^3	Powder factor*
For 9-in-Dia Holes, 25 ft Deep, 10 ft Loaded, 207 lb of Ammonium Nitrate		
20 × 18	333	0.62
18 × 16	267	0.78
16 × 14	207	1.00
14 × 12	156	1.33
12 × 10	111	1.87
For 6-in-Dia Holes, 25 ft Deep, 16 ft Loaded, 147 lb of Ammonium Nitrate		
18 × 16	267	0.55
16 × 14	207	0.71
14 × 12	156	0.94
12 × 10	111	1.32
10 × 8	74	1.99
For 5-in-Dia Holes, 25 ft Deep, 17 ft Loaded, 109 lb of Ammonium Nitrate		
16 × 14	207	0.52
14 × 12	156	0.70
12 × 10	111	0.98
10 × 8	74	1.47
8 × 6	44	2.46

* Pounds of ammonium nitrate, density 47 lb/ft^3, per cubic yard of burden.

Table 13.19 Powder Factor for Drill Pattern of Fig. 13.19

Hole dia, in	Hole depth, ft	Load depth, ft	Charge Lb	Charge Lb per ft
5	25	17	108.63	6.39
6	25	16	147.36	9.21
9	25	10	207.20	20.72

Spacing, ft	Burden, yd^3	Powder factor* 9-in holes	9- and 6-in holes	9- and 5-in holes	6-in holes	6- and 5-in holes	5-in holes
8 × 8	59	3.51	3.00	2.68	2.50	2.17	1.84
10 × 10	93	2.23	1.91	1.70	1.58	1.38	1.17
12 × 12	133	1.56	1.33	1.19	1.11	0.96	0.82
14 × 14	194	1.07	0.91	0.81	0.76	0.66	0.56
16 × 16	237	0.87	0.75	0.67	0.62	0.54	0.46
18 × 18	300	0.69	0.59	0.53	0.49	0.43	0.36
20 × 20	370	0.56	0.48	0.43	0.40	0.35	0.29
22 × 22	448	0.46	0.40	0.35	0.33	0.29	0.24

* Pounds of ammonium nitrate, density 47 lb/ft^3, per cubic yard of rock.

found adequate, whereas good results have been obtained in soft shale with a 50% reduction in the charge, to $1\frac{1}{4} \times 4$ in, and the same hole spacing. Detonation cord from each hole is attached to a trunk line, which when fired causes each hole to detonate instantaneously.

Stemming can be done several ways. In one method, after the charge has been placed in a hole,

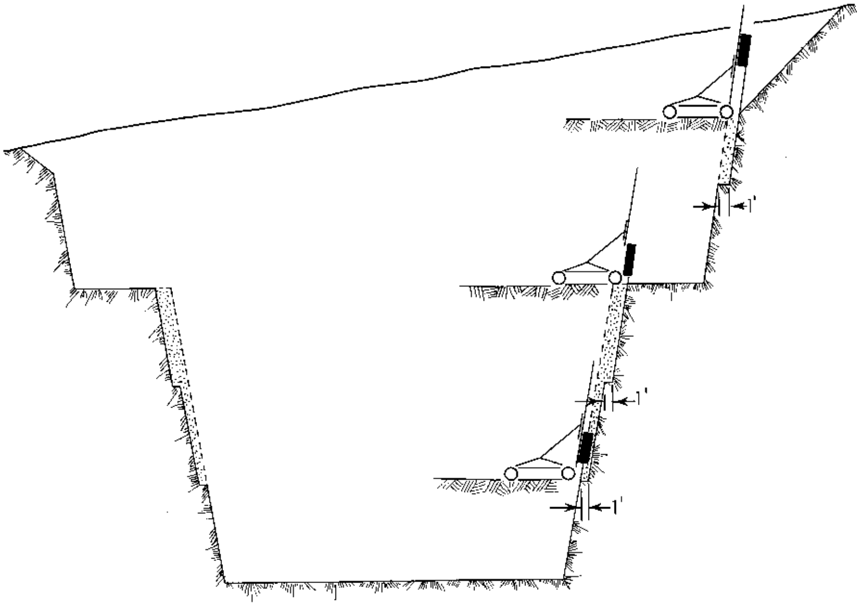

Fig. 13.20 Placement of a drill in a multilift cut.

clean stone chips or sand that will pass a $\frac{3}{8}$-in standard sieve is placed on top. For best results, the stemming should be worked around the charges by holding the end of the detonation cord in the center of the hole and working it up and down. Another stemming method is to push newspaper into the hole until it reaches the top charge. On top of the paper, the hole is stemmed with drill cuttings or other suitable available material.

