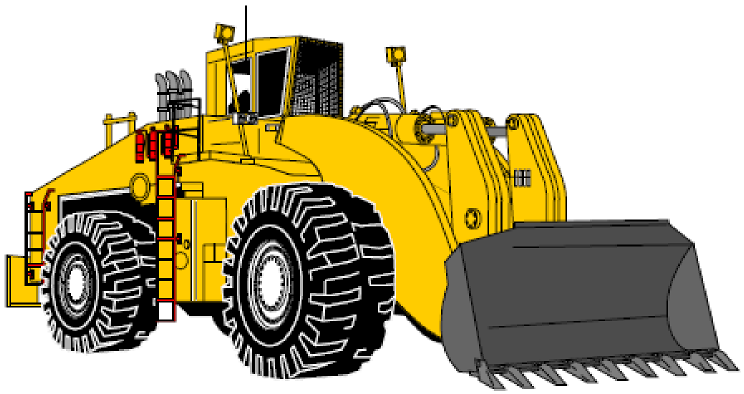
Arab Academy for Science, Technology & Maritime Transport
College of Engineering & Technology
Construction & Building Engineering

CB 524
Methods and Equipment for Construction 2
Equipment Productivity



Instructor: Ahmed Elyamany

Courtesy of Dr. Ahmed Alhady

MAJOR PRODUCTIVITY FACTORS

- Soil features.
- Equipment capacity.
- Equipment power.

Soil Features

- The constructor is interested in how a material will handle during the construction process.
- Steel and concrete are homogeneous as their behavior can be predicted.
- Soil and rock are heterogeneous as they are rarely uniform.

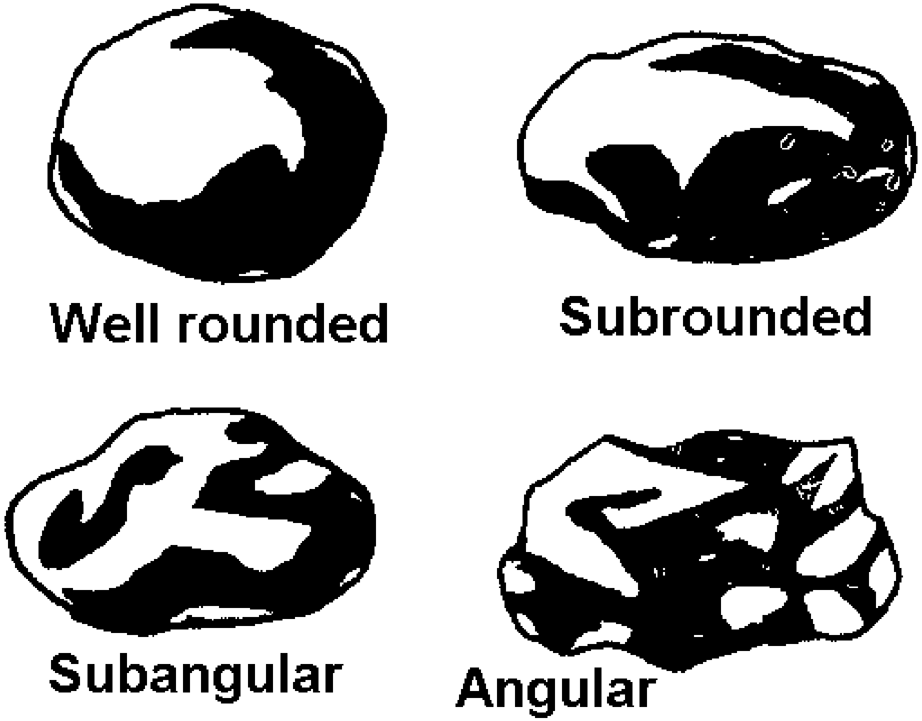
Soil Types

ORGANIC SOILS

Usually have to be removed before building.

Soil Types

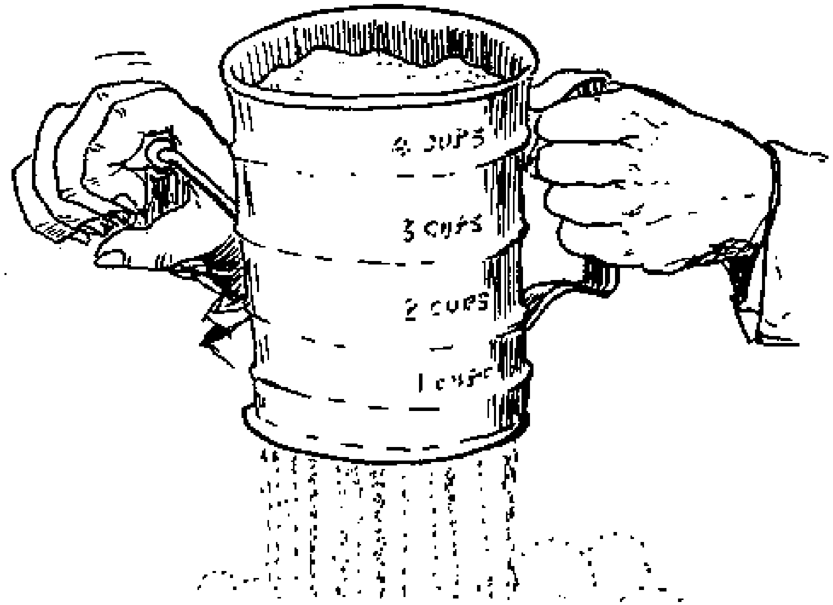
NON-COHESIVE



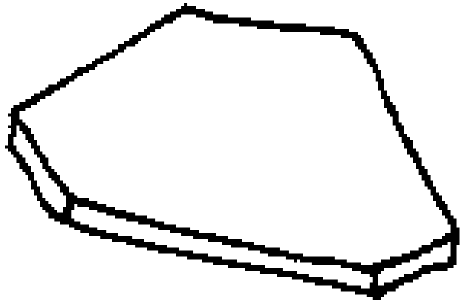
Bulky shaped soil grains

Soil Types

COHESIVE



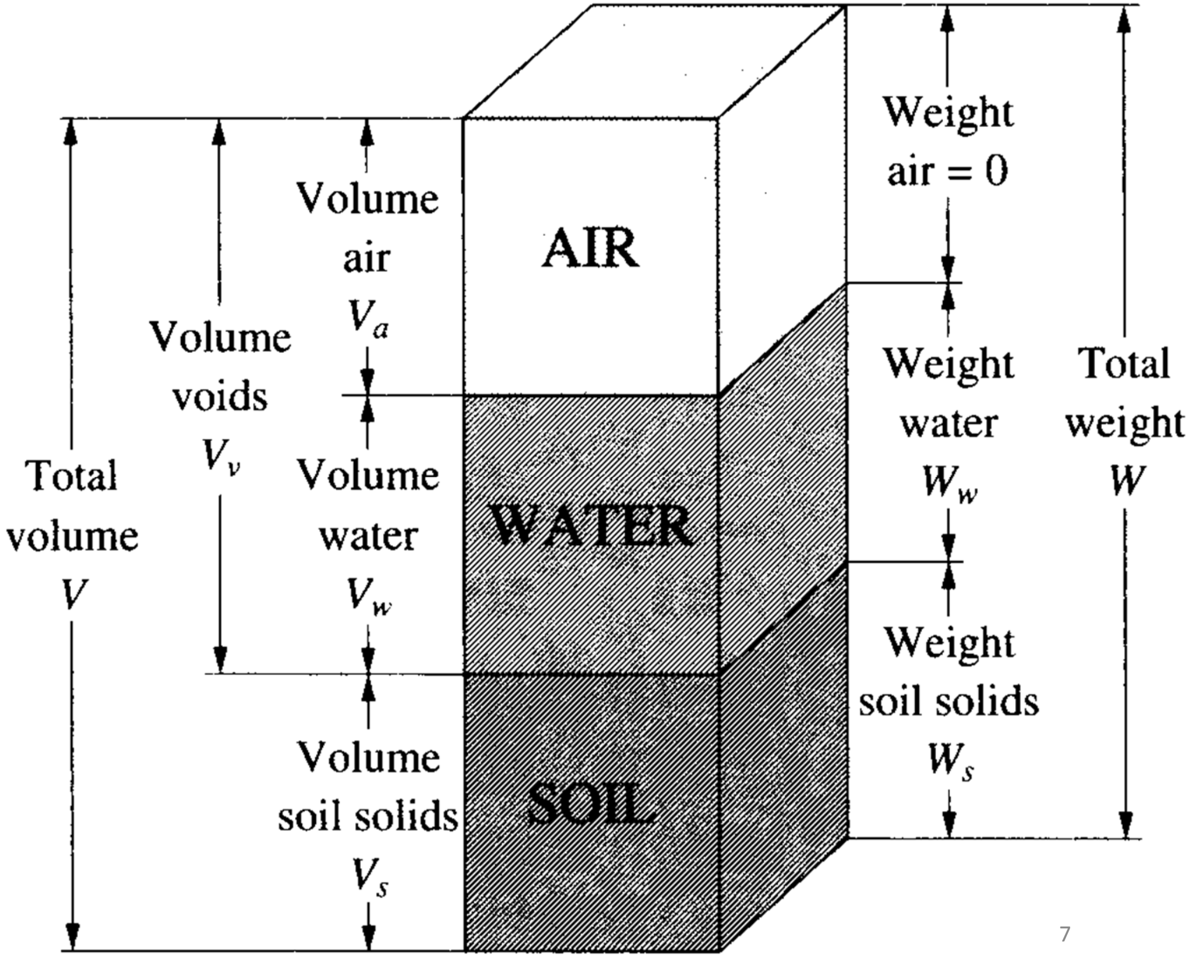
Small grained
< #200 Mesh sieve



Platy shaped
soil grains

Soil Mass

Composed of air, water, and solid particles.



