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CHARACTERISTICS AND PROBLEMS OF COLLAPSIBLE SOILS

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16. ABSTRACT

In designing and constructing water resources projects, the Bureau of Reclamation has encountered collapsing soils in several different parts of the United States. Collapsible soils are defined as any unsaturated soil that goes through a radical rearrangement of particles and great decrease in volume upon wetting, additional loading, or both. Collapsible soils are found throughout the world in soil deposits that are eolian, loessial, subaerial, mudflows, alluvial, residual, or are manmade fills. These soils are typically found in arid or semiarid regions and have a loose structure; that, is a large void ratio, and a water content much lower than saturation. Soil collapse due to wetting can cause severe damage to canals, dams, pumping plants, powerplants, pipelines, roads, buildings, fields, and miscellaneous structures associated with irrigation projects. Existence of these metastable soils has long been recognized by Reclamation, and extensive studies have been performed to establish methods to identify, sample, test, and stabilize or mitigate their detrimental behavior for water resources structures. Methods of identifying, sampling, testing, and treating collapsible soils are discussed.

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by

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Denver, Colorado

February 1992

UNITED STATES DEPARTMENT OF THE INTERIOR ★ BUREAU OF RECLAMATION

Mission: As the Nation's principal conservation agency, the Department of the Interior has responsibility for most of our nationally owned public lands and natural and cultural resources. This includes fostering wise use of our land and water resources, protecting our fish and wildlife, preserving the environmental and cultural values of our national parks and historical places, and providing for the enjoyment of life through outdoor recreation. The Department assesses our energy and mineral resources and works to assure that their development is in the best interests of all our people. The Department also promotes the goals of the Take Pride in America campaign by encouraging stewardship and citizen responsibility for the public lands and promoting citizen participation in their care. The Department also has a major responsibility for American Indian reservation communities and for people who live in Island Territories under U.S. Administration.

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INTRODUCTION

Collapsible soils are found throughout the world in soil deposits that are eolian, loessial, subaerial, colluvial, mudflow, alluvial, residual, or manmade fills. Collapsible soils are defined as any unsaturated soil that goes through a radical rearrangement of particles and greatly decreases in volume upon wetting, additional loading, or both. Typically these soils are found in arid or semiarid regions and have a loose soil structure, i.e. a large void ratio and a water content far less than saturation. Typically the structure of these low-unit weight, unconsolidated sediments consists of coarser particles bonded at their contact points by the finer silt and/or clay fraction, or possibly by surface tension in the water at the air-water interfaces.

The addition of water is a widely used explanation for triggering soil collapse. Collapse can also occur, however, as the result of load application, or wetting, or both. Thus collapse can occur either by increasing the stress above the soil strength or by lowering soil strength below the stress. Whatever the physical basis of the bond strength, all collapsible soils are weakened by adding water. Decreased strength is more immediate in cases where the grains are held together by capillary suction, slow in the case of chemical cementing, and much slower in the case of clay buttresses. Thus it may take long periods of time, even years, for the total collapse to take place. Typical collapsible soil structures are shown on figure 1.

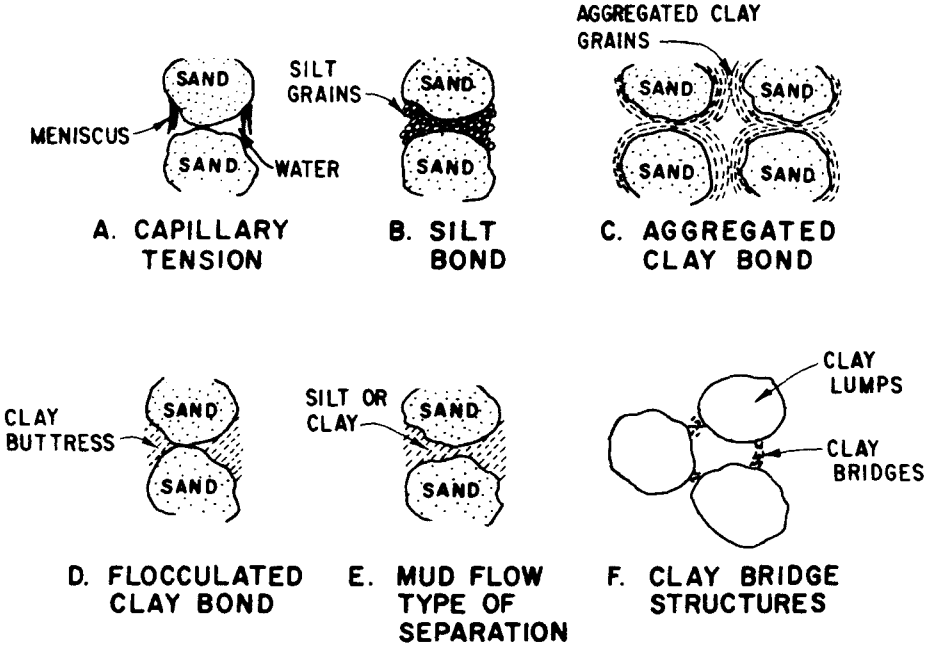

Figure 1. - Typical collapsing soil mechanisms which hold loose, bulky grains in place.

