3

Equipment Productivity

Tom Iseley
Blackhawk-PAS, Inc., South Carolina

Sanjiv Gokhale
Vanderbilt University

3.1 Introduction

Whether a construction contract is unit price, lump sum, or cost-plus; whether the construction project is to be linear (i.e., concept Æ design Æ procurement Æ construction) or fast-track (i.e., design/build), the cost of construction is a major factor in all projects. The major factors that impact construction costs are materials, labor, equipment, overhead, and profit. The cost of equipment for civil engineering construction projects can range from 25 to 40% of the total project cost.

Figure 3.1 illustrates the ability to influence the construction cost of a project. The greatest influence to construction cost occurs at the front end of the project. Assumptions made by design engineers during the conceptual and design phases of a project dictate the choice of equipment that will be used for the particular project, just as it will dictate the choice of materials used in construction. Thus, sometimes the design may, in fact, restrict the best and most cost-effective solutions from being utilized. For example, many sewer projects are designed on the basis of traditional specifications, materials, and equipment, when more advanced materials, techniques, and equipment may, in fact, be safer, more environmentally and socially acceptable, and more cost-effective. This is especially true of sewer projects in urban areas, where modern construction techniques, such as microtunneling and pipebursting, utilizing new pipe materials such as glass fiber-reinforced polymers (GRP) and high-density polyethylene (HDPE), are replacing the traditional dig and replace methods of sewer construction.

It is important for design engineers and construction engineers to be knowledgeable about construction equipment. Construction equipment is an integral part of the construction process. The cost of construction is a function of the design of the construction operation.

This chapter will provide an overview of construction equipment selection and utilization processes. It will describe typical equipment spreads associated with two major classifications of civil engineering construction projects: heavy/highway and municipal/utility. Methods for determining equipment productivity and cost will be discussed.

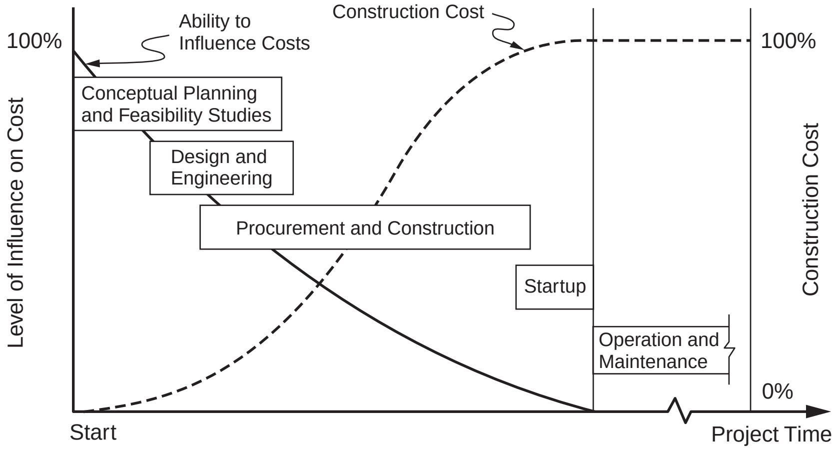


FIGURE 3.1 Ability to influence construction cost over time. (*Source:* Hendrickson, C. and Au, T. *Project Management for Construction.* Prentice Hall, Englewood Cliffs, NJ.)

3.2 Heavy/Highway Construction Projects

These projects include new road construction, dams, airports, waterways, rehabilitation of existing roadways, marine construction, bridges, and so on. Each project can be segmented into various phases or operations. The equipment spread selected for a specific construction operation is critical to the success of the project.

Figure 3.2(a) illustrates a typical sequence of activities for the construction of a new highway. This highway project contains culverts and a bridge. While there will be some overlap in equipment utilization, each activity must be evaluated carefully to identify all operations in the activity and to ensure that the equipment selected for each operation is compatible with the tasks to be completed. Figure 3.2(b) lists the activities associated with the project, the duration of each, and whether the activities are critical or noncritical. The intent is not to provide a detailed description of each activity but to illustrate how equipment selection and utilization are a function of the associated variables. For example, the first activity (clearing and grubbing) is critical, as no activity can begin until the project site is cleared. Even though clearing land is often considered to be a basic, straightforward activity, it is still more an art than a science. The production rates of clearing land are difficult to forecast, because they depend on the following factors:

- The quantity and type of vegetation
- Purpose of the project
- Soil conditions
- Topography
- Climatic conditions
- Local regulations
- Project specifications
- Selection of equipment
- Skill of operators

To properly address these variables requires research and a thorough evaluation of the site to determine the following:

- Density of vegetation
- Percent of hardwood present

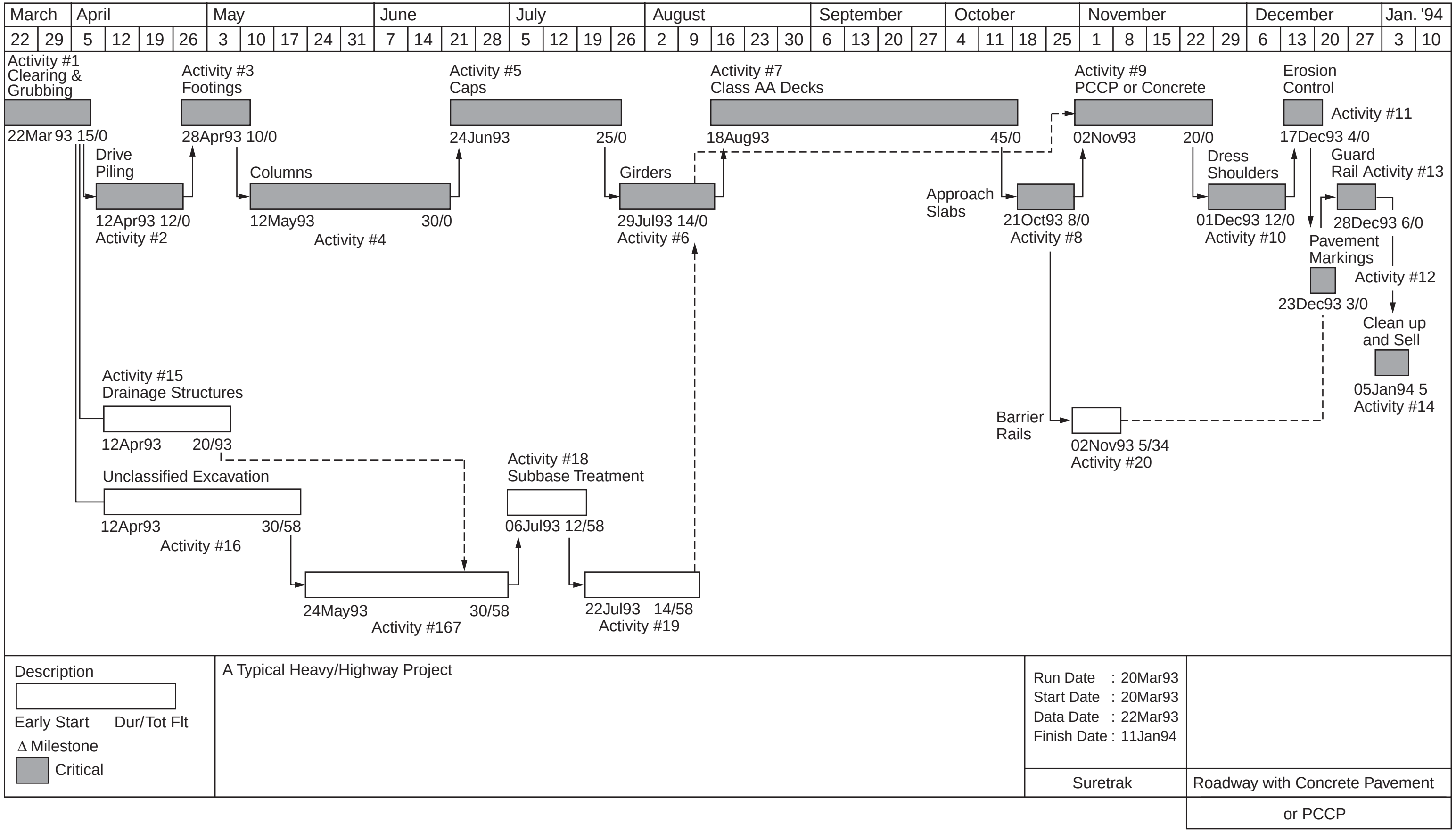


FIGURE 3.2 (a) Typical sequence of activities for a new highway project; (b) activities associated with a new highway project.