In most blasting procedures, it is good practice to have as much confinement as possible. In presplitting, some means must be provided to allow excess gases to escape. Use of detonation cord and top firing produces best results. Most instant blasting caps have so much delay that breakage occurs in the wall if they are used. To reduce noise and vibration, delay connectors may be used between groups of two or more holes.

The cost of presplitting per cubic yard excavated depends on the distance between walls or volume to be removed per square foot of presplit wall. Presplitting eliminates the need for small-diameter holes for a primary blast, moving of material from behind a pay line, and scaling of slopes. If presplitting is not required and no pay will be received for material excavated behind a pay line set 18 in beyond the design slope, then, to control excess excavation, small-diameter blast holes would be drilled near the slope at a minimum spacing of 6 ft. These holes would be the same diameter as presplit holes in most cases. Usually, two rows of these holes would be required. The primary blast holes would be at a greater distance from the design slope than for presplitting. When presplitting is used, the spacing of the primary blast holes can be rearranged to produce well-broken rock that will load more easily at less cost.

A cost comparison between presplitting and conventional blasting should compare the cost of blasting the entire cut without presplitting with the cost of presplitting, rearranging the primary blast, and shooting. Generally, presplitting will cost less. For most formations, this will be true when the ratio of cubic yards excavated to square feet of presplit wall exceeds 1.5:1.

13.18 Vibration Control in Blasting

Explosive users should take steps to minimize vibration and noise from blasting and protect themselves against damage claims.

Before blasting, an explosive user should conduct a survey of nearby structures. Experienced, qualified personnel should make this survey. They should carefully inspect every structure within a preselected distance, at least 500 ft. for cracks, deformation from any cause, and other damage that could be claimed. They should make a written report of all observations, wall by wall, and take pictures of all previous damage. This is known as a preblast survey and should be well documented for future use in case of a claim.

Any rock excavation project is a part of some community and has an effect on the surrounding environment. The explosive user can be a good neighbor, enjoying that position, or an undesirable one and suffer the consequences. The decision as to whether the explosive user is an asset or a liability is not made by people familiar with blasting problems. Quarries and rock excavation projects, therefore, should be operated with the realization that any right to exist will have to be proved by behavior acceptable to the community.

To be a good neighbor, an explosive user must not make noise, create vibrations, or throw projectile rocks. The first and last factors are easy to control if proper supervision and good guidance are used. If a neighbor does not hear or see the blast, annoyance is greatly diminished.

Noise and throw are best controlled during drilling and loading cycles. No explosives should be loaded closer to the ground surface than the least dimension used for drill-hole spacing. In other words, put explosives in the bottom of holes and use as much stemming as possible; when noise occurs, energy has been wasted. Using larger holes, with resulting wide spacing, will usually produce oversize stone in the top of the shot. This can be controlled by the use of small (satellite) holes drilled to a shallow depth, below the top of the explosives, between large-diameter holes. This is one method used to get explosives evenly distributed.

Extreme care should be exercised with detonating cord. Nothing makes a sharper and more startling noise. When detonating cord is demanded, a low-noise-level cord should be used, and it should be covered with some material that will not contaminate the desired product. Considerable depth of covering is required to control noise: Experience dictates not less than 3 ft for $\frac{1}{4}$-cord.

Knowledge of human habits and how to use the surrounding environment will greatly help reduce complaints. Set off blasts while people are busy with their daily tasks. Bear in mind that weather conditions affect noise transmission. Blasting during cloudy, overcast weather is like shooting in a room that has a roof. Use other noise- and vibration-producing elements of the surrounding environment for dampening or overriding effects, for example, scheduling and performing blasts while a freight train passes or while a jet airplane is taking off.