The existence of these soils throughout the world and difficulties with building on them have long been recognized. The neglect in studying these soils is understandable because they are usually present in predominantly arid regions where economic developments are limited. However, with development of irrigation projects in some of these areas, large quantities of water are now being placed on lands where farming had not been attempted before and, consequently, problems of soil collapse had not become evident. Soil collapse due to hydrocompaction (wetting) can cause severe damage to canals, dams, pumping plants, pipelines, roads, buildings, fields, and miscellaneous structures associated with irrigation projects and has been identified as one of the most destructive forms of land subsidence. These soil

collapse movements are not related to ground-water withdrawal. Delineation between stable areas and areas of potentially collapsible soils is therefore a very difficult task facing geotechnical engineers.

Many collapsing soils exist to considerable depth, often 30 m or more and up to 200 m, but always in areas where the ground-water table is deeper. The amount of collapse and its rate are affected by the mineralogy of the materials present; initial void ratio; stress history of the materials; the shape of the bulky grains and their size distribution; inplace water content; pore sizes and shapes; any cementing agents; thickness of the soil layer; and amount of added load, either hydrostatic or structural. The amount of collapse can be large, as evidenced by up to 5 m of settlement of a large irrigation canal in the west central part of the San Joaquin Valley in California.

SUMMARY OF PROPERTIES

A variety of factors and conditions are present with collapsing soils. Specific qualities have been found for specific collapsing soils in a given area, but frequently these qualities do not apply to other collapsing soils. Since the quantity of settlement that will be destructive varies from one facility or structure to another, it is necessary to determine the amount of possible settlement to promote efficient design at a specific site or for a given project. The following general conclusions might then apply.

- Collapsing soils have been found in all types of areas - in mountainous areas, on plains, and in arid and humid regions. However, within restricted geographic areas the identification of a source of a soil deposit or type of land shape such as an alluvial fan may aid in locating similar collapsible soils.

- The amount and rate of collapse appear to be affected by many things, including mineralogy, percentage of clay, shape of grains, grain size distribution, moisture content, void ratio, pore sizes and shapes, cementing agents, and others. Atterberg limits values, in combination with other soil properties, are widely used in identifying these soils. Many collapsing soils have liquid limits below 45 and plasticity indexes below 25, and usually much lower, often in the nonplastic range.

- A water content inplace that is well below 100 percent saturation is required for collapse but the optimum saturation percentage for maximum collapse is usually between about 13 and 39 percent. Some soils may even initially gain strength as the water content increases. Some soils collapse when wetted, without additional loading other than the added water, but will decrease in volume even more with added load surcharge. Other soils require additional loading for any collapse to occur.

- Simple routine tests can indicate whether soils are collapse-susceptible and more complex tests provide data to determine the amount and rate of collapse. None of the tests, however, replicate field conditions, and correlations and corrections may need to be made as experience and additional data are accumulated. These factors very likely will not be directly transferrable from one area to another.

IDENTIFICATION OF COLLAPSIBLE SOILS

A geotechnical engineer needs to be able to readily identify the soils that could collapse and to determine the amount of collapse that might occur. Soil deposits most likely to collapse are:

1. Loose fills.

2. Altered windblown sands.

3. Hillwash or alluvial fans of low unit weight.

4. Decomposed granite or other acidic igneous rocks.

In some cases the geotechnical engineer is concerned about the time required for collapse to occur, especially if it might cause differential settlement beneath a structure.

The identification and prediction of soil collapse have proven difficult because no single criterion can be applied to all collapsible soils. Routine and sophisticated tests do not always reliably indicate the presence of collapsible soils because of the many different configurations which hold the bulky grains in place. To date, most criteria for determining susceptibility to collapse are based on relationships among the porosity, void ratio, water content, and inplace dry unit weight.

FIELD OBSERVATIONS

With an understanding of the basic principles of the phenomenon and with experience, the likelihood of soil collapse settlement can be recognized from a fresh soil profile in the field. The following points must, however, be considered.

1. Collapse settlement will not occur in soils which lie below the water table, because the condition of partial saturation is an essential prerequisite to collapse.

2. If the soil is silty or clayey, it will likely have a stiff or hard consistency due to partial saturation. Therefore, during site inspection the in situ water content must be considered and judgment made on a sample which has been wetted. Errors in assessment of collapse susceptibility have been made simply because the engineer examining a dry profile has forgotten that the subsoil will become wetted after completion of the structure.

There is a very simple field test which can be used to assist in assessing the collapse potential of a soil profile. A block of material about hand size is taken from the side of a test pit, from auger boring cuttings, or other sources. It is broken into two pieces and each is trimmed until they are approximately equal in volume. One specimen is then wetted and molded in the hands to form a damp ball. The volume of this ball is then compared with the volume of the undisturbed specimen. If the wetted ball is obviously smaller than the undisturbed piece, there is potential for soil collapse.

