Chapter F-4
Drilling Fluids

4-1. Purpose of Drilling Fluids

Most rotary drilling methods, with the exception of augering methods, require the use of drilling fluids. Drilling fluids perform several functions. The primary functions include cleaning the cuttings from the face of the drill bit, transporting the cuttings to the ground surface, cooling the drill bit, lubricating the drill bit and drill rods, and increasing the stability of the borehole. In addition, there are a number of secondary functions. Some of the more significant secondary functions are suspending the cuttings in the hole and dropping them in surface disposal areas, improving sample recovery, controlling formation pressures, minimizing drilling fluid losses into the formation, protecting the soil strata of interest, facilitating the freedom of movement of the drill string and casing, and reducing wear and corrosion of the drilling equipment.

4-2. Types of Drilling Fluids

Nearly all of the Corps of Engineers drilling and sampling is accomplished using one or more of four general types of drilling fluid: compressed air, foam, clear water, and water-based mud. Air and water generally satisfy the primary functions of a drilling fluid. However, additives must often be added to these fluids to overcome specific downhole problems. Air with additives is referred to as “foam.” A freshwater- or saltwater-based drilling fluid with additives is commonly called “drilling mud.” A fifth type of drilling fluid is the oil-in-water emulsion or oil-based mud. However, this category of drilling fluids is not commonly used for geotechnical engineering investigations and therefore is not discussed herein.

a. Compressed air. Compressed air is a very effective drilling fluid for drilling in dry formations in arid climates, in competent consolidated rock, or in frozen ground. Only minor modifications to a conventional drilling rig and drill bits are required to drill with compressed air as compared to drilling with mud. An air compressor with its complement of pressure gauges, safety valves, storage tank, etc., is required. A delivery hose is needed to connect the air supply to the kelly of the drill rig. A deflector should be placed over the borehole to deflect the cuttings which are brought to the surface by the compressed air. When drilling frozen formations, refrigeration equipment may be required to chill the compressed air before it is pumped into the borehole, especially if the ambient temperature is warmer than about -5 deg C (23 deg F). If the relative humidity is high, provisions should also be made for defrosting the chiller.

Conventional drill bits may be used for drilling most formations with air. Drag bits have been used to drill soft to medium formations, frozen fine-grained soils, and ice. Roller bits generally have performed satisfactorily in medium to hard formations. However, it has been found that larger discharge nozzles may be required to drill with air as compared to drilling with water or mud.

Both air pressure and volume of air are important for the successful use of air as the drilling fluid. The effective use of air as a drilling fluid requires a high volume of air to efficiently remove cuttings from the hole. High pressure alone will not assure a sufficient volume of air and could damage the formation. In general, a low-pressure, i.e., 350 kilopascals (kPa) or 50 psi, high-volume capacity compressor is more economical and desirable than a high-pressure, low-volume system.

The minimum annular uphole velocities must be varied for each drilling condition encountered. Annular velocities on the order of 20 to 25 m/sec (4,000 to 5,000 ft/min) with upper limits of 45 m/sec (9,000 ft/min) have been found to be satisfactory for many materials. The higher upward velocities should be used cautiously as they may tend to erode the walls of the borehole. Equation 4-1 can be used to estimate the size of the air compressor which will produce the appropriate volume of air:

$$Q = \frac{V\,(D_h^{\,2} - d_o^{\,2})}{12.732} \qquad (4\text{-}1)$$

where

Q = compressor capacity, dm^3/sec

V = air return velocity, m/sec

D_h = borehole diameter, cm

d_o = drill pipe outside diameter, cm

Once the flow rate or compressor capacity has been selected, the pressure requirements should be checked to ensure that the compressor will meet the minimum requirements and that the pressure ratings of the pipes and fittings will not be exceeded. The pressure range for the compressor can be estimated from Equation 4-2 (O'Neil 1934):

$$p_g = \frac{Q\,(T_1)^{0.5}}{3.5366\,d_i^{\,2}\,C} - 101 \qquad (4\text{-}2)$$

where

p_g = gauge pressure, kPa

Q = compressor capacity, dm^3/sec

T_1 = upstream temperature (absolute, deg F)
= 459.7 + [1.8 × (upstream temperature, deg C) + 32]

d_i = inside diameter of drill pipe or coupling, cm

C = coefficient of flow; use 0.65 for sharp-edged orifices

An example of the use of Equations 4-1 and 4-2 follows. The upward velocity of air required to carry the cuttings to the surface was estimated to be 25 m/sec (5,000 ft/min). The diameter of the borehole was assumed to be 19.7 cm (7.75 in.); this value corresponds to the OD of the 15.2- by 19.7-cm (6- by 7-3/4-in.) core barrel. It was also assumed that flush coupled NW drill rods would be used. The OD of NW drill rods is 6.668 cm (2.625 in.), the ID is 5.715 cm (2.250 in.), and the ID of the couplings is 3.493 cm (1.375 in.). The upstream air temperature was estimated as 20 deg C (68 deg F). Using the values of V = 25 m/sec (5,000 ft/min), D_h = 19.7 cm (7.75 in.), and d_o = 6.668 cm (2.625 in.), the minimum compressor capacity was determined to be 675 dm^3/sec (1,430 ft^3/min) according to Equation 4-1. Using values of T_1 = 20 deg C (68 deg F or 527.7 deg absolute) and d_i = 3.493 cm (1.375 in.), the gauge pressure was determined by Equation 4-2 as 452 kPa (65 psi).

If the compressor capacity calculated according to Equation 4-1 or the pressure calculated according to Equation 4-2 is approximately equal to the capacity of the compressor or the piping, a more rigorous determination of these parameters should be conducted before the acquisition and mobilization of the equipment is initiated. It should be noted that leaks, head losses, frictional warming of the air, etc., were not considered for the example. It was also assumed that the smallest orifice was the ID of the coupling. However, it is probable that smaller orifices, such as fluid ports on the drill bit, would constrict the flow of compressed air. Therefore, consideration of all aspects of drilling with air should be addressed before the design of the system is finalized. A number of references on compressed air technology are available in the literature.

Compressed air has several advantages over other types of drilling fluids. Generally, air more efficiently cleans the drill bit which extends its life, probably as a result of less grinding of the cuttings. Although rotary bit speeds are practically identical to drilling with water and muds, air drilling is usually faster than mud drilling due in part to the increased weight (approximately 20 percent) on the drill bit. However, in softer formations the penetration rate must be reduced to prevent squeezing around the bit and blocking fluid ports. Accurate logging of material changes can be easily noted as the cuttings, which generally vary from a fine powder to the size of a thumb nail, are uncontaminated. For example, during an investigation of a landslide, subtle changes of moisture content can be more easily detected using compressed air than when using water or drilling mud. When formations containing expansive clays and shales or gypsum are drilled using air, water is not used and therefore cannot be imbibed by the soil. When the drilling is in cavernous material, the expense of lost circulation of drilling muds is eliminated. In cold climates, the potential of freezing the drilling mud is eliminated when compressed air is used as the drilling fluid.

The use of compressed air for the drilling fluid also has disadvantages. Core drilling with air may present specific problems because of constrictions in the flow path, i.e., the head of the core barrel, past the bit, and past the small annular area between the core barrel and the wall of the hole, especially if coring systems designed for use with water are used. When drilling is in caving formations, too large an annulus may result; the return velocity of the air will decrease and may become inadequate to lift the soil cuttings. Air works best as a drilling fluid when free water is not present in the material being drilled; however, dust suppression may be required to prevent the adverse health effects of breathing the expelled dust, especially when drilling is in siliceous materials and in confined areas such as drainage and grouting galleries. The presence of water in the hole or from cuttings of wet but not saturated clay or shale formations reduces the capacity of the air to carry cuttings from the hole and often causes the cuttings to ball and cling to the drill bit, drill rod, and walls of the borehole. When this condition occurs, the chance of the drilling tools getting stuck in the hole is increased. Moreover, the pressure at the bottom of the borehole may be increased sufficiently to fracture the formation. Consequently, the use of air for drilling most clays and shales is not recommended.

b. Foam. Foam or mist may be added to compressed air to enhance its performance, especially when too much water is encountered when air drilling formations such as clays and shales. Foam will help keep the cuttings separated, reduce the effects of balling and sticking, assist in removing water from the drill hole, and allow larger cuttings to be removed from the hole with the same volume of air. Because the removal of larger cuttings from the bottom of the hole is enhanced and thus helps to assure better cleaning of the hole, faster bit penetration due to less grinding of cuttings and longer bit life result.

