1. *Filtration*

Filtration is used to separate nonsettleable solids from water and wastewater by passing it through a porous medium. The most common system is filtration through a layered bed of granular media, usually a coarse anthracite coal underlain by a finer sand.

Filters may be classified according to the types of media used as follows:

- Single-media filters: These have one type of media, usually sand or crushed anthracite coal.
- Dual-media filters: These have two types of media, usually crushed anthracite coal and sand.
- Multi-media filters: These have three types of media, usually crushed anthracite coal, sand, and garnet.

In water treatment all three types are used; however, the dual- and multimedia filters are becoming increasingly popular. In advanced tertiary wastewater treatment, nearly all the filters are dual- or multimedia types.

Many particles in water are too small to remove by sedimentation alone. Filtration removes microorganisms and suspended matter from water not receiving sedimentation treatment, or it eliminates precipitated particles and flocs remaining after sedimentation. Filtration was actually developed prior to the discovery of the germ theory by Louis Pasteur in France. The first sand filter beds were constructed in the early 1800s in Great Britain.

Particle removal is accomplished only when the particles make physical contact with the surface of the filter medium. This may be the result of several mechanisms, as shown in Figure 1. Larger particles may be removed by straining. That is, the particle is larger than the pore, so it is trapped. Particles may also be removed by sedimentation as they progress through the filter. Others may be intercepted by and adhere to the surface of the medium due to inertia. Filtration efficiency is greatly increased by destabilization or coagulation of the particles prior to filtration. This reduction in the particle charge increases particle agglomeration and reduces the forces necessary to trap particles within the filter.

1.1 Gravity Granular-Media Filtration

Gravity filtration through beds of granular media is the most common method removing colloidal impurities in water processing and tertiary treatment of wastewater.

The mechanisms involved in removing suspended solids in a granular-media filter are complex, consisting of interception, straining, flocculation, and sedimentation as shown schematically in Figure 1. Initially, surface straining and interstitial removal results in accumulation of deposits in the upper portion of the filter media. Because of the reduction in pore area, the velocity of water through the remaining voids increases, shearing off pieces of capture floc and carrying impurities deeper into the filter bed. The effective zone of removal passes deeper and deeper into the filter. Turbulence and the resulting increased particle contact within the pores promotes flocculation, resulting in trapping of the larger floc particles. Eventually, clean bed depth is no longer available and breakthrough occurs, carrying solids out in the underflow and causing termination of the filter run.

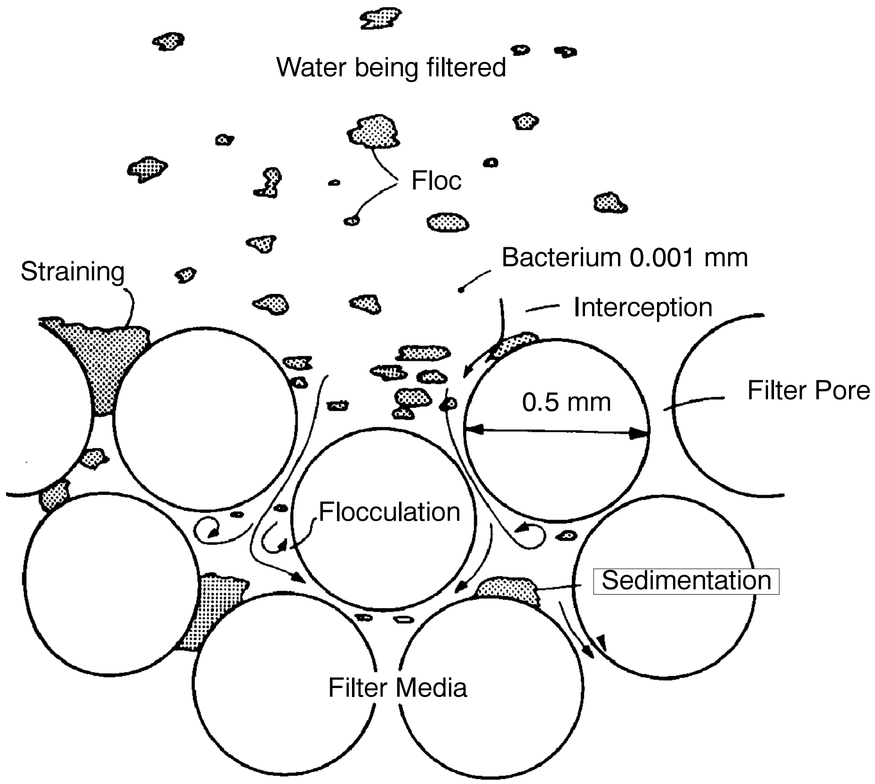


Figure 1. Schematic diagram illustrating straining, flocculation, and sedimentation actions in a granular-media filter.

Microscopic particulate matter in raw water that has not been chemically treated will pass through the relatively larger pores of a filter bed. On the other hand, suspended solids fed to a filter with excess coagulant carryover from chemical treatment produces clogging of the bed pores at the surface. Optimum filtration occurs when impurities in the water and coagulant concentration cause "in-depth" filtration. The impurities neither pass through the bed nor are all strained out on the surface, but a significant amount of flocculated solids is removed throughout the entire depth of the filter.

1.2 Turbidity

Turbidity is a measurement of the clarity of water. It is predominantly used for potable water monitoring, although it is occasionally used to assess wastewater treatment processes. Clouded water is caused by suspended particles scattering or absorbing the light. Thus, turbidity is an indirect measurement of the amount of suspended matter in the water. However, since solids of different sizes, shapes, and surfaces reflect light differently, turbidity and suspended solids do not correlate well. Turbidity is normally gauged with an instrument that measures the amount of light scattered at an angle of 90° from a source beam. Turbidity is important in potable water because microorganisms attach to suspended particles.

1.3 Slow Sand Filtration

The early filtration units developed in Great Britain used a process in which the hydraulic loading rate is relatively low. Typical slow sand filtration velocities are only about 0.4m/hr. At these low rates, the filtered contaminants do not penetrate to an appreciable depth within the filtration medium. The filter builds up a layer of filtered contaminants on the surface, which becomes the active filtering medium. This active filtration layer is termed a *schmutzdecke*. When the filter is first started after cleaning, the filtered water must be wasted until the filtration efficiency increases as the schmutzdecke is formed. Most of Europe has retained the lower loading rates (or slow sand filtration), whereas the United States developed and primarily uses rapid sand filtration.

Slow sand filters are cleaned by taking them off line and draining them. The organic or contaminant layer is then scraped off. The filter can then be restarted. After water quality reaches an acceptable level, the filter can then be put back on line.

1.4 Rapid Sand Filtration

In rapid sand filtration much higher application velocities are used. Filtration occurs through the depth of the filter. A comparison of rapid and slow sand filtration is shown in Table 1. In the United States, filter application rates are often expressed as volumetric flow rate per area, or gal/min-ft^2, which is actually a velocity with atypical units.

Table 1. Filtration Rates.

Filtration Type	Application Rate	
	m/hr	gal/ft^2-day
Slow Sand	0.04 to 0.4	340 to 3400
Rapid Sand	0.4 to 3.1	3400 to 26,000

Figure 2 shows a typical rapid sand filter in normal operation. The water above the filter provides the hydraulic head for the process. The filter medium is above a larger gravel, rock, or other media for support. Below the rock is usually an underdrain support of some type. This is simply a porous structure to support the filter medium. The water flows through the filter and support media, exiting from a pipe below.