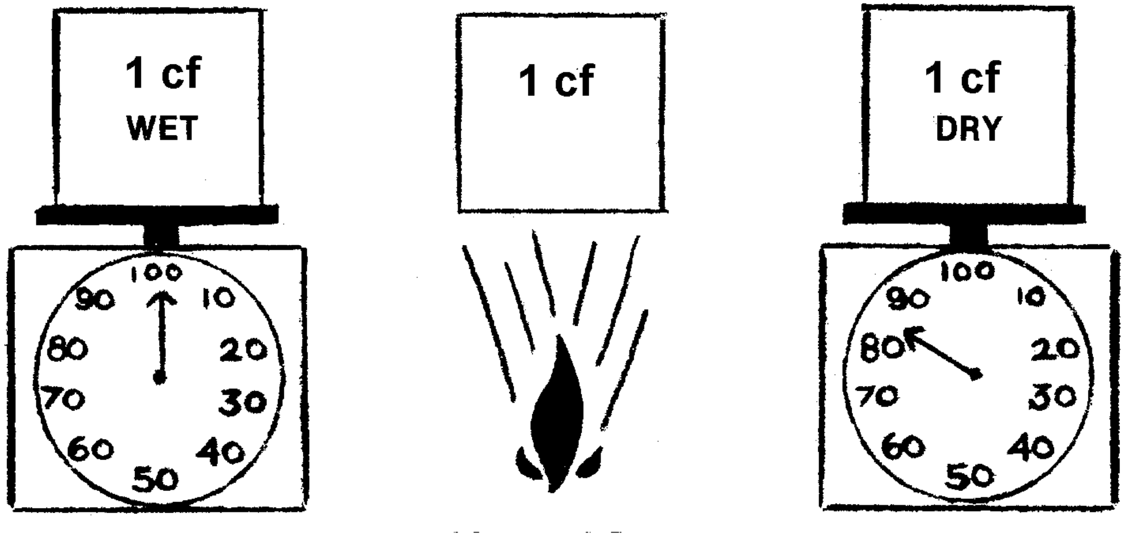
Soil Weight-Volume Relationships

$$\text{Unit weight}(\gamma) = \frac{\text{total weight of soil}}{\text{total soil volume}} = \frac{W}{V}$$

$$\text{Dry unit weight } (\gamma_d) = \frac{\text{weight of soil solids}}{\text{total soil volume}} = \frac{W_s}{V}$$

$$\text{Water content}(\omega) = \frac{\text{weight of water}}{\text{weight of solids}} = \frac{W_w}{W_s}$$

Water Content



$$\omega = \frac{\text{Wet Weight} - \text{Dry Weight}}{\text{Dry Weight}}$$

$$\omega = \frac{100 - 85}{85} = 0.18 \text{ or } 18\%$$

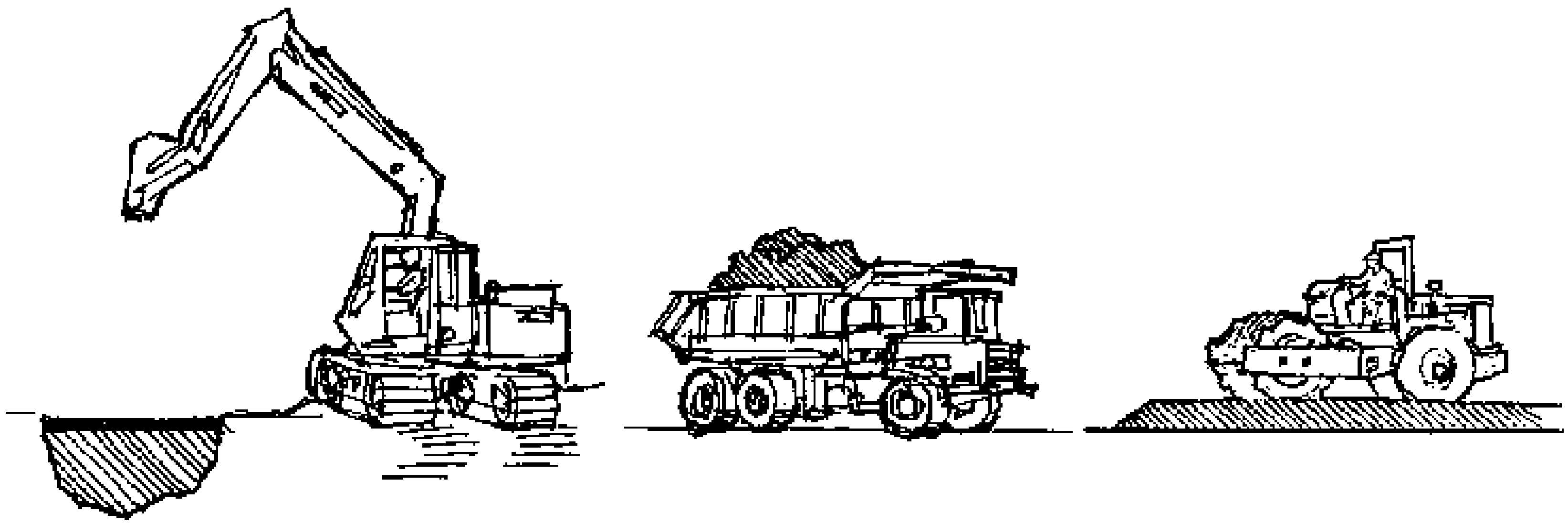
Soil Weight-Volume Relationships

Dry unit weight is related to **unit weight** by **water content**,

$$\gamma_d = \frac{\gamma}{1+\omega}$$

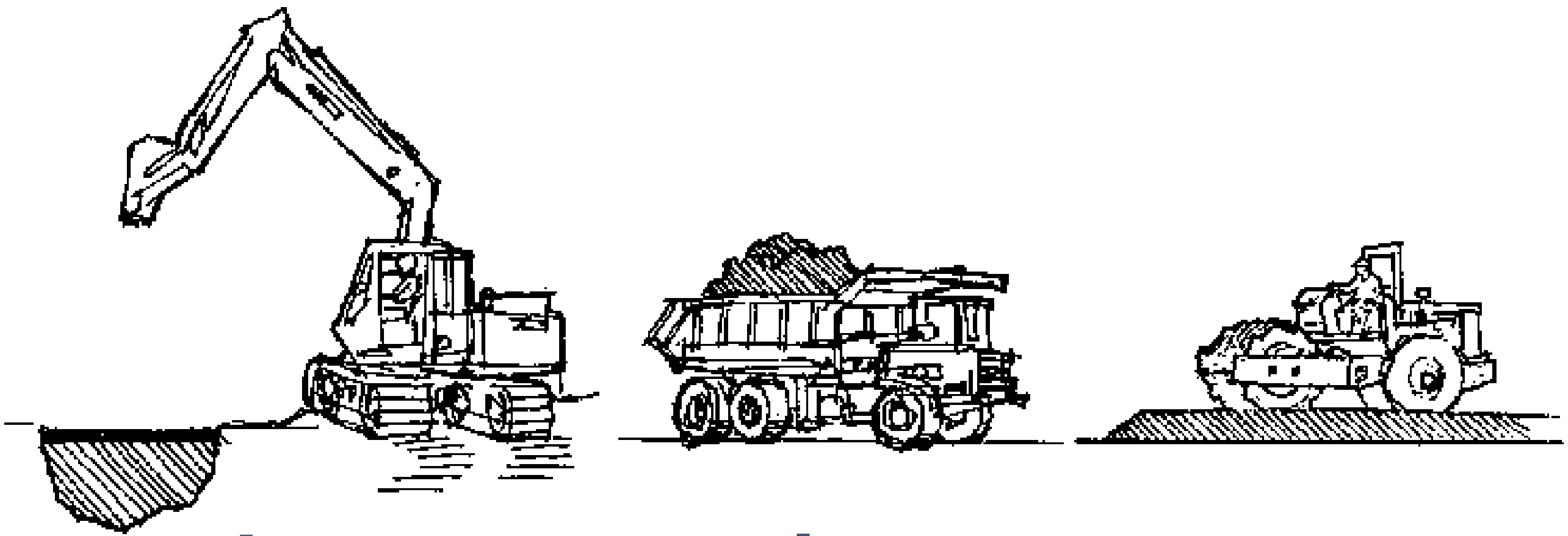
Soil Weight-Volume Relationships

When you move rock and dirt the only thing that stays constant is the weight of the solid particles.



Volumetric Measure

- Bank cubic yards (bcy)
- Loose cubic yards (lcy)
- Compacted cubic yards (ccy)



bcy lcy ccy

Volumetric Measure

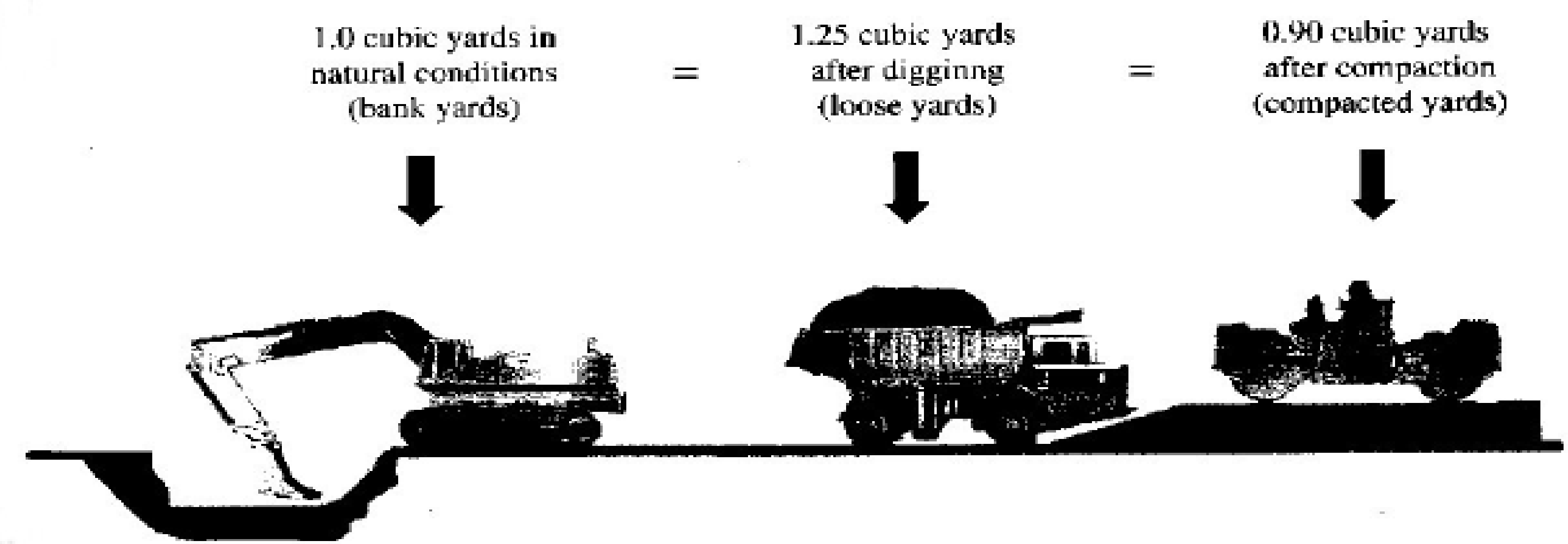


FIGURE 4.2 | Material volume changes caused by processing.