Foam is also used as a dust suppressant and will reduce air loss, which allows drilling through lost circulation zones.

Foaming agents are generally biodegradable mixtures of surfactants. During drilling operations, a mixture of the foaming agent and water is injected into the compressed air stream between the compressor discharge and the top of the hole at a rate of 1,000 to 2,000 dm^3/hr (265 to 530 gal/hr), although this rate may be adjusted for the conditions encountered. The foam ranges from a mist of as little as 0.25 dm^3 (1/2 pint) foaming agent per 380 dm^3 (100 gal) of injection water to a stiff foam consisting of a mixture of bentonite slurry and/or organic polymer, water, and foaming agent. The foam mist is generally adequate to suppress dust, combat small water inflow, and remove sticky clay, wet sand, and fine gravel in holes with few hole problems. Stiffer foam is required as the hole diameter and depth increase, gravel or cuttings become larger, water inflows become significant, or unstable hole conditions are encountered. Injection of mist or foam may require an increased return velocity of 30 percent or more as compared to strictly air drilling. Because foam drilling is not commonly used in Corps of Engineers activities, it is recommended that anyone planning to use foam drilling should investigate available products and manufacturer's recommendations.

c. Clear water. Water is generally a cost-effective and efficient drilling fluid which has been used for numerous drilling operations. The drilling fluid is formed naturally by mixing clear water with cuttings of soil from the formation which is being drilled. In some instances, such as the drilling of formations in which temperatures are naturally at or slightly above 0 deg C (32 deg F), ice water or a brine of ice water and salt may be used as the drilling fluid.

Drilling with clear water has several attributes. Cuttings drop easily from suspension. Clear water is preferred when bedrock core drilling for dam site investigations or hydraulic pressure testing is required. Water losses or gains during drilling are excellent qualitative indicators of zones of potential seepage and zones which require grouting. If pressure tests are to be conducted, water in joints, fractures, or bedding planes is less likely to influence the apparent permeability of the formation as compared to the effects of drilling mud. If geotechnical strength tests are to be made on cores, water may be less likely to alter the apparent strength along preexisting discontinuities than drilling muds which may have constituents with lubricating qualities. Clear water may be used where formation water pressures are normal or subnormal, although it does not work well in highly permeable or water-sensitive formations.

Water alone is a poor hole stabilizer, may cause clays and shales to swell, does not suspend cuttings well when the pump is shut off, and offers minimal lubrication and no control of fluid loss. Therefore, it is often imperative that certain inorganic or organic constituents be added to water to control the properties of the drilling mud, such as weight or density, viscosity, and filtration characteristics, which better satisfy drilling needs.

d. Water-based muds. These fluids are the workhorses of most geotechnical drilling and sampling operations. The most common additive to form a water-based mud is bentonite, although polymers have been developed and perform well for most drilling operations. These drilling fluids plus appropriate additives fulfill all primary and secondary purposes listed in paragraph 4-1. The primary disadvantages of using drilling mud are: a large volume of drilling fluid (water) is required, and a high potential for hole erosion exists. As a rule of thumb, the volume of mud required to drill a hole is approximately three times the volume of the hole. The flush or return velocity of the drilling fluid coupled with its viscosity is potentially hazardous to erodible materials in boreholes.

Uphole mud velocities which are required to carry cuttings from the boring vary as a function of the size and density of the cuttings and the viscosity and weight or density of the drilling mud. Typical uphole velocities range from 0.2 to 0.7 m/sec (40 to 140 ft/min). Equation 4-1 may be used to size the mud pump capacity.

(1) *Bentonite mud*. Bentonite is the most commonly used drilling fluid additive and consists of finely ground sodium bentonite clay. When mixed with water, the resulting slurry has a viscosity greater than water, possesses the ability to suspend relatively coarse and heavy particles, and tends to form a thin, very low permeability cake on the walls of the borehole. Because of these attributes, bentonite drilling mud is superior to water as a drilling fluid for many applications. Bentonite for drilling is generally available in a standard grade which complies with the American Petroleum Institute (API) Specification 13A (American Petroleum Institute 1983). A high yield grade, which contains organic polymers, generally produces approximately the same viscosity as the standard grade with one-half the amount of bentonite. It should be noted, however, that the standard grade bentonite may contain peptizing agents and organic additives. For environmental drilling where additives are unacceptable, pure sodium bentonite is available from several suppliers.

(2) *Polymer mud*. Both natural and synthetic organic polymers are available that will produce drilling muds with desirable properties. Although the cost of most polymer additives is greater than the cost of bentonite, the lubricating quality of many polymer muds is excellent and can noticeably reduce bit and rod wear. As compared to bentonite muds, polymer muds often contain a lower solids content. Although polymer muds may lack the gel strength which is required to suspend particles or to form a satisfactory filter cake as compared to bentonite muds, polymer muds can be pumped at much higher viscosities. Consequently, the water loss due to poorer filter cake properties is partially mitigated by reduced seepage of the very viscous mud into the formation. A natural polymer, which has been used for drilling wells and piezometers, is made from the Guar bean; it degrades naturally because of the action of enzymes and returns to the viscosity of water within a few days.

(3) *Bentonite/polymer mud*. It is sometimes advantageous to prepare drilling muds composed of both bentonite and polymer with water. The low solids viscosity properties of organic polymers when combined with the filtration properties of a bentonite mud yields a mud with excellent characteristics for many applications. When the combination mud is prepared, the bentonite should be added to the water before the polymer is added.

4-3. Properties of Water-Based Muds

Drilling muds have four basic properties that determine the behavior of the mud as a drilling fluid: viscosity, density, gel strength, and filtration. Several other properties, although of lesser importance, need to be checked, especially if problems are anticipated or encountered. These properties include sand content, pH (alkalinity or acidity), and calcium content (hard water). Although tests are available to measure each of these properties, simple field tests for viscosity and density, coupled with an understanding of drilling and the capabilities of available mud products, can satisfy the drilling needs for most geotechnical investigations.

Table 4-1 summarizes each property, its desirable limits and control, and its influence on drilling operations. Table 4-2 is a summary of additives/chemicals which can be mixed with drilling mud to control properties or minimize/eliminate problems encountered during drilling operations. Although these tables give a general overview of desirable drilling mud properties, special problems may require technical assistance from drilling mud manufacturing companies.

a. Viscosity. Viscosity is defined as the resistance offered by a fluid (liquid or gas) to flow. The thicker a particular fluid is the higher its viscosity. Accurate measurement of the viscosity of drilling mud is dependent on a number of factors and requires special equipment. The basic factors which affect the viscosity of a mud are the viscosity of the base fluid (water); the size, shape, and number of suspended particles; and the forces existing between particles as well as between particles and the fluid.

For field applications, a qualitative viscosity measure can be obtained by the Marsh funnel, which is shown in Figure 4-1. The funnel viscosity is the time in seconds for 1 quart (0.946 dm^3) of mud to pass through the Marsh funnel, expressed as seconds per quart (sec/qt). To determine the viscosity using the Marsh funnel, hold the funnel in an upright position and place a finger over the outlet. Pour the test sample, which has just been taken from near the pump suction end of the mud pit, through the screen into top of the funnel until the level of drilling mud just reaches the bottom of the screen. Place a cup under the funnel outlet. Remove the finger from the outlet and time the number of seconds for one quart of fluid to flow from the funnel into the cup. The number of seconds is recorded as the funnel viscosity. If available, a stopwatch should be used for measuring the time. The usual range of Marsh funnel viscosities for good effective bentonite mud is 32 to 38 sec/qt (34 to 40 sec/dm^3); for polymer muds, funnel viscosities of 40 to 80 sec/qt (42 to 85 sec/dm^3) are reasonable. For comparison, the funnel viscosity of fresh water is 28 sec/qt (30 sec/dm^3) at 20 deg C (68 deg F).

As a general rule, viscosity should be maintained as low as possible to provide the required hole stability and water loss control. Thin mud does the best job of cleaning the bit and optimizing the drilling rate, but thick muds are needed to remove coarse gravel from the hole. Marsh funnel viscosity readings should be taken routinely and recorded on the boring log.

