Collapsible Soil

This module provides guidance for the investigation, identification, evaluation, mitigation, and reporting of collapsible soil.

Overview

Collapsible soil is unsaturated soil that undergoes a rearrangement of particles and reduction in volume upon wetting, additional loading, or both (Clemence & Finbarr, 1981 & Knodel, 1992). Naturally occurring collapsible soil consists of sand and silt sized particles arranged in a loose “honeycomb” structure held together by small amounts of water-softening cementing agents, such as clay or calcium carbonate, or by capillary suction (Knodel, 1992 & Coduto et al., 2016). Collapsible soil typically possesses a low dry unit weight and high void ratios, and gravel may also be present. Figure 1 provides a conceptual illustration of collapsible soil structure loaded before and after wetting:

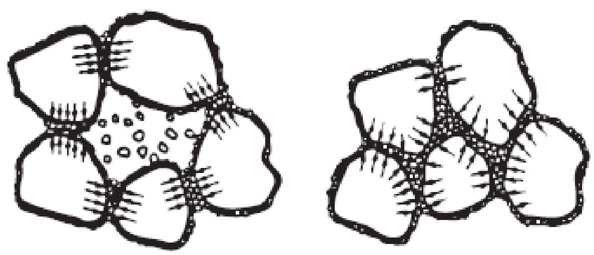

Figure 1: Conceptual illustration of collapsible soil structure (Houston et al., 1988).

Collapse in these materials is also known as *hydroconsolidation*, *hydrocompression*, or *hydrocollapse* (Coduto et al., 2016). Collapse settlements of two to three feet are common in the southwestern United States, and up to 15 feet occurred at a large irrigation canal in the San Joaquin Valley, California (Clemence & Finbarr, 1981; Knodel, 1992; and Howayek et al., 2011).

Four conditions are necessary for soil collapse to occur:

1. An open, partially unstable, partially saturated fabric.
2. Sufficient total stress to make the soil structure metastable.
3. Presence of a bonding agent or sufficient soil suction to stabilize the soil in the metastable condition.
4. Addition of water, which reduces soil suction, or softens/destroys the bonding agent, thereby causing shear failures at the inter-aggregate or inter-particle contacts.

Occurrence

The magnitude and rate of collapse is complex and is affected by the minerology; initial void ratio; stress history; grain size, shape and distribution; initial water content; pore size and shape; matric suction; cementing agents and the degree of bonding; layer thickness; wetting source, depth and rate; and loading (Knodel, 1992).

Naturally Occurring Collapsible Soil

Naturally occurring collapsible soil may be surficial or extend to considerable depths and may be widespread or localized in extent. Collapsible soil naturally occur in the following geologic materials:

- Aeolian Deposits – Wind deposited materials including windblown sand dunes, loess, aeolic beaches, volcanic dust deposits, and others. These deposits are common in arid and semi-arid climates.
- Alluvial Deposits – Water deposited materials such as alluvial fans and flows. These deposits are also common in arid and semi-arid climates.
- Colluvial Deposits – Gravity deposited materials that accumulate at the base of mountains, hillsides, slopes, etc. including slopewash.
- Residual Soil – Soil formed in-place by the weathering of rock.
- Volcanic tuff, gypsum, loose sands cemented by soluble salts, dispersive clays, and sodium rich montmorillonite clays (Clemence & Finnbarr, 1981).

Collapse in Deep Compacted Fills

Soil collapse has been observed in deep compacted fills such as those constructed for highway embankments and within canyon fills. All compacted soil types are susceptible to collapse including clean sand, silty and clayey sands, and fine-grained materials (clays and silts). For compacted clayey fills, clayey soil with 10 to 40% clay fraction exhibit the highest collapse potential (Lawton et al., 1992).