Vibrations caused by blasting are propagated with a velocity V, ft/s, frequency f, Hz, and wavelength L, ft, related by

$$L = \frac{V}{f} \tag{13.16}$$

Velocity v, in/s, of the particles disturbed by the vibrations depends on the amplitude of the vibrations A, in.

$$v = 2\pi f A \tag{13.17}$$

If the velocity v_1 at a distance D_1 from the explosion is known, the velocity v_2 at a distance D_2 from the explosion may be estimated from

$$v_2 \approx v_1 \left(\frac{D_1}{D_2}\right)^{1.5} \tag{13.18}$$

The acceleration a, in/s^2, of the particles is given by

$$a = 4\pi^2 f^2 A \tag{13.19}$$

For a charge exploded on the ground surface, the overpressure P, psi, may be computed from

$$P = 226.62 \left(\frac{W^{1/3}}{D}\right)^{1.407} \tag{13.20}$$

where W = maximum weight of explosives, lb per delay

D = distance, ft, from explosion to exposure

The sound pressure level, decibels, may be computed from

$$dB = \left(\frac{P}{6.95 \times 10^{-28}}\right)^{0.084} \tag{13.21}$$

For vibration control, blasting should be controlled with the scaled-distance formula:

$$v = H\left(\frac{D}{\sqrt{W}}\right)^{-\beta} \tag{13.22}$$

where β = constant (varies for each site)

H = constant (varies for each site)

Distance to exposure, ft, divided by the square root of maximum pounds per delay (Fig. 13.21) is known as **scaled distance**.

Most courts have accepted the fact that a particle velocity not exceeding 2 in/s will not damage any part of any structure. This implies that, for this velocity, vibration damage is unlikely at scaled distances larger than 8 (see Fig. 13.22).

Without specific information about a particular blasting site, the maximum weight of explosives per delay should conform with explosive weight and distance limits to prevent vibration damage. This conforms with a scaled distance of 50 or greater without known facts (Fig. 13.21).

To control vibration, the scaled-distance formula should be applied for each blasting location. If formations vary around the site, each formation will have a different formula, which should be computed. The more blasts used in determining the formula constants, the more accurate the scaled-distance formula becomes. Only two easily determined factors must be known: distance from seismograph and maximum weight of explosive used with any delay. Once a safe scaled distance has been determined, the need to use a seismograph for vibration measurements of future blasts is unlikely. Particle velocity can be computed with actual measured distance and known maximum weight of explosives used with any delay.

There is a direct relationship between particle velocity (vibration) and number of complaints expected from families exposed. This is shown in Fig. 13.23.

When a complaint is received, it should be handled firmly and expeditiously. Following are some suggestions:

Assign one person the primary responsibility for handling complaints. This person should be mature and capable of communicating with complainants who are sincerely upset and afraid of not only property damage but bodily injury. A minimum of two employees should, preferably,