For most drilling operations, acceptable limits can be obtained by adding approximately 22.7 kg (50 lb) of bentonite per 375 dm^3 (100 gal) of water. Because the characteristics of the additives of polymer muds are quite different than those of bentonite, the solids content of polymer mud is much lower than the solids content of bentonite mud of the same viscosity. Natural clay muds which occur as a result of drilling with clear water are inferior to bentonite muds in their ability to increase viscosity. Much more clay is needed to achieve a given viscosity; the resulting mud will have a higher density and generally poorer qualities than a bentonite drilling mud has.

b. Density. Density is defined as the weight per unit volume of drilling fluid. It is commonly reported as kilograms per cubic meter (kg/m^3) as well as pounds per gallon (lb/gal) or pounds per cubic foot (pcf). The desired density, which is frequently incorrectly called weight, for most drilling situations is usually less than 1,080 kg/m^3 (9.0 lb/gal) and can be easily determined by a mud balance which is shown in Figure 4-2.

To determine the density of the drilling fluid with the mud balance, fill the cup to capacity with fresh, screened mud. Place the lid on the cup and rotate the lid until it is firmly seated. Make sure that some drilling mud is squeezed out the vent hole. Wash or wipe the excess mud from the exterior of the balance. After the exterior surface of balance has been dried, seat the balance with its knife edge on the stand and level by adjusting the rider. Read the mud density from the inside edge of the rider as indicated by the marker on the rider. Any of the scales on the rider may be used to express the mud density, although kilograms per cubic meter or pounds per gallon are the most commonly used scales. The calibration of the mud balance can be easily checked by filling the cup with fresh water. It should read 1,000 kg/m^3 (8.34 lb/gal).

An increase in density of the drilling mud is a measure of how much drilled material is being carried in suspension and recirculated. Excess suspended solids are objectionable for several reasons. First, the cuttings are generally abrasive and increase wear on the mud pump, drill string, and bit. Regrinding of the cuttings also tends to decrease the rate of drilling progress. A thicker filter cake will be formed on the walls of the borehole as a result of the higher concentration of solids. As a result of the greater hydrostatic pressure caused by the higher concentration of solids, hydraulic fracturing of the formation is more likely to occur. Lastly, a denser fluid has greater buoyancy; therefore, the cuttings are less likely to settle out in the mud pit.

The density of the drilling mud should be routinely determined. Although there are situations when dense drilling fluids are desirable, measures should be taken when the density becomes too high. The density of a bentonite mud can be decreased by adding water or increased by adding a finely ground, high specific gravity additive such as barite (barium sulfate). Polymer muds are not capable of suspending a weighting agent because they have little or no gel strength. However, since many polymers are compatible with salt solutions, polymer muds with densities of over 1,380 kg/m^3 (11.5 lb/gal) can be made by mixing the polymer with a saturated calcium chloride solution.

c. Gel strength. The measure of the capability of a drilling fluid to hold particles in suspension after flow ceases is referred to as gel strength (thixotropy). Gel strength results from the electrical charges on the individual clay platelets. The positively charged edges of a platelet are attracted to the negatively charged flat surfaces of adjacent platelets. In a bentonite mud in which the particles are completely dispersed, essentially all the bonds between particles are broken while the mud is flowing. When the mud pump is shut off and flow ceases, the attraction between clay particles causes the platelets to bond to each other. This coming together and bonding is termed flocculation. This edge to face flocculation results in an open card-house structure capable of suspending cuttings and sand and gravel particles. This property also suspends finely ground, high specific gravity material such as barite (G_s = 4.23) when high-density drilling muds are required. The capability of keeping cuttings in suspension prevents sandlocking (sticking) the tools in the borehole while drill rods are added to the string and minimizes sediment collecting in the bottom of the hole after reaming and before going back in the hole with a sampler. A drawback to this property is that cuttings do not readily settle out of the drilling mud in the mud pit and may be recirculated, thus resulting in grinding of particles by the drill bit, increased mud density, increased mud pump wear, and lower penetration rate. Polymer drilling fluids have essentially no gel strength.

d. Filtration. Filtration refers to the ability of the drilling fluid to limit fluid loss to the formation by deposition of mud solids on the walls of the hole. During drilling operations, the drilling fluid tends to move from the borehole into the formation as a result of hydrostatic pressure which is greater in the hole than in the formation. As the flow of drilling fluid (water) occurs, the drilling fluid solids are deposited on the walls of the borehole and thereby significantly reduce additional fluid loss. The solids deposit is referred to as a filter cake. The ideal filter cake is thin with minimal intrusion into the formation. The thickness of the filter cake for a particular mud is generally a function of the permeability of the formation. For example, the filter cake in a clay interval of the borehole would be thinner than in a sand interval.

Clean, well-conditioned bentonite drilling mud will deposit a thin filter cake with low permeability. Natural clay muds which result from drilling with clear water have much less desirable filtration properties than does high-grade sodium montmorillonite (bentonite). The natural clay mud will deposit a much thicker (can be more than 30 times thicker) filter cake than that of bentonite mud. A thick filter cake has a number of disadvantages which include the possibility that the cake may be eroded by circulating drilling fluid, may cause the drill pipe to stick, or may cause reduced hydrostatic pressure and partial collapse of the walls of the borehole during tool removal. The reentry of drilling equipment into the borehole lined with a thick filter cake could result in a pressure surge with an accompanying increased potential for hydrofracture of the formation. Polymer muds are low solids muds and do not form a filter cake as such. However, polymers tend to reduce fluid loss because they have a high affinity for water and form swollen gels which tend to plug the formation pores in the borehole wall. The data presented in Table 4-3 may be useful in correcting the problem of lost circulation.

4-4. Mixing and Handling

Water quality, method of mixing, and mud pit design are important to the effective use of water-based drilling muds. Water for bentonite muds should have a pH of 7 to 9.5, but should not have calcium hardness in excess of 100 parts per million (ppm); the chloride content should be less than 500 ppm. Polymer muds may work in either fresh or salty water, although some polymer additives do not work well in water with high pH or that contains more than 3-ppm iron. Manufacturers' literature should be checked for water quality recommendations when drilling mud additives are selected.

Effective dispersion and hydration of the drilling mud solids is dependent on proper mixing. Sprinkling or pouring the dry additives into the water and relying on the drill rig pump to mix will result in a lumpy mud with excessive additives for the mud properties achieved. A simple, yet effective, mud mixer can be fabricated as illustrated in the schematic diagram in Figure 4-3. Figure 4-4 is a photograph of jet mixer for introducing solids such as bentonite into the drilling mud. High-shear mechanical mixers will also effectively mix the mud materials.

Cuttings which are transported from the drill bit to the surface by the drilling mud must be dropped prior to recirculation to minimize regrinding. Although the viscosity and density of the mud control these characteristics, the properties of the mud can be enhanced by careful design of the mud pit in which cuttings are deposited. The mud pit may be either a dug pit or a fabricated portable mud pit; the latter is recommended in most cases. In either case, the pit should be designed to allow adequate time for the cuttings to settle out of the mud before it is recirculated. Considerations in the design of the mud pit should include: (a) the mud should flow slowly in thin sheets; (b) it should change directions frequently; and (c) it should flow as far as possible. To accomplish these considerations, the design of the mud pit should be shallow with a large rectangular surface area. Baffles can be used to force the mud to change directions frequently. The volume of the mud pit should be approximately three times larger than the volume of the hole to be drilled. A schematic diagram and a photograph of a portable mud pit are given in Figures 4-5 and 4-6, respectively.

Excessive cuttings are seldom a problem when core drilling but are common when drilling without sampling in sands and gravels. In some cases, it may be very difficult to obtain acceptable rates of settlement of the cuttings in the mud pit. Consequently, the cuttings may be recirculated and reground during recirculation. Desanding cones are available which effectively remove extraneous solids that do not settle out in the mud pit. Figure 4-7 shows a small desanding cone.

4-5. Drilling and Sampling Problems

During conventional drilling and sampling operations, unanticipated problems may be encountered. For example, an unstable formation or a zone of lost circulation may be encountered, or samples may be extremely difficult to recover or of very poor quality. The technology presented in Table 4-3, when used in conjunction with data presented in Tables 4-1 and 4-2, can be used to design a high-quality drilling fluid which can be applied for a wide range of drilling and sampling conditions encountered during geotechnical investigations. For most cases, a properly designed drilling fluid can minimize adverse drilling and sampling problems while simultaneously enhancing the capabilities of and extending the life of the drilling and sampling equipment. Selected topics are discussed in the following paragraphs.

a. Hole stabilization.