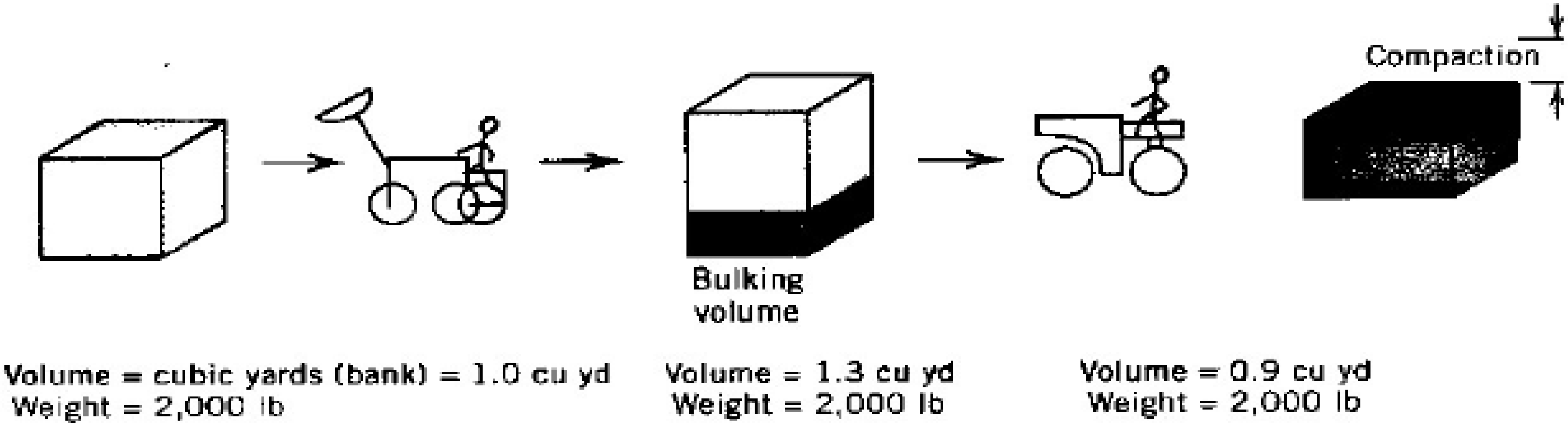
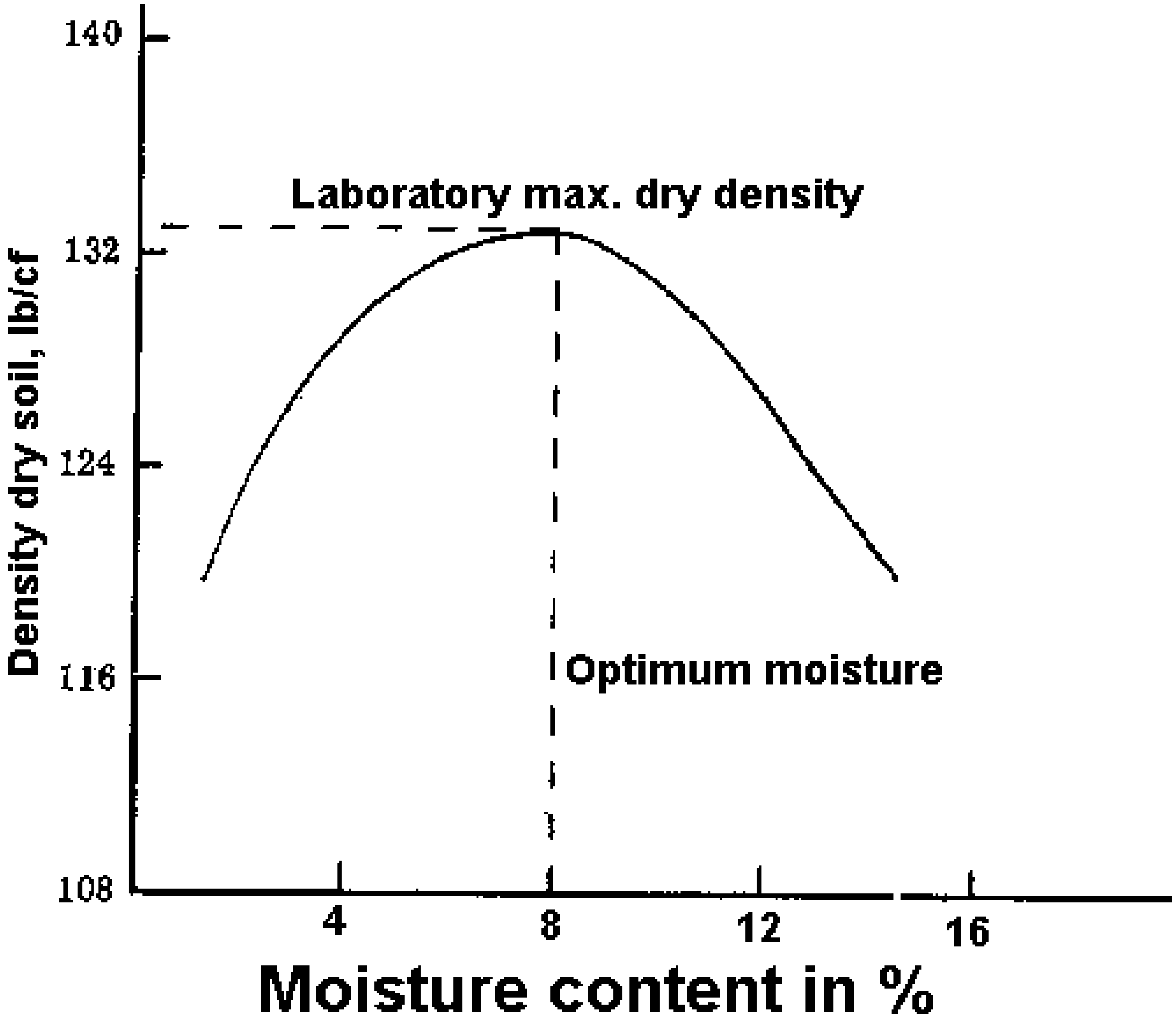


Figure 10.1 Volume relationships.

COMPACTION

Each soil has its particular Optimum Moisture Content (OMC) at which a corresponding Maximum Density can be obtained for a given amount of compactive input energy.

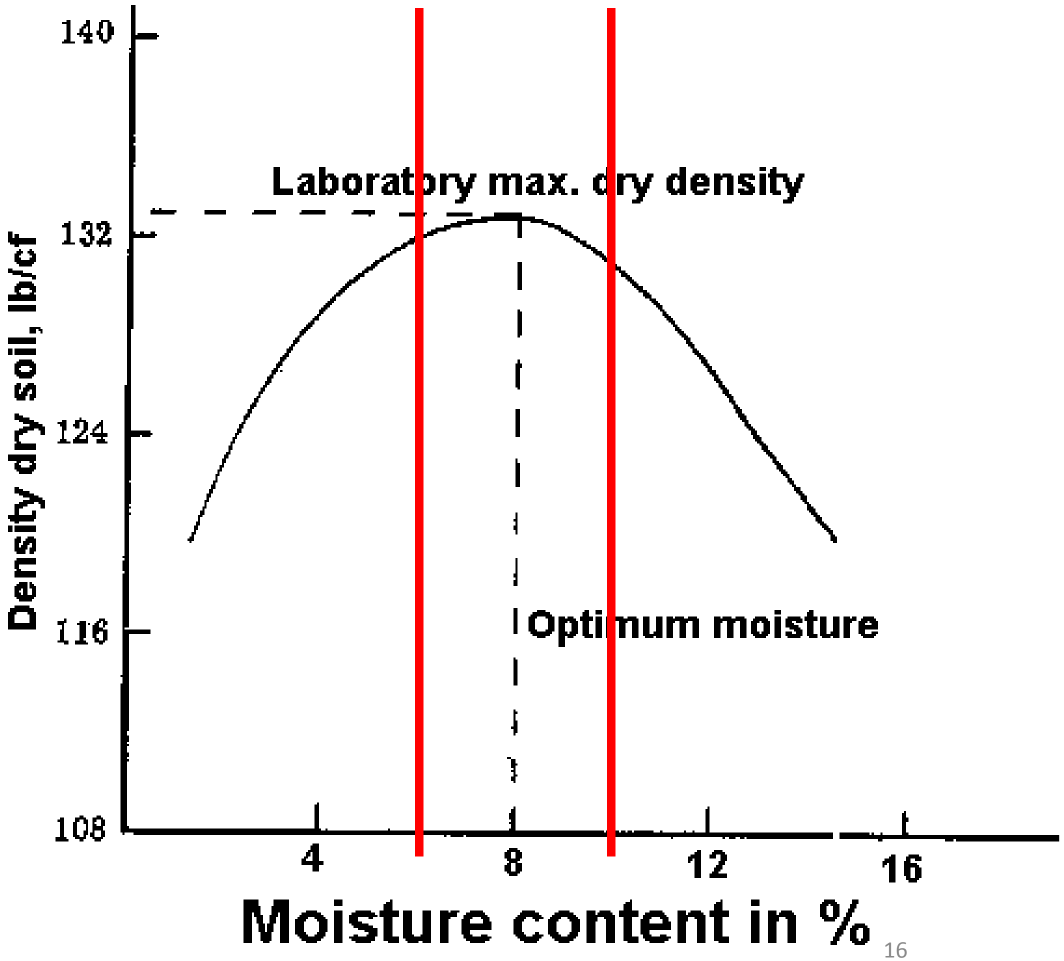
COMPACTION



140
132
124
116
108
Laboratory max. dry density
Optimum moisture
Density dry soil, lb/cf
4
8
12
16
Moisture content in %

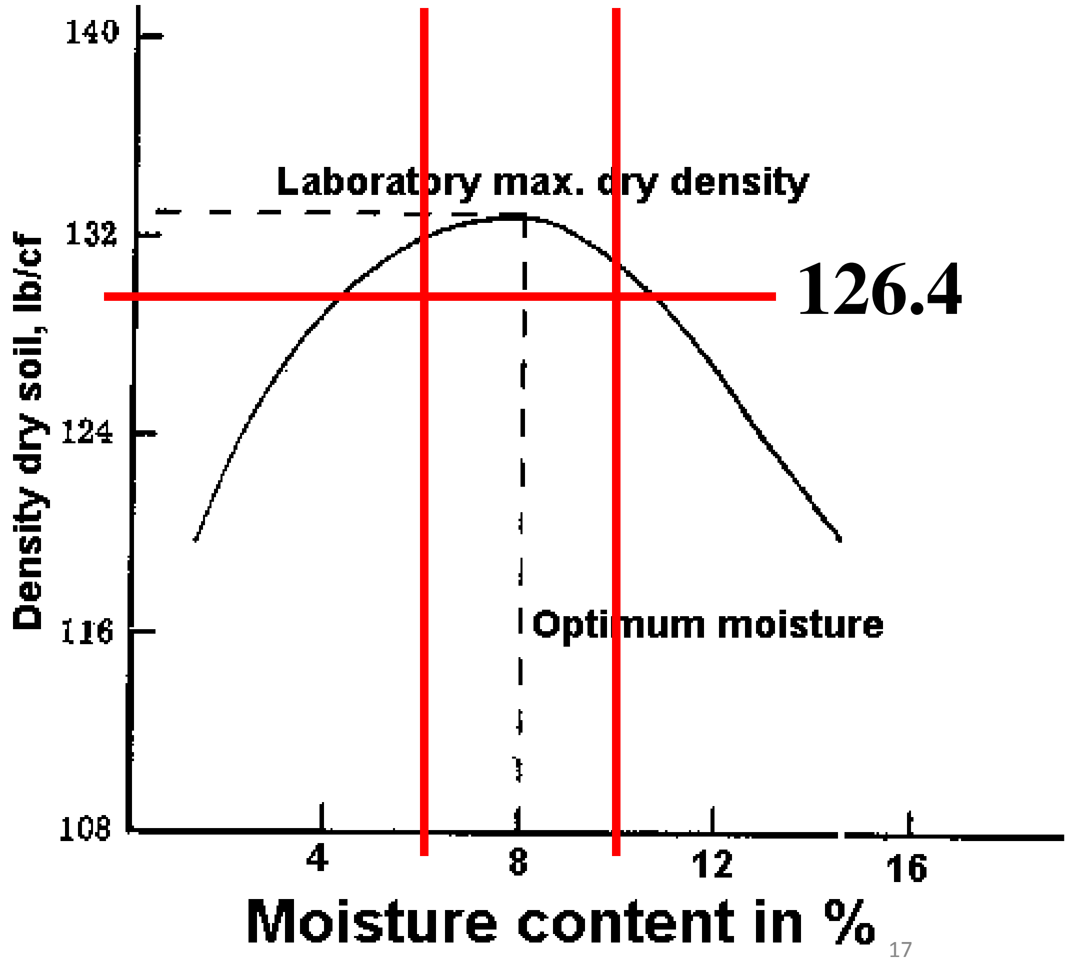
COMPACTION SPECIFICATIONS

Typically specifications give an acceptable range of water content, OMC ± 2% for example.