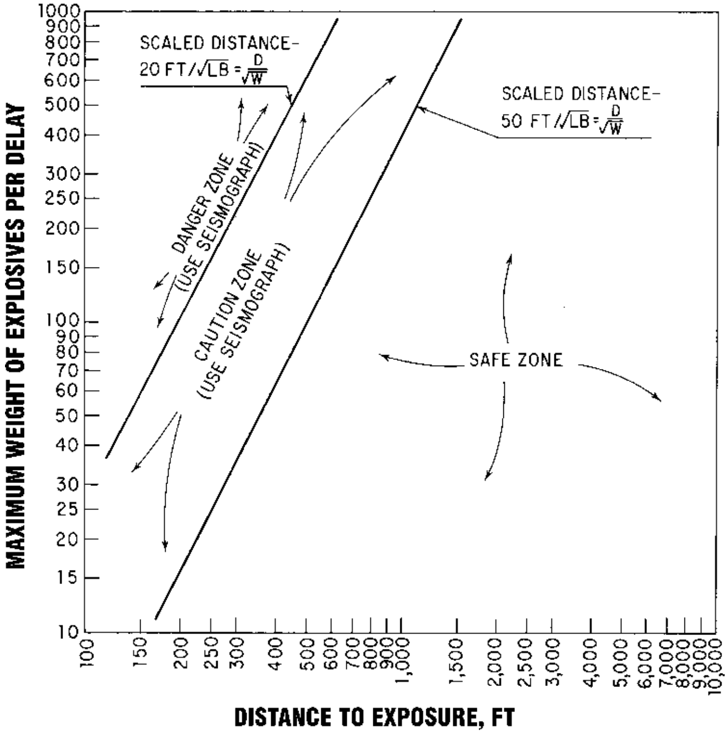

Fig. 13.21 Explosive weight and distance limits for prevention of damage from the vibrations of blasting.

be detailed because the primary employee may not always be available. The primary employee should always be held responsible and informed of all complaints.

Before blasting begins, the public should be advised about whom to contact for any information. When a complaint is received, record the complainant's name, address, and telephone number. Ask at what time the blast was felt and heard. Ask if blast was felt or heard first. Was the complainant's building included in the preblast survey?

Employees handling complaints should be courteous but firm, never apologizing or saying that fewer explosives will be used in the future. Never admit or imply any possible damage until your consultant has advised you of the findings. A completely informed public will want progress, and that is what your organization owes its success to.

Inform the complainants that a consulting engineer has been retained to design and control your blasting, and this consultant is concerned with nothing but facts. This consultant has been retained to protect the public, to help you do a more efficient job, and to inform the blaster of any potential liability. An independent consultant will know if and where damage may have occurred, probably before the property owner does.

Emphasize that your organization does blasting as a normal operation and has enjoyed success for a considerable length of time, that you have very competent personnel with years of experience, and that you are producing work as efficiently as possible with the least inconvenience to everyone.

People are afraid of noise made by explosives. Noise can be controlled by proper drilling, loading, and stemming. If a shot cannot be seen or heard, your complaints will be few. Remember, it takes only one hole that is not properly tamped to blow out, and then everyone believes the entire shot was not controlled.