(1) *Caving*. Caving is often associated with uncemented sands and gravels, especially when removing samples from the hole. The problem can usually be remedied by maintaining excess hydrostatic pressure in the borehole. During drilling, circulating water is often adequate to maintain hole stability. However, when the pump is shut off, the water level in the borehole tends to drop to the water level in the formation. In order to maintain a fluid level in the hole above the groundwater level, a filter cake is required for filtration control of the drilling mud. Either bentonite or bentonite/polymer mud can be used to build a filter cake that effectively controls caving. The viscosity of the mud should be as low as practical to provide a stable hole. Polymer muds can sometimes be used for this purpose, although the cost of a polymer mud is generally greater than the cost of a bentonite mud of similar viscosity.

If samples are taken in a mud stabilized hole in sand or gravel, the sampler should be withdrawn slowly from the hole to avoid creating negative hydrostatic pressure below the sampler. Care is also necessary to ensure that the mud level in the borehole is maintained above the static water level as the sampler and rods are withdrawn. A suggested method to help maintain a constant fluid level in the borehole and to reduce the negative hydrostatic pressure below the sampler is to operate the mud pump at a low pressure and flowrate as the rods are withdrawn. An alternative method is to pump mud from the pit to the top of the hole through the bypass hose. Fractured clays may also cause a hole to cave which can generally be controlled in the same manner as for caving sands or gravels.

(2) *Squeezing ground*. Squeezing ground can result from either high lateral stresses acting on weak soils or expansive clays or shales imbibing water from the drilling fluid and swelling into the borehole. In most cases, squeezing and hole deformation occur soon after encountering the particular formation. The importance of maintaining stable hole conditions cannot be overemphasized. Once the stable cylindrical shape is lost, hole stability becomes a greater problem.

A good example of when it may be necessary to exceed the recommended maximum mud density of 1,080 kg/m^3 (9.0 lb/gal) is to counteract the high lateral stresses which often exist in foundation clays very near or beneath large embankments. The use of bentonite mud weighted with barite can be very effective in preventing squeezing due to the lateral stresses. However, weighted drilling mud should not be used for drilling through the embankment, as the embankment material could be hydrofractured by the hydrostatic pressure of the drilling fluid.

Because of the potential for hydraulic fracturing, it is desirable to drill an embankment without drilling fluid. One method is the use of augers. However, if it is not possible to conduct the drilling without a drilling fluid, clear water or water-based mud may be the only suitable solution to the problem but should be used only with extreme caution. The viscosity, density, and gel strength of the mud should be kept to a minimum. Drilling tools should be raised and lowered very gently. The fluid pump should be engaged slowly. The recirculation of solids in the drilling fluid should be carefully monitored and minimized.

After the hole has been drilled through the embankment, casing should be set through the embankment and seated in the foundation material. The water or low density mud which had been used to drill the embankment can then be removed from the borehole and replaced with bentonite mud weighted with barite before the potentially squeezing foundation soils are drilled.

Swelling clays and shales can be stabilized by polymer muds. Polymer muds form a protective coating on the water sensitive materials which inhibits swelling of either the borehole wall or cores in the sample barrel. Polymer muds also inhibit the dispersion of the clayey cuttings into the drilling mud which tends to make the clay cuttings less sticky and less likely to adhere to each other. Hence, the potential for hydrofracturing is reduced.

b. Control of hydrostatic pressure. It is sometimes necessary to drill formations where the piezometric surface is above the ground surface. If this situation occurs, such as near the downstream toe of a dam, advanced planning is required to ensure that the flow of water in the borehole is controlled.

Suggested methods for controlling excess hydrostatic pressures in boreholes include the use of casing filled with water or drilling mud, the use of weighted drilling mud, and the use of a wellpoint system. If the piezometric surface is less than approximately 0.3 to 0.6 m (1 to 2 ft) above the ground surface, a section of casing may be extended above the ground surface and filled with water or drilling mud prior to commencing the drilling operations. This height of the casing was selected as representative of the clearance between the bottom of the drill rig and the ground surface. When the proper head of water is maintained in the casing, the flow of fluid into or out of the borehole can be minimized.

If the piezometric surface is greater than about 0.6 m (2 ft) above the ground surface, a wellpoint system or the use of weighted drilling mud may be required. The increase of mud density which is needed to balance the formation pressures can be achieved by adding barite to a bentonite mud or by using a polymer mud in a calcium chloride solution. When weighted drilling muds are used, care should be exercised to ensure that hydrofracturing of the subsurface formation does not occur. A discussion of the design and installation of a wellpoint system to control excess hydrostatic pressures is not within the context of this manual.

The following example is cited for estimating the required mud density (weighted mud) to balance the hydrostatic pressure in the aquifer:

Problem:

A 6 m (20 ft) layer of clay overlies an aquifer in sandy soil. The piezometric surface of the aquifer is 2-1/2 m (8 ft) above ground surface. What is the density of the drilling mud required to balance the hydrostatic pressure in the aquifer?

Solution:

The critical fluid pressure (P_c) which must be balanced during drilling is the pressure at the top of the sand (6 m of clay plus 2-1/2 m hydrostatic head above the clay strata). The unit weight of water (γ_w) is 1,000 kg/m^3 (8.34 lb/gal). The fluid pressure of a column of water (P_w) is 9.8 kPa/m (0.43 psi/ft) of height.

$$
\begin{aligned}
P_c &= \text{height of piezometric surface above ground surface} * P_w \\
&= \text{8-1/2 m} * 9.8 \text{ kPa/m}
\end{aligned}
$$

$$
\begin{aligned}
P_c &= 83 \text{ kPa} \\
&= 12 \text{ psi}
\end{aligned}
$$

The mud density (γ_m) required to balance P_c at the sand and clay interface can then be calculated.

$$
\begin{aligned}
\gamma_m &= (P_c * \gamma_w) / (P_w * \text{depth to sand}) \\
&= (83 \text{ kPa} * 1{,}000 \text{ kg/m}^3) / (9.8 \text{ kPa/m} * 6 \text{ m})
\end{aligned}
$$

γ_m = 1,410 kg/m^3
= 11.7 lb/gal

Discussion:

It should be noted for the example that the factor of safety with respect to flow of water is 1.0. This condition is most desirable. If the mud density is too low, groundwater will tend to flow into the borehole and increase the potential for piping of formation materials. If the mud density is too high, the potential for hydrofracturing of the formation is increased.

To maintain a factor of safety of 1.0, the following guidance is offered. Make an estimate of the required density of the drilling mud to balance the excess hydrostatic pressure, as illustrated in the example. During drilling operations, frequent observations of the flow of water (or drilling mud) into or out of the borehole should be made. If groundwater tends to flow into the borehole, the density of the drilling mud should be increased slightly. If there is no tendency for seepage of groundwater into the borehole, the weight of the drilling mud may be excessive and should be decreased slightly until an equilibrium condition is obtained. This condition can be accomplished by adding clear water to the drilling mud until the groundwater tends to slowly seep into the borehole. It is imperative that an equilibrium condition for the hydrostatic pressures is maintained to ensure stability of the foundation conditions.

c. Improved sample recovery.

(1) *Soil sampling*. The overall quality of the soil samples is generally better when a bentonite based drilling mud, as compared to other drilling fluids, is used. Several explanations are available. The use of mud with a fixed-piston sampler results in a more effective seal at the piston with less chance of sample loss. Furthermore, bentonite mud forms a filter cake (membrane) on the bottom of the sample; the hydrostatic forces act on this membrane in the same manner as on the walls of the borehole to hold the sample in the sampling tube. The ability to maintain the drilling fluid level at or near the top of the hole increases the possibility of a full sample recovery because of buoyancy effects; the buoyancy effects are very important, especially when sampling sands below the water table. Fluid pressure can be controlled to prevent both squeezing and sand heaving. Heaving is particularly undesirable in liquefaction studies where small changes in density and stress relief are very important.

Bentonite or bentonite/polymer muds are usually suitable for most soil sampling applications. Weighted bentonite mud may be required to reduce hole squeezing or to balance high hydrostatic pressures. Mud migration into tube samples or into the virgin material in the bottom of the borehole has been observed to be minimal. However, the comparison of gradations from SPT samples and fixed-piston thin-walled tube samples of sands suggests mud contamination of the SPT samples as evidenced by a higher percentage of fines.