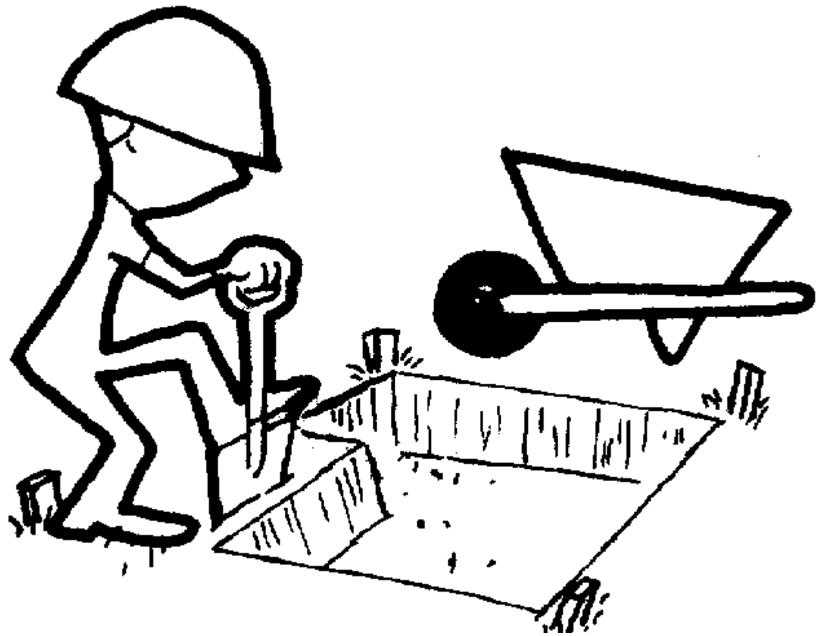
COMPACTION SPECIFICATIONS

The specification also sets a minimum density, 95% of max. dry density for a specific test



EXERCISE

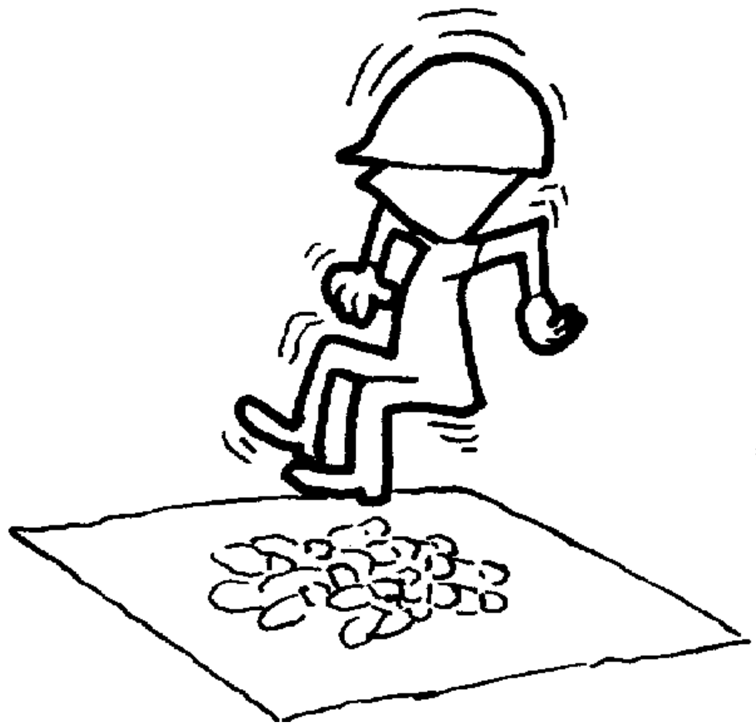
The excavated material has a



- **unit weight (γ) of 94.3 pcf**
- **water content (ω) of 8%.**

EXERCISE

The embankment will be compacted to



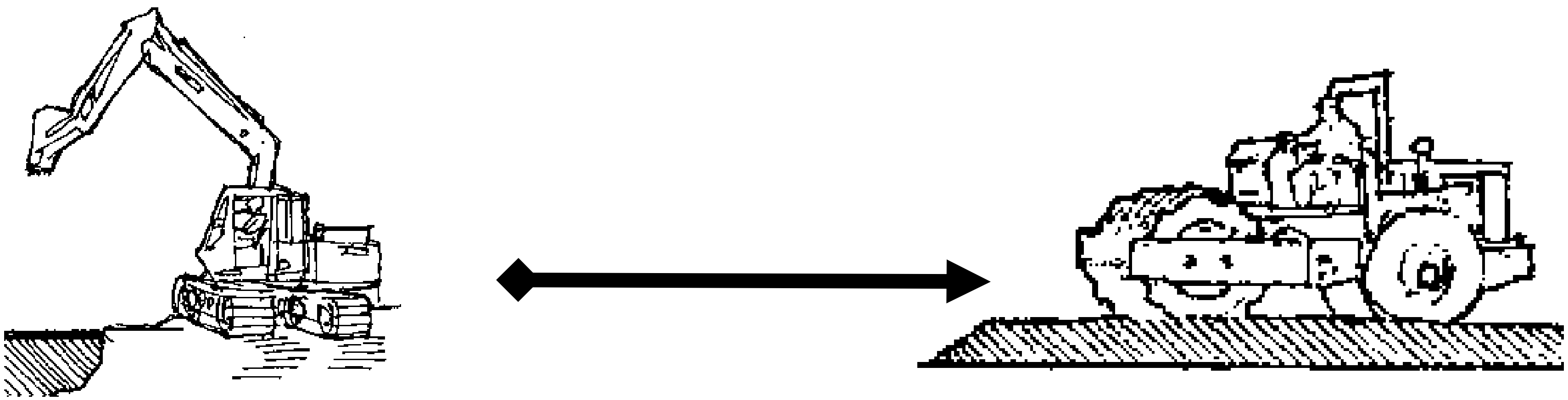
- **dry unit weight (γ_d) of 114 pcf**
- **water content (ω) of 12%.**

EXERCISE

- The net section of the embankment is 113,000 cy.
- How many cubic yards of excavation will be required to construct the embankment?

EXERCISE

- As material is moved from the excavation to the compacted fill the only constant is the weight of the solid particles (γ_d).



EXERCISE
Step 1

Weight of the solid particles which make up the embankment (fill).

a dry unit weight (γ_d) of 114 pcf

113,000 cy embankment

$$113{,}000\ \text{cy} \times \frac{27\ \text{ft}^3}{\text{cy}} \times 114\ \text{lb/ft}^3$$

Conversion factor cy to ft^3

EXERCISE
Step 2

- Use **relationship γ_d - γ** to calculate the **dry unit weight** of the excavated material.
- a unit weight (γ) of **94.3 pcf**
- a water content (ω) of **8%**

- $\gamma_d = \dfrac{94.3\,\mathrm{ft}^3}{1+0.08} \Rightarrow$ **87.31 pcf**

EXERCISE
Step 3

- Calculate the **weight of the solid** particles which make up the excavation (cut).

$$x\ cy \times \frac{27\ ft^3}{cy} \times 87.31\ lb\ /\ ft^3$$

EXERCISE
Step 4

- **The weights must be equal therefore:**

$$x\ cy \times \cancel{\frac{27\ ft^3}{cy}} \times 87.31\ lb/\ ft^3 \quad =$$

$$113{,}000\ cy \times \cancel{\frac{27\ ft^3}{cy}} \times 114\ lb/\ ft^3$$

Conversion factors cancel out.

EXERCISE
Step 4

Weights must be equal therefore:

$$x = 113{,}000\ cy \times \frac{114\ lb / ft^3}{87.31\ lb / ft^3}$$

$x =$ 147,535 cy

excavated material required

EXERCISE

- Check the water requirements.
- Will a water truck be needed on the job or will it be necessary to dry the material?

EXERCISE
Step 1

Water content (ω) is?

$$= \frac{\text{weight of water in soil}}{\text{weight of soil solids}} = \frac{W_w}{W_s}$$

Weight of water/cf = ω x Ws

EXERCISE
Step 1
Water from Cut

$$147{,}535 \text{ cy}$$ **Vol. Cut**

$$\times 87.31 \text{ pcf}$$ γ_d

$$\times 27 \text{ cf/cy}$$ **conversion factor**

$$\times 0.08$$ (ω)

$$= \text{lb of water}$$

EXERCISE
Step 1
Water from Cut

$$147{,}535\ cy \times 87.31\ pcf \times 27\ cf\ /\ cy \times 0.08$$

= 27,825,120 lb water delivered with the borrow material

EXERCISE
Step 2
Water needed at the Fill

$113{,}000 \text{ cy}$	**Vol. Emb**
$\times 114 \text{ pcf}$	γ_d
$\times 27 \text{ cf/cy}$	**conversion factor**
$\times 0.12$	**(ω)**
$= \text{lb of water}$	

EXERCISE
Step 2
Water needed at the Fill

$$113{,}000\ cy \times 114\ pcf \times 27\ cf\ /\ cy \times 0.12$$

= 41,737,680 lb water needed at the fill

EXERCISE
Step 3
Water Deficiency

Needed at the fill	41,737,680 lb
Delivered w/ cut	27,825,120 lb
Water deficiency	13,912,560 lb

EXERCISE
Step 4
Convert to Gallons

$$\frac{\text{Water deficiency } 13{,}912{,}560 \text{ lb}}{\text{Water weights } 8.33 \text{ lb/gal}}$$

Need to add 1,670,175 gallons

EXERCISE
Step 5
Gallons per cy

Water deficiency	**1,670,175 gal**
Volume of cut	**147,535 cy**

Need 11.3 gal/cy

Adding Water

Reducing Moisture

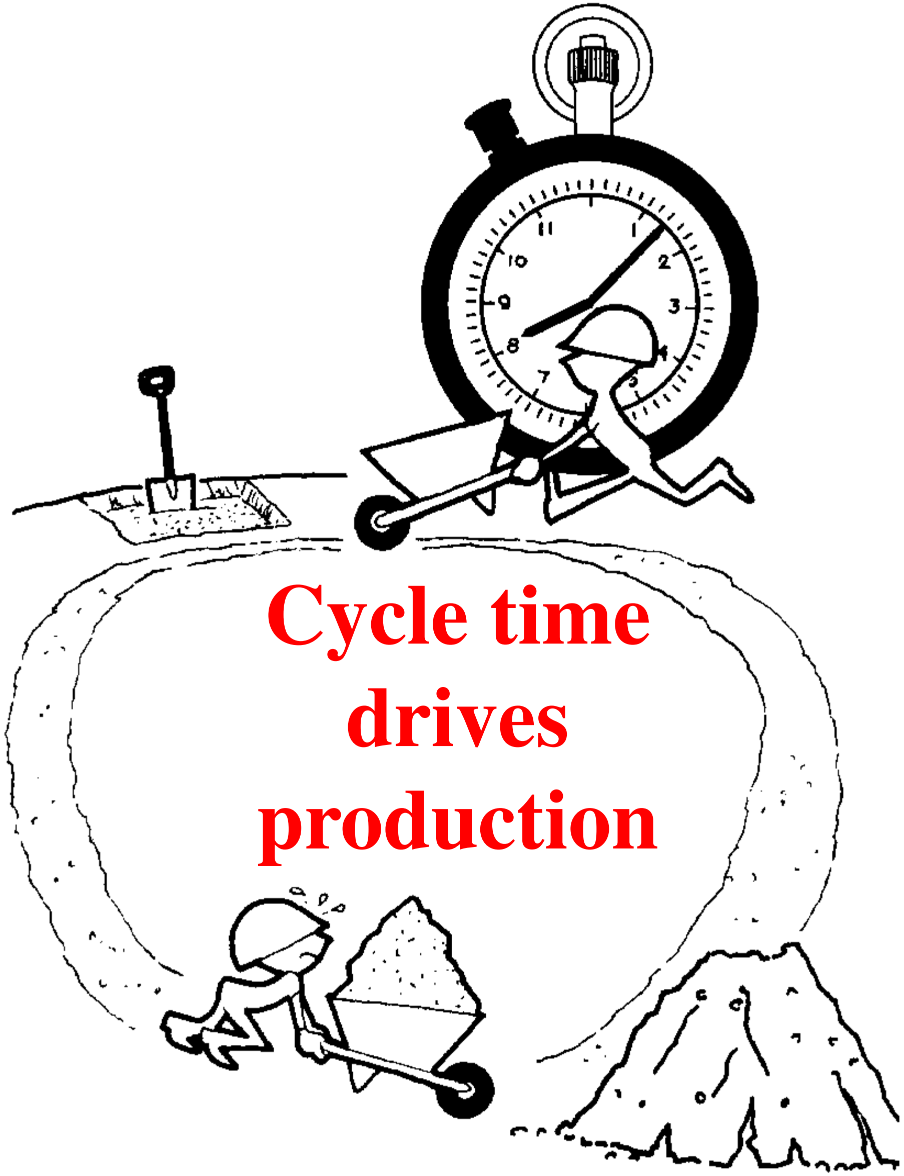
Disking a heavy clay fill to reduce moisture.