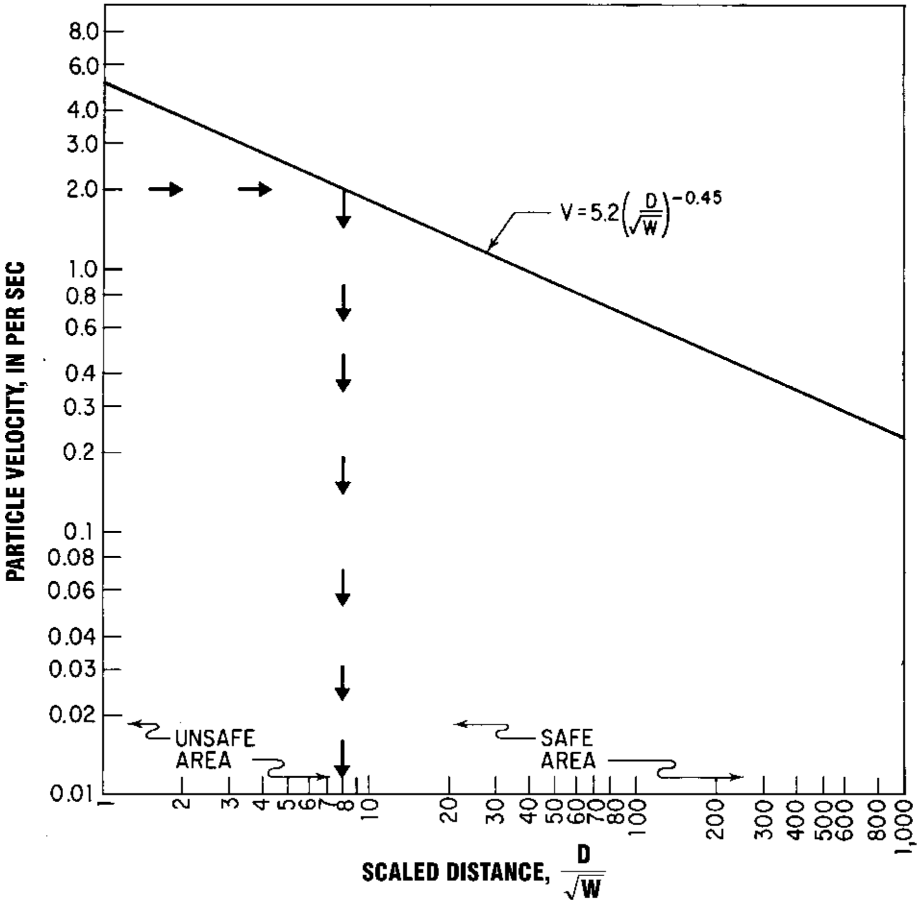

Fig. 13.22 Relationship between particle velocity (vibration) and scaled distance for a specific site for which $H = 5.2$ and $\beta = 0.45$ in Eq. (13.22). For a maximum particle velocity of 2 m/s, the scaled distance is 8. Hence, vibration damage is unlikely at scaled distances larger than 8.

Safe blasting is not only demanded and practical, but essential.

13.19 Compaction

This is the process by which soils are densified. It may be done by loading with static weight, striking with an object, vibration, explosives, or rolling. Compaction is used to help eliminate settlement and to make soil more impervious to water. Compaction is costly, and for some embankments, the results cannot be justified because reduced settlement and other desired benefits are not economical.

For a given soil and given compactive effort, there is an optimum moisture content, expressed in percent of soil dry weight, which gives the greatest degree of compaction. ASTM D698, AASHTO T99, and a modified AASHTO method are widely used for determining moisture content. The modified method may be specified if the soil engineer's investigation indicates that T99 will not yield the desired consolidation. In these tests, soil density of a compacted sample is plotted against percent of moisture in the sample. Maximum density and optimum moisture for the sample can be determined from the resulting curve (Fig. 13.24).

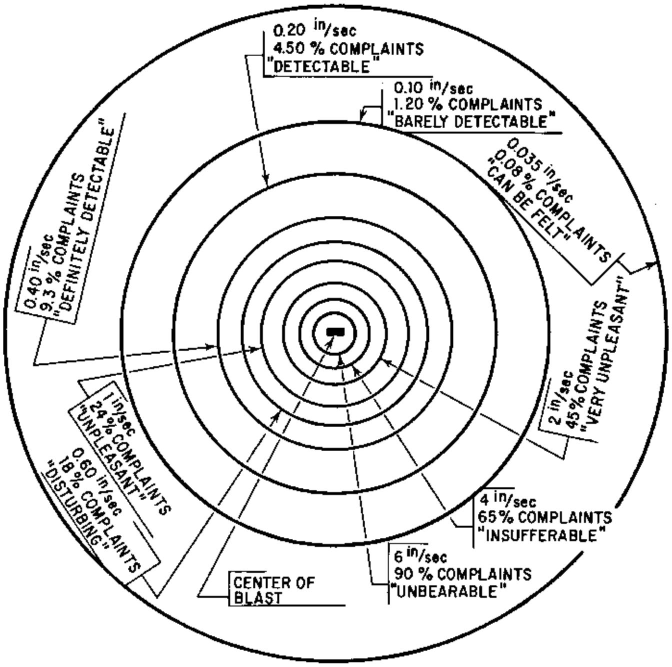

Fig. 13.23 Public reaction to blasting is indicated by the percentage of the total number of families exposed to a specific particle velocity that should be expected to complain, plotted to a logarithmic scale.

Compaction to be obtained on embankments is expressed as a percent of maximum density. For example, 90% compaction means that the soil in place in the field should have a density of 90% of the maximum obtained in the laboratory. Moisture content should not vary more than 3% above or below optimum. To obtain proper compaction in the field, moisture must be controlled and compactive effort applied to the entire lift.