Activity Number	Activities on Critical Path	Duration (Days)
1.	Clearing and Grubbing	15
2.	Drive Piling for Bridge	12
3.	Construct Footings for Bridge Foundation	10
4.	Construct Columns for Bridge Foundation	30
5.	Construction Column Caps	25
6.	Construct Girders for Bridge Deck	14
7.	Construct Class AA Bridge Deck	45
8.	Construct Approach Slabs	8
9.	Place Pavement	20
10.	Dress Road Shoulders	12
11.	Erosion Control	4
12.	Pavement Markings	3
13.	Guard Rail	6
14.	Project Clean Up and Final Inspection	5
Activity Number	**Activities Not on Critical Path**	**Duration (Days)**
15.	Drainage Structures	20
16.	Unclassified Excavation	30
17.	Borrow	30
18.	Subbase Treatment	12
19.	Asphaltic Base	14
20.	Barrier Rails	5

FIGURE 3.2 (continued).

- Presence of heavy vines
- Average number of trees by size category
- Total number of trees

A method for quantifying the density of vegetation and the average number of trees per size category is described in Caterpillar [1993] and Peurifoy and Schexnayder [2002, p. 179].

The most common type of construction equipment used for clearing and grubbing activities is a bulldozer. The term *bulldozer* is used to define a tractor mounted with a dozing blade. Tractor size can vary from less than 70 flywheel horsepower (FWHP) to more than 775 FWHP. Dozing blades are available in many types. The appropriate blade depends on the job to be accomplished. For example, types of blades include the following:

U — universal
SU — semiuniversal
S — straight
P — power angle and tilt
A — angling
V — tree cutter

Caterpillar [1993, pp. 1–39–1–41] provides a detailed description and illustration of various blades commonly used. To maximize production, it is important to ensure that the tractor and dozer blade are properly matched. The two major factors to be considered in selecting the proper blade and tractor are material to be moved and tractor limitations. For example, weight and horsepower of the tractor determine its ability to move material. Particle size, particle shape, voids, and water content are the main factors affecting the level of difficulty of moving material.

Caterpillar [1993] and Peurifoy and Schexnayder [2002] utilize the following relationship to estimate the time required to perform various operations, such as felling trees with bulldozers and piling in windows with bulldozers:

$$T = B + M_1N_1 + M_2N_2 + M_3N_3 + M_4N_4 + DF \tag{3.1}$$

where T = time required per acre, minutes

B = base time required for a bulldozer to cover an acre with no trees requiring splitting or individual treatment, minutes

M = time required per tree in each diameter range, minutes

N = number of trees per acre in each diameter range, obtained from field survey

D = sum of diameter in feet of all trees per acre, if any, larger than 6 ft in diameter at ground level

F = time required per foot of diameter for trees larger than 6 ft in diameter, minutes

While industry average data exist for the variables in Eq. (3.1), which correlate operation duration with FWHP of bulldozers, a firm's historic database should provide improved accuracy in forecasting production. Such a database can be developed by project owner representatives and constructors. This database could then be used for future projects and comparison with industry averages.

Many large constructors do not maintain such detailed databases. For example, the equipment selected for the clearing and grubbing activities for the project illustrated in Fig. 3.2 was based on estimator experience. When questioned about the selection process, the estimator stated that he made his selection based on the fact that the project consisted of more than 25 acres of timber with trees larger than 24 in. diameter. If there had been less than 25 acres with less than 24-in. in diameter trees, he would have selected smaller equipment.

The type of production estimating used by this constructor is extremely effective when experienced estimators are responsible for making the necessary decisions. However, a more detailed database would permit decisions to be made at a lower level by less experienced people without sacrificing accuracy. This would allow the more experienced estimator to utilize his or her time more effectively. In addition, a more detailed database would provide better information to substantiate the impact if a change in conditions should develop.

Table 3.1 illustrates major equipment requirements for each activity shown in Fig. 3.2. The equipment listed can be categorized as follows: bulldozers, excavators, compactors, graders, scrapers, spreaders, cranes, loaders, trucks, and miscellaneous (asphalt spreaders, screeds, water trucks, power brooms, farm tractors, generators).

Although it is beyond the scope of this chapter to provide an in-depth analysis of the estimated productivity of each of the above classes of equipment, this analysis is provided in the references cited at the end of this chapter. Several categories of machines are discussed in general terms. Equipment manufacturers also provide reliable productivity information.

It is important to be able to segment a project into its basic activities, as illustrated in Fig. 3.2. Each activity must then be further segmented into its basic operations. Individual operations within an activity are unique and require specific combinations of equipment to be executed in a cost-effective manner. Each machine selected will have a unique operation within an activity; the operation is a function of the cycle time of the machines needed to execute it. The machines must be selected so that their productivities balance. The durations of the activities listed in Fig. 3.2 are a function of the operations necessary to accomplish the activity.

Duration estimating is extremely important, but, because of the many variables involved, it is not an easy task. Excellent simulation methods and computer software programs are available to help project managers evaluate more precisely the impact of variables of operations and processes [Halpin and Riggs, 1992].

TABLE 3.1 Equipment Selected for Typical Heavy/Highway Project (See Fig. 3.2)

	Equipment Description				
Activity Number	No. of Units	Size	Type	Equipment Cost/Unit	Remarks
1	2	285–340 FWHP	Bulldozers	$424,000	Provide: Track-type 2 — U blades 1 — Rake
	1	160–180 FWHP	Bulldozer	$157,000	Provider: Track-type w/P blade
	1	140–160 FWHP	Hydraulic excavator	$440,000	
2	1	65–75 ton	Crane	$343,000	Provide: 1 — pile-driving hammer
				$83,000	1 — set of cable leads
				$44,000	1 — drill and power pack
				$132,000	
3,4,5	1	50–75 ton	Crane	$314,000	
	1	Small	Generator	$33,000	50 KW
6	2	75–100 ton	Cranes	$660,000	
7	1	50–75 ton	Crane	$313,000	
	1	Medium	Generator	$110,000	150 KW
	1	150 CFM	Air compressor	$13,000	
	1		Bridge screed	$44,000	
	1		Concrete pump truck	$192,000	
8	1	140–160 FWHP	Hydraulic excavator	$440,000	
	1		Clarey screed	$8,500	
	1	63–70 FWHP	Bulldozer	$72,000	
9	1		Compactor	$82,000	Smooth Drum roller
	1		Compactor	$66,000	Pneumatic roller
	1		Power broom	$20,000	Broce model T-20
	1		Asphalt spreader	$193,000	Barber-Green BFS-185
10	1	75–90 FWHP	Bulldozer	$83,000	Track-type
	1	135–145 FWHP	Motor grader	$126,000	12G
	1	175–180 FWHP	Scraper	$237,000	Provide: elevating equipment/model 615
11	3	50–70 FWHP	Farm tractors	$44,000	Provide: miscellaneous attachments
	2	1800–3000 gal	Water trucks	$4,000	
12					Subcontract work
13					Subcontract work
14	1	135–145 FWHP	Motor grader	$127,000	
	1	75–90 FWHP	Bulldozer	$83,000	Track-type
	1	118–133 FWHP	Hydraulic excavator	$176,000	
	1		Dump truck	$68,000	
15	1	118–133 FWHP	Hydraulic excavator	$176,000	
	1	75–90 FWHP	Bulldozer	$82,000	Track-type
	1	145–170 FWHP	Front-end loader	$82,000	Provide: rubber-tired type
	4		Compactors	$82,000	Provide: vibra-plate tamps
	1	Small	Compactor	$22,000	Provide: self-propelled roller
16, 17	6	350–450 FWHP	Scrapers	$330,000	Model 631E
16, 17	1	320–370 FWHP	Bulldozer	$605,000	Push tractor for scrapers
	2	120–140 FWHP	Bulldozers	$82,000	To level and spread material
	1	140–160 FWHP	Hydraulic excavator	$440,000	
	1	180–200 FWHP	Motor grader	$247,000	16G
	1	175–215 FWHP	Compactor	$198,000	Provide: self-propelled roller
	1	10,000 gal	Water truck	$44,000	
	1	250–300 FWHP	Farm tractor	$116,000	Provide: 24–28 in plow
18	3		Soil stabilizers	$165,000	Type: Raygo
	4	1800–3000 gal	Water trucks	$28,000	
	1		Compactor	$165,000	Provide: self-propelled
	1		Compactor	$82,000	Sheep-foot roller
	2	135–145 FWHP	Motor graders	$82,000	Provide: pneumatic roller
			Truck	$44,000	

TABLE 3.1 (continued) Equipment Selected for Typical Heavy/Highway Project (See Fig. 3.2)

	Equipment Description				
Activity Number	No. of Units	Size	Type	Equipment Cost/Unit	Remarks
19	1		Compactor	$82,000	Smooth drum roller
	1		Compactor	$66,000	Pneumatic roller
	1		Power broom	$20,000	Broce model T-20
	1		Asphalt spreader	$192,000	Barber Green BFS-185

Note: Equipment costs represent estimated market value. They illustrate the size of investment that must be recovered.

It is important to ensure that the project is designed for constructibility. Project designers must be knowledgeable concerning construction processes and the variables impacting total life-cycle costs.