Deep compacted fills that meet typical compaction specifications during construction may still be susceptible to collapse after wetting. A case study of wetting-induced settlements from two residential developments in San Diego County constructed over deep canyon fills up to 80 feet in depth is discussed by Brandon et al. (1990). The canyon fills consisted of clayey sand and sandy lean clay that were compacted on average to 92% relative compaction and between 1% above and 1% below optimum moisture content. The fills subsequently became wetted with irrigation after construction. For compacted fills over 20 feet thick, up to 18 inches of hydrocollapse were observed.

Sources of Wetting

Wetting that can trigger soil collapse may be shallow or deep, local or widespread, and intense or gradual (Clemence & Finbarr, 1981). Collapse may occur within partially or fully saturated conditions after wetting. However, increasing levels of saturation often result in greater collapse settlements. Note that most soil do not reach 100% saturation in the field from wetting.

Sources of wetting include (Coduto et al., 2016):

- Changes in groundwater level
- Infiltration from irrigation of landscaping or crops
- Leakage from lined or unlined canals
- Leakage from pipelines and storage tanks
- Leakage from swimming pools
- Leakage from reservoirs
- Seepage from septic tanks and leach fields
- Infiltration of rainwater resulting from unfavorable changes in surface drainage
- Infiltration from stormwater best management practices (BMPs)
- Increase in creek/river levels or diversions of creeks/rivers

Investigation

Perform a site visit to identify the existence of localized perched or static groundwater and identify other potential hazards or conditions that may not be evident from the desktop study (e.g., distressed pavement/areas, water infiltration or flow traces.)

If a potential for collapsible soil is identified during the desktop study, develop a field investigation program for indirect and direct identification methods (see below) of collapsible soil.

Collect relatively undisturbed samples from shallow test pits or hollow stem auger borings. Wash-type drilling methods are not recommended because they utilize drilling mud or fluids that have the potential to alter the collapsible soil characteristics (e.g., in-situ dry unit weight, natural moisture content) during sampling since collapsible soil is sensitive to wetting.

Several sampler types may be used to collect samples for indirect and direct identification methods. For shallow soil, block / chunk samples are preferred. Conventional thin-walled samplers (e.g., Shelby Tube) or Modified California (i.e., Mod Cal) samplers may be used to obtain relatively undisturbed samples depending upon soil type or laboratory tests

When collecting relatively undisturbed samples, look for the “honeycomb” soil structure or cementation as a potential indicator of collapsible soil.

When evaluating the potential for soil collapse note that:

- No identification method is solely adequate to fully describe soil collapse
- Laboratory tests should be site-specific
- The evaluation should consider results from both indirect and direct identification methods

Indirect Identification Methods

Indirect identification methods include qualitative criteria based on in-situ dry unit weight, natural moisture content, degree of saturation, particle size analyses, and Atterberg limits.

A variety of criteria are available for identifying collapsible soil based on in-situ dry unit weight, natural water content, degree of saturation, Atterberg limits, and gradation. Table 1 summarizes suggested qualitative criteria for collapse potential.

Table 1: Summary of Criteria for Collapse Potential (CP)

Author (year)	Method	Criteria
Clevenger (1958)	$r_d < 80\ lb/ft^3$ $r_d > 90\ lb/ft^3$	Subject to Large settlement Subject to Small settlement
Feda (1964)	$K_L = (\frac{w_o}{S} - PL)/PI$	For S<100%, if K_L>0.85, the soil is considered subject to collapsible
Ayadat and Hanna (2007)	$CP = a(r_d - 15.27) + bw_o + 17$ $a = -0.036C_u - 1.379$ $b = 0.0006C_u^2 - 0.089C_u + 1.3$	CP<1, collapse will not occur CP>1, collapse is susceptible

Where, r_d = in-situ dry density (kN/m^3), w_o = in-situ moisture content, S = degree of saturation, PL = plastic limit, PI = plastic index, LL = liquid limit, C_u = coefficient of uniformity (D_{60} /D_{10}).

Figure 2 displays a graphical form identifying collapse potential based on measurements of dry unit weight and liquid limits values. The area above the 100% saturation line is considered susceptible to collapse, while below the line to be expandible when wetted. The collapse potential tends to increase with decreasing in-situ dry density and liquid limits.