POWER

"Why does a machine only travel at 10 mph when its top speed is 30 mph?"

POWER

Speed affects cycle time



Cycle time drives production

Production determines cost

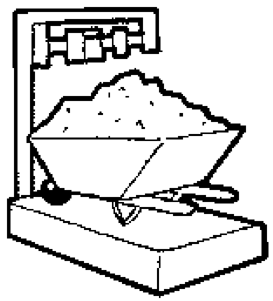
PAYLOAD

The payload capacity of construction excavation and hauling equipment can be expressed either

Volumetrically

or

Gravimetrically



Power Required

Factors affecting equipment power:

- **Rolling Resistance (RR):**

“It is the power resulted from internal equipment friction and friction developed between the wheels or tracks and the traveled surface”.

- **Grade Resistance (GR):**

“It is the power resulted from slope of the traveled way”.

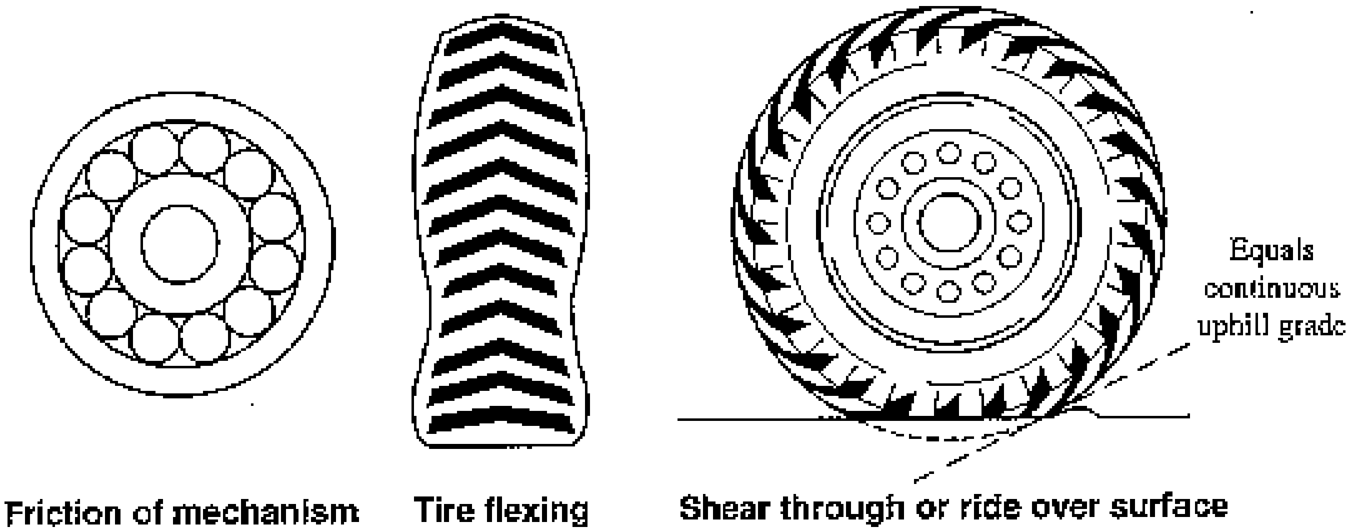
ROLLING RESISTANCE

Rolling Resistance is a measure of the force (lb/ton) that must be overcome to rotate a wheel over the surface on which it makes contact.

ROLLING RESISTANCE

Rolling Resistance is caused by

- **Internal friction**
- **Tire flexing**
- **Tire penetrating the surface**



ROLLING RESISTANCE

If tire penetration is known

Rolling Resistance (lb) =

$$RR = [40 + (30 \text{ X } TP)] \text{ X } GVW$$

- **TP = Tire Penetration, inches (may be different for haul and return)**
- **GVW = Gross Vehicle Weight, tons**

ROLLING RESISTANCE

If tire penetration is not known, Rolling Resistance (lb/ton) can be estimated from Table

Table 10.2 Typical Rolling Resistance Factors (Caterpillar Tractor Co.)

A hard, smooth stabilized roadway without penetration under load (concrete or blacktop)	40 lb/ton
A firm, smooth-rolling roadway flexing slightly under load (macadam or gravel-topped road)	65 lb/ton
Snow-packed	50 lb/ton
Loose	90 lb/ton
A rutted dirt roadway, flexing considerably under load; little maintenance, no water (hard clay road, 1 in. or more tire penetration)	100 lb/ton
Rutted dirt roadway, no stabilization, somewhat soft under travel (4 to 6 in. tire penetration)	150 lb/ton
Soft, muddy, rutted roadway, or in sand	200–400 lb/ton

ROLLING RESISTANCE

Example

For an equipment of 70 ton weight that penetrate the road surface with 1.5 inch,

RR = [40+1.5(30)] lb/ton X 70 tons

= 5,950 lb.

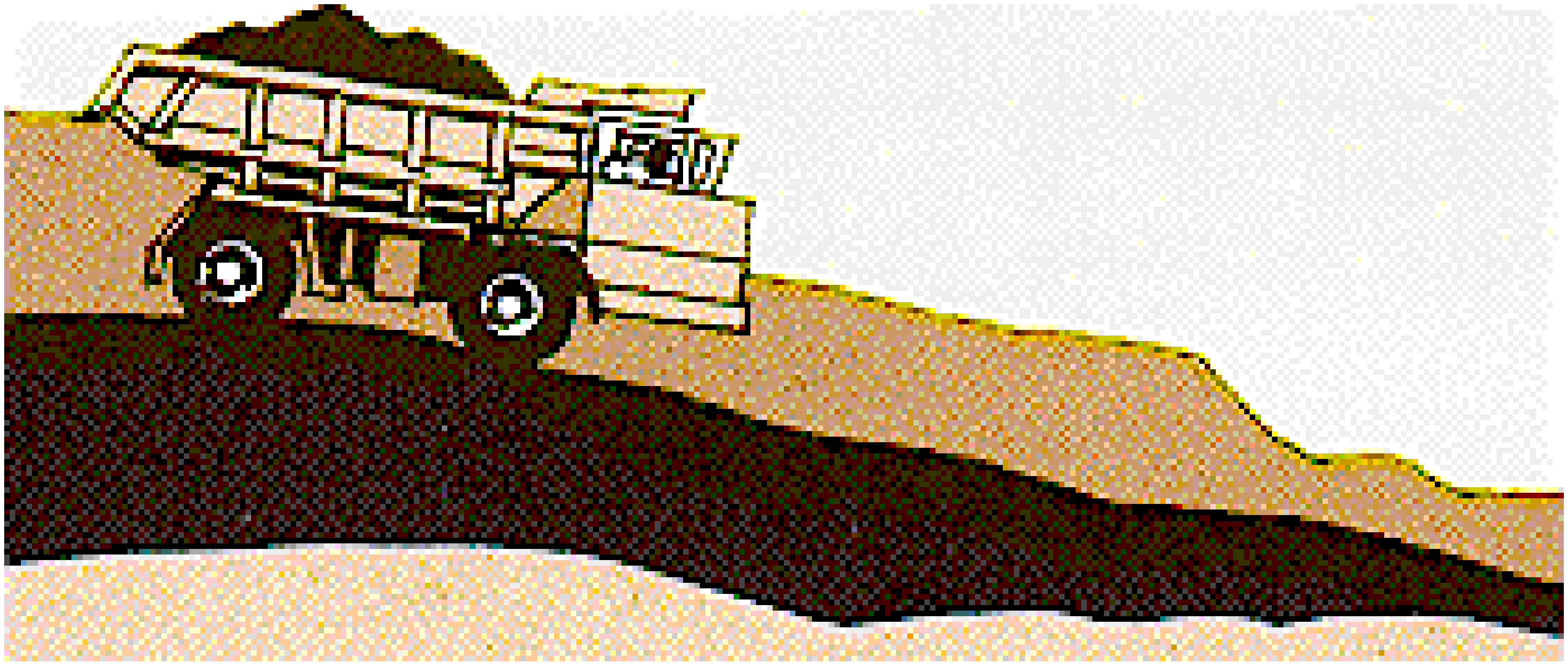
If penetration is not mentioned, substitute it with zero in RR equation.

HAUL ROAD CONDITION

If haul roads are well maintained rolling resistance is low and production improves.
Good haul roads require graders and water trucks, so there is a cost.

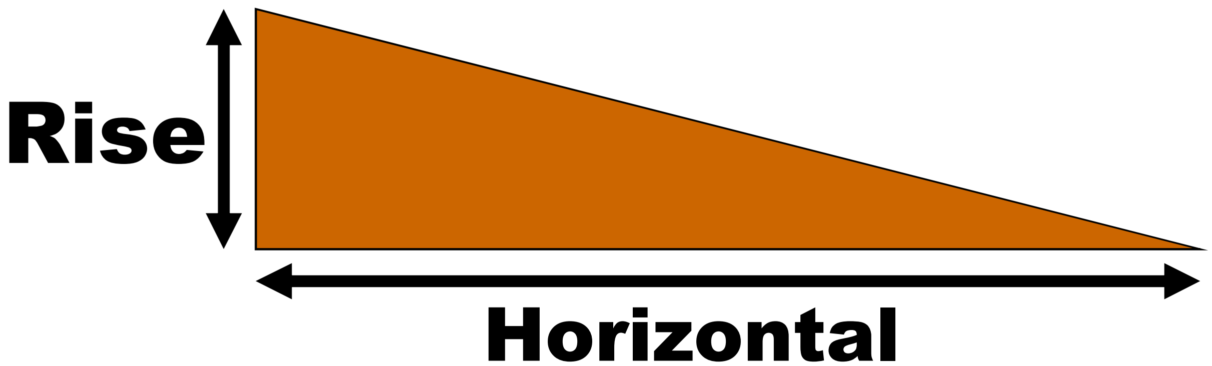
GRADE RESISTANCE

We seldom find a haul road which is level from point of load to point of dump.