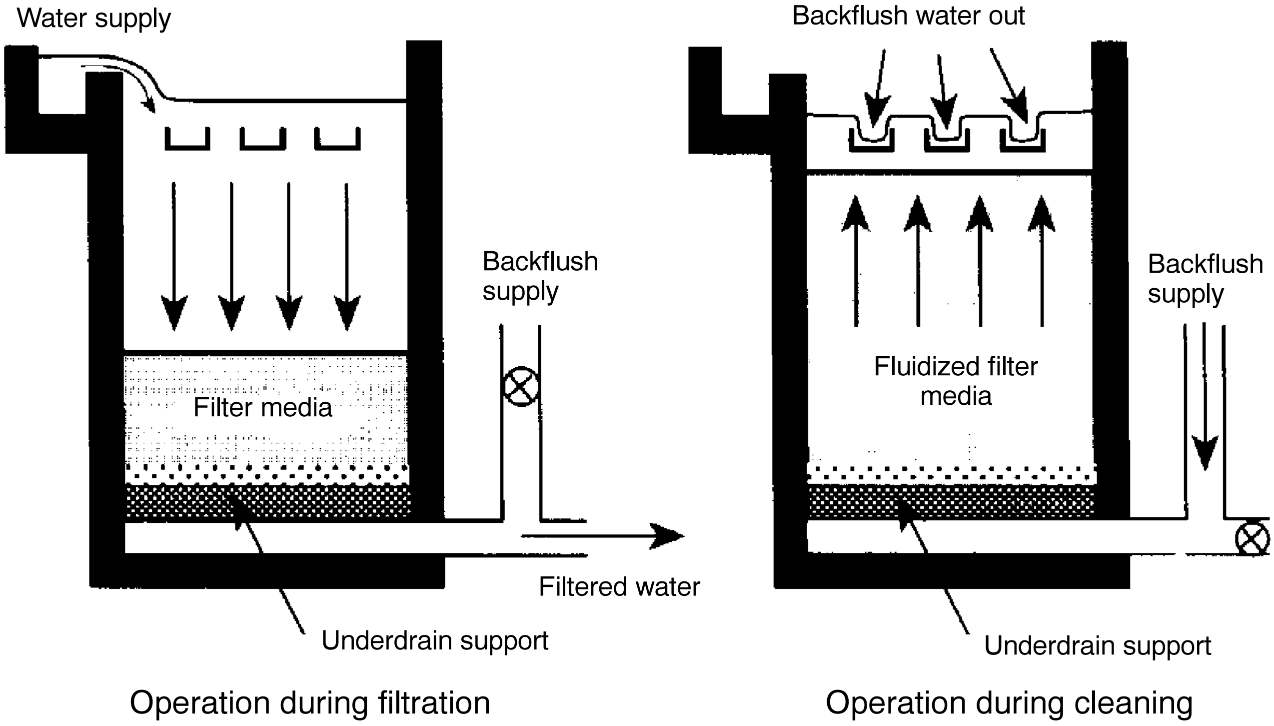


Figure 2. Cross-section of a rapid sand filter.

Most modern filters employ two separate filter media in layers. The lower layer is composed of a dense, fine media, often sand. The upper layer is composed of a less dense, coarse media, often anthracite coal. The coarse upper layer removes larger particles before they reach the fine layer, allowing the filter to operate for a longer period before clogging.

As the filter begins to clog from accumulated solids, less water will pass through it. At some point cleaning is required. Usual filter operation before cleaning is from a few hours to 2 days. Cleaning is accomplished by reversing the flow of water to the filter, or backwashing, as shown at the right in Figure 2. The backwash velocity is sufficient to ***fluidize*** the bed - that is, to suspend the bed with the reverse flow. After backwashing, the filter is again placed in operation. In larger plants, the backwashing operation is automatic. In smaller plants, the operation is often controlled by operating personnel.

1.5 Traditional Filtration

A typical scheme for processing surface supplies to drinking-water quality, shown in Figure 3, consists of flocculation with a chemical coagulant and sedimentation prior to filtration. Under the force of gravity, often by a combination of positive head and suction from underneath, water passes downward through the media that collect the floc and particles. When the media become filled or solids break through, a filter bed is cleaned by backwashing where upward flow fluidizes the media and conveys away the impurities that have accumulated in the bed. Destruction of bacteria and viruses depends on satisfactory turbidity control to enhance the efficiency of chlorination.

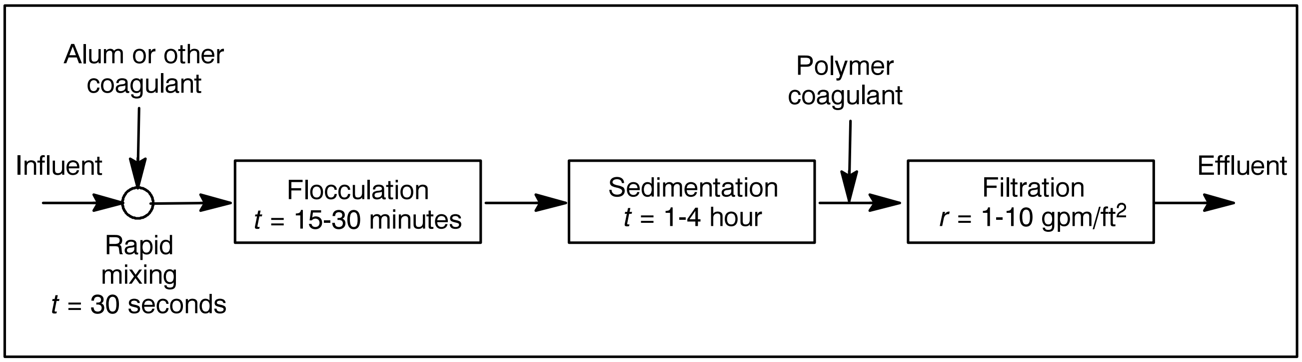


Figure 3. Flow diagram for a traditional surface-water treatment systems.

Filtration rates following flocculation and sedimentation are in the range of 2-10 gpm/ft^2 (1.4-6.8 l/m^{2}s) with 5 gpm/ft^2 (3.4 l/m^{2}s) normally the maximum design rate.

1.6 Direct Filtration

The process of direct filtration, diagrammed in Figure 4, does not include sedimentation prior to filtration. The impurities removed from the water are collected and stored in the filter. Although rapid mixing of chemicals is necessary, the flocculation stage is either eliminated or reduced to a mixing time of less than 30 minutes. Contact flocculation of the chemically coagulated particles in the water takes place in the granular media. Successful advances in direct filtration are attributed to the development of coarse-to-fine multimedia filters with greater capacity for "in-depth" filtration, improved backwashing systems using mechanical or air agitation to aid cleaning of the media, and the availability of better polymer coagulants.

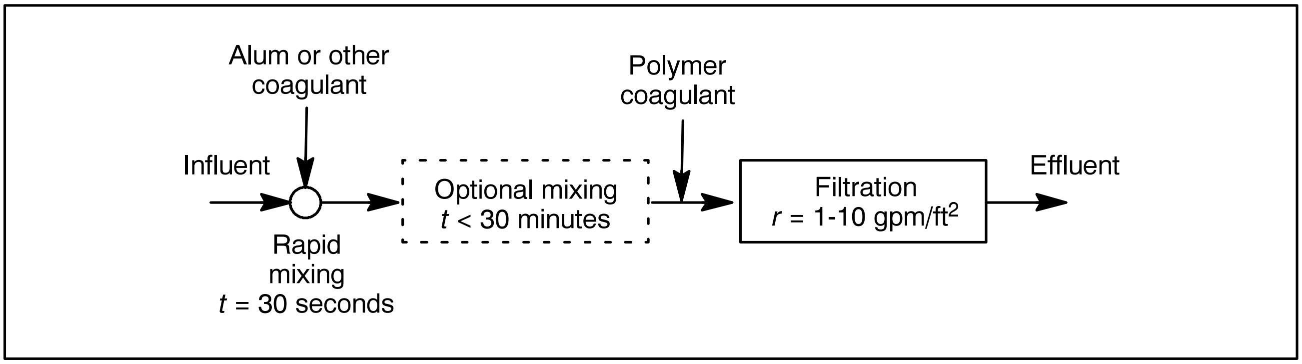


Figure 4. Flow diagram for a direct filtration of a surface-water supply or tertiary treatment of wastewater.