LABORATORY TESTING

Because low unit weights indicate a loose structure, the inplace dry unit weight is a good parameter for collapse prediction. Other properties used have included water content, void ratio, liquid limit, percent saturation, plastic limit, plasticity index, and specific gravity. Various collapse criteria are summarized and discussed in papers by Thornton and Arulanandan (1975) and Nowatzki (1985).

An easily applied criterion requiring only dry unit weight and liquid limit values was successfully used to delineate potentially collapsible soils for the San Luis Canal in the San Joaquin Valley in California. This criterion states that the soil voids in a soil mass must be sufficient to contain enough water for the soil to be at its liquid limit (Bureau of Reclamation, 1980; Gibbs and Bara, 1962). Soil unit weights that plot above the line shown in figure 2 are in a loose condition and when fully saturated will have a water content greater than the liquid limit. The liquid limit is a water content, determined by a standard laboratory test (Atterberg limits), which represents the weakest plastic condition of the soil or the condition at which it is approaching the liquid state. When the soil has a low unit weight such that its void space is sufficiently large to hold the liquid limit water content or more, saturation can easily cause a liquid limit consistency at which the soil offers little resistance to deformation. If the voids are greater than this amount, saturation would result in a water content in excess of the liquid limit and the potential for collapse would be high. If collapse did not occur, the soil would surely be in a very sensitive condition (Knodel, 1980). Although this criterion does not directly consider the time effects of cementation it is still very useful because as mentioned previously, all collapsible soils are weakened by wetting, whether immediately or eventually.

The laboratory one-dimensional consolidation test is another useful test to assess collapse potential. A specimen is trimmed from an undisturbed sample at inplace unit weight and water content to fit into the consolidometer ring. The specimen can then be loaded to some standard value as suggested by Knight (1963) or to some value representing a known field or design condition. At the end of this loading the specimen is flooded with water and left for a given time interval. Following wetting, the consolidation test is carried on to its maximum loading. The collapse potential can be evaluated based on the change in specimen height (volume) due to wetting as shown in figure 3 and summarized in the table below. This value is only a guide to collapse potential and is dependent upon many variables, but with sufficient testing can be very useful to establish values for specific geographic areas.

Jennings and Knight (1975) have suggested some values for collapse potential which are shown below.

CP (collapse potential) values

Percent volume change	Severity of problem
0 - 1	No problem
1 - 5	Moderate trouble
5 - 10	Trouble
10 - 20	Severe trouble
> 20	Very severe trouble