Equipment Productivity

Once the equipment needs for an activity have been identified, the next step is to conduct an equipment productivity analysis to select the optimum size. The objective is to determine the number of units and the size of equipment that would permit the constructor to accomplish the activity with a duration resulting in the lowest cost.

Because most civil engineering construction projects are awarded based on lowest cost, it is of utmost importance to the constructor to select the proper equipment spread providing the lowest construction cost for the project. The project is segmented into various activities; therefore, the lowest cost must be determined for each activity.

Bulldozer Productivity

When a constructor lacks reliable historical data, most bulldozer equipment manufacturers will provide production information. Manufacturer's production information is useful in conducting a comparative analysis when developing a conceptual estimate or schedule. Production data provided by manufacturers (or any other source) must be applicable to a particular situation.

For example, Caterpillar [1993] contains excellent production curves for estimating dozing production in units of loose cubic yards (LCY) of materials per hour (LCY/h). Figure 3.3 illustrates a typical production curve from Caterpillar [1993, p. 1–58]. This information is based on numerous field studies made under varying job conditions. These production curves provide the maximum uncorrected production based on the following conditions:

1. 100% efficiency (60-min hour — level cycle)
2. Power shift machines with 0.05 min fixed times
3. Machine cuts for 50 ft (15 m), then drifts blade load to dump over a high wall. (Dump time — 0 sec)
4. Soil density of 2300 lb/LCY (1370 kg/m^3)
5. Coefficient of traction: track machines — 0.5 or better, wheel machines — 0.4 or better
6. Hydraulic-controlled blades are used
7. Dig 1F; carry 2F; return 2R (1F — first forward gear, etc.)

As long as the conditions that the production curves are based on are understood, they can be used for other conditions by applying the appropriate correction factors using the following relationship:

$$\text{Production}\left(\text{LCY/hr}\right) = \text{Maximum production}\left(\text{from production curve}\right) \times \text{Correction factor} \tag{3.2}$$

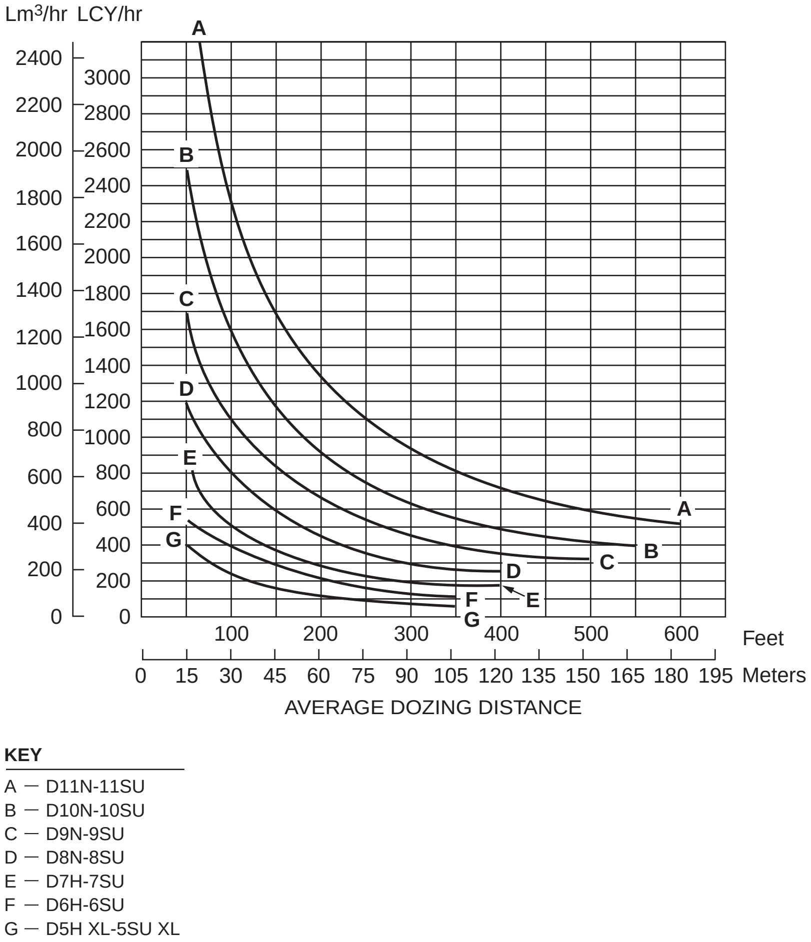


FIGURE 3.3 Typical production curve for estimation of dozing production. A-D11N-11SU, a bulldozer as manufactured by Caterpillar, Inc. with a model number D11N utilizing an SU-type blade designed for use with a D11 machine can be expected to move the volume of earth per hour as indicated by the A curve on this chart for a specific distance. For comparative purposes, the FWHP of each machine is D11N — 770, D10N — 520, D9N — 370, D8N — 285, D7H — 215, and D6H — 165. (*Source: Caterpillar Performance Handbook,* 24th ed., 1993. Caterpillar, Peoria, IL, p. 1–58.)

Common correction factors are provided for such variables as operator skill, type of material being handled, method of dozing [i.e., dozing in a slot or side-by-side dozing, visibility, time efficiency (actual minutes per hour of production), transmission type, dozer blade capacity, and grades]. Caterpillar [1993, pp. 1–59–1–60] is an excellent source for correction factors and provides an excellent example of how to use production curves and correction factors.

When easy-to-use production curves do not apply to a particular situation, the basic performance curves must be utilized. Manufacturers provide a performance curve for each machine. Track-type tractor performance curves are in the form of drawbar pull (DBP) versus ground speed, and rubber-tired-type machine performance curves are in the form of rimpull (RP) versus ground speed.

The DBP vs. speed curves will be discussed in this section, and the RP vs. speed curves will be discussed later in connection with rubber-tired scrapers.

Drawbar horsepower is the power available at the tractor drawbar for moving the tractor and its towed load forward. Figure 3.4 illustrates the transfer of power from the flywheel to the drawbar.

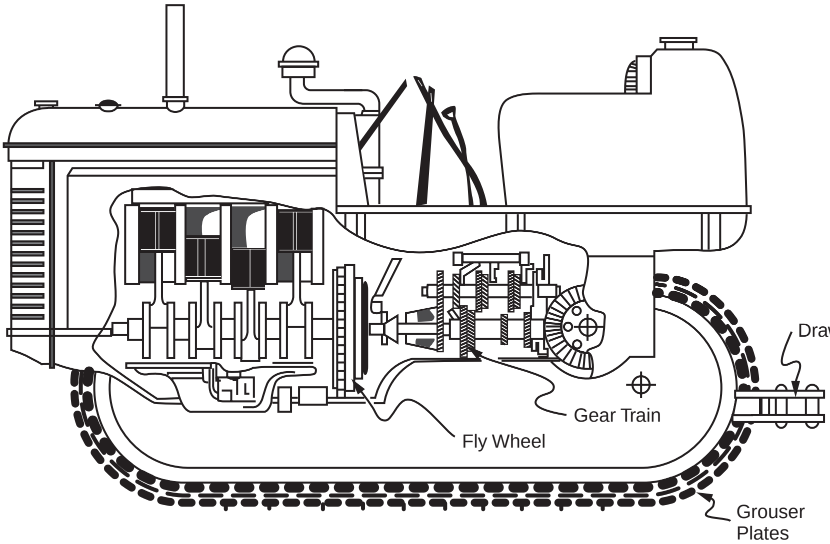


FIGURE 3.4 Characteristics of typical crawler tractors. (*Source:* Carson, A.B. 1961. *General Excavation Methods*. McGraw-Hill, New York.)

The relationship between DB horsepower, DB pull, and speed can be expressed as follows:

$$\text{DBHP} = \frac{\text{DBP}(\text{lb}) \times \text{speed}(\text{mph})}{375} \tag{3.3}$$

where DBHP = drawbar horsepower
DBP = drawbar pull (pounds)
Speed = ground speed (miles per hour)
375 = conversion factor

For example, to obtain the compaction required in activity 17 in Fig. 3.2, tillage may be necessary to accelerate drying of the soil. This tillage could be accomplished with a 24 to 28 in. agricultural plow pulled behind a track-type tractor. Production requirements could demand that this tillage operation needs to move at a speed of 3 mph and would impose a 22,000 lb DBP. Thus, the tractor must be able to apply at least

$$\frac{22{,}000 \text{ lb DBP} \times 3 \text{ mph}}{375} = 176 \text{ DBHP}$$

However, as can be seen in Table 3.1, for activity 17, a 250 to 300 FWHP rubber-tired farm tractor was selected by the constructor. Obviously, this decision for a more powerful, rubber-tired machine was made because a higher production rate was needed to keep all operations in balance.