Surface waters with low turbidity and color are most suitable for processing by direct filtration. Based on experiences cited in the literature, waters with less than 40 units of color, turbidity consistently below 5 units, iron and manganese concentrations of less than 0.3 and

0.05 mg/l, respectively and algal counts below 2000/ml can be successfully processed. Operational problems in direct filtration are expected when color exceeds 40 units or turbidity is greater than 15 units on a continuous basis. Potential problems can often be alleviated during a short period of time by application of additional polymer. Tertiary filtration of wastewaters containing 20-30 mg/l of suspended solids following biological treatment can be reduced to less than 5 mg/l by direct filtration. For inactivation of viruses and a high degree of bacterial disinfection, filtration of chemically conditioned wastewater precedes disinfection by chlorine.

The feasibility of filtration without prior flocculation and sedimentation relies on a comprehensive review of water quality data. The incidence of high turbidities caused by runoff from storms and blooms of algae must be evaluated. Often, pilot testing is valuable in determining efficiency of direct filtration compared to conventional treatment, design of filter media, and selection of chemical conditioning. Filtration rates in direct filtration are usually 1-6 gpm/ft^2 (0.7-4.1 l/m^{2}s) somewhat lower than the rates following traditional pretreatment.

1.7 Description of a Typical Gravity Filter System

A cutaway view of a gravity filter is shown in Figure 5. During filtration, the water enters above the filter media through an inlet flume. After passing downward through the granular media (24-30 inches in thickness) and the supporting gravel bed, it is collected in the underdrain system and discharged through the underdrain pipe. During backwashing, wash water passing upward through the filter carries out the impurities that accumulated in the media. After entering the underdrain pipe, it is distributed by the underdrain flows upward, hydraulically expanding the filter media. The water is collected in the wash-water troughs that discharge to the outlet flume. While backwashing, the agitator arms rotate and spray water into the expanded bed to loosen any impurities that adhere to the grains of filter media.

Typical construction of a gravity filter system in a water treatment plant is illustrated in Figure 6. The filters are placed on both sides of a pipe gallery that contains inlet and outlet piping, wash-water inlet lines, and wash-water drains. The gallery is decked by an operating floor where control consoles are placed near the filters. A clear well for storage of filtered water is located under a portion of the filter bed area.

1.8 Filter Media

Broadly speaking, filter media should possess the following qualities:

1. Coarse enough to retain large quantities of floc,
2. Sufficiently fine particles to prevent passage of suspended solids,
3. Deep enough to allow relatively long filter runs, and
4. Graded to permit backwash cleaning.

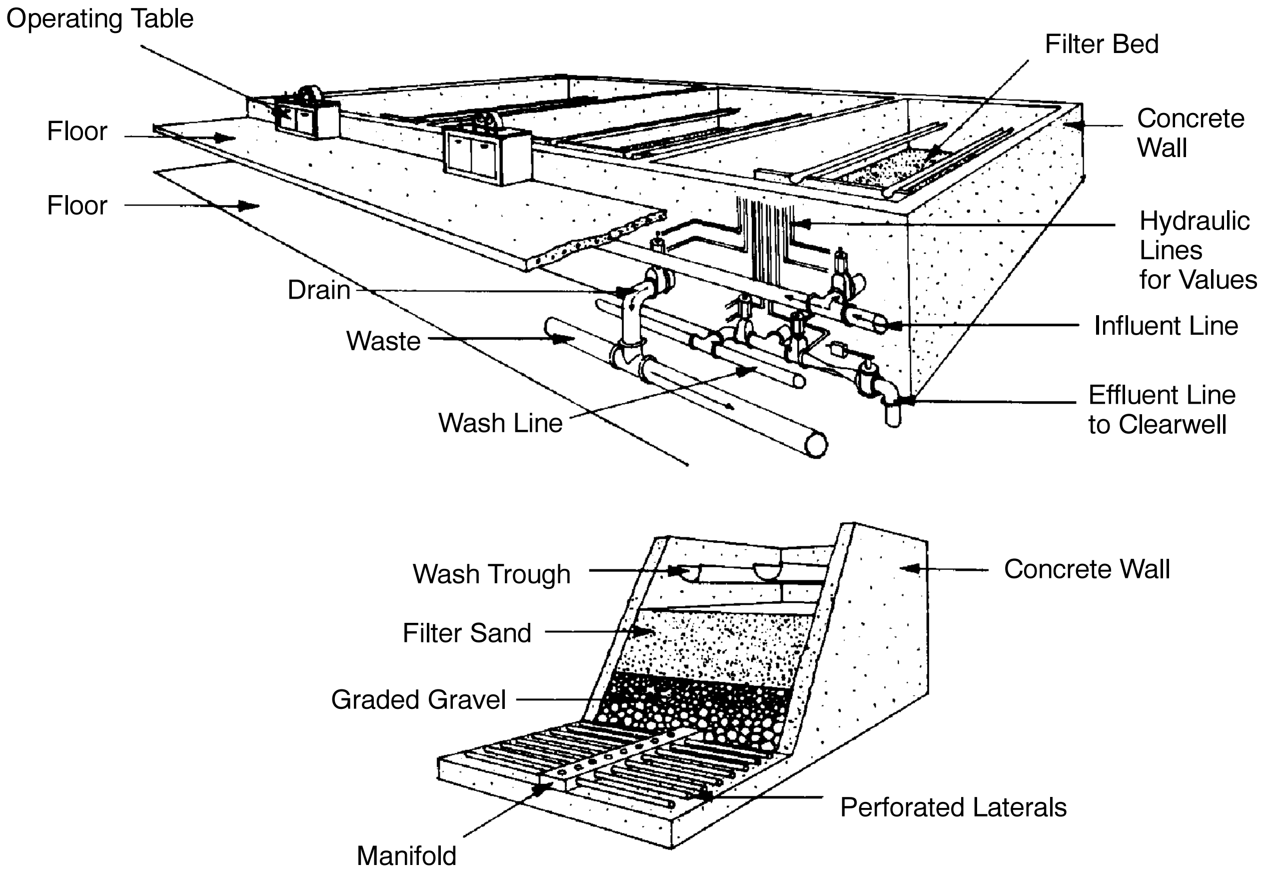


Figure 5. Typical gravity filter system in water treatment.

These attributes are not a compatible. For example, a very fine sand retains floc, which also tends to shorten the filter run, while for a course sand the opposite would be true. Recent trends are toward coarse sands and dual-media beds of anthracite overlying sand so that high rates of filtration can be obtained.