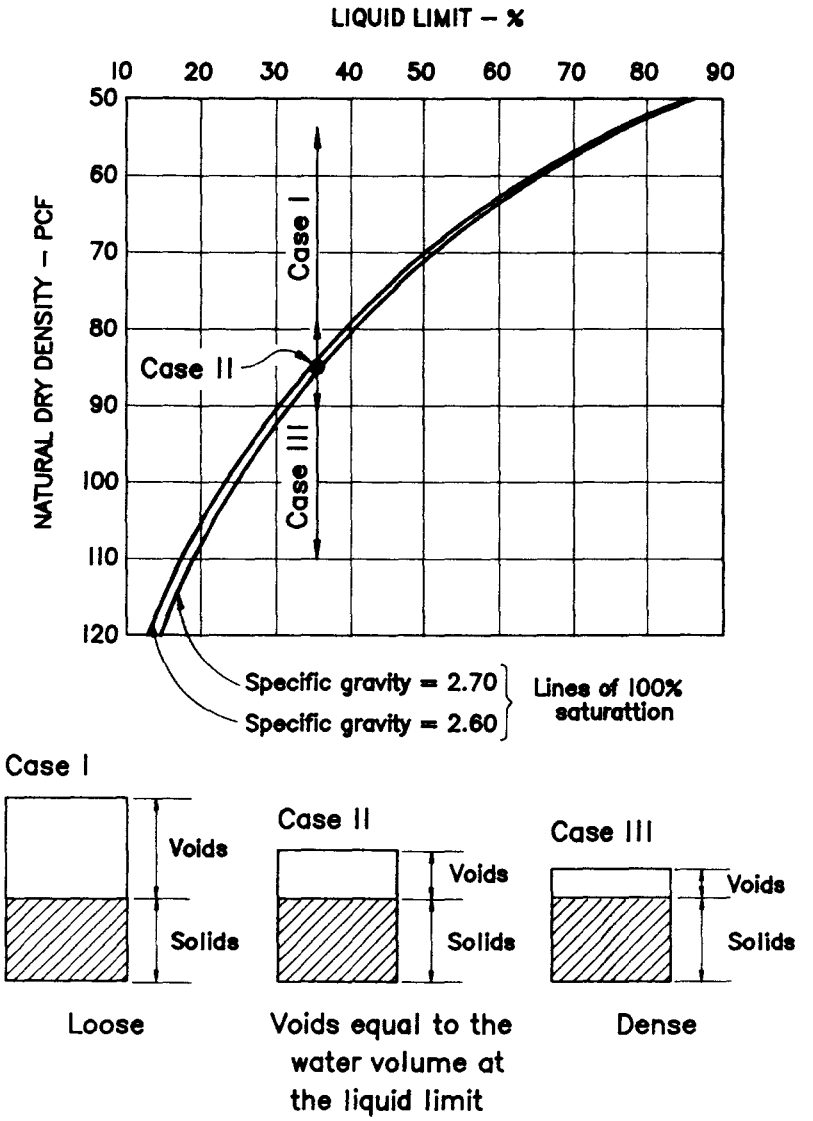

Figure 2. - A criterion for evaluating soil collapse.

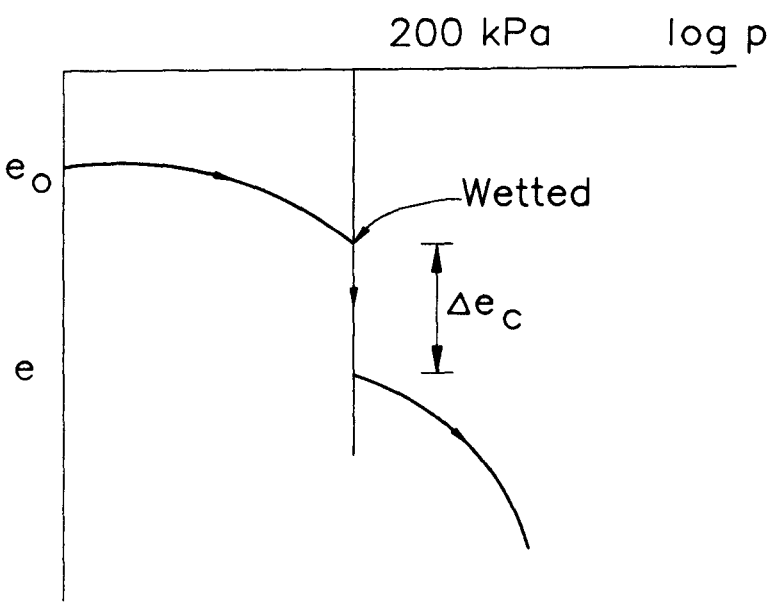

Figure 3. - Typical collapse potential test result.

Nowatzki (1985) states, however, that from an engineering viewpoint, collapse susceptible soils begin to pose problems only when the collapse due to wetting exceeds approximately six to eight percent. So again, damage from collapsing soils depends upon the specific structure and the specific situation under study.

Data from the consolidation test and the liquid limit-dry unit weight chart, considered together, usually give a reliable indication of collapse susceptibility and can complement analyses using any other criteria. The one-dimensional consolidation test is recommended as the primary method of soil collapse characterization. For most projects, settlement analyses should be performed considering the actual superimposed stresses, strata thickness, and tolerance of the structure to movement, rather than employing only empirical criteria. It is often better to perform more somewhat simpler tests than fewer more sophisticated tests. An abbreviated consolidation test using fewer loadings than normal and wherein the specimen is wetted at a pressure equal to the overburden stress plus structural load provides data as reliable as other more sophisticated tests and is simpler to perform. It should be recognized that consolidation tests do not duplicate field conditions because the specimens are submerged in laboratory testing, whereas collapse in situ occurs at some critical percent of saturation below full saturation.

For laboratory consolidation test results to be reliable, it is extremely important to obtain very high quality, undisturbed soil samples that are truly representative of the soils in question. Very carefully obtained hand-cut blocks, properly protected and transported to the laboratory, provide the best results. Undisturbed samples taken with a hollow-stem auger are also acceptable since this is currently the only method available to obtain high quality undisturbed samples at depth without the use of drill mud or other fluids. Push- or drive-tube samples are **not** acceptable as soil structure is altered during sampling. Laboratory specimens trimmed from such samples will yield erroneous test results.

The geotechnical engineer should use care in applying the various criteria to test values and should never rely on unit weight values alone to assess collapse susceptibility since different types of soil may be stable at quite different ranges of unit weight. The only instance might be where extensive studies have been performed in a concentrated geographic area and data and analyses have shown that soils below or above a certain inplace unit weight will or will not collapse under specific design or operating conditions. It is also important to determine soil type and to study the characteristics of plasticity, water holding capacity, and the effects of wetting in regard to overall soil collapse (Knodel, 1980). Time for total collapse to occur may also be an important consideration since this may sometimes take long periods of time, even years. The point is that all of these guidelines should be used with care, discretion, and good engineering judgment, and should be adapted to the particular case study.