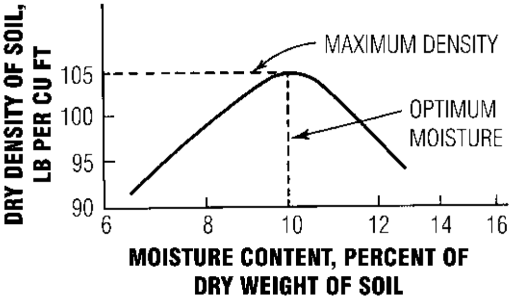

Fig. 13.24 Maximum-density graph.

In-Place Density Tests ▪ Several ASTM standard test methods are available for determination of soil density in the field. The two types most frequently used are nuclear methods (ASTM D2992), applicable for shallow depths, and the sand-cone, or calibrated-sand, method (D1556).

Nuclear methods offer the advantage over the others in the relative ease with which the tests can be made. They eliminate the need for digging holes and collecting samples. More tests can be carried out per day than by the other methods. Also, they have the advantage of being more nearly nondestructive tests, thus permitting immediate detection of apparent erratic measurements. Since nuclear methods measure density of the soil near the surface, however, they preclude examination of the soil in depth.

In these tests, a gamma-ray source and a gamma-ray detector placed on, into, or adjacent to the soil to be tested are used to determine the total or wet density of the soil. A counter or scaler capable of automatic and precise timing is generally used to report the rate at which gamma rays emitted by the source and modified by the soil arrive at the detector. This rate depends partly on the density of the underlying soil. The scaler reading is converted to measured wet density with the aid of a calibration curve that relates soil density to nuclear count rate as determined by correlation tests of soils with known average density. The nuclear methods are normally suitable for test depths of about 2 to 12 in.

The sand-cone method is used to determine in the field the density of compacted soils in earth embankments, road fill, and structure backfill, as well as the density of natural soil deposits, aggregates, soil mixtures, or other similar materials. It is not suitable, however, for soils that are saturated or soft or friable (crumble easily). The method requires that a small hole be dug in the soil to be tested. Hence, the soil should have sufficient cohesion to maintain stable sides. It should be firm enough to withstand, without deforming or sloughing, the pressures involved in forming the hole and placing the test apparatus over it. Furthermore, the hole should not be subjected to seepage of water into it.

All soil removed from the hole is weighed, and a sample is saved for moisture determination. Then, the hole is filled with dry sand of known density. The weight of sand used to fill the hole is determined and used to compute the volume of the hole. Characteristics of the soil are computed from

$$\text{Volume of soil, ft}^3 = \frac{\text{weight of sand filling hole, lb}}{\text{density of sand, lb/ft}^3} \tag{13.23}$$

$$\%\ \text{moisture} = \frac{100(\text{weight of moist soil} - \text{weight of dry soil})}{\text{weight of dry soil}} \tag{13.24}$$

$$\text{Field density, lb/ft}^3 = \frac{\text{weight of soil, lb}}{\text{volume of soil, ft}^3} \tag{13.25}$$

$$\text{Dry density} = \frac{\text{field density}}{1 + \%\ \text{moisture}/100} \tag{13.26}$$

$$\%\ \text{compaction} = \frac{100(\text{dry density})}{\text{max dry density}} \tag{13.27}$$

Maximum density is found by plotting a density-moisture curve, similar to Fig. 13.25, and corresponds to optimum moisture. Table 13.20 lists recommended compaction for fills.