A filter medium is defined by ***effective size*** and ***uniformity coefficient***. The effective size is the 10-percentile diameter; that is, 10% by weight of the filter material is less than this diameter. The uniformity coefficient is the ratio of the 60-percentile size to the 10-percentile size. In water treatment, the conventional sand medium has an effective size of 0.45-0.55 mm, a uniformity coefficient less than 1.65, and a bed depth of 24-30 in. For dual-media filters, the top anthracite layer has an effective size of 0.8-1.2 mm, a uniformity coefficient of less than 1.85, thickness of a few inches to two thirds of the total filter thickness of 24-30 in., and is underlain by a sand filter layer as described above. The supporting coarse sand layer between the filter sand and the underlying gravel has an effective size of 0.8-2.0 mm and a uniformity coefficient less than 1.7. The coarsest layer of gravel required is determined by the kind of underdrain and size of openings for passage of filtered and backwash water.

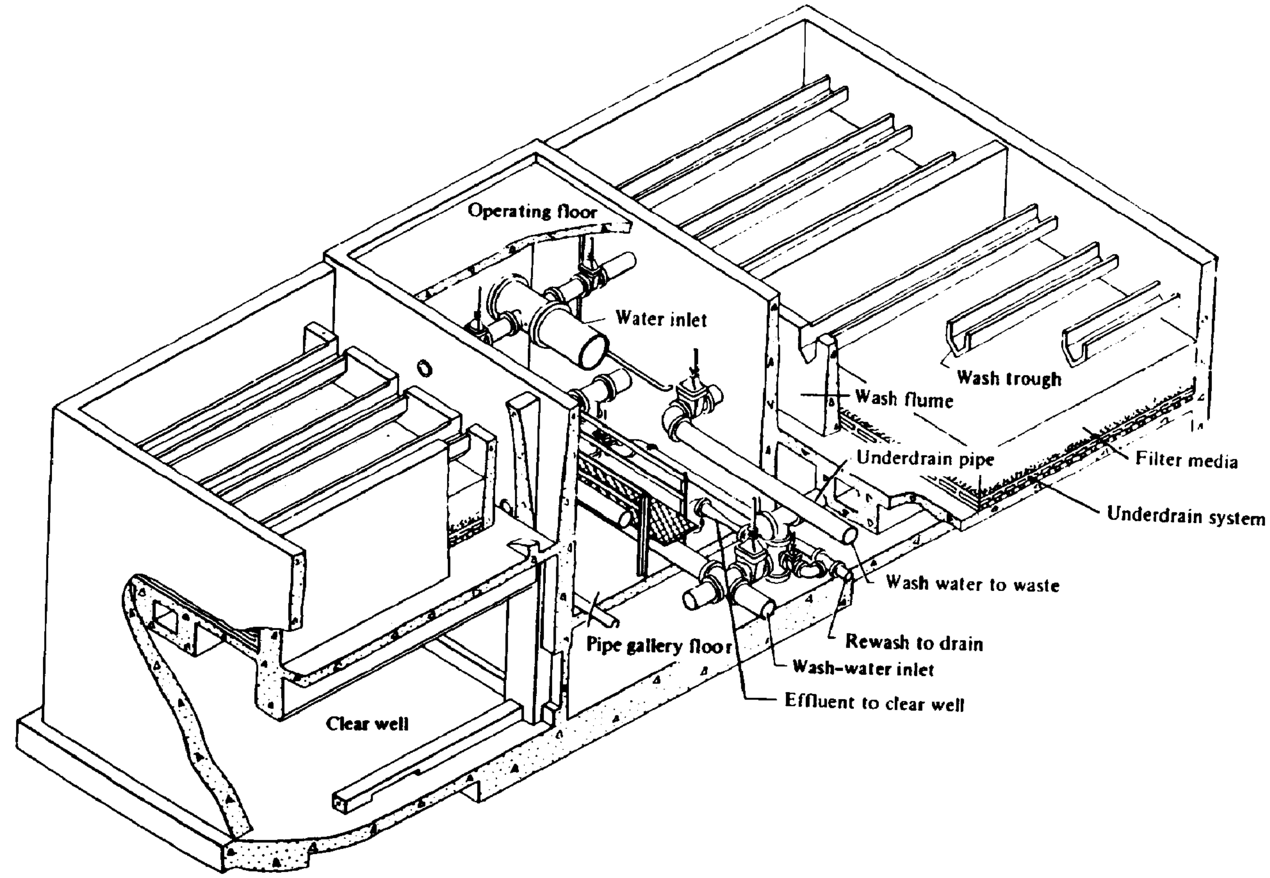


Figure 6. Typical gravity filter system in water treatment.

A sand filter bed with a relatively uniform grain size can provide effective filtration throughout its depth. If the grain-size gradation is too great, effective filtering is confined to the upper few inches of sand. This results because the finest sand grains accumulate on the top of the bed during stratification after backwashing. The problem of surface plugging of sand filters led to development of dual-media filters. A dual-media filter consists of a sand [specific gravity (sg), 2.65] layer topped with a bed of anthracite coal medium (1.4 - 1.6 sg). The coarser anthracite top media layer pores about 20% larger than the sand medium. These openings are capable of adsorbing and trapping particles so that floc carried over in clarified water does not accumulate prematurely on the filter surface and plug the sand filter

Unconventional filters, are dual-media with coarse anthracite having an effective size of about 1.5 mm and a low uniformity coefficient to provide a greater volume of voids to collect impurities and extend filter runs of highly turbid surface waters and wastewaters. To avoid problems in backwashing, the recommended effective size of the underlying sand medium is 0.75 to 0.90 mm for anthracite densities of 1.45 to 1.65. The use of a single-medium coarse-sand filter is practiced in Europe. For example, sand with a size range of 0.9-1.5 mm and about 1.0 m depth has been used in surface-water treatment plants. These filters are scoured with concurrent air and water at nonfluidizing velocity followed by a brief wash at high velocity with water alone. Triple-media filters comprising anthracite, sand, and garnet layers have been used for many years in the United States. Both dual- and triple-media filters are substantially better than the conventional sand filter in providing longer filter runs with a corresponding reduction in required backwash water. In comparing these two filters, however, the benefit fit of adding a third layer has not been well demonstrated.

1.9 Multimedia Filters

These filters, which have more than one medium, may be open gravity filters or pressure filters. In water treatment, they have become more popular in recent years. In advanced and tertiary waste treatment, they are the main type of filters that have been used successfully. Dual-media filter beds usually employ anthracite and sand; however, other materials have been used, such as activated carbon and sand. Multimedia filter beds generally use anthracite, sand, and garnet. However, other materials have been used, such as activated carbon, sand, and garnet. Also, dual- and multimedia filters using ion exchange resins as one of the media have been tried. In some of these filters, the media may have additional characteristics other than removing particles. For example, activated carbon removes dissolved organic substances.

The main advantages of multimedia filters compared to single-medium filters are longer filtration runs, higher filtration rates, and the ability to filter a water with higher turbidity and suspended solids. The advantages of the multimedia filters are due to:

1. the media particle size,
2. the different specific gravities of the media, and
3. the media gradation.

These result in a filter with a larger percent of the pore volume being available for solids storage. In the single-medium filter, the pore volume available for solids storage is in the top portion of the bed, whereas in the multimedia filter, the available pore volume is extended deep within the filter bed. Because of the deep penetration of accumulated floc, these filters are frequently referred to as “deep bed filters.” The single-medium filters are rarely used in wastewater or advanced wastewater treatment because of short filter runs. As a result of the large pore volume available for floc storage, the multimedia filters can be used in advanced or tertiary wastewater treatment and still have a reasonable filter run.