Figure 3.5 is a DBP vs. speed performance curve for model D8N track-type tractor as manufactured by Caterpillar, Inc. The same type curves are available from all other manufacturers, whether domestic or foreign. As illustrated, once the demand has been defined in terms of the necessary DBP required to perform the task, the gear range and ground speed are determined for a specific machine. Obviously, this speed is critical information when trying to determine the cycle times for each machine at work. The cycle times are essential in determining how long each operation will take, and the length of each operation defines the duration of each activity shown in Fig. 3.2.

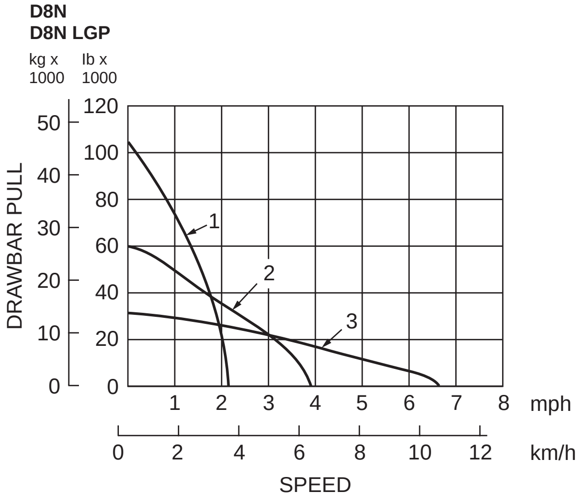


FIGURE 3.5 Drawbar pull vs. ground speed power shift. 1 — 1st gear, 2 — 2nd gear, 3 — 3rd gear. (*Source: Caterpillar Performance Handbook*, 24th ed., 1993. Caterpillar, Peoria, IL, p. 1–58.)

Excavator Productivity

Excavators are a common and versatile type of heavy construction equipment. As in the project illustrated by Fig. 3.2, excavators are used to accomplish many activities, such as lifting objects, excavating for trenches and mass excavation, loading trucks and scrapers, and digging out stumps and other buried objects.

The production of an excavator is a function of the digging cycle, which can be divided into the following segments:

1. Time required to load the bucket
2. Time required to swing with a loaded bucket
3. Time to dump the bucket
4. Time to swing with an empty bucket

This cycle time depends on machine size and job conditions. For example, a small excavator can usually cycle faster than a large one, but it will handle less payload per cycle. As the job conditions become more severe, the excavator will slow. As the soil gets harder and as the trench gets deeper, it takes longer to fill the bucket.

Other factors that greatly impact excavator production are digging around obstacles such as existing utilities, having to excavate inside a trench shield, or digging in an area occupied by workers.

Many excavator manufacturers provide cycle time estimating data for their equipment. This information is an excellent source when reliable historical data are not available. If an estimator can accurately predict the excavator cycle time and the average bucket payload, the overall production can be calculated as follows:

$$\frac{\text{Production}}{(\text{LCY/hr})} = \frac{\text{Cycles}}{\text{hr}} \times \frac{\text{Average bucket payload}\,(\text{LCY})}{\text{Cycle}} \tag{3.4}$$

Caterpillar [1993, pp. 4–106–4–107] provides estimated cycle times for common excavators with bucket size variations. These values are based on no obstructions, above average job conditions, above average operator skill, and a 60 to 90° angle of swing. Correction factors must be applied for other operating conditions.

TABLE 3.2 Cycle Estimating Chart for Excavators

Model	E70B	311	312	E140	320	E240C	325	330	235D	350	375
Bucket size	280	450	520	630	800	1020	1100	1400	2100	1900	2800
L	0.37	0.59	0.68	0.82	1.05	1.31	1.44	1.83	2.75	2.5	3.66
(yd³)											
Soil type		Packed Earth					Hard Clay				
Digging depth											
(m)	1.5	1.5	1.8	1.8	2.3	3.2	3.2	3.4	4.0	4.2	5.2
(ft)	5	5	6	6	8	10	10	11	13	14	17
Load buckets (min)	0.08	0.07	0.07	0.09	0.09	0.09	0.09	0.09	0.11	0.10	0.11
Swing loaded (min)	0.05	0.06	0.06	0.06	0.06	0.07	0.06	0.07	0.10	0.09	0.10
Dump bucket (min)	0.03	0.03	0.03	0.03	0.03	0.05	0.04	0.04	0.04	0.04	0.04
Swing empty (min)	0.06	0.05	0.05	0.05	0.05	0.06	0.06	0.07	0.08	0.07	0.09
Total cycle time (min)	0.22	0.21	0.21	0.23	0.23	0.27	0.25	0.27	0.33	0.30	0.34

Source: Caterpillar, 1993. *Caterpillar Performance Handbook*, 24th ed., p. 4–106. Caterpillar, Peoria, IL.

Table 3.2 illustrates the level of detailed information available from manufacturers on specific machines. This table presents information on four Caterpillar excavators commonly used on civil engineering projects.

Once the cycle time is determined, either by measuring or estimating, the production can be determined by the following relationship:

$$\text{LCY/60-min hr} = \text{Cycles/60-min hr} \times \text{Average bucket payload (LCY)} \qquad (3.5)$$

where,

$$\text{Average bucket payload} = \text{Heaped bucket capacity} \times \text{Bucket fill factor} \qquad (3.6)$$

This production is still based on production occurring the full 60 min of each hour. Since this does not occur over the long term, job efficiency factors are presented at the lower left corner of Table 3.3 and applied as follows:

$$\text{Actual Production (LCY/hr)} = \text{LCY/60-min hr} \times \text{Job efficiency factor} \qquad (3.7)$$

Example 1

Determine the actual production rate for a Cat 225D hydraulic excavator (150 FWHP) as required for activity 16, unclassified excavation, for the project represented in Fig. 3.2. It is estimated that the realistic productive time for the excavator will be 50 min/hr. Thus, the job efficiency factor will be 50/60 = 0.83. The soil type is a hard clay.

Solution.

$$\text{Average bucket payload} = \text{Heaped bucket capacity} \times \text{Bucket fill factor}$$

Enter Table 3.2 and select

1. 1.78 LCY bucket capacity for a Cat 225D
2. 0.25 min total cycle time

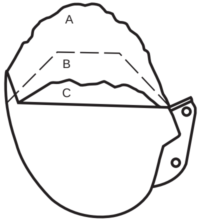
$$1.51\ \text{LCY} = 1.78\ \text{LCY} \times 0.85$$

TABLE 3.3 Cubic Yards per 60-Minute Hour

Estimated Cycle Times		Estimated Bucket Payload[b] — Loose Cubic Yards																		Estimated Cycle Times	
Seconds	Minutes	0.25	0.50	0.75	1.00	1.25	1.50	1.75	2.00	2.25	2.50	2.75	3.00	3.25	3.50	3.75	4.00	4.50	5.00	Cycles per Min	Cycles per Hr
10.0	.17																			6.0	360
11.0	.18																			5.5	330
12.0	.20	75	150	225	300	375														5.0	300
13.3	.22	**67**	**135**	**202**	**270**	337	404	472	540	607	675	742	810	877	945	1012	1080	1215	1350	4.5	270
15.0	.25	**60**	**120**	**180**	**240**	**300**	**360**	**420**	480	540	600	660	720	780	840	900	960	1080	1200	4.0	240
17.1	.29	**52**	**105**	**157**	**210**	**262**	**315**	**367**	**420**	**472**	**525**	**577**	630	682	735	787	840	945	1050	3.5	210
20.0	.33	**45**	**90**	**135**	**180**	**225**	**270**	**315**	**360**	**405**	**450**	**495**	**540**	**585**	**630**	**675**	**720**	810	900	3.0	180
24.0	.40	**37**	**75**	**112**	**150**	**187**	**225**	**262**	**300**	**337**	**375**	**412**	**450**	**487**	**525**	**562**	**600**	675	750	2.5	150
30.0	.50	30	60	**90**	**120**	**150**	**180**	**210**	**240**	**270**	**300**	**330**	**360**	**390**	**420**	**450**	**480**	510	600	2.0	120
35.0	.58	26	51	77	102	128	**154**	**180**	**205**	**231**	**256**	**282**	**308**	**333**	**360**	**385**	**410**	462	613	1.7	102
40.0	.67					112	135	157	180	202	**225**	**247**	**270**	**292**	**315**	**337**	360	405	450	1.5	90
45.0	.75									180	200	220	240	260	280	300	320	360	400	1.3	78
50.0	.83																			1.2	72

Job Efficiency Estimator

Work Time/Hour	Efficiency
60 min	100%
55	91%
50	83%
45	75%
40	67%



Average Bucket Payload =
(Heaped Bucket Capacity) ¥ (Bucket Fill Factor)

Material	Fill Factor Range (Percent of Heaped Bucket Capacity)
Moist loam or sandy clay	A —100–110%
Sand and gravel	B — 95–110%
Hard, tough clay	C — 80–90%
Rock — well blasted	60–75%
Rock — poorly blasted	40–50%

---

[a] Actual hourly production = (60 min h production) ¥(job efficiency factor)

[b] Estimated bucket payload = (amount of material in the bucket) = (heaped bucket capacity) ¥(bucket fill factor)

Numbers in boldface indicate average production.