(2) *Rock coring*. Core recovery and overall sample quality can be improved in some situations. In most cases, clear water is the most desirable and cost-effective drilling fluid for rock core drilling. However, drilling muds, especially polymer muds, have specific applications, e.g., polymer muds can be effective in reducing the swelling of clay shales. In some instances, swelling shales are effectively cored with apparently good recovery; however, due to their swelling in the core barrel they are essentially destroyed when the swollen core is removed from the barrel.

Polymer muds have also been effective in improving core recovery and reducing mechanical core breakage during drilling of generally competent rock containing weaker shale partings, bands, and thin beds. The overall strength of the rock mass is generally controlled by the geometry and strength of the much weaker shale seams. In too many cases, these weak zones are represented by a core loss. Sheared surfaces often exist in the weak zones and are also lost during drilling. Because of the superior lubricating qualities of polymer muds, their low solids content, and nonwetting properties, they offer improved recovery of the critical shale zones which eliminates worst case strength assumptions. In addition, the uphole velocity of the drilling fluid can be reduced because of the increased viscosity of the mud; the effect is to reduce the probability of washing away weak bedrock materials.

The three factors following must be considered if a drilling mud is to be used: the effects of a "slick" polymer mud on laboratory test results, especially if the sample contains open fractures or bedding planes which must be tested, the impact on borehole hydraulic pressure test results if mud migrates into the fractures, and the ease with which the mud releases the cuttings in the surface settling pit especially if the cuttings are fine, as from diamond drilling operations.

d. Enhanced pump capacity. Because excessive pump capacity has a negative impact on core recovery, many drill rigs used for geotechnical investigations have pumps which are ideal for core drilling but are somewhat undersized for nonsampling drilling, such as for cleaning the borehole between soil samples or for installation of piezometers or wells or various types of instrumentation. To overcome this problem, proper design of the drilling mud and the effective use of the drilling equipment must be considered. Recall that hole cleaning is controlled by the uphole velocity of the drilling fluid as well as its viscosity and density. As given by Equation 4-1, the uphole velocity is dictated by the pump capacity and the area of the annulus between the drilling tools and the walls of the borehole. For most cases, the diameter of the hole is predetermined by sampling or instrumentation requirements. However, the viscosity and density of the drilling fluid can be enhanced by additives. In most situations, it is better to increase viscosity while keeping mud density as low as possible. Bentonite or bentonite/polymer muds are usually the most effective means of making a drilling mud of the required viscosity. If a very high viscosity is needed, a polymer mud might be most effective since it is a low solids mud and has a very low gel strength which would allow better removal of the cuttings. The use of weighted mud can be advantageous when large cuttings or gravel must be removed from the hole.

e. Solids recirculation. Recirculation of excessive solids results in increased density of the drilling mud. The adverse effects include a reduced rate of drilling with an increased potential for hydraulic fracturing, an increase of the thickness of the filter cake which is more easily eroded and contributes to a less stable hole as compared to a thin filter cake, and excessive abrasive solids in the drilling mud which cause significant wear to the mud pump and the drilling tools. In most cases, a well-designed portable mud pit and a carefully selected low solids mud with an appropriate gel strength coupled with regular mud density measurements will control the problem. However, desanders may be needed when drilling large-diameter or deep holes in sands and gravels.

The addition of polymer additives to the drilling fluid also acts to reduce wear on drill rods, core barrels, and pumps. The benefits are most noticeable when drilling abrasive rock types such as sandstones and rock containing chert. In addition to the reduced wear, the drilling operations are often smoother with less rod "chatter" resulting in less broken core. Although the concentration of polymer additives for this purpose is relatively low, the potential impact on hydraulic pressure test results must be considered. Experience as well as the manufacturer's recommendations should dictate the choice and concentration of the additives.

4-6. Limitations and Precautions

As with all other aspects of planning and executing a quality drilling and sampling program, all facets of the selected drilling fluid should be understood and considered. A discussion of limitations and precautions for the use of drilling fluids for selected drilling and sampling operations follows.

a. Hydraulic fracturing. Hydraulic fracturing of earth dam embankments is a concern whenever a drilling fluid is used in the fill. The potential for hydraulic fracturing has been directly attributed to the use of compressed air as the drilling fluid; hence, the use of compressed air for drilling in earth dams is prohibited by ER 1110-2-1807. Likewise, the potential for hydraulic fracturing to occur whenever water or water-based drilling mud are used also exists. However, it is easier to control the drilling fluid pressures when using water or mud than when using compressed air. Therefore, the risk of hydraulic fracturing is minimized. For these reasons, dry drilling methods which do not use a circulating fluid, such as dry hole augering, may offer an ideal solution for specific problems of drilling in embankment dams. Unfortunately, dry drilling methods are not always practical or even possible for many cases.

Several factors should be considered when water or water-based drilling mud are used for drilling in embankment dams. The sensitivity of an embankment to fracturing is dependent upon the strength properties, the tightness of lift planes, and the stress distribution in the compacted embankment. Hydraulic fracturing is most critical in and perhaps most likely to occur in the impervious core. The pressure which is needed to extend a fracture may be less than the pressure required to initiate the fracture. Hydraulic fracturing is more likely to occur when using core barrel sampling devices, e.g., the Denison or Pitcher sampler, because drilling fluid must flow at high pressures through the small annular space between the sampler and borehole wall. Poorly maintained piston-type mud pumps exhibit pressure surges which can easily fracture the embankment.

If the wet drilling method is required, the equipment is in good working order, and the samplers have been carefully selected, several precautions should be observed. The viscosity and density of the drilling mud should be kept at the minimum required to clean and stabilize the hole. The viscosity and density should be checked frequently during drilling operations. Polymer or bentonite/polymer muds may be used to keep the gel strength low. The drilling tools should be raised and lowered in the hole slowly and smoothly. Rotating the tools as they are raised and lowered may also be helpful. The pump should be engaged slowly to begin circulation. Due to the recirculation of cuttings, the mud weight will tend to increase with drilling time. Until an experience base has been developed, use a maximum allowable density of 1,080 kg/m^3 (9.0 lb/gal). If this density is exceeded, replace the used mud with freshly mixed mud. Select drilling methods which minimize the formation of a mud collar which tends to create zones of high pressure in the drilling fluid below the obstructions. Fishtail bits cut long ribbons which tend to form obstructions. Long-toothed roller bits rotated at fairly high angular velocities with little downward pressure create kernel-like, easily transported cuttings. Polymers reduce the tendency of clays to become sticky.

b. Formation permeability. If a mudded borehole is ultimately to be used for the installation of a water well, piezometer, pore pressure device, or monitoring well or if it is to be pressure tested, one must assume that a filter cake was formed and that it has invaded the pore space of granular materials, the fractures of bedrock, or even clays to some unknown distance. To have an efficient water well or observation device or to avoid erroneous chemical analyses from monitoring wells, it is important that the filter cake be broken down and removed and the permeability of the drilling mud invaded portion of the formation be restored. Restoration of the formation requires careful attention to and the evaluation of development techniques. Often, an effective first step is to flush mud from the hole and replace it with clear water after setting the pipe and screen but before adding the filter pack. An alternative procedure consists of drilling with mud to a point just above the tip, filter, and seal interval. Casing is then set to the bottom of the mud-filled hole and carefully sealed. The mud is either bailed from the casing or flushed out and replaced with clear water. The hole is then drilled with clear water to the final depth, the device set, and the filter and seal placed. The remainder of the backfill is placed concurrent with pulling the casing. A degradable natural polymer made from the Guar bean has also been used for drilling wells and piezometers. Although the polymer reportedly degrades naturally because of the action of enzymes and returns to the viscosity of water within a few days, the effects of the degradation of this product on the chemical analysis of water should be considered.

c. Environmental drilling. It is preferable to drill monitoring wells for the investigation of hazardous and toxic waste sites with dry drilling methods, such as the hollow-stem auger or churn drill methods. However, in many cases mud rotary drilling is the most effective and practical method. When mud is used for environmental drilling, certain precautions should be observed and practiced. Very complete and careful development of monitoring wells is mandatory both to restore aquifer permeability and to remove as much of the drilling mud as possible in order to minimize potential impact of the drilling fluid additives on the groundwater chemistry. A chemical analysis of drilling muds and additives should be performed (and obtained from the supplier). All organic polymer muds should be avoided. Products identified as "beneficial bentonites" contain organic additives which enhance viscosity and should not be used for this purpose. Standard bentonite, which is commonly used for monitoring well drilling, also contains minor amounts of additives and perhaps should be avoided. Pure bentonite muds are available and are marketed specifically for monitoring well construction. Although pure bentonite has apparent chemical advantages, it will not mix and hydrate as quickly and easily as standard or beneficiated bentonites.

d. Effect on strength testing. Samples for strength testing should be carefully inspected for drilling mud infiltration, especially into open fractures and bedding planes. Either bentonite or polymer mud could tend to alter the apparent shear strength along these discontinuities.