Jennings and Knight (1975) have also proposed a method to predict the amount of collapse settlement of a soil for design purposes using results of a double consolidation test. The critical difficulty with interpreting results of this procedure is that it is virtually impossible to obtain and test two soil specimens with identical physical properties, even if both specimens are trimmed from the same undisturbed sample.

The most accurate test would be one conducted in the field where wetting occurred with the actual structural load in place. However, these tests are expensive and time consuming, and still only show the effect in the very small area tested.

SAMPLING METHODS FOR COLLAPSIBLE SOILS

When sampling low unit weight materials for laboratory testing, it is extremely important to obtain undisturbed samples whose structure or void ratio has not been altered by the sampling process. The loose structure of these materials makes it difficult to obtain undisturbed samples for inplace unit weight determination and for laboratory testing. Dry sampling, if possible, is most desirable because if drilling fluid (mud) is used with rotary drill rigs for sampling at depth, there is always the possibility the fluid will penetrate the soil ahead of the sampler and change the properties of the soil. Also any loading or pressure applied during wet rotary drilling can consolidate the soil being sampled. High quality undisturbed hand-cut block samples can be obtained from test pits or test trenches, but when samples are required from greater depths other sampling methods are required. In general it is not practical to excavate test pits and obtain hand-cut samples beyond about 6 to 10m in depth if a mechanical backhoe excavator is used for the excavation. Even lesser depths might result if the test pits are hand dug. These test pit depths may also be further limited by the presence of a high water table or by layers of cohesionless materials.

All undisturbed soil samples are costly to obtain and all should be handled carefully through every step of the process; i.e., obtaining the sample in the field; identifying, logging, handling, and packing of the sample; transporting the sample to the laboratory; and cutting and placing specimens in the test machines in the laboratory. *Adequate care and treatment of undisturbed samples should never be compromised.* A sample which has been disturbed, but is submitted to the laboratory for testing as an undisturbed sample, is of less value than no sample at all, since the results of tests may lead to erroneous conclusions and faulty foundation design. All samples should be taken and handled carefully, and should be representative of the soils being studied.

Hand-Cut Samples

Hand-cut samples can generally be obtained with less disturbance than samples procured by other methods and therefore is the preferred method of sampling. This type of sampling must be done carefully and with appropriate cutting tools to prevent disturbance or cracking of the sample. The sample must be prevented from drying or wetting during the trimming, handling, and transporting processes. The hand-cut sample should be protected with plastic wrap and layers of lightweight textile (cheesecloth) and wax to prevent moisture loss and to minimize damage to the sample during transportation to the laboratory and during handling in the laboratory. The sample, after it is protected with at least three layers of wax and textile, should be placed in a firmly constructed wooden box with secure packing between the walls of the box and the sample. The sample is then ready for transportation to the laboratory. These procedures are outlined in USBR 7100 in the *Earth Manual* (Bureau of Reclamation, 1990).

Mechanical Drilling Methods

For all types of mechanical sampling methods, it is important that the drill rig and sampler be properly maintained and kept thoroughly clean. It is best if the work can be done in the dry when sampling collapsible soils.

It may be possible to obtain high quality undisturbed samples in collapsible soils using drill mud or other fluids, but only with very experienced and careful drill rig operators who are interested in obtaining samples and not in how quickly the hole can be completed. If drilling and sampling are to be performed using drill fluid, there are several double-tube samplers which will perform in these materials. If these samplers are used, they should be fitted with rigid noncorrosive metal or plastic liners into which the sample moves as the sampler advances downward. The sample in the rigid metal or plastic liner can then

be easily removed from the sampler, the ends trimmed and sealed, and readied for shipment to the laboratory. It is always best to use a large diameter sampler [at least 6-in (150-mm)] to provide the least disturbed sample for laboratory testing.

If double-tube samplers and drilling fluid are used to sample low unit weight soils, special attention should be paid to ensure that the sample fits snugly, but is not forced into the liner so that inplace unit weight is maintained. Great care should be exercised to ensure that bit clearance is correct and that percent sample recovery is very near 100 percent. This confirms that the samples are not being consolidated during sampling. After advancing the drill hole to sampling depth, great care should be taken to clean the bottom of the hole of slough just prior to sampling so the top of the undisturbed sample will be as free of soil contaminated with drill mud as possible. After the sample is retrieved, the ends of the sample in the rigid liner should be carefully trimmed of contaminated soil before sealing with a mechanical packer or a wooden disk and wax. If a wooden disk is used, it should never be secured with a nail through the wall of the rigid liner since this disturbs the sample. The largest practical diameter sampler should always be used because this provides the highest quality undisturbed sample for laboratory testing. The various double-tube samplers and their characteristics are discussed in various reports and other literature, as well as in USBR 7105 in the *Earth Manual* (Bureau of Reclamation, 1990).