Source: Caterpillar. 1993. *Caterpillar Performance Handbook*, 24th ed. Caterpillar, Peoria, IL.

Enter Table 3.3 and select an average production rate based on a work time of 60 min/hr. Select the column headed by a 1.5 LCY bucket payload and the row that represents a 0.25 min cycle time. From this, the average production is determined to be 360 LCY per 60-min hr.

$$\text{Actual production} = \text{LCY}/60\text{-min hr} \times \text{Job efficiency factor}$$

$$299 \text{ LCY}/\text{hr} = 360 \text{ LCY}/60\text{-min hr} \times 0.83$$

When an excavator is used for trenching, the desired rate of production often needs to be expressed in lineal feet excavated per hour. The trenching rate depends on the earth-moving production of the excavator being used and the size of the trench to be excavated.

Scraper Production

Scrapers provide the unique capability to excavate, load, haul, and dump materials. Scrapers are available in various capacities by a number of manufacturers, with options such as self-loading with elevators, twin engines, or push-pull capability.

Scrapers are usually cost-effective earthmovers when the haul distance is too long for bulldozers yet too short for trucks. This distance typically ranges from 400 to 4000 ft; however, the economics should be evaluated for each project.

The production rate of a scraper is a function of the cycle time required to load, haul the load, dump the load, and return to the load station. The times required to load and dump are usually uniform once established for a specific project, while travel times can vary a significant amount during the project due to variation of the travel distance. The load time can be decreased by prewetting the soil and designing the operation to load downgrade.

It is common practice for a push tractor during the loading operation to add the necessary extra power. The pattern selected for the tractor-assisted loading operation is important in the design of the operation to maximize production. The standard patterns are back tracking, chain, and shuttle. A thorough description of these patterns is provided in Peurifoy and Schexnayder [2002, p. 222].

The performance of a scraper is the function of the power required for the machine to negotiate the job site conditions and the power that is available by the machine. The power required is a function of rolling resistance (RR) and the effect of grade (EOG). RR is the force that must be exerted to roll or pull a wheel over the ground. It is a function of the internal friction of bearings, tire flexing, tire penetration into the surface, and the weight on the wheels.

Each ground-surface type has a rolling resistance factor (RR_F) associated with it. However, as a general rule, the RR_F consists of two parts. First, it takes at least a 40 lb force per each ton of weight just to move a machine. Second, it takes at least a 30 lb force per each ton of weight for each inch of tire penetration. Therefore, the RR_F can be determined as follows:

$$RR_F = 40 \text{ lb}/\text{ton} + 30 \text{ lb}/\text{ton}/\text{inch of penetration} \tag{3.8}$$

Rolling resistance is then calculated by using the RR_F and the gross vehicle weight (GVW) in tons:

$$RR = RR_F \times GVW \tag{3.9}$$

RR can be expressed in terms of pounds or percent. For example, a resistance of 40 lb/ton of equipment weight is equal to a 2% RR.

The EOG is a measure of the force due to gravity, which must be overcome as the machine moves up an incline, but is recognized as grade assistance when moving downhill. Grades are generally measured in percent slope. It has been found that for each 1% increment of adverse grade, an additional 20 lb of resistance must be overcome for each ton of machine weight. Therefore, the effect of grade factor (EOG_F) can be determined by:

$$\text{EOG}_F = \left(20\ \text{lb/ton/\% grade}\right) ¥ \left(\text{\% of grade}\right) \tag{3.10}$$

The EOG is then calculated by:

$$\text{EOG} = \text{EOG}_F ¥ \text{GVW} \tag{3.11}$$

The total resistance (TR) associated with a job site can be calculated by:

$$\text{Machine moving uphill: TR} = \text{RR} + \text{EOG} \tag{3.12}$$

$$\text{Machine moving on level ground: TR} = \text{RR} \tag{3.13}$$

$$\text{Machine moving downhill: TR} = \text{RR} -\ \text{EOG} \tag{3.14}$$

Once the power requirements are determined for a specific job site, a machine must be selected that has adequate power available. Available power is a function of horsepower and operating speed. Most equipment manufacturers provide user-friendly performance charts to assist with evaluating the influence of GVW, TR, speed, and rimpull. Rimpull is the force available between the tire and the ground to propel the machine.

The relationship of the power train to rimpull for a rubber-tired tractor can be expressed as follows:

$$\text{Rimpull} = \frac{375 ¥ \text{HP} ¥ \text{Efficiency}}{\text{Speed}\ \left(\text{mph}\right)} \tag{3.15}$$

Figure 3.6 illustrates information available from a typical performance chart. The following example illustrates how this information can be utilized.

Example 2

A scraper with an estimated payload of 34,020 kg (75,000 lb) is operating on a total effective grade of 10%. Find the available rimpull and maximum attainable speed.

$$\text{Empty weight} + \text{payload} = \text{Gross weight}$$

$$43{,}945\ \text{kg} + 34{,}020\ \text{kg} = 77{,}965\ \text{kg}$$

$$(96{,}880\ \text{lb} + 75{,}000\ \text{lb} = 171{,}880\ \text{lb})$$

Solution. Using Fig. 3.6, read from 77,965 kg (171,880 lb) on top of the gross weight scale down (line B) to the intersection of the 10% total resistance line (point *C*).

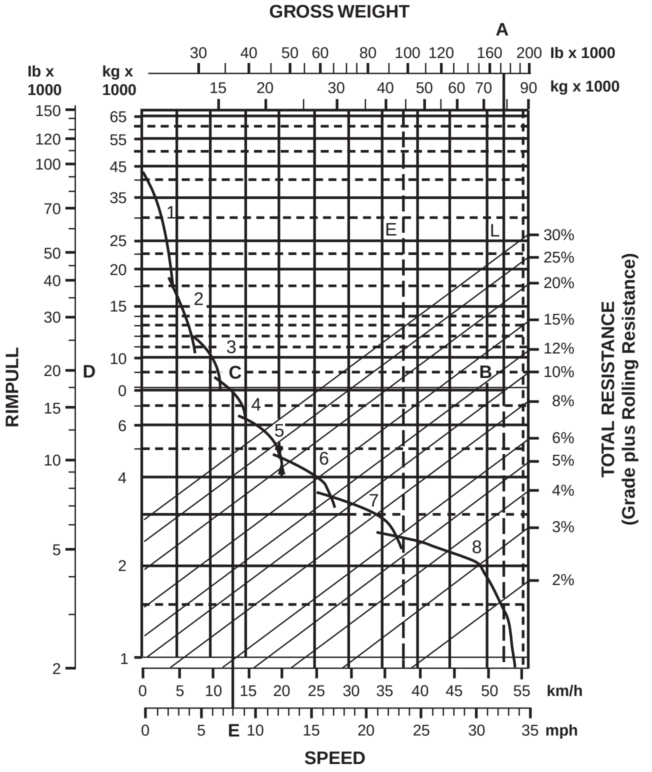
Go across horizontally from *C* to the Rimpull Scale on the left (point *D*). This gives the required rimpull: 7593 kg (16,740 lb).

Where the line *CD* cuts the speed curve, read down vertically (point *E*) to obtain the maximum speed attainable for the 10% effective grade: 13.3 km/h (8.3 mph).

The vehicle will climb the 10% effective grade at a maximum speed of 13.3 km/h (8.3 mph) in fourth gear. Available rimpull is 7593 kg (16,740 lb).

3.3 Municipal/Utility Construction Projects

Municipal/utility construction involves projects that are typically financed with public funds and include such things as water and sewer pipelines, storm drainage systems, water and wastewater treatment facilities, streets, curbs and gutters, and so on. Much of the same equipment listed in Fig. 3.2 is utilized for this type of construction. The productivity rates are determined the same way.



KEY

1 — 1st Gear Torque Converter Drive
2 — 2nd Gear Torque Converter Drive
3 — 3rd Gear Direct Drive
4 — 4th Gear Direct Drive
5 — 5th Gear Direct Drive
6 — 6th Gear Direct Drive
7 — 7th Gear Direct Drive
8 — 8th Gear Direct Drive

KEY

A — Loaded 77 965 kg (171,880 lb)
B — Intersection with 10% total resistance line
C — Intersection with rimpull curve (4th gear)
D — Required rimpull 7756 kg (17,100 lb)
E — Speed 12.9 km/h (8 mph)

FIGURE 3.6 Rimpull-speed-gradeability curves. (*Source: Caterpillar Performance Handbook*, 24th ed., 1993. Caterpillar, Peoria, IL.)