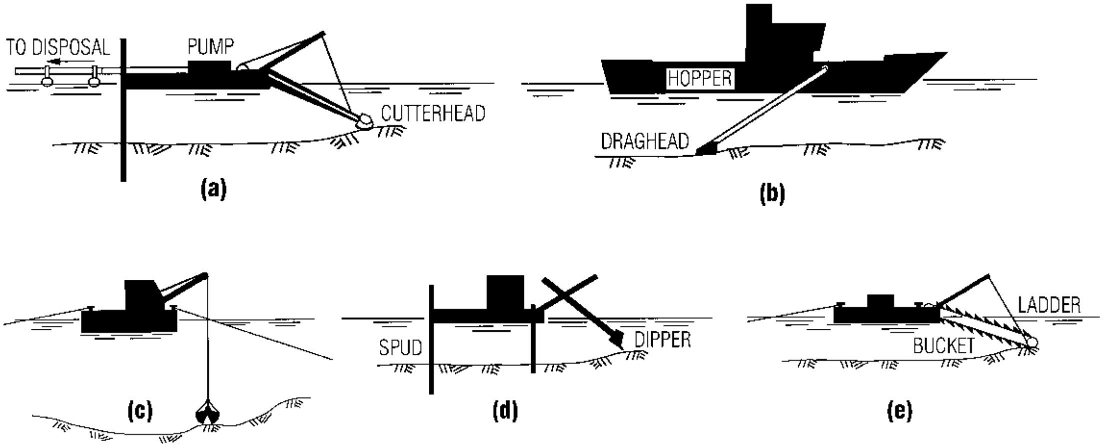

Fig. 13.25 Types of dredges, (*a*) cutterhead; (*b*) trailing hopper; (*c*) grab; (*d*) dipper; (*e*) ladder.

Table 13.20 Recommended Compaction of Fills

Dry density, lb per ft³	Recommended compaction, %
Less than 90	—
90–100	95–100
100–110	95–100
110–120	90–95
120–130	90–95
Over 130	90–95

A mistake commonly made in the field is application of compactive effort when either insufficient or excessive moisture is present in the soil. Under such conditions, it is impossible to obtain recommended compaction no matter how great the effort.

Compaction Equipment ▪ A wide variety of equipment is used to obtain compaction in the field (Table 13.21). Sheepsfoot rollers generally are used on soils that contain high percentages of clay. Vibrating rollers are used on more granular soils.

To determine maximum depth of lift, make a test fill. In the process, the most suitable equipment and pressure to be applied, psi of ground contact, also can be determined. Equipment selected should be able to produce desired compaction with four to eight passes. Desirable speed of rolling also can be determined. Average speeds, mi/h, under normal conditions are given in Table 13.22. Compaction production can be computed from

Table 13.22 Average Speeds, Mi/h, of Rollers

Grid rollers	12
Sheepsfoot rollers	3
Tamping rollers	10
Pneumatic rollers	8

$$\text{yd}^3/\text{h} = \frac{16WSLFE}{P} \qquad (13.28)$$

where W = width of roller, ft

S = roller speed, mi/h

L = lift thickness, in

F = ratio of pay yd^3 to loose yd^3

E = efficiency factor (allows for time losses, such as those due to turns): 0.90, excellent; 0.80, average; 0.75, poor

P = number on passes

Table 13.21 Compaction Equipment

Compactor type	Soil best suited for	Max effect in loose lift, in	Density gained in lift*	Max weight, tons
Steel tandem 2–3 axle	Sandy silts, most granular materials, some clay binder	4–8	Average	16
Grid and tamping rollers	Clays, gravels, silts with clay binder	7–12	Nearly uniform	20
Pneumatic small tire	Sandy silts, sandy clays, gravelly sands and clays, few fines	4–8	Uniform to average	12
Pneumatic large tire	All (if economical)	To 24	Average	50
Sheepsfoot	Clays, clay silts, silty clays, gravels with clay binder	7–12	Nearly uniform	20
Vibratory	Sands, sandy silts, silty sands	3–6	Uniform	30
Combinations	All	3–6	Uniform	20

* Density diminishes with depth.

13.20 Dredging

Dredges are used for excavating in or under water. They may be classified by the method used for excavation and the method of transporting and disposing of the excavated material.

13.20.1 Methods of Excavation

Hydraulic, or suction, dredges are the most widely used type of dredge. They move material by suction and pumping through pipes.

Plain suction dredges often have the suction pipe mounted in the bow. They may use water jets to loosen the material to be moved. Plain suction dredges perform well in sand. They remain stationary and dredge a depression into which the surrounding sand flows. They can dredge to a depth of 85 m.

Cutterheads are often used on suction dredges to cut or loosen material to permit handling by the suction line and discharge pipes (Fig. 13.25*a*).