1.9.1 Dual-Media Filters

The dual-media filter, consisting of a layer of coarse anthracite coal above a layer of fine sand, is one technique for increasing the pore volume of a filter. Figure 7(b) shows the grain and pore size in a dual-media filter, and Figure 7(a) shows these characteristics for a single-medium filter. It can be seen from the pore size profile that the available pore volume of the dual-media filter will be greater than the single-medium filter. The available pore volume, however, will not be as large as the total pore volume because of the fine to coarse gradation within each layer. Ideally, the available pore volume would be maximum at the top of the filter and gradually decrease to a minimum at the bottom of the filter.

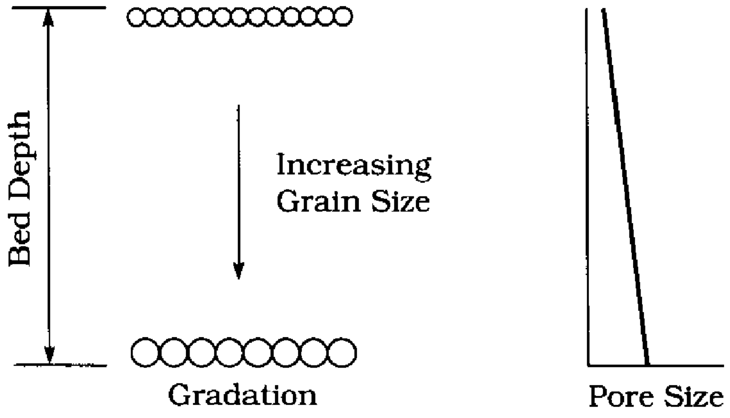
Usually, a dual-media filter consists of an 18- to 24-in. (457- to 610-mm) layer of crushed anthracite coal overlaying a 6- to 12-in. (152- to 305-mm) layer of sand. Coal has a specific gravity 1.2 to 1.6, and sand has a specific gravity of 2.65. During the first backwash, the sand layer remains below the coal as a result of its higher specific gravity and its grain size relative to the coal particles. After the first backwash, there will not be a distinct interface between the two layers, but instead there will be a blended region of both coal particles and sand grains.

The size and characteristics of the anthracite and sand media and the thickness of the layers depend upon whether the filter is to be used for water or wastewater treatment. Filtration rates may vary from 2 to 10gal/min-ft^2 (1. 36 to 6 79 l/s-m^2); however, a rate ranging from 3 to 6gal/min-ft^2 (2,04 to 4.08 l/s-m^2) is common.

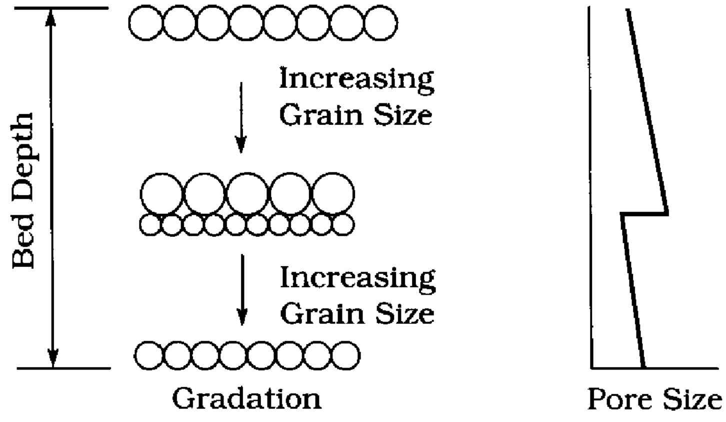
1.9.2 Mixed-Media Filters

The ideal filter has a pore size and gradation as shown in Figure 7(c). The pore size is greatest at the top of the bed and gradually decreases to a minimum at the bottom. The available pore volume, like the pore size, is maximum at the top of the bed and decreases to a minimum at the bottom. The media have a gradation which is from coarse at the top to fine at the bottom. The ideal filter may be approached by using a dual-media filter of crushed anthracite coal above sand and placing a third, very dense media below the sand. This allows the third medium to be very fine and still remain in the lower depths during backwashing. The resulting filter is referred to as a mixed-media filter since there is some intermixing between the layers during backwashing. Garnet, which has a specific gravity of about 4.2, has been found to be ideal as the third medium. Ilmenite, having a specific gravity of about 4.5, is also used but to a lesser extent. The anthracite, sand, and gannet or ilmenite are properly sized to allow some intermixing of the media during backwash. After backwashing there will be no distinct interface between the media layers. The filter bed will approach the ideal, as shown in Figure 7(c), which has a gradual decrease in pore size with increasing depth.

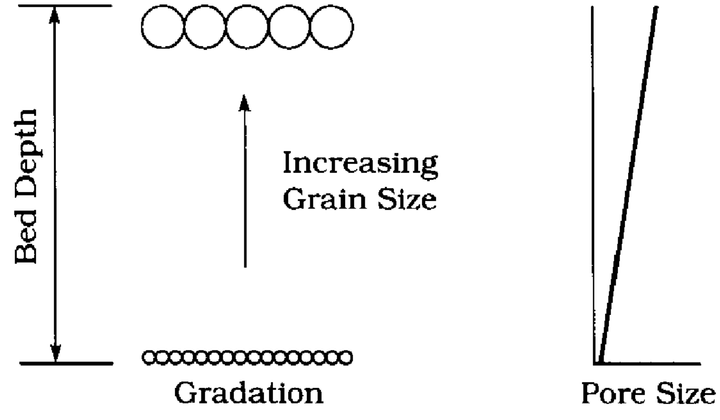
Since the pore size decreases from the top to the bottom of the filter, the filter will have a large available pore volume extending throughout the depth of the filter bed. About 3 in. (76mm) of coarse garnet or ilmenite is placed under the third layer to prevent fine particles from entering the underlaying gravel. The size and characteristic of the media and the thickness of the layers placed in the filter depend upon the type of service for the filter - that is, whether it is for water or wastewater treatment. The filtration rates that have been used in water treatment or advanced waste water treatment are from 2 to 12 gap/min-ft^2 (1.36 to 8.15 l/s-m^2); however, a rate ranging from 3 to 6 gal/min-ft^2 (2.04 to 4.08 l/s-m^2) is common.



(a) Single-Medium Filter



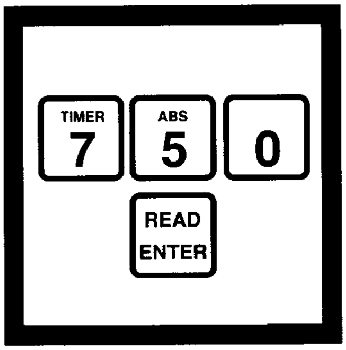
(b) Dual-Medium Filter



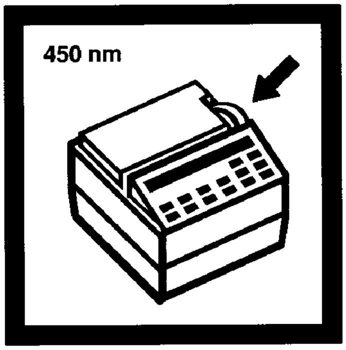
(c) Ideal Filter

Figure 7. Gradation and pore size in various filters.