Until recently, the only method for obtaining undisturbed samples at depth without using drilling fluids was by use of push-tube or drive-tube samplers. These samplers are also sometimes called Shelby Tube samplers. Even though push-tube samplers were used extensively in the past, they should *not* be used to obtain undisturbed samples in low unit weight soils because they produce an unacceptable sample for analysis of soil collapse susceptibility. With improved laboratory investigative techniques such as use of x-ray radiographic examination, it was found that push-tube sampling caused severe deformation and compaction of samples from low unit weight soil profiles. As a result, an investigation was performed to determine whether a newly developed hollow-stem auger sampler could be used to obtain less disturbed samples in low unit weight soils (Casias, 1987). Results were positive and the hollow-stem auger sampler is now used extensively in cases where samples need to be taken at depth without use of drilling fluid. It has also been exclusively used for obtaining undisturbed samples from existing compacted earth embankment dams since it eliminates the risk of hydraulically fracturing the earth embankment through use of drilling fluid.

Several drilling equipment suppliers now market the hollow-stem auger sampler system in the United States and even wire-line systems are being manfactured and used.

The hollow-stem auger sampler (with rigid liner) is currently (1991) the best tool for obtaining undisturbed samples at depth in low unit weight soils. Again, the larger diameter [about 6- and 8-in (150- and 210-mm)] samplers should be used as they provide the highest quality samples for laboratory testing. Depending upon the type of soil, soil conditions, and drill rig capability, samples can be obtained from depths up to 100 to 130 ft (30 to 40 m). In ideal conditions, augers have been used to depths of about 200 ft (60 m). A sketch of the hollow-stem auger sampling system is shown in figure 4.

Guidelines to observe when sampling with the hollow-stem auger system are:

1. Keep the hole clean during auger advancement to get a straight hole. Do not force the auger and be sure it is carrying up all the cuttings. Be sure to clean the hole of cuttings before trying to withdraw the auger. In certain instances, a small amount of water or bentonite slurry may be added to the downhole cuttings so the auger can keep turning and does not bind due to friction on the

flights. Water or slurry should be added with caution and discussed with the engineer in charge before use.