Trailing, or drag, dredges have the suction pipe mounted on the side and extending toward the stern (Fig. 13.25*b*). This type of dredge, often employing a draghead attachment and cutting a small bank with each pass, is widely used for maintenance dredging of shoaling in navigation channels.

Bucket, or mechanical, dredges excavate with grab buckets, dippers, and bucket ladders.

Grab dredges (Fig. 13.25*c*), also known as clamshells or orange peels, are often used close to obstructions, such as docks, piers, and other marine structures, and for the corner of cuts. These dredges can operate to large depths, limited only by the length of wire from the boom to the bucket. They perform well in silts and stiff mud. Performance is poor, however, in hard, consolidated materials, and this type of dredge is not suitable for hard clays.

Dipper dredges are used for excavating broken rock or hard material (Fig. 13.25*d*). As is the case for power shovels, operating depth is limited by the length of boom.

Ladder dredges employ a continuous chain of buckets to excavate material and transport it to the dredges (Fig. 13.25*e*). Commonly used for sand and gravel dredging and mining, they also work well in soft clays and rock. Disadvantages of ladder dredges include high maintenance costs, inability to operate in rough water, and the need for mooring lines and anchors, which may interfere with navigation traffic.

Bucket dredges can cause considerable turbidity due to material escaping from the buckets. Consequently, in some locations, bucket-dredge operation is limited during "environmental windows," such as fish migration periods.

13.20.2 Transportation and Disposal

Disposal of dredged material, often as difficult as the dredging itself, is a serious concern.

Bucket dredges typically discharge dredged material into a scow or barge, into a hopper in the dredge itself, or onto an onshore disposal area, if it is within reach.

Pipeline dredges transport dredged material by direct pumping through a floating pipeline to the disposal area. They are normally referred to by the size of their discharge pipeline.

Hopper dredges, floating counterparts of scrapers, transport dredged material in the dredge hoppers to a disposal area. The hopper dredges may be unloaded by opening the hoppers and bottom-dumping the material or by pulling alongside a mooring barge at the disposal area and connecting to a pipeline. Use of this type of dredge is indicated in situations where the distance to a disposal area is too large to permit pumping the full distance by pipeline. This type of dredge, however, has the disadvantage that it must stop excavating during transport.

A third form of disposal is **side casting** dredged materials in a direction that permits the current to carry them away from the project area. This method of disposal is used for dredging of navigation inlets to remove shoaling.

Water-injection dredging (WID), a newer dredging and disposal method, uses water injected through jets in a horizontal pipe to fluidize fine-grained materials, such as sand and silt. The fluidized sediment is carried away from the project site by a density current or natural currents. For projects characterized by fine sediments, favorable currents, and nearby deep water for reception of dredged material, WID is an alternative to conventional dredging and disposal. Advantages include low cost, no need for pipes to transport dredged material, and little disruption of navigation traffic as would occur with conventional pipelines. Also, turbidity is less with WID since the fluidized material stays within about 2 ft of the bottom.

13.20.3 Dredge Production Rates

Prediction of production rates for dredges is extremely complex. Production rates depend on many factors: soil type, uniformity, and grain size; digging depth, work-face height, tides and currents, pipeline length, and disposal elevation; nearby navigation traffic; and equipment maintenance and crew training.

Measurement of dredging quantities for progress and payment also can be difficult. The standard method used by those who require dredging work (government officials, shippers, marina owners) is the in situ volume based on pre- and postdredging surveys. Payment is made for dredging down to a design depth and width, plus a tolerance.

A method of measurement more favorable to dredge operators, however, is the volume or weight transported by the dredging equipment. Unless close controls are maintained, this method is rarely satisfactory to the paying authority, who does not want to pay for overexcavation beyond specified dimensions.

Another method is to measure the dredged material after disposal. This, however, is suitable only when the objective of the dredging is to create a fill.

13.20.4 Permits and Authorizations

A permit is needed for dredging in or over any navigable water in the United States, in accordance with requirements of Section 10 of the 1899 Rivers and Harbors Act. Also, Section 404 of the Clean Water Act requires authorization for practically all dredging discharges. These permits are administered by the U.S. Army Corps of Engineers.

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