It is beyond the scope of this chapter to attempt a descriptive comparison of the various types of construction and equipment in this division. In the preceding section, a typical heavy/highway project was presented with an itemized list of the typical equipment associated with each activity. In this segment, the emphasis will be placed on advanced technology, while the emphasis in the section on heavy/highway equipment was on traditional equipment. In recent years, more concern has been placed on the impact of construction activities on society. As a result, the trenchless technology industry has expanded greatly. Trenchless technology includes all methods, equipment, and materials utilized to install new or rehabilitate existing underground infrastructure systems.

While *trenchless technology* is a relatively recent expression (it was coined in the mid-1980s), the ability to install pipe without trenching is not new. Methods such as auger boring and slurry boring have been used since the early 1940s. Until recently, these methods were used primarily to cross under roadways and railroads. The trend today is to utilize the trenchless concept to install complete underground utility and piping systems with minimum disruption and destruction to society and the environment, safely, and at the lowest total life-cycle cost.

Figure 3.7 is a classification system of the trenchless methods available to install new systems. Each method involves unique specialized equipment. The methods are described in detail in Iseley and Tanwani

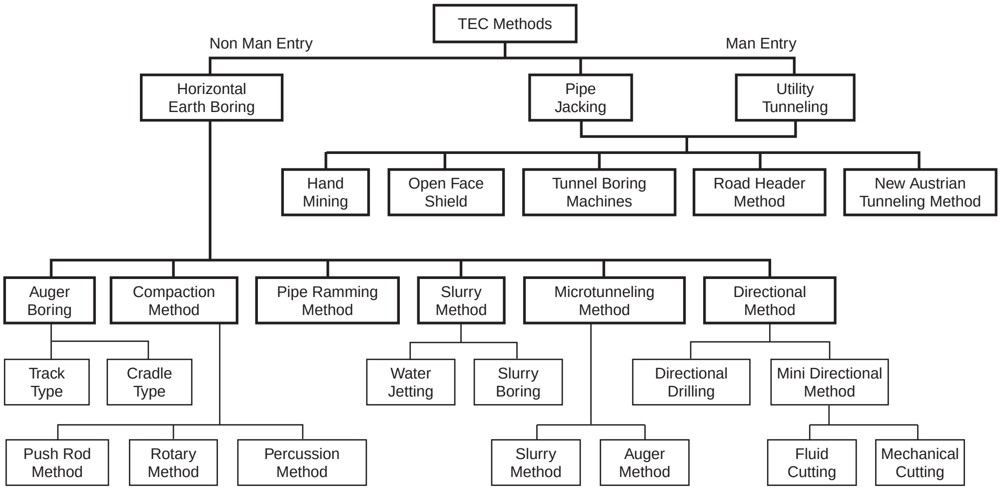


FIGURE 3.7 Trenchless excavation construction (TEC) classification system.

[1993]. No one method is compatible with all installations. Each project should be evaluated separately; the method selected should be compatible, safe, and cost-effective and should provide a high probability of success.

Only the microtunneling technique will be described in this chapter. This technique is well suited for installing sanitary and storm sewer pipelines, which require high degrees of accuracy for alignment and grade. For an excellent introduction to some of the other more common trenchless techniques used to install underground pipelines, the reader is referred to Iseley and Gokhale [1997].

Microtunneling systems are laser-guided, remote-controlled, pipe-jacking systems. In most instances, because of their high accuracy, the product pipe is installed in one pass. Most machines have the capability to counterbalance the earth pressure at the work face continuously, so that dewatering is not required.

These systems were developed in Japan in the mid-1970s, introduced in Germany in the early 1980s, and first used in the U.S. in 1984. Figure 3.8 shows the growth of the microtunneling industry in the

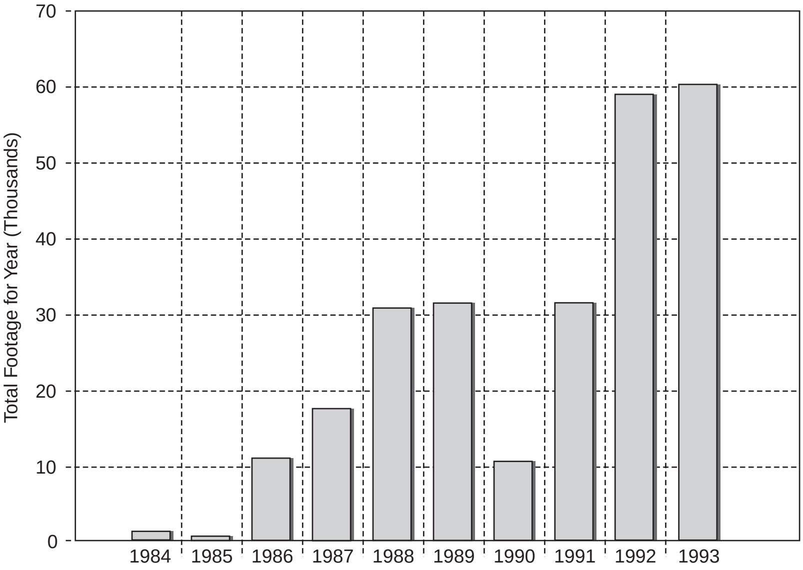


FIGURE 3.8 Total U.S. microtunneling footage by year.

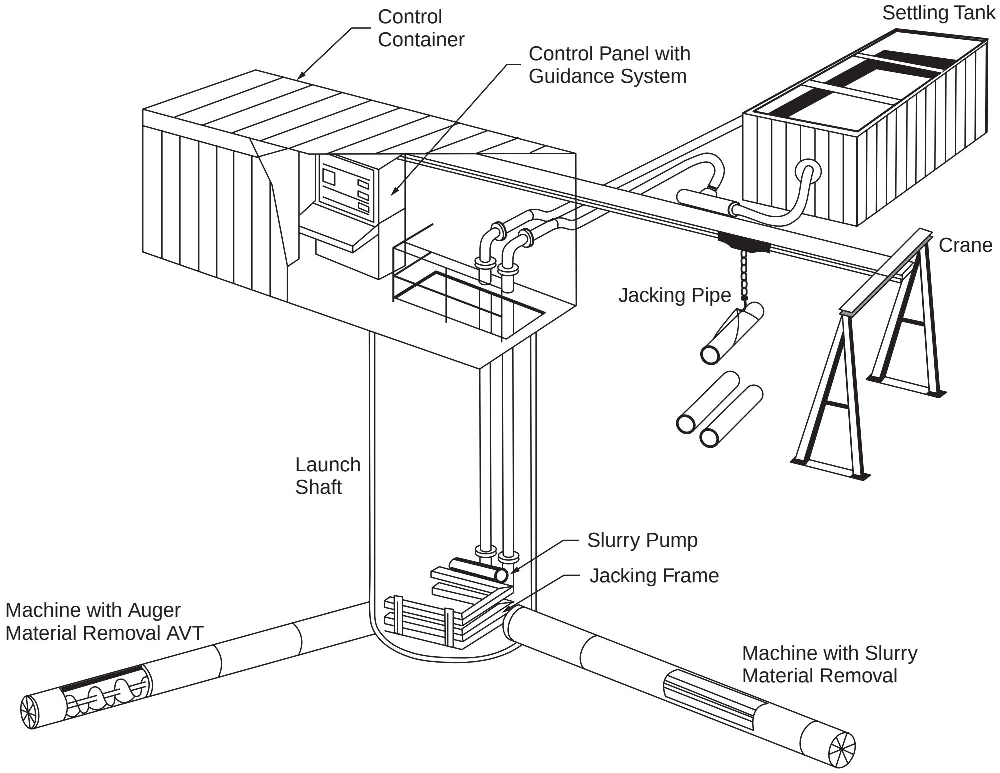


FIGURE 3.9 Auger and slurry microtunneling systems.

U.S. By mid-1993, more than 50 mi of pipe had been installed by this method. The industry continues to grow in demand because of its extraordinary capability. For example, in a residential Houston, TX area, microtunneling was used in 1987 to install almost 4 mi of gravity sewer lines (10 to 24 in. diameter), because the residents did not want their neighborhood torn apart by traditional methods. In 1989, in Staten Island, NY, this method was used to install a 5-ft diameter gravity sewer at a depth of 80 ft, under 60 ft of groundwater, with the longest single drive 1600 linear feet. It was installed at an accuracy of ±1 in. horizontal and vertical. In 1992–93, two raw water intake lines were installed, one above the other, in Jordan Lake, near Carey, NC. These examples and many others are helping engineers realize the unique capability of microtunneling to solve complex problems safely, cost-effectively, and with minimum environmental impact.

Figure 3.9 illustrates the two basic types of systems. They provide similar capabilities but are differentiated by their spoil removal systems. One provides a slurry spoil transportation system, and the other provides an auger spoil removal system.

Figure 3.10 is a schematic drawing that illustrates the basic components and systems of the microtunneling methods.

The microtunneling process consists of five independent systems: the mechanized excavation system, the propulsion system, the spoil removal system, the guidance control system, and the pipe lubrication system.