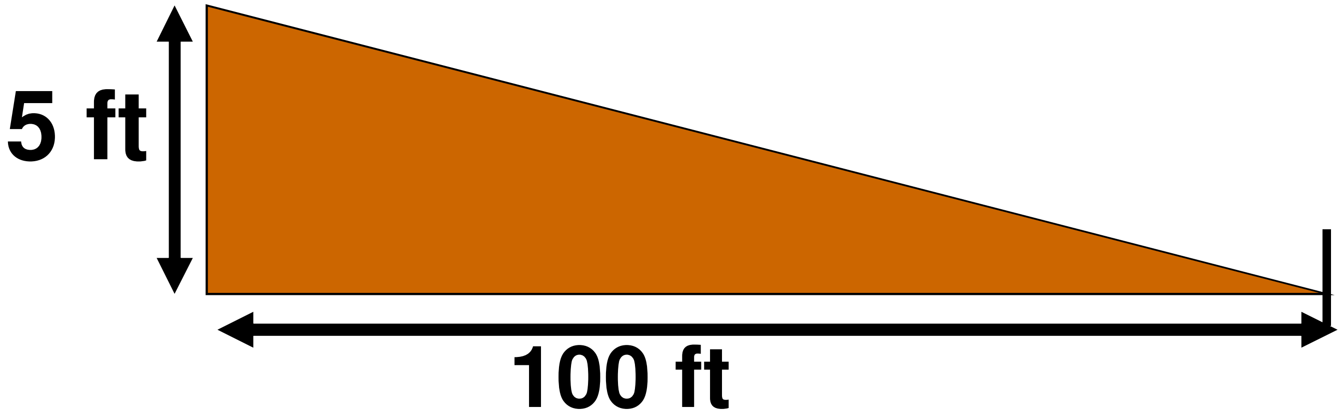
GRADE RESISTANCE

Grades are measured in % slope: the ratio between vertical rise (fall) and horizontal distance in which the rise/fall occurs.



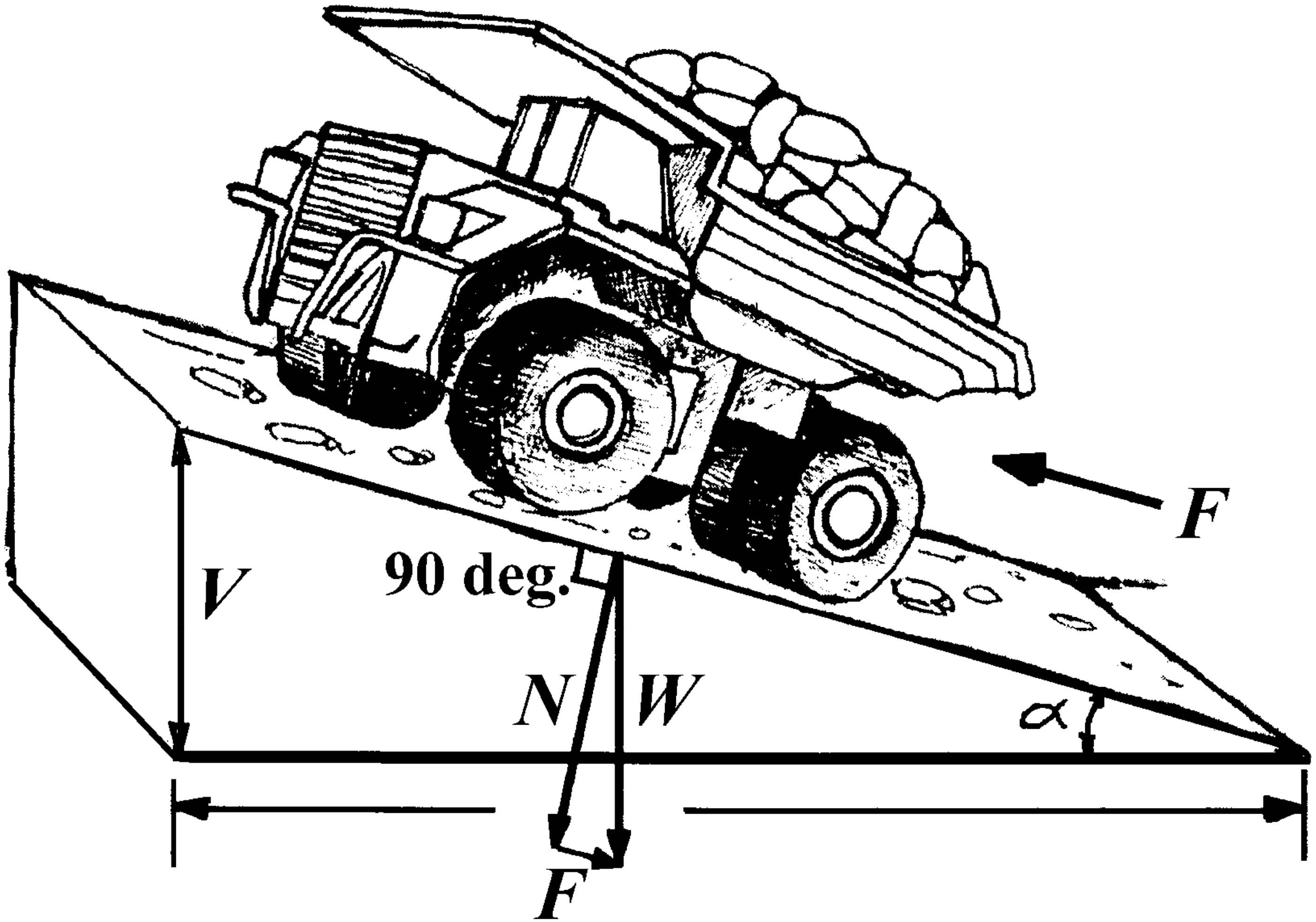
GRADE RESISTANCE

Grade example: 5 ft fall in 100 ft horizontal travel.



$$\frac{5\ \text{ft}}{100\ \text{ft}} \times 100 = 5\%$$

GRADE RESISTANCE



GRADE RESISTANCE

For small angles (% grade):

$$GR = 20 \text{ lb/ton} \times GVW \times \% \text{ grade}$$

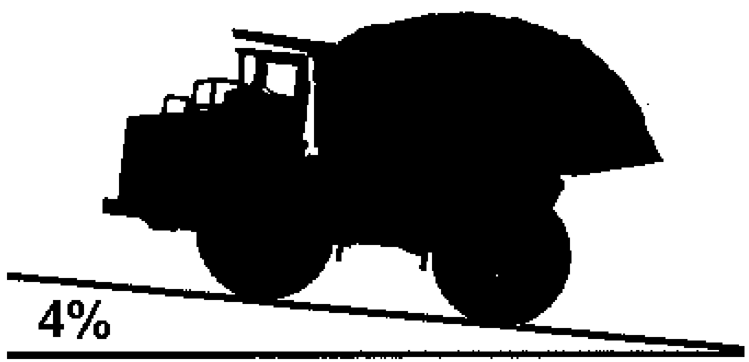
GRADE RESISTANCE

Example

A truck with a 23 ton GVW is moving up a 4% grade. What is the force required to overcome grade resistance?

$$GR = 20 \text{ lb/ton} \times 23 \text{ ton} \times 4\% \text{ grade}$$

$$GR = 1{,}840 \text{ lb}$$



GRADE ASSISTANCE

Gravity assists the machine when traveling down grade.

That force is referred to as Grade Assistance

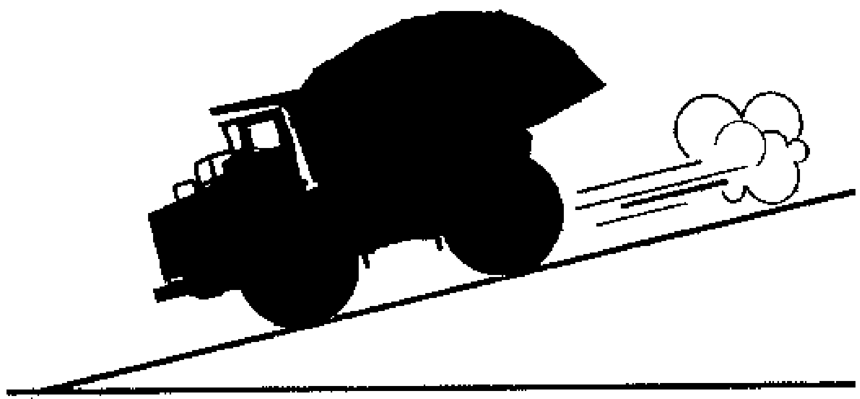
GRADE ASSISTANCE

Example

Our truck has dumped its load, the GVW is now 12 ton and on the return it is moving down the 4% grade. What is the force required to overcome grade resistance?