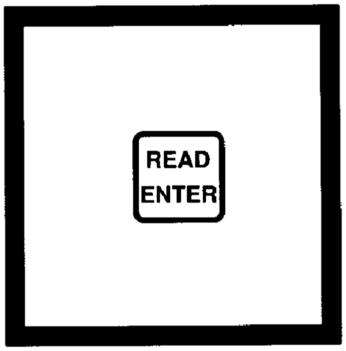
1.10 Turbidity – Absorptometric Method – HACH DR/2000



1. Enter the stored program number for turbidity.
Press: **7 5 0 READ/ENTER**
The display will show:
DIAL nm TO 450

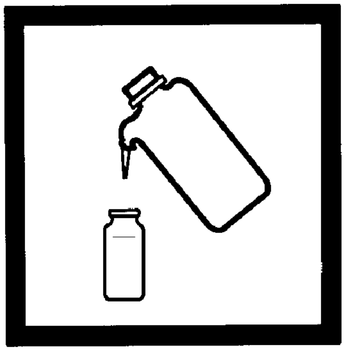


2. Rotate the wavelength dial until the small display shows: **450 nm**

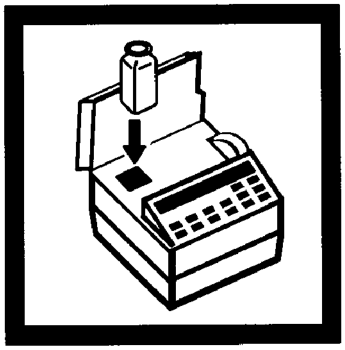


3. Press: **READ/ENTER**

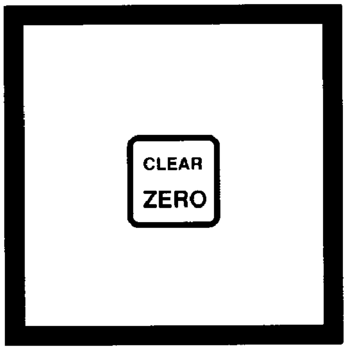
The display will show:
FTU TURBIDITY



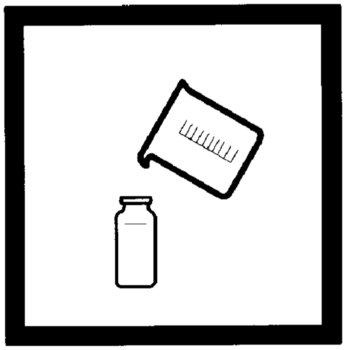
4. Pour 25 mL of demineralized water (the blank) into a sample cell.



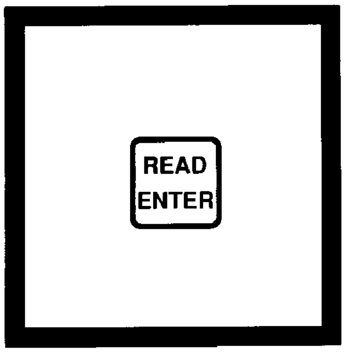
5. Place the blank into the cell holder. Close the light shield.



6. Press: **ZERO**
the display will show:
WAIT then:
0. FTU TURBIDITY



7. Pour 25 mL of sample into another sample cell and place this sample into the cell holder. Close the light shield.



8. Press: **READ/ENTER** The display will show: **WAIT** then the result in Formazin Turbidity Units (FTU) will be displayed.

2. *Mechanical Analysis of Soil*

Mechanical analysis is the determination of the size range of particles present in a soil, expressed as a percentage of the total dry weight. There are two methods generally used to find the particle-size distribution of soil: (1) ***sieve analysis*** - for particle sizes larger than 0.075 mm in diameter, and (2) ***hydrometer analysis*** - for particle sizes smaller than 0.075 mm in diameter. The basic principles of sieve analysis and hydrometer ever analysis are briefly described in the following two sections.

2.1 Sieve Analysis

Sieve analysis consists of shaking the soil sample through a set of sieves that have progressively smaller openings. Table NO TAG lists the U.S. standard sieve numbers and the sizes of openings.

Table 2. U.S. Standard Sieve Sizes.

Sieve Number	Opening (mm)
4	4.750
6	3.350
8	2.360
10	2.000
16	1.180
20	0.850
30	0.600
40	0.425
50	0.300
60	0.250
80	0.180
100	0.150
140	0.106
170	0.088
200	0.075
270	0.053

First the soil is oven dried and then all lumps are broken into small particle before they are passed through the sieves. Figure 8 shows a set of sieves in a sieve shaker used for conducting the test in the laboratory. After the completion of the shaking period the mass of soil retained on each sieve is determined. When cohesive soils are analyzed, it my be difficult to break lumps into individual particles. In that case, the soil may be mixed with water to make a slurry and then washed through the sieves. Portions retained on each sieve are collected separately and oven dried before the mass retained on each sieve is measured.

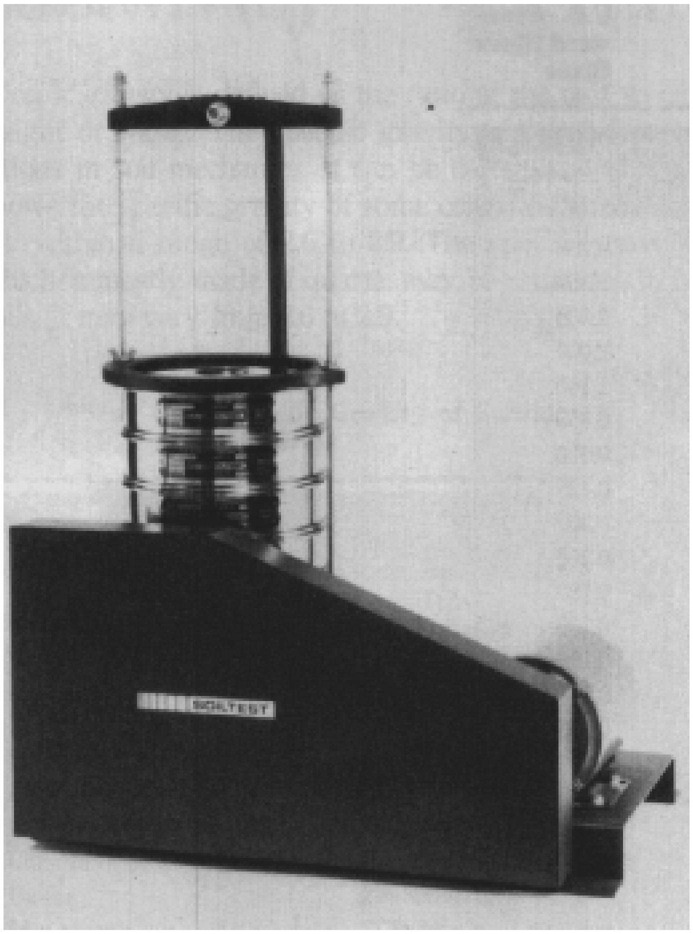


Figure 8. Set of sieves in a sieve shaker.

The results of sieve analysis are generally expressed in terms of the percentage of the total weight of soil that passed through different sieves. Table 3 shows an example of the calculations required in a sieve analysis.

Table 3. Sieve Analysis (Mass of Dry Soil Sample = 450 g).

Sieve Number	Diameter (mm)	Mass of soil retained on each sieve (g)	Percent of soil retained on each sieve (g)	Percent passing (%)
10	2.000	0	0	100.00
16	1.180	9.90	2.20	97.80
30	0.600	24.66	5.48	92.32
40	0.425	17.60	3.91	88.41
60	0.250	23.90	5.31	83.10
100	0.150	35.10	7.80	75.30
200	0.075	59.85	13.30	62.00
Pan	--	278.99	62.00	0

2.2 Hydrometer Analysis

Hydrometer analysis is based on the principle of sedimentation of soil grains in water. When a soil specimen is dispersed in water, the particles settle at different velocities, depending on their shape, size, weight, and the viscosity of the water. For simplicity, it is assumed that all the soil particles are spheres.