The Mechanized Excavation System

The cutter head is mounted on the face of the microtunnel boring machine and is powered by electric or hydraulic motors located inside the machine. Cutting heads are available for a variety of soil conditions, ranging from soft soils to rock, including mixed-face conditions and boulders. The microtunnel machines

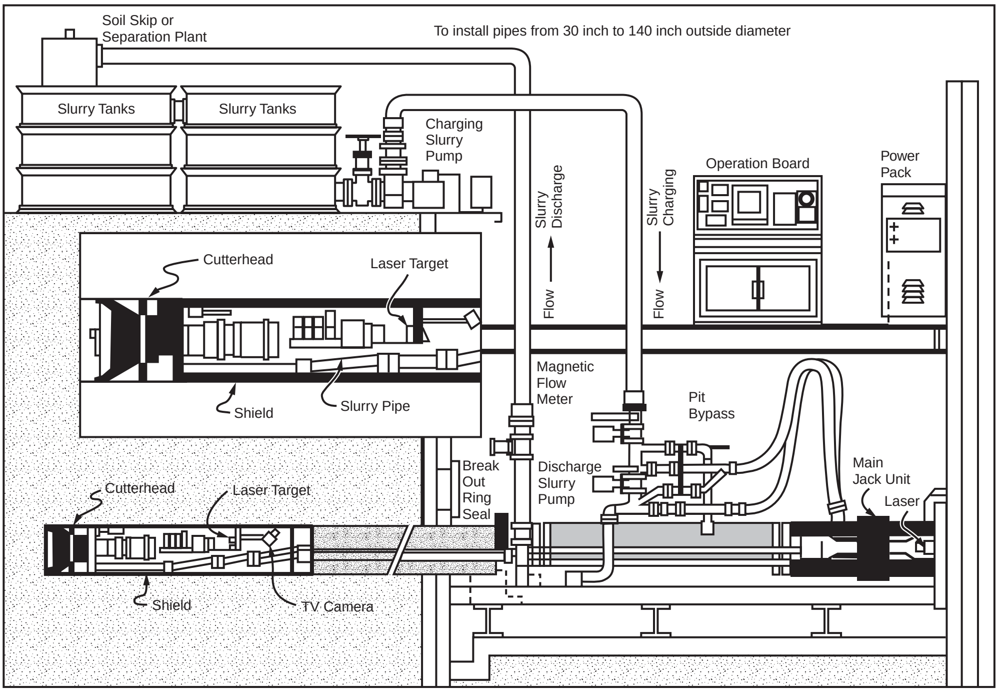


FIGURE 3.10 Slurry microtunneling system.

may operate above or below the groundwater. Each manufacturer produces unique cutting heads. These machines have been used successfully on projects where rock is encountered with unconfined compressive strength up to 30,000 psi. Also, they can handle boulders and other obstructions that are up to 30% of the diameter of the machine by incorporating crushing capability in the head. This crushing mechanism reduces the boulder to 1 in. particles that can be removed by an auger or by the slurry spoil removal system.

The boring machine also houses the articulating steering unit with steering jacks and the laser control target. Additional components that may be located in the microtunnel boring machine, depending on the type of machine, include the rock crusher, mixing chamber, pressure gauges, flow meters, and control valves.

Most machines have the capability of counterbalancing the actual earth pressure and the hydrostatic pressure independently. The actual earth pressure is counterbalanced by careful control over the propulsion system and spoil removal system. This force is carefully regulated to stay higher than the actual earth pressure but lower than the passive earth pressure so that subsidence and heave are avoided. The groundwater can be maintained at its original level by counterbalancing with slurry pressure or compressed air.

The Guidance Control System

The heart of the guidance control system is the laser. The laser provides the alignment and grade information for the machine to follow. The laser beam must have an unobstructed pathway from the drive shaft to the target located in the machine. The laser must be supported in the drive shaft so that it is independent of any movement that may take place as a result of forces being created by the propulsion system. The target receiving the laser information can be an active or passive system. The passive system consists of a target that receives the light beam from the laser; the target is monitored by a closed-circuit TV system. This information is then transferred to the operator's control panel so that any necessary adjustments can be made. The active system consists of photosensitive cells that convert information from the laser into digital data. The data are electronically transmitted to the control panel so that the operator is provided with a digital readout pinpointing the target the laser beam is hitting. Both active and passive systems have been used extensively in the U.S. and around the world; both systems have been found to be reliable.

The Propulsion System

The microtunneling process is a pipe-jacking process. The propulsion system for the microtunneling machine and the pipe string consists of a jacking frame and jacks in the drive shaft. The jacking units have been specifically designed for the microtunneling process, offering compactness of design and high thrust capacity. That capacity ranges from approximately 100 tons to well over 1000 tons, depending on the soil resistance that must be overcome. The soil resistance includes resistance from face pressure and resistance from friction and adhesion along the length of the steering head and the pipe string. Jacking force estimates may be based on drive length, ground conditions, pipe characteristics, and machine operating characteristics, specifically on overcut and lubrication. A reliable estimate of the required jacking force is important to ensure that the needed thrust capacity will be available and that the pipe will not be overloaded.

The propulsion system provides two major pieces of information to the operator: the total force or pressure being exerted by the propulsion system and the penetration rate of the pipe being pushed through the ground. The penetration rate and the total jacking pressure generated are important for controlling the counterbalancing forces of the tunnel boring machine to maintain safe limits.

The types of pipe typically used for microtunneling include concrete, clay, steel, PVC, and centrifugally cast fiberglass-reinforced polyester pipe (GRP).

The Spoil Removal System

Microtunneling spoil removal systems can be divided into the slurry transportation system and the auger transportation system. Both systems have been used extensively in this country and abroad and have been successful. In the slurry system, the spoil is mixed into the slurry in a chamber located behind the cutting head of the tunnel-boring machine. The spoil is hydraulically removed through the slurry discharge pipes installed inside the product pipe. This material is then discharged into a separation system. The degree of sophistication of the spoil separation system is a function of the type of spoil being removed. The effluent of the separation system becomes the charging slurry for the microtunneling system; thus, the system is closed loop.

Because the slurry chamber pressure is used to counterbalance the groundwater pressure, it is important that the velocity of the flow as well as the pressure be closely regulated and monitored. Regulation is accomplished by variable speed charging and discharging pumps, bypass piping, and control valves. As a result of this capability to counterbalance the hydrostatic head accurately, these machines have worked successfully in situations with extremely high hydrostatic pressures. The machine can be completely sealed off from external water pressure, allowing underwater retrieval, as was successfully accomplished on two recent projects at Corps of Engineer's lakes. The auger spoil removal system utilizes an independent auger system in an enclosed casing inside the product pipe for spoil removal. The spoil is augered to the drive shaft, collected in a skip, and hoisted to a surface storage facility near the shaft. Water may be added to the spoil in the machine to facilitate spoil removal. However, one of the advantages of the auger system is that the spoil does not have to reach pumping consistency for removal.

The Control System

All microtunneling systems rely on remote control capability, allowing operators to be located in a safe and comfortable control cabin, typically at the surface, immediately adjacent to the drive shaft, so the operator can visually monitor activities in the shaft. If the control cabin cannot be set up adjacent to the drive shaft for visual monitoring, a closed-circuit TV system can be set up in the shaft to allow the operator to monitor activities using a TV monitor. A key ingredient to a successful project is the operator's skill. The operator must monitor numerous bits of information continuously fed to the control panel, evaluate this information, and make decisions regarding future actions. Information relayed to the control panel is audible as well as visual, as sounds generated in the microtunneling machine are sent to the operator. Other information that must be monitored includes the line and grade of the machine, cutterhead torque, jacking thrust, steering pressures, slurry flow rates and pressures for slurry systems, and rate of advancement.

The sophistication of the control system varies from totally manual to completely automatic. With the manual system, the operator evaluates all information and makes necessary decisions regarding correcting actions. It is the responsibility of the operator to record all information at appropriate intervals during the pipe-jacking procedure. All monitoring and recording of data is automated; the computer provides a printout on the condition of the various systems at selected time intervals. Systems using fuzzy logic are available for making necessary corrections in the operational process. This allows the machine to automatically acquire, evaluate, and compare the data to corrections typically utilized for the existing condition. The machine will then make those corrections. With this system, the operator monitors the actions to ensure that the automatic corrections are those that the operator thinks are appropriate. Manual override of the automatic corrections is also possible.

The Pipe Lubrication System

The pipe lubrication system consists of a mixing tank and the necessary pumping equipment, which transmits the lubricant from a reservoir near the shaft to the application points inside the machine or along the inside barrel of the pipe. Pipe lubrication is optional but recommended for most installations, particularly for lines of substantial length. The lubricant can be a bentonite or polymer-based material. For pipe systems less than 36 in. diameter, the application point is at the machine steering head at the face of the tunnel. For sizes greater than 36 in., application points can be installed at intervals throughout the pipe. Lubrication can substantially reduce the total thrust required to jack the pipe.