GA = 20 lb/ton x 12 ton x -4% grade

GA = -960 lb



GRADE ASSISTANCE

Example

For an equipment of 70 ton weight that go uphill of percent grade 4%, then,

GR= 4% x 20 (lb/ton) x 70 (tons) = 5,600 lb

If the percent grade is 4% downhill, then,

GR = - 4 x 20 x 70 = - 5,600 lb

TOTAL RESISTANCE

Total Resistance = Rolling Resistance + Grade Resistance

TR = RR + GR

or

TR = RR - GA

POWER REQUIRED
Previous Example

- **Uphill road,**

Power Required = RR + GR

PR = 5,950 + 5,600 = 11,550 lb

- **Downhill road,**

Power Required = RR - GR

PR = 5,950 - 5,600 = 350 lb

POWER REQUIRED

Typical Haul Road Profile

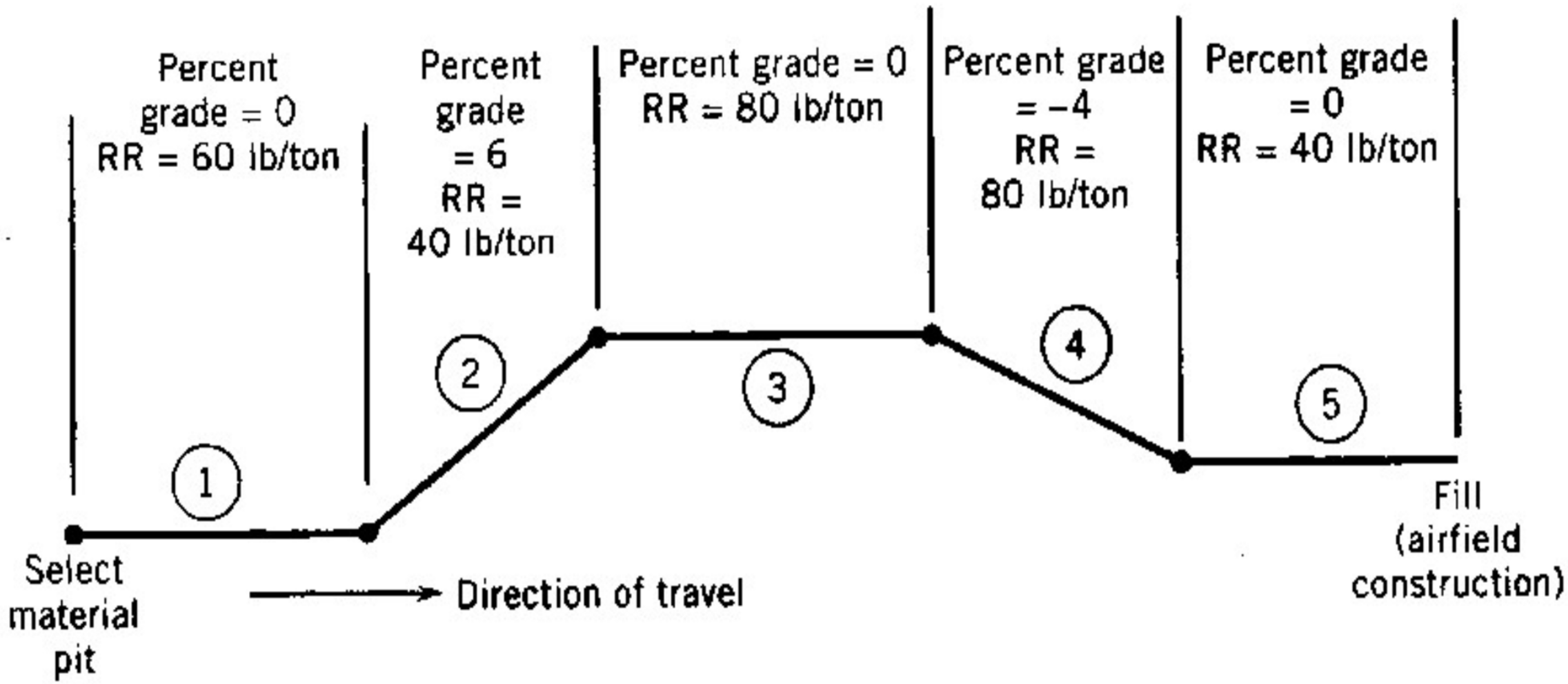


Figure 10.4 Typical haul road profile.

POWER REQUIRED

Example

Table 10.3 Calculations for Haul Road Sections[a]

Section	Percent Grade (%)	Grade Resistance (lb)	Rolling Resistance (lb)	Power Required (lb) RR+GR
1	0	0	60x70= 4,200	4,200
2	6	6x20x70= 8,400	40x70= 2,800	Max 11,200
3	0	0	80x70= 5,600	5,600
4	−4	-4x20x70= −5,600	80x70= 5,600	0
5	0	0	40x70= 2,800	2,800

[a] All calculations assume travel from pit to fill.

POWER AVAILABLE

- The available power depends on engine size and the drive gear (being used).
- Lower gears sacrifice speed to provide more power and vice versa.
- Drawbar pull is available power in tracked equipment
- Pounds Rimpull is available power in wheeled equipment.

POWER AVAILABLE

At normal load for long periods

At abnormal loads for short periods to meet power requirement at special times

Table 10.4 Speed and Drawbar Pull (270 hp) (Track-Type Tractor)

	Speed				Drawbar Pull Forward[a]			
	Forward		Reverse		At Rated rpm		Maximum at Lug	
Gear	mph	km/h	mph	km/h	lb	kg	lb	kg
1	1.6	(2.6)	1.6	(2.6)	52,410	(23,790)	63,860	(28,990)
2	2.1	(3.4)	2.1	(3.4)	39,130	(17,760)	47,930	(21,760)
3	2.9	(4.7)	2.9	(4.7)	26,870	(12,200)	33,210	(15,080)
4	3.7	(6.0)	3.8	(6.1)	19,490	(8,850)	24,360	(11,060)
5	4.9	(7.9)	4.9	(7.9)	13,840	(6,280)	17,580	(7,980)
6	6.7	(10.8)	6.8	(10.9)	8,660	(3,930)	11,360	(5,160)

[a] Usable pull will depend on traction and weight of equipped tractor.

POWER AVAILABLE

		Pounds Rimpull	
Gear	Speed (mph)	Rated (lb)	Maximum (lb)
1	2.6	38,670	49,100
2	5.0	20,000	25,390
3	8.1	12,190	15,465
4	13.8	7,185	9,115
5	22.6	4,375	5,550

- **Rimpull =275*hp*E/V** (kg)
  E = Rimpull efficiency (normally around 85%)
  V = Speed (km/hr),
  hp = horsepower

- **Rimpull =375*hp*E/V** (lb)
  E = Rimpull efficiency (normally around 85%)
  V = Speed (mi/hr),
  hp = horsepower

POWER AVAILABLE
RIMPULL EXAMPLE

- A wheel-tractor of 140-hp and weight of 12.4 tons. It moves using the first gear with speed of 5.2 Km/hr. The road slope = +2%. Tire penetration is 1 inch and rimpull efficiency = 85%.
- What is the maximum available Rimpull to tow?

POWER AVAILABLE
RIMPULL EXAMPLE

- ✓Rimpull = 275*140*0.85/5.20=6,293 kg
- ✓RR = (40+30*1)*12.4*0.4534= 393.6 kg
- ✓GR = 2*20*12.4*0.4534 = 224.9 kg
- ✓Max. avail. Rimpull = 6,293-GR-RR

  = 6,293 - 393.6 - 224.9 = 5674.5 kg

(Assuming that the available power is the same as the usable power).

USABLE POWER

- It was assumed that the available power is usable wherever it can be developed.
- But, environmental conditions play a major role in determining whether the power available can be utilized under operating conditions.

USABLE POWER

- Three major factors affect the available power:

1. Road surface traction characteristics (wheeled equipment only) transfer power to the ground.
2. The altitude (pressure) at which operations are conducted (oxygen reduction at high altitude reduces power).
3. Effect of temperature.

USABLE POWER

"Coefficient of traction" is a measure of the ability of a particular surface to receive and develop the power being delivered to the driving wheels.

The power, which can Be developed in a Given surface can be calculated as follows:

Table 10.5 Coefficients of Traction

Materials	Rubber Tires	Tracks
Concrete	.90	.45
Clay loam, dry	.55	.90
Clay loam, wet	.45	.70
Rutted clay loam	.40	.70
Dry sand	.20	.30
Wet sand	.40	.50
Quarry pit	.65	.55
Gravel road (loose, not hard)	.36	.50
Packed snow	.20	.25
Ice	.12	.12
Firm earth	.55	.90
Loose earth	.45	.60
Coal, stockpiled	.45	.60

Driving wheels weight only

Usable pounds pull = (coefficient of traction) × (weight on drivers)

USABLE POWER

- The total equipment weight is considered when determining RR and GR; however, the weight on driving wheels is only considered in case of usable power since it is the weight that press both the wheels and the surface.
- Most equipment packages show the load distribution for all wheels in both empty and loaded cases.
- For a scraper, next Figure shows this load distribution.

USABLE POWER

In Determining Weight on Drivers

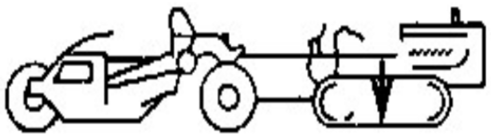
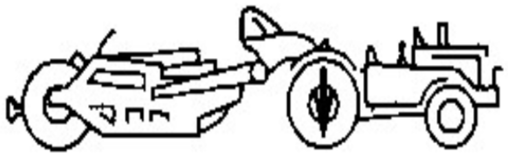
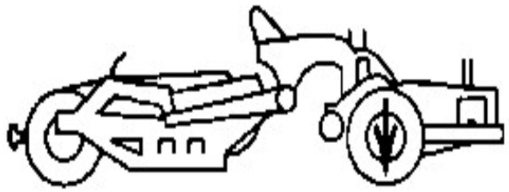
		
For track-type tractor	For four-wheel tractor	For two-wheel tractor
Use total tractor weight	Use weight on drivers shown on spec sheet or approximately 40% of vehicle gross weight	Use weight on drivers shown on spec sheet or approximately 60% of vehicle gross weight

Figure 10.7 Determination of driver weights.

USABLE POWER
Example

- A 30-cy-capacity, two-wheel tractor-scraper is operating in dry sand and carrying 26-ton load. The job superintendent is concerned about the high rolling resistance of the sand (RR=400lb/ton) and the low sand traction. The scraper has a gross weight of 127,800 lb; however, the weight on driving wheels is 66,456 lb. Is it proper for the scraper to carry out the assigned load in a level road? If there is a problem, What about using wet sand?
- Coefficient of traction for dry sand? 0.2
- Coefficient of traction for wet sand? 0.4

USABLE POWER

Example

- To check whether there is a problem of carrying the assigned load, we have to calculate the power required (PR) and compare it to the power usable (PU).
- If PR > PU, then the scraper is not going to move and either the load or the ground surface has to change.
- If PU > PR, then the scraper is in good shape.
- Hence, calculate PR and PU.

USABLE POWER

Example

- PR = RR because GR = 0 for level road.
- PR= 400x127,800lb/2000(lb to ton)= 25,560lb
- PU = coefficient of traction x weight on driving wheels.
- PU = 0.2 x 66,456lb = 13,291.2 lb (dry sand)
- Then, PR > PU where the developed power with the ground surface is half the required.
- Ground conditions has to be changed. Let us try to wet the sand.

USABLE POWER

Example

For wet sand:

- PR= 400x127,800lb/2000(lb/ton)= 25,560lb
- PU = 0.4x66,456lb = 26,582.4 lb (dry sand)
- Then, PU > PR.
- The problem can be solved by spreading water over the sandy road that the scraper is working on.

USABLE POWER

Example

- For maximum engine performance, the ratio of oxygen to fuel must be constant.
- The higher the altitude above sea level, the lower the engine efficiency. Therefore, The usable power will be lower than standard conditions.
- The engine horsepower capabilities are reduced according the equipment location from the sea level.

USABLE POWER

ALTITUDE EFFECT

- Approximate Method
- For 4 cycle gas and diesel engines: reduce the equipment hp by 3% for every 300 m (330 yd) after the 1st 300 m (330 yd) above the sea level.

USABLE POWER

ALTITUDE EFFECT

- Approximate Method
- **For 2 cycle diesel engines:** reduce the equipment hp by 1.5% for every 300 m (330 yd) between the sea level and the altitude of 1,800 m (1980 yd). Above this altitude, reduce hp by 3% for every 300 m (330 yd).

USABLE POWER

ALTITUDE EFFECT

- Approximate Method
- For turbocharged 2 or 4 cycle diesel engines: **no loss in power up to 3,000 m (3,300 yd).**
- Turbocharger is a mechanical component mounted on the engine which forces air to the pistons. This solves the problem of oxygen level decrease.

USABLE POWER

ALTITUDE EFFECT

- 2-cycle engine of 100 hp at sea level. What is its available power at 3,000 m (3,300 yd) altitude?
- Solution:

  Available hp = 100 – [0.015*100*1,800/300] – [0.03*100*(3,000-1,800)/300] = 100 – 9 – 12 = 79 hp.

USABLE POWER

ALTITUDE EFFECT

AVERAGE BAROMETRIC PRESSURES
FOR VARIOUS ALTITUDES ABOVE SEA LEVEL
IN CM OF MERCURY

ALTITUDE ABOVE SEA LEVEL (m)	BAROMETRIC PRESSURE (cm Hg)
0	76.00
300	73.40
500	71.65
1,000	67.80
1,500	63.35
2,000	59.40
2,500	56.00
3,000	52.40
3,500	50.35

USABLE POWER
Temperature Effect

- As temperature increases, engine performance decreases and vice versa.
- Empirically, reduce the equipment hp at 16 °C (60 °F)by 1% for each 5.5 °C (42 °F) above 16 °C (60 °F).
- Empirically, increase the equipment hp at 16 °C (60 °F) by 1% for each 5.5 °C (42 °F) below 16 °C (60 °F).
- °C = (F-32)/1.8

USABLE POWER
Temperature Effect

- An equipment engine has 100 hp at 16 ℃. What is its available power at 27 ℃?