4-7. Good Drilling Practices

Careful drilling practices used in conjunction with a drilling fluid which is most suitable for the purpose(s) of the geotechnical investigation will optimize drilling progress and sample quality while minimizing sample disturbance. To effectively apply this technology, a number of factors must be considered and practiced. Know the purpose of the drilling or sampling program, the geology of the area, and the drilling equipment and its capability. Become familiar with drilling fluid additives and the effects of each on drilling operations. Keep field operations as simple as possible to effectively complete the job; a well designed portable mud pit, Marsh funnel, and mud balance are satisfactory for most situations. Maintaining a low mud density minimizes viscosity, reduces pressure within the borehole annulus caused by the circulating fluid, and minimizes the filter cake thickness. Start the mud pump slowly to avoid excessive pump pressures due to the gel (thixotropic) strength of the mud. Operate pump pressures as low as possible to minimize surge pressures. Raise and lower the drill string slowly to minimize hydrostatic pressure changes. Drill formations no faster than solids are removed from the drill bit. Anticipate problems before they develop; take precautions to reduce the effects of the potential problems.

Table 4-1
Properties of Drilling Mud (after N.L. Baroid / N.L. Industries, Inc.)

Property	Influences	Desirable Limit	Control
Density (Weight)	Drilling rate Hole stability	Less than about 1,080 kg/m^3 (9.0 lb/gal) (mud balance)	Dilute with water or remove solids to decrease Add barium to increase
Viscosity	Cuttings transport Cuttings settlement Circulation pressures	34-40 sec/dm^3 (32-38 sec/qt) (Marsh funnel and measuring cup)	Add water, phosphates, or lignites to thin Add bentonite or polymers to thicken
Filtration	Wall cake thickness	Very thin (less than 0.2 cm {1/16 in.})	Control density and viscosity of mud Polymers
Sand content	Mud density Abrasion to equipment Drilling rate	Less than 2 percent by volume	Add water to lower viscosity Good mud pit design Use desander
pH (Acidity or alkalinity)	Mud properties Filtration control Hole stability Corrosion of equipment	8.5 to 9.5 (Neutral is 7.0)	Increase with sodium carbonate Decrease with sodium bicarbonate
Calcium content[1] (Hard water)	Mud properties Filtration control	Less than 100 parts per million (ppm) calcium	Pretreat mixing water with sodium bicarbonate

[1] For other salts, dilute salt content with fresh water or use organic polymers in the drilling fluid.

Table 4-2
Control of Drilling Mud Properties (after N. L. Barold / N. L. Industries, Inc.)

Description	Velocity	Filtration	Lost Circulation	pH	Wetting Agent	Calcium Remover	Shale/Clay Control	Weight Material
Sodium Montmorillonite (Standard bentonite)	X	X						
Polymer muds	X	X					X	
Flake mica			X					
Shredded organic fiber			X					
Crushed nut hulls			X					
Ground paper/ cellophane film			X					
Sodium bicarbonate/ soda ash				X		X		
Sodium hydroxide/ caustic soda				X		X		
Water soluble detergent					X			
Barium sulfate								X

Table 4-3
Borehole Problems (after N. L. Baroid / N. L. Industries, Inc.)

Problems	Symptoms	Necessary Conditions	Treatment	Minimize Potential Problems
Stuck pipe (differential sticking)	Good circulation at normal pressures Cannot rotate drill rods Cannot pull drill string Bit may not be the bottom of the borehole	Permeable zone Thick mud cake on wall of hole Hydrostatic pressure of drilling fluid exceeds hydrostatic pressure in formation	Work drill pipe Reduce mud density Add surfactant / lubricant	Minimize fluid density and solids content Minimize filtration rate with thin filter cake Lower friction between filter cake and drill rods
Loss of circulation	More fluid is being pumped into hole than is being returned Level of fluid in mud pit drops	Normal fractures Induced fractures Highly permeable formations Cavermous formations	Stop drilling and allow mud to seep into fractures (self-healing) Raise drill string above loss zone and introduce lost circulation materials Seal must be in loss zone and not on face of boring Treat gently after sealing May be necessary to use casing or grout	Examine fluid properties (density, viscosity, and filtration) frequently Observe careful drilling practices
Unstable hole	Hole enlargement Tight hole Fill on bottom of borehole after trip to surface	Structural instability of weak formations due to rotation and vibration of drill rods, pressure surge or swab, or excessive pump pressures Wetting of clays and shales	Lower pump pressures Add friction reducers and/or polymers to drilling mud	Examine fluid properties frequently Observe careful drilling practices

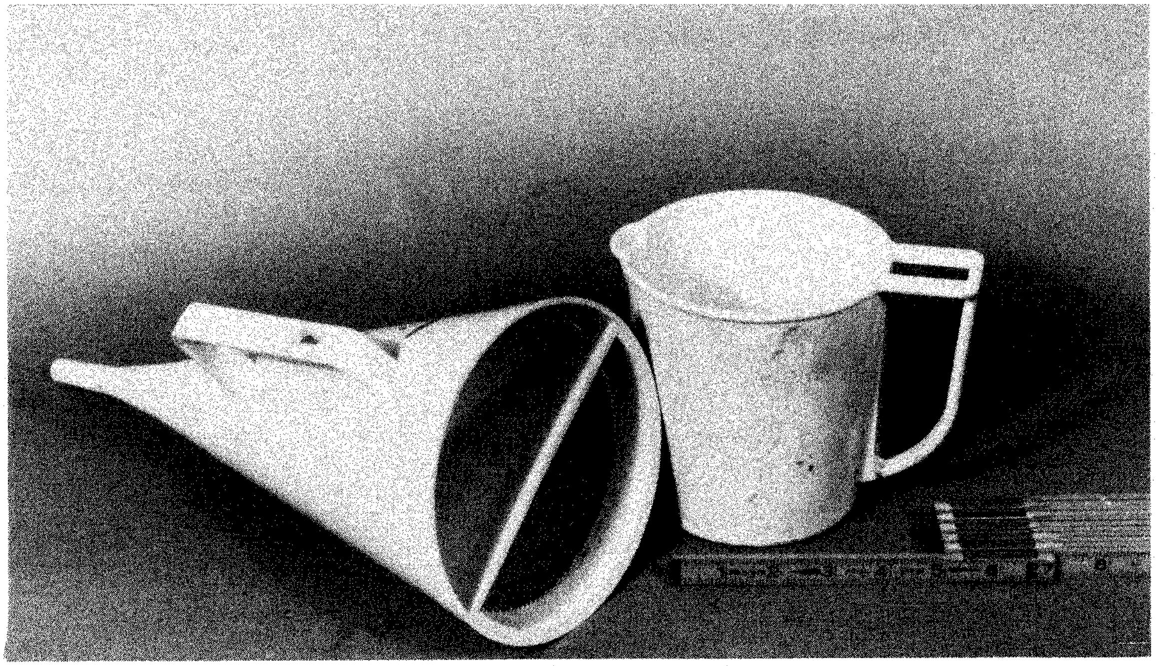

Figure 4-1. Photograph of a Marsh funnel and a one quart (0.95 dm^3) measuring cup for determining the viscosity of drilling mud