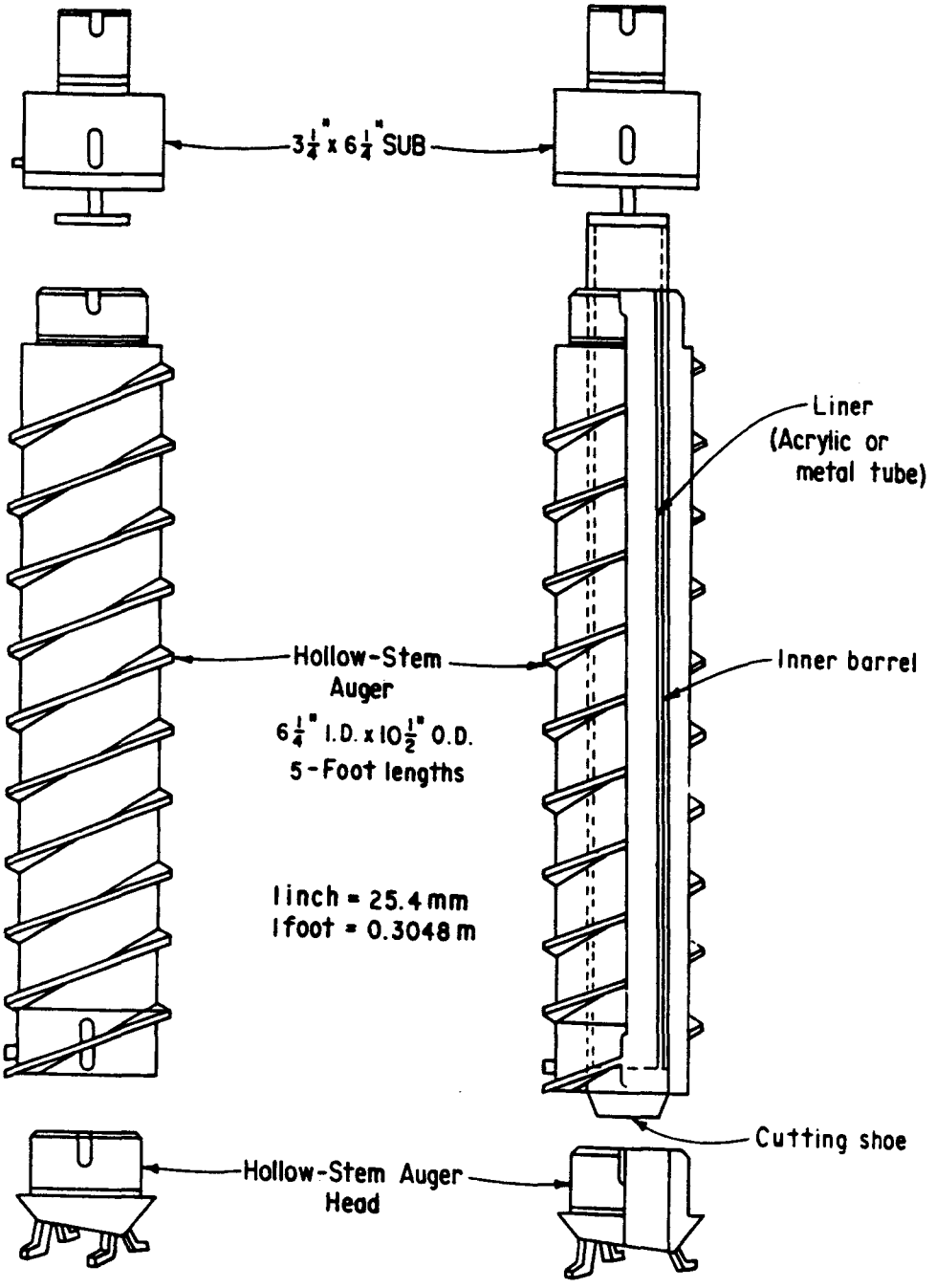

Figure 4. - Hollow-stem auger sampling system.

2. Check to be sure the inside diameter of the cutting bit does not taper to a smaller diameter from the cutting edge to the sample tube liner edge. The bit should be straight-sided or tapered very slightly the other way, i.e., smaller diameter at the cutting edge and larger diameter at the sample tube liner end.

3. There should be no shoulder where the inside diameter of the sample tube liner meets the inside diameter of the sampler cutting bit, i.e., the inside diameter of the liner should always be as large or slightly larger than the inside diameter of the cutting bit.

4. Always check for percent sample recovery. If it is not 100 percent, bit clearance needs to be adjusted since this could indicate that the sample is being consolidated as it is being forced into the sample liner tube. This is especially critical when sampling low unit weight soils.

5. Bit clearance may need to be changed to correspond to depth. The deeper the depth at which sampling is being performed, the more clearance needed because of stress relief in the samples. Keep just enough clearance so the sample is just snug, but not being forced into the sample tube liner. Bit clearance is based on the ratio of the inside diameter of the cutting bit to the inside diameter of the sample tube liner. It may be necessary to use bits of several different clearances (inside diameters) on the same hole, possibly even in the same soil, so an assortment of bits of different inside diameter should always be available. The inside diameter of the bit should be clearly stamped on each bit.

6. For a sample of 2.75-in (about 70-mm) diameter, a bit diameter of about 2.68 to 2.71 in is a good place to start (2.5 to 1.5 percent clearance). About the same *percent* clearance is also appropriate for larger diameter samples.

7. To obtain the best quality samples, sampling runs should be no more than 24 to 30 in (600 to 750 mm) in length. The 5-foot (1.5-m) long sample tube liners can be cut in half and one of the halves can then be used as a spacer in the upper part of the sampler barrel during sampling.

8. The inner barrel cutting shoe (bit) should extend beyond the outer barrel cutting teeth about 3 in (about 75 mm) so the sample will not be disturbed by the cutting teeth. For softer soils this distance may be greater, while for harder soils it may be less.

9. Use of sample (core) catchers is discouraged for undisturbed sampling.

10. The inside edge of *all* sample tube liners should always be checked to be sure there are no burrs or rough spots left as a result of cutting the liner to length. Sample tube liners should be of constant diameter, or as nearly constant as possible so the sample will move into the liner smoothly. The wall of the sample tube liners should be thick enough so the tube is rigid and will not flex when filled with soil, taken from the sampler, handled, and transported to the laboratory.

TREATMENT METHODS

Many methods have been used for treating collapsible soils. The method selected depends upon several factors such as the depth of the collapsible soil deposit, the type of structure to be built, the capability of the structure to withstand settlement, the likelihood of the foundation to become wetted, and the stresses imposed on the foundation by a structure. Although attempts are sometimes made to prevent wetting, the

probability of wetting foundation soils at some point in the life of a given project is high, especially for agricultural irrigation projects.

In assessing mitigation measures, the issue of shallow or deep deposits must be considered, and that distinction is often not clearcut. Some mitigation measures such as compaction with rollers or tampers, will almost certainly not produce results for deep deposits, and may or may not work for shallow deposits. In any case, each situation must be evaluated and often several methods are tried before satisfactory results are achieved. If collapsible soils are identified in foundations for structures, including canals, a prime objective should be to stabilize those soils before construction. It is much less expensive to solve the problem at that point rather than after the project is built. Then maintenance costs are reduced; project operation is more efficient; and the lives of structures are extended.

Prevention or minimization of damage due to collapsible soils can be categorized as follows:

1. Induce collapse by wetting prior to construction or foundation loading, often called hydrocompaction.

2. Decrease foundation pressures.

3. Solidify the soil so that it is unaffected by addition of water and does not lose shear strength.

4. Remove collapsible soils.

5. Densify collapsible soils by methods other than hydrocompaction.

6. Other methods, including piles, caissons, deep blasting combined with prewetting, etc.

Methods from each of these categories have been used and particular aspects of each are discussed in the following sections (Luehring, 1988).