- Solution:

Available hp = 100 – [1*(27-16)/5.5] =

= 100 – 2 = 98 hp.

USABLE POWER

COMBINED EFFECT OF ALTITUDE AND TEMPERATURE

- Standard conditions are set as sea level altitude, 16 ℃ (60 ℉) average temperature, and 76 cm mercury (Hg) [29.92 inch Hg] average barometric pressure.

- If the equipment manual provide you with the horsepower hp or fwhp, it will be at the standard conditions. It is the project manager responsibility to calculate the available hp or fwhp in the site.

USABLE POWER

COMBINED EFFECT OF ALTITUDE AND TEMPERATURE

$$\text{Horsepower available} = \text{rated hp} \times \frac{P_{\text{actual}}}{P_{\text{std}}}\sqrt{\frac{T_{\text{std}}}{T_{\text{actual}}}} \qquad (4\text{-}28)$$

where P_{actual} = altitude at which the machine will be operated, in in. Hg (inches of mercury), barometric pressure (see Table 4-6)

P_{std} = standard condition altitude, usually sea level, 29.92 in. Hg

T_{actual} = Rankine temperature at which the machine will be operated

T_{std} = standard condition temperature, in Rankine units, usually 60°F, which equals 520°R

USABLE POWER

COMBINED EFFECT OF ALTITUDE AND TEMPERATURE

TABLE 4-6
Average barometric pressures for various altitudes

Altitude above sea level (ft)	0	1,000	2,000	3,000	4,000	5,000	6,000	7,000	8,000	9,000	10,000
Barometric pressure (in. Hg)	29.92	28.86	27.82	26.80	25.82	24.87	23.95	23.07	22.21	21.36	20.55

USABLE POWER

COMBINED EFFECT OF ALTITUDE AND TEMPERATURE

A tractor is powered by a four-cycle diesel engine. When tested under standard conditions, the engine developed 130 fwhp. What is the probable hp at an altitude of 3,660 ft, where the average daily temperature is 72 F?

USABLE POWER

COMBINED EFFECT OF ALTITUDE AND TEMPERATURE

fwhp for std condition = 130

P_{std}= 29.92 in
P_{actual}= 26.15 in (from 4-6)

T_{std}= 460 + 60 = 520 R
T_{actual}= 460 + 72 = 532 R

USABLE POWER

COMBINED EFFECT OF ALTITUDE AND TEMPERATURE

Find the fwhp available, substituting the equation:

$$hp = 130 \times \frac{26.15}{29.92}\sqrt{\frac{520}{532}} = 112.7hp$$

Thus the probable horsepower of engine will be reduced to 112.7 as a result of the increased altitude and temperature.

PERFORMANCE CHART

- Performance charts for individual machine models are published by equipment manufacturers.

- These charts allow the equipment estimator/ planner to analyze a machine's ability to perform under a given set of job and load conditions.

PERFORMANCE CHART

- The performance chart is a graphical representation of the power and corresponding speed that the engine and transmission can deliver.
- The load condition is stated as either rimpull or drawbar pull.

PERFORMANCE CHART

- It should be noted that the rimpull-speed relationship is inverse since vehicle speed increases as rimpull decreases.
- If the gear ratios or rolling radius of a machine is changed, the entire performance curve will shift along both the rimpull and speed axles.

PERFORMANCE CHART

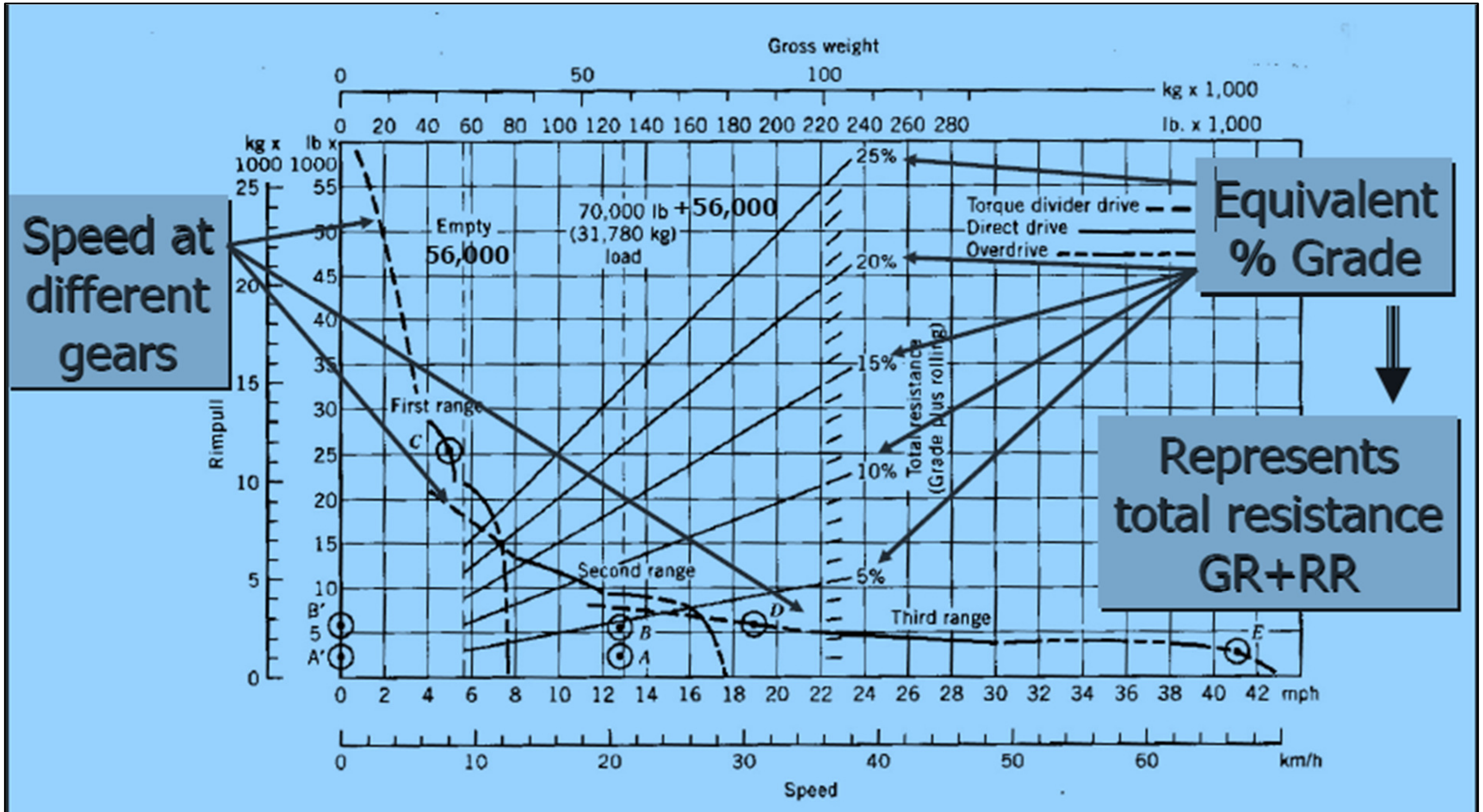


Figure 10.5 Gear requirements chart-35-ton, off-highway truck (Caterpillar Tractor Co.).

PERFORMANCE CHART

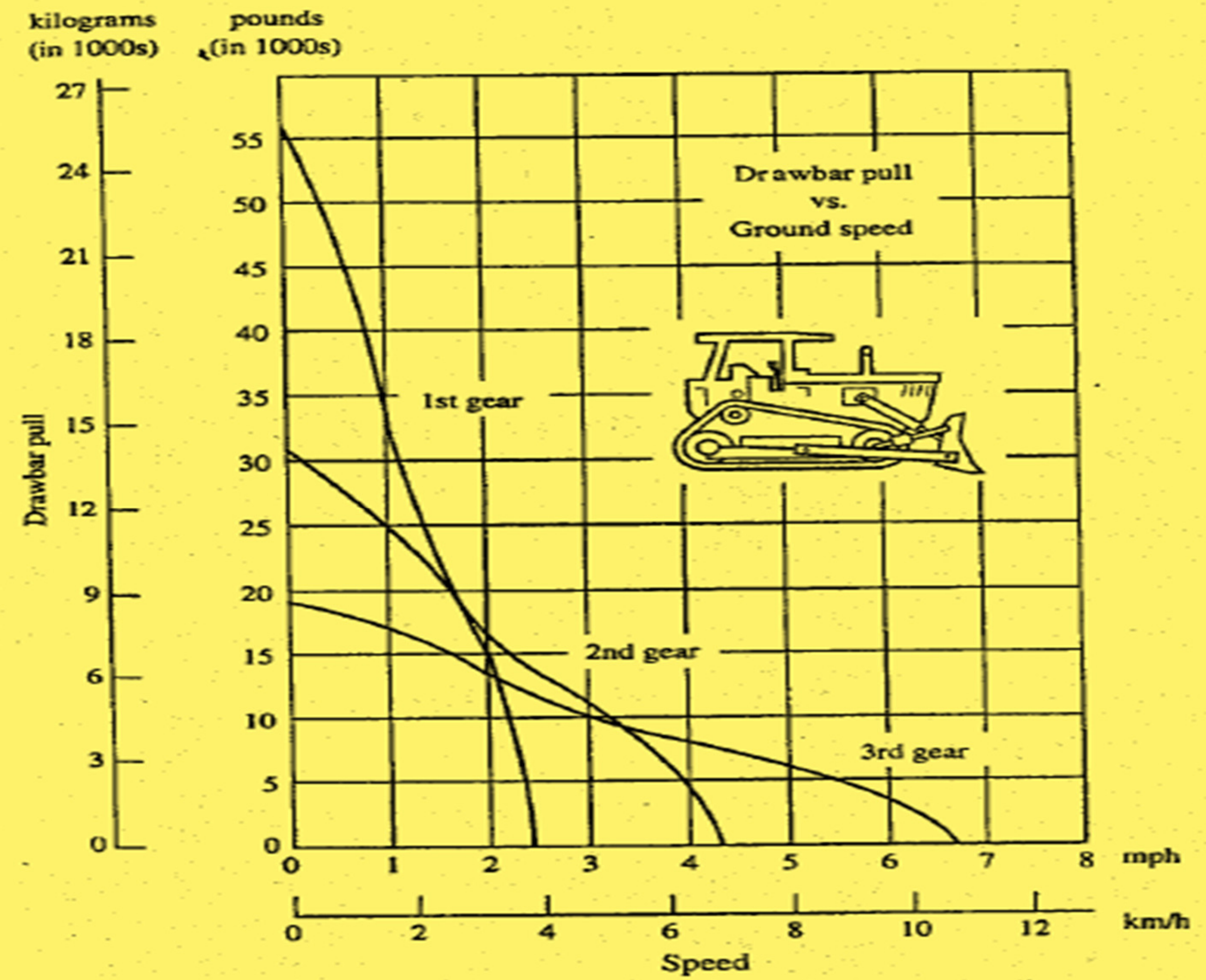


FIGURE 6.9 Drawbar pull performance chart for a crawler tractor.
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Thank You