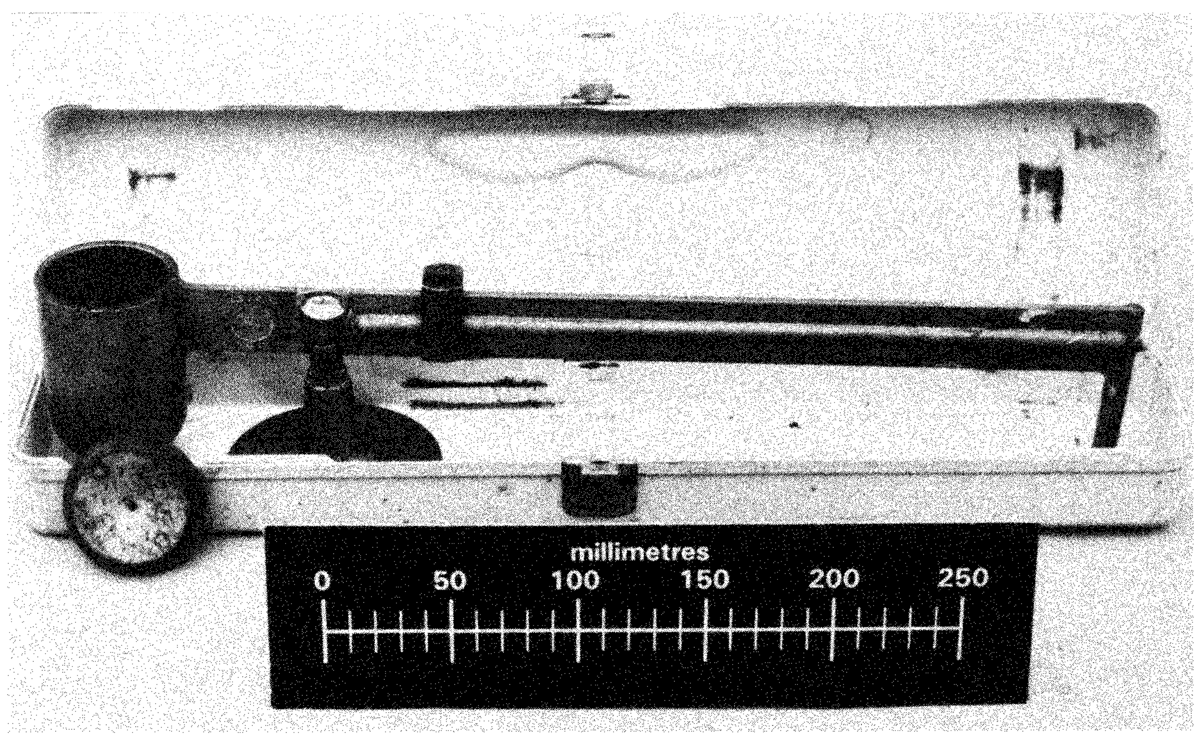

Figure 4-2. Mud balance for determining the density of drilling mud

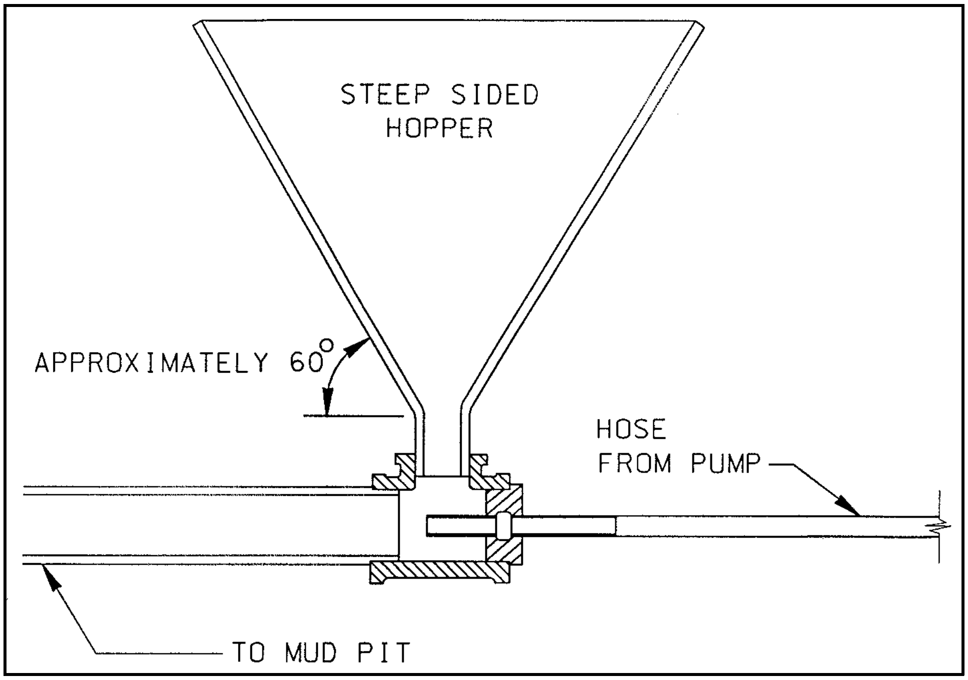

Figure 4-3. Schematic of a steep sided hopper mud mixer

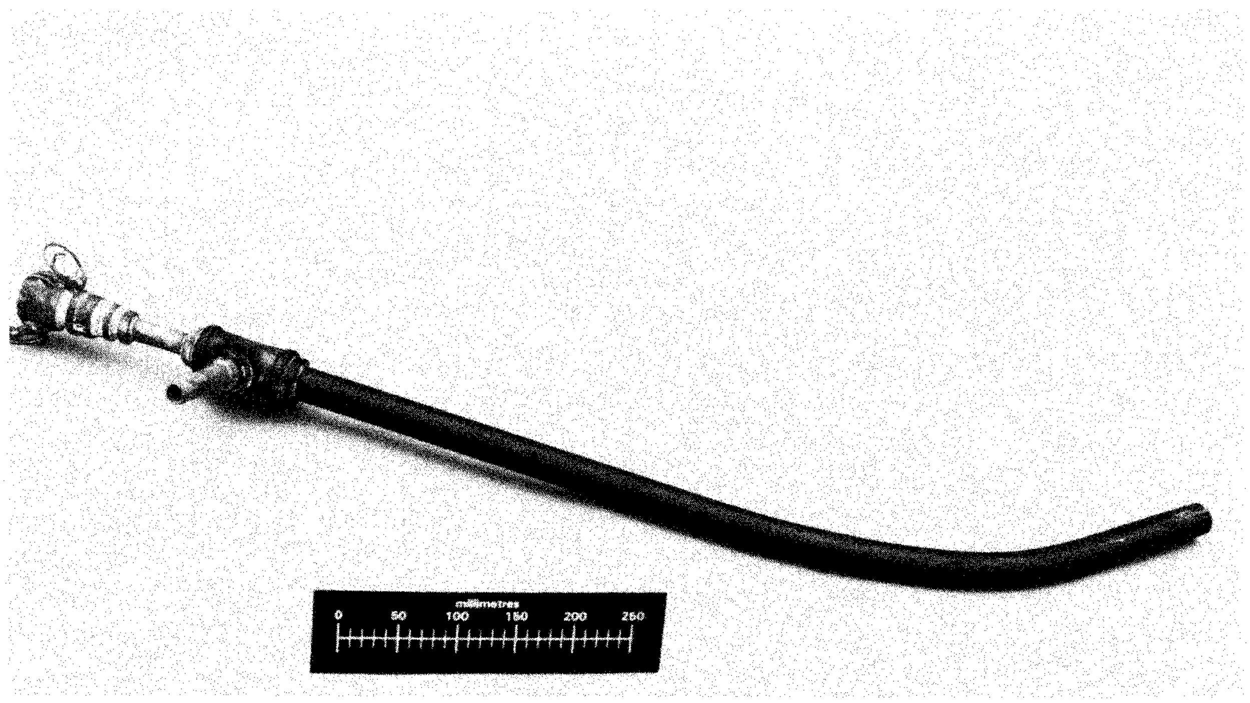

Figure 4-4. Photograph of a jet mud mixer