2.3 Particle-Size Distribution Curve

The results of mechanical analysis (sieve and hydrometer analyses) are generally presented by semi-logarithmic plots known as ***particle-size distribution curves***. The particle diameters are plotted in log scale, and the corresponding percent finer in arithmetic scale. As an example, the particle-size distribution curves for two soils are shown in Figure 9. The particle-size distribution curve for soil A is the combination of the sieve analysis results presented in Table 3 and the results of the hydrometer analysis for the finer fraction. When the results of sieve analysis and hydrometer analysis are combined, a discontinuity generally occurs in the range where they overlap. This is because soil particles are generally irregular in shape. Sieve analysis gives the intermediate dimension of a particle; hydrometer analysis gives the diameter of a sphere that would settle at the same rate as the soil particle.

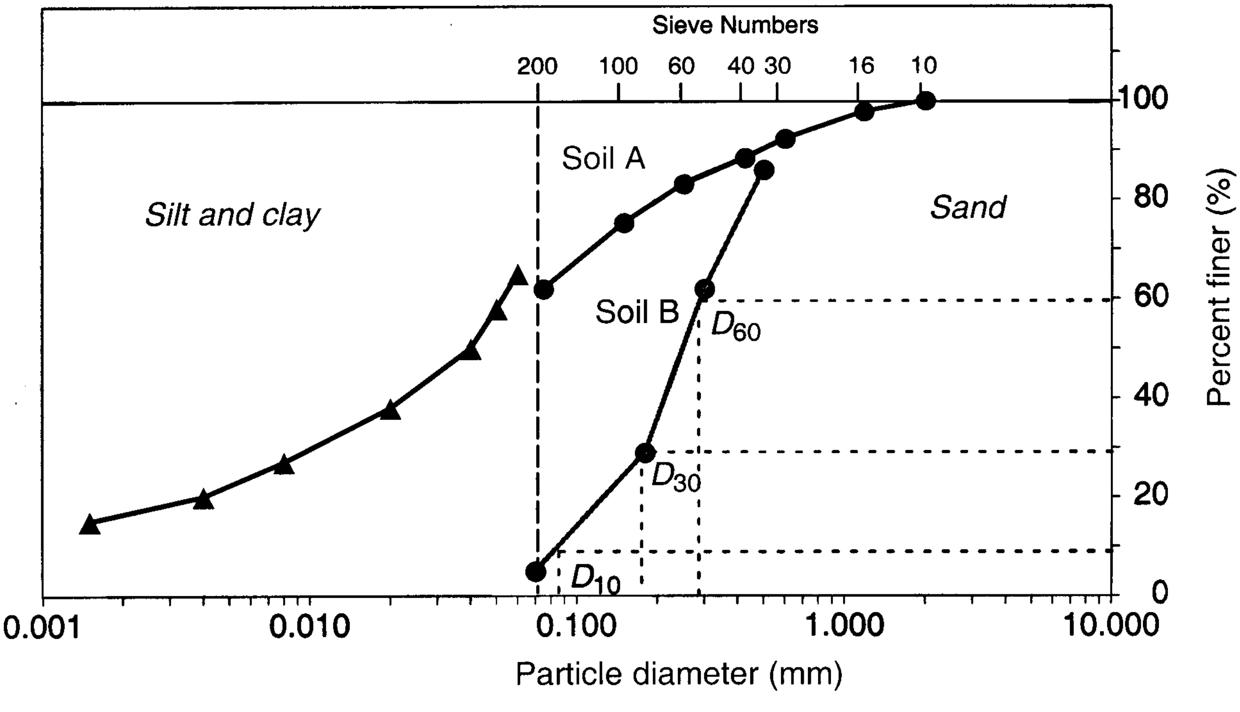


Figure 9. Particle-size distribution curves.

The percentages of gravel, sand, silt, and clay-size particles present in a soil can be obtained from the particle-size distribution curve. According to the Unified soil classification soil A in Figure 9 has:

- *Gravel* (size limit - greater than 4.75 mm) = 0%
- Sand (size limits - 4.75 to 0.075 mm) = percent finer than 4.75 mm diameter - percent finer than 0.075 mm diameter = 100 - 62 - 38%
- Silt and clay (size limit - less than 0.075 mm) = 62%

2.4 Recommended Procedure

1. Weigh to 0.1 g each sieve which is to be used. Make sure each sieve is clean before weighing it.
2. Select with care a test sample which is representative of the soil to be tested; break the soil into its individual particles with the fingers or a rubber-tipped pestle.
3. Weigh to 0.1 a specimen of approximately 500 g of oven-dried soil. If the soil to be tested has many particles coarser than the openings in a No. 4 sieve, a larger weight of soil should be used.
4. Sieve the soil through a nest of sieves by hand shaking. Using a motion of horizontal rotations or using a mechanical shaker, if available. At least 10 minutes of hand sieving is desirable for soils with small particles.
5. Weigh to 0.1 g each sieve and the pan with the soil retained on them.
6. Subtract the weights obtained in step 1 from those of step 5 to give the weight of soil retained on each sieve. The sum of these retained weights should be checked against the original soil weight.
7. If a sizable portion of soil is retained on the No. 200 sieve, it should be washed. This is done by placing the sieve and retained soil in a pan and pouring clean water on the screen. Use a spoon or glass rod to stir the slurry. Recover the soil which is washed through; dry and weigh it. The weight of soil recovered should be subtracted from the weight retained on the No. 200 sieve and added to the weight retained in the pan as determined in step 6.

2.5 Discussion of Procedure

The method of weighing the sieve plus soil rather then attempting to remove the soil from the sieve for weighing is suggested because it has been found that soil is often lost during the removing. Even using this suggested procedure, be careful to minimize the lose of soil during the sieving.

Step 4 recommends that the sieving consist of approximately 10 minutes of horizontal shaking. A horizontal motion was suggested instead of a vertical one since it has been found more efficient and since less soil escapes from the nest of sieves during horizontal shaking. The amount of shaking required depends on the shape and number of particles. As an example of the fact that the shaking time required is increased as the number of particles is increased, for crushed quartz it was found that, in a given time, the percentage passing was 25% less for a 250-g sample than it was for a 25-g sample. Since a given weight of a fine-grained soil contains more particles than an equal weight of a coarse-grained one, more shaking time is necessary for the finer-grained soils.

2.6 Calculations

Percentage retained on any sieve:

$$= \frac{\text{weight of soil retained}}{\text{total soil weight}} \times 100\% \tag{1}$$

Cumulative percentage retained on any sieve:

$$= \sum \text{Percentage retained} \tag{2}$$

Percentage finer than an sieve size:

$$= 100\% - \sum \text{Percentage retained} \tag{3}$$

2.7 Effective Size, Uniformity Coefficient, and Coefficient of Gradation

The particle-size distribution curves can be used for comparing different soils. Also, three basic soil parameters can be determined from these curves, and they can be used to classify granular soils. Them parameters are:

- Effective size
- Uniformity coefficient
- Coefficient of gradation

The diameter in the particle-size distribution curve corresponding to 10% finer is defined as the ***effective size***, or D_{10}. The ***uniformity coefficient*** is given by the relation:

$$C_u = \frac{D_{60}}{D_{10}} \tag{4}$$

where C_u is the uniformity coefficient and D_{60} is the diameter corresponding to 60% finer in the particle-size distribution

The ***coefficient of gradation*** may he expressed as:

$$C_c = \frac{D_{30}^2}{D_{60} \times D_{10}} \tag{5}$$

where C_c is the coefficient of gradation and D_{30} diameter corresponding to 30% finer.