Induce Collapse Prior to Construction

For water conveyance structures where foundation wetting after construction is unavoidable, the most effective method of collapsing soils prior to construction is by surficially ponding water along the alignment. Infiltration wells should be used with this method to ensure that the soils become wetted to depth and to accelerate the process of collapse. Prewetting by ponding, in conjunction with surcharge loading, can decrease the overall time required for collapse to occur. In some instances, the embankments for the ponds have served as a surcharge load. Surface sprinkling has also been used for prewetting, but again, infiltration wells should be used to speed the process. With sprinkling, however, there is no hydraulic loading or embankment loading as there is when ponds are used. In arid regions, prewetting by any method provides the additional benefit of increasing the soil water content for easier construction excavation and enhanced soil compaction.

Decrease Foundation Pressures

This method is only effective for concentrated structure sites such as pumping plants or canal structures, but cannot be used for the canal itself. The most commonly used techniques to decrease foundation loading are to use floating foundations, to decrease soil loads by removing material equal to the structure weight, or to use piles or caissons.

Solidify the Soil

Various chemical stabilization techniques have been investigated to mitigate collapse of soils; however, none of these have proven practical for line structures such as canals. Thermochemical processes have also been studied, but only in the laboratory. Use of lime or portland cement will stabilize collapse-susceptible soils, but they need to be intimately mixed with the soil and then compacted near optimum water content. Essentially the same stabilizing effect can be achieved to minimize collapse potential with only soil compaction but without the additive. Solidifying soil with additives is not practical for water resources projects.

Remove Collapse Susceptible Soils

Removal and recompaction of collapsible soils is economical only if they are at shallow depths and then only for concentrated structural sites.

Densify Collapsible Soils

The two methods most often used to densify collapsible soils at depth are dynamic compaction and vibrocompaction. *Dynamic compaction* consists of using a large crane or tripod to drop large, heavy weights (e.g. 15 tons or more) from heights [e.g. 50 ft (15 m) or more] to densify low unit weight soils. The weight is dropped on a regular grid pattern covering the site and the depressions made by the dropped weight are filled with select material. Depending upon the situation, the process may be repeated several times until the desired unit weights are reached to the desired depth. Maximum depth of treatment by this process is about 35 ft (10 m), more or less. This method is only economical for concentrated structure sites. The *vibrocompaction* technique makes use of a large vibrofloat probe suspended from a crane. Vibration is produced by an eccentric weight inside the probe which is driven by an electric or hydraulic motor. Powerful water jets are located near the tip and along the sides of the probe. The probe is gradually lowered through the soil to be treated using only vibration, water jets, and its own weight to advance. The probe is raised and lowered and gravel is fed into the hole and worked into the surrounding soil. As this process progresses, the soils are reworked and compressed into a higher unit weight state. As with dynamic compaction, this method is only economical for concentrated structure sites.

Other Methods

Some densification can be effected on surface soils by *deep plowing or ripping*, and then wetting soils to a water content above optimum before compacting with a heavy vibratory roller. Plowing or ripping can be done to about 3 ft (1 m) depth, so the total effective depth of treatment by this method is about 6 ft (2 m). *Piles or caissons* can be used for concentrated structures if the collapsible soils do not extend to great depth. Use of displacement piles in conjunction with foundation prewetting prior to driving has distinct advantages over other types of piles. As a displacement pile is driven, it displaces and compacts the loose soil surrounding it and provides a more dense foundation. When using piles or caissons it is important that they be placed at a depth sufficient to provide bearing on soils not subject to collapse.

SUMMARY OF TREATMENT METHODS

A wide variety of methods are available and have been used to reduce effects of collapsible soils. Most methods are used occasionally, and yet no single method is used exclusively. From review of the

literature it appears that prewetting is still the most often used and most effective technique to stabilize collapsible soils before construction.

An optimization study should be conducted before deciding on the final method to employ. Each alternative remedial method should be analyzed for expected cost, expected result, probability of success, applicability to problem at hand, and effectiveness of treatment. It may be that more than one method should be evaluated on actual test sections in the field before selecting the one to be used for the entire project; or more than one method may prove viable depending upon the extent of the project and variability of soils. Very often the least complicated procedure produces the best result.

Transfer of load to noncollapsible soils below the collapsible soils by use of piles, stone columns, piers, etc. is usually very effective but is often not the most economical alternative. Removal and recompaction of collapsible soils can be very effective but is limited by depth considerations and is usually used for shallow deposits. Minimizing wetting after construction is always good engineering practice, but for agricultural irrigation projects, it is nearly impossible to achieve. Dynamic compaction using a very heavy weight dropped from great height is also effective, but again, is limited to depths of about 35 to 50 ft (10 to 15 m) depending upon soil profile. For deep collapsible soils, prewetting is probably the best alternative, but when shallow collapsible soils are present, it is usually used in combination with other measures such as compaction or surcharge loading. Other measures such as deep blasting, chemical stabilization, displacement piles, etc. are often effective methods but are usually used only in special cases.

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