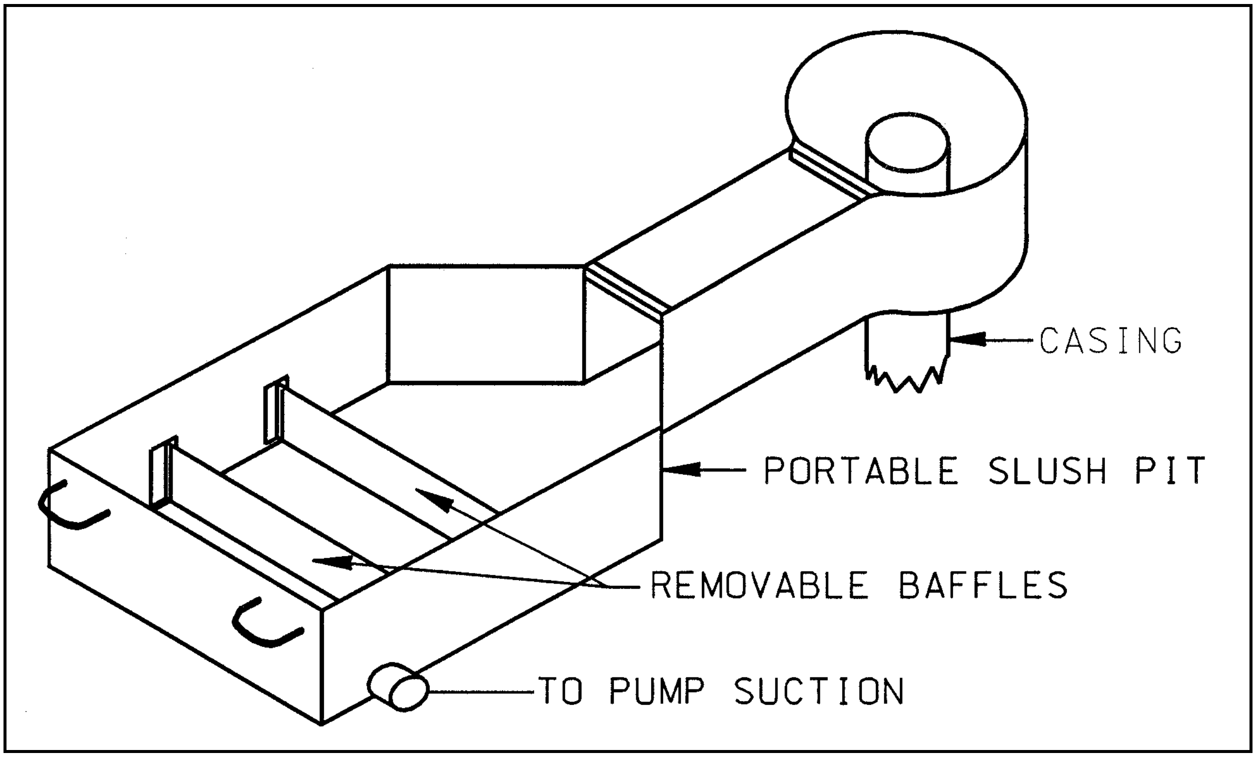

Figure 4-5. Sketch of a portable mud pit

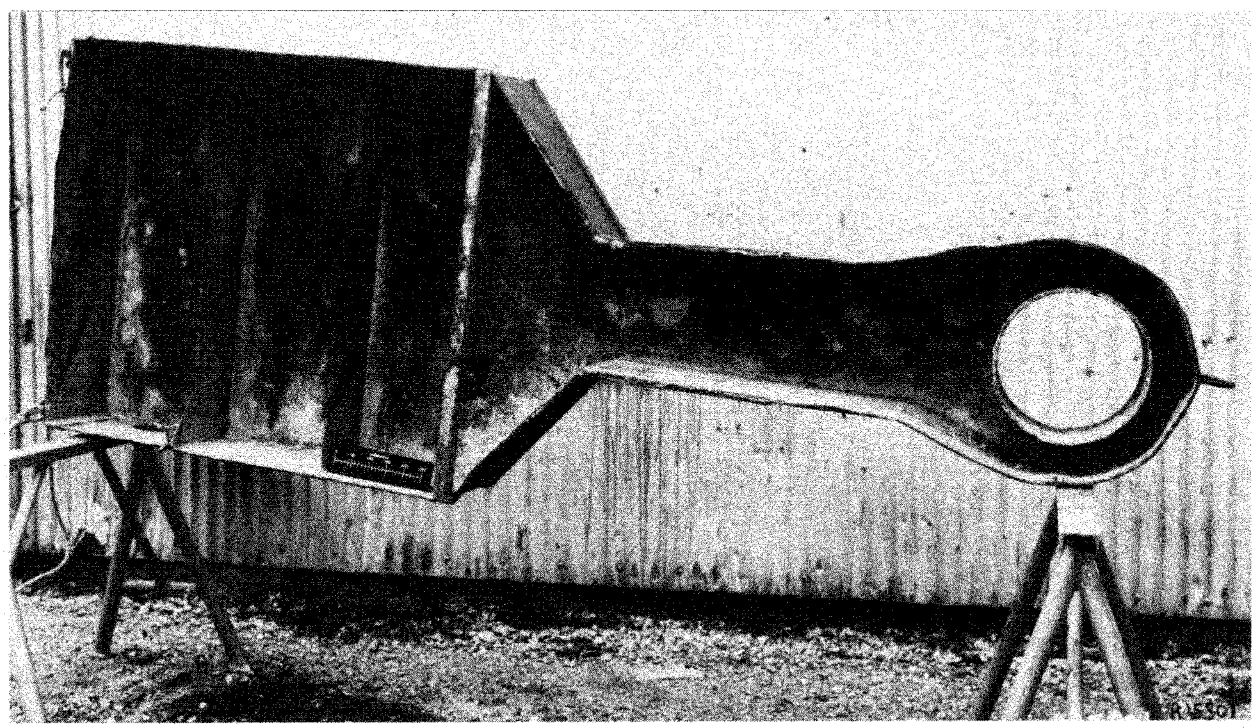

Figure 4-6. Photograph of a portable mud pit

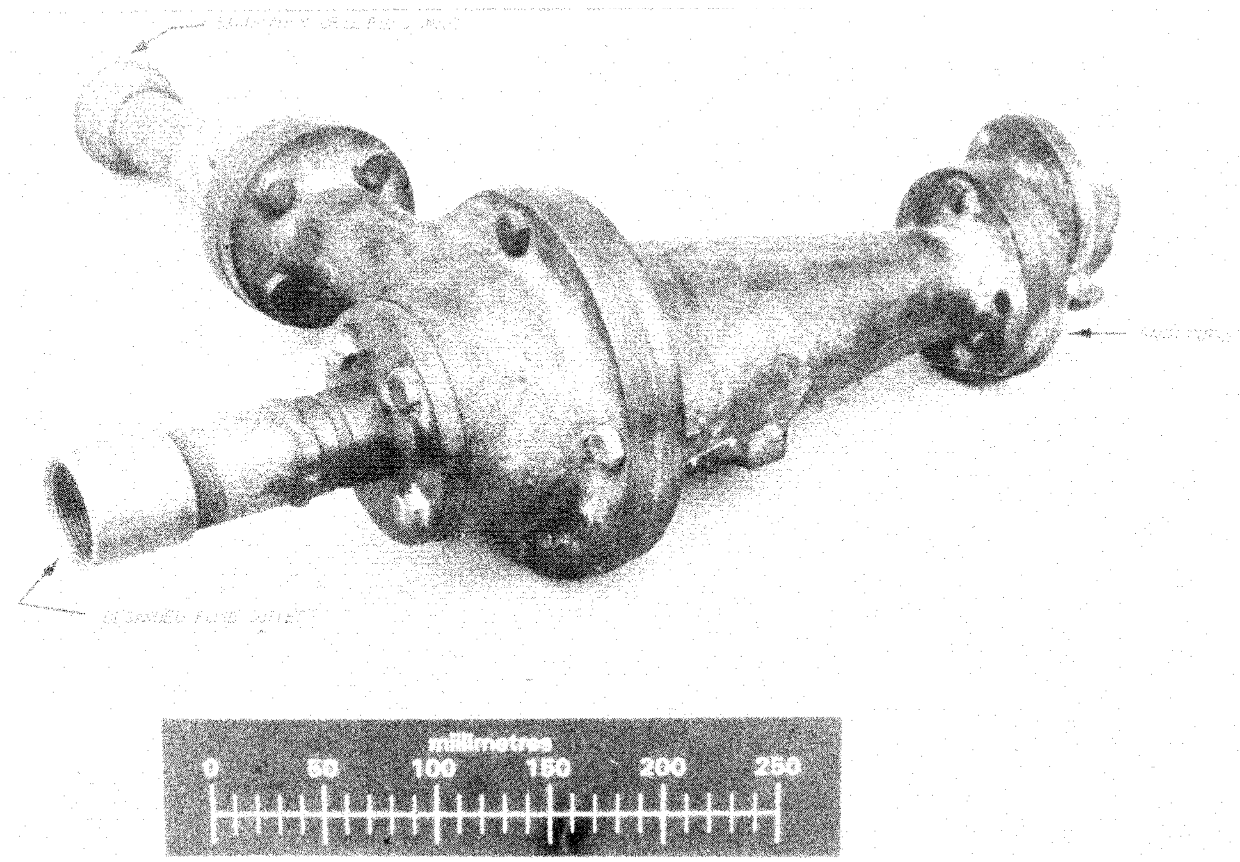

Figure 4-7. Photograph of a small desanding cone