Equipment Cost

The cost of the project must include the cost of equipment needed to build the project. The constructor must be able to determine, as accurately as possible, the duration of each piece of equipment required for each activity of the project. He or she must then be able to apply cost factors to this time commitment. The cost factor should represent the actual equipment cost experienced by the constructor. If the cost is too low, the equipment will not pay for itself. If the rate is too high, it may result in not being competitive. To know the true equipment cost requires accurate record keeping.

The constructor can lease equipment or purchase equipment. If equipment is leased, determining equipment cost is straightforward, because the rental rate will be established. If the equipment is to be purchased, the anticipated owing and operating (O&O) cost will need to be determined.

Associated Equipment Distributors publishes an annual compilation of nationally averaged rental rates for construction equipment. The following need to be taken into consideration when considering the leasing option:

1. **Time basis of the rates quoted —** It is common practice in the industry to base rates on one shift of 8 h/d, 40 h/week, or 176 hr/month. If these hours are exceeded, an extra fee can be charged.
2. **Cost of repairs —** The lessor usually bears the cost of repairs due to normal wear and tear, and the lessee bears all other costs. Normal wear and tear would be expected to result from the use of the equipment under normal circumstances. This can lead to disputes, because in many cases, normal wear and tear is difficult to distinguish.

3. **Operator —** Unless specifically stated otherwise, the operator is not included in the rental rates.
4. **Fuel and lubricants —** Unless specifically stated otherwise, the lessee is responsible for the cost of fuel, lubricants, and all preventive maintenance work while the equipment is being rented.
5. **Condition of equipment —** It is standard practice for the equipment to be delivered to the lessee in good operational condition and to be returned to the lessor in the same condition less normal wear and tear.
6. **Freight charges —** Unless specifically stated otherwise, the rental rates are f.o.b. the lessor's shipping point.
7. **Payment and taxes —** Normally, rental rates are payable in advance, and no license, sale, or use taxes are included in the rates.
8. **Insurance —** It is standard practice for the lessee to furnish the lessor a certificate of insurance prior to equipment delivery.

The factors influencing the calculation of owning and operating costs are investment and depreciation (ownership costs) and maintenance, repairs, lubrication, and fuel (operating costs). If a firm has similar equipment, they should have reliable historical data to help forecast the cost that should be applied to a specific piece of equipment. Many times, however, this is not the case. Therefore, the constructor must use an approximation based on assumed cost factors. Most equipment manufacturers can provide valuable assistance in selecting cost factors that should apply to the type of work being considered.

Whether rental rates or O&O costs are being utilized, they should eventually be expressed as total hourly equipment cost without operator cost. This facilitates the determination of machine performance in terms of cost per units of material. For example,

$$\text{Top machine performance} = \frac{\text{Lowest possible equipment hourly cost}}{\text{Highest possible hourly productivity}}$$

$$\text{Top machine performance} = \frac{\text{Cost/hr}}{\text{Units of material/hr}} = \frac{\text{Cost(\$)}}{\text{Units of material}}$$

Caterpillar [1993], Peurifoy and Schexnayder [2002], and *Production and Cost Estimating* [1981] contain detailed information on how to develop O&O costs. These references contain numerous examples that show how to apply specific factors.

The following is a summary of the principles presented in Peurifoy and Schexnayder [2002]:

I. Ownership costs (incurred regardless of the operational status)
  A. Investment costs
    1. Interest (money spent on equipment that could have been invested at some minimum rate of return)
    2. Taxes (property, etc.)
    3. Equipment productivity
    4. Insurance storage

Investment costs can be expressed as a percentage of an average annual value of the equipment ($\bar{p}$). For equipment with no salvage value:

$$\bar{p} = \frac{p(N+1)}{2N}$$

where p is the total initial cost and N is the useful life in years. For equipment with salvage value:

$$\bar{p} = \frac{p(N+1) + S(N-1)}{2N}$$

Example 3

$$\begin{aligned} \text{Interest on borrowed money} &= 12\% \\ \text{Tax, insurance, storage} &= \underline{\ 8\%} \\ \text{Total} &= 20\% \\ \text{Investment cost} &= 0.20\overline{p} \end{aligned}$$

- B. Depreciation (the loss in value of a piece of equipment over time due to wear, tear, deterioration, obsolescence, etc.)

II. Operation costs

- A. Maintenance and repair
  1. Depends on type of equipment, service, care
  2. Usually taken into consideration as a ratio or percentage of the depreciation cost
- B. Fuel consumed
  1. Gas engine = 0.06 gal/FWHP-h
  2. Diesel engine = 0.04 gal/FWHP-h
- C. Lubricating oil

FWHP-h is the measure of work performed by an engine based on average power generated and duration. Two major factors that impact the FWHP-h are the extent to which the engine will operate at full power and the actual time the unit will operate in an hour.

$$\text{TF} = \text{Time factor} = \frac{50\text{ min}}{60} \text{¥} 100 = 83.3\%$$

$$\text{EF} = \text{Engine factor} = \frac{\%\text{ of time at full load}}{\%\text{ of time at less than full load}}$$

$$\text{OF} = \text{Operating factor} = \text{TF ¥ EF}$$

$$\text{Fuel consumed} = \text{OF ¥ Rate of consumption}$$

The amount of lubricating oil consumed includes the amount used during oil changes plus oil required between changes.

$$q = \frac{\text{FWHP ¥ OF ¥ 0.006 \#/FWHP-hr}}{7.4\ \text{\#/gal}} = \frac{c}{t} = \frac{\text{gal}}{\text{hr}}$$

where OF is the operating factor, *c* is the crankcase capacity in gallons, *t* is the number of hours between changes, and # is pound.

Example 4

Hydraulic excavator.

160 FWHP — diesel engine
Cycle time = 20 s
Filling the dipper = 5 s at full power
Remainder of time = 15 s at half power
Assume shovel operates 50 min/h

$$\text{TF} = \frac{50}{60} \text{¥} 100 - 83.3\%$$

Engine factor:

$$\begin{array}{lrl} \text{Filling} & 5/20\times 1 = & 0.25 \\ \text{Rest of Cycle} & 15/20\times .50 = & \underline{0.375} \\ & \text{TOTAL} & 0.625 \end{array}$$

$$\text{OF} = \text{TF}\times\text{EF}\times 0.625\times 0.833 = 0.520$$

$$\frac{\text{Fuel consumed}}{\text{hr}} = 0.52\times 160\times 0.04 = 3.33\ \text{gal / hr}$$

3.4 Preventive Maintenance

Preventive maintenance (PM) is necessary for sound equipment management and protection of a company's assets. Minimum corporate PM standards should be established. Specific maintenance procedures should be available from the equipment department on most major pieces of equipment. If specific standards are not available, the manufacturer's minimum maintenance recommendations need to be used. A functioning PM program will comprise the following:

1. The PM program will be written and have specific responsibilities assigned. Company, division, and/or area managers will have the responsibility of seeing that the program works as designed.
2. Periodic service and inspections on all equipment in operation will be performed, documented, and reported (in writing). Each division/area will implement the service and inspection using the equipment manufacturers' recommendations as guidelines. For major pieces of equipment, this will be defined by the equipment department.
3. A systematic method of scheduling and performing equipment repairs will be implemented.
4. A fluid analysis program with regular sampling (including, but not limited to, testing for aluminum, chromium, copper, iron, sodium, silicon, plus water and fuel dilution) will be implemented.
5. All necessary permits will be acquired.
6. Federal, state, and local laws that affect the trucking industry will be followed.

3.5 Mobilization of Equipment

The following are factors that should be taken into consideration to facilitate and expedite mobilization of equipment:

1. Type and size of equipment
2. Number of trucks and trailers needed to make the move
3. Rates (company charges or rental charges)
4. Equipment measurements (weight, height, width, length)
5. Permits (vary with state)
6. Federal, state, and local laws affecting the trucking industry

The purpose of mobilization is to maximize efficiency and minimize cost by using rental or company trucks. This requires research on the above items by using equipment dealer support, appropriate law enforcement agencies, and so on.

Acknowledgments

The author would like to express his sincere appreciation to Danny A. Lott for his input. He has over 18 years of professional management experience with two leading corporations in construction and

communications. For the past eight years he has been the equipment maintenance and truck operations manager for T. L. James and Company, Inc., Ruston, LA. He provided a wealth of insight into the approach and substance of this chapter.

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Further Information

A good introduction to practical excavation methods and equipment is in *General Excavation Methods* by Carson.

Construction Planning, Equipment and Methods by Peurifoy and Schexnayder is particularly helpful for practical techniques of predicting equipment performance and production rates.

An excellent introduction to trenchless techniques used to install new underground utility and piping systems is *Trenchless Excavation Construction Equipment and Methods Manual* developed by the Trenchless Technology Center at Louisiana Tech University.