For the particle-size distribution curve of soil B shown in Figure 8, the values of D_{10} D_{30} and D_{60} are 0.096 mm, 0.16 mm and 0.24 mm, respectively. The uniformity coefficient and coefficient of gradation are:

$$C_u = \frac{D_{60}}{D_{10}} = \frac{0.24}{0.096} = 2.5$$

$$C_c = \frac{D_{30}^2}{D_{60} \times D_{10}} = \frac{(0.16)^2}{0.24 \times 0.096} = 1.1$$

The particle-size distribution curve shows not only the range of particle sizes present in a soil but also the type of distribution of various size particles. This is demonstrated in Figure 10. Curve I represents a type of soil in which most of the soil grains are the same size. This is called ***poorly graded*** soil. Curve II represents a soil in which the particles are distributed over a wide range, termed ***well graded***. A well graded soil will have a uniformity coefficient greater than about 4 for gravels and 6 for sands, and a coefficient of gradation between 1 and 3 (for gravels and sands). A soil might have a combination of two or more uniformly graded fractions. Curve III represents such a soil. This type of soil is termed ***gap graded***.

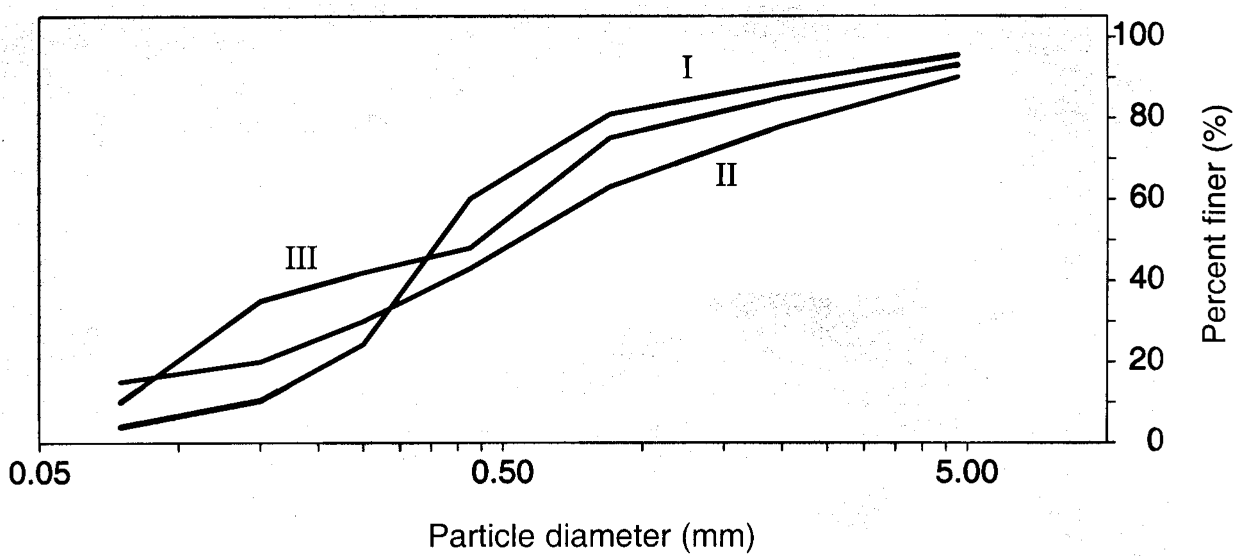


Figure 10. Different types of particle-size distribution curves.

2.8 Example Sieve Analysis

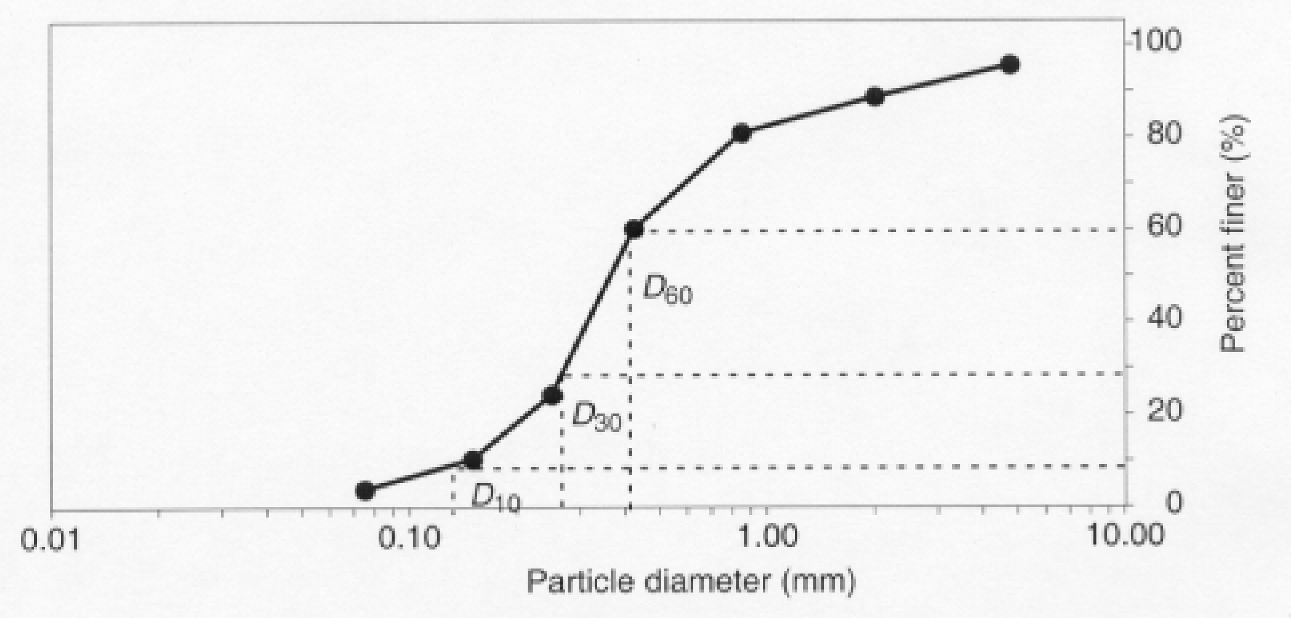
From the results of a sieve analysis, shown below, determine: (a) the percent finer than each sieve and plot a grain-size distribution curve, (b) D_{10}, D_{30}, D_{60} from the grain-size distribution curve, (c) the uniformity coefficient, C_u, and (d) the coefficient of gradation, C_c.

Sieve Number	Diameter (mm)	Mass of soil retained on each sieve (g)
4	4.750	28
10	2.000	42
20	0.850	48
40	0.425	128
60	0.250	221
100	0.150	86
200	0.075	40
Pan	--	24

The following table can be prepared for obtaining the percent finer:

Sieve Number	Mass of soil retained on each sieve (g)	Percent retained on each sieve (%) Equation (1)	Cumulative Percent retained on each sieve (%) Equation (2)	Percent finer (%) Equation (3)
4	28	4.54	4.54	95.46
10	42	6.81	11.35	88.65
20	48	7.78	19.13	80.87
40	128	20.75	39.88	60.12
60	221	35.82	75.70	24.30
100	86	19.93	89.63	10.37
200	40	6.48	96.11	3.89
Pan	24	3.89	100.00	0
	617			

The plot of the grain-size distribution is shown below:



The particle diameters defining 10%, 30%, and 60% finer from the grain-size distribution curve are estimated as: D_{10} = 0.14 mm , D_{30} = 0.27 mm, and D_{60} = 0.42 mm.

$$C_u = \frac{D_{60}}{D_{10}} = \frac{0.42}{0.14} = 3.0$$

$$C_c = \frac{D_{30}^2}{D_{60} \times D_{10}} = \frac{(0.27)^2}{0.42 \times 0.14} = 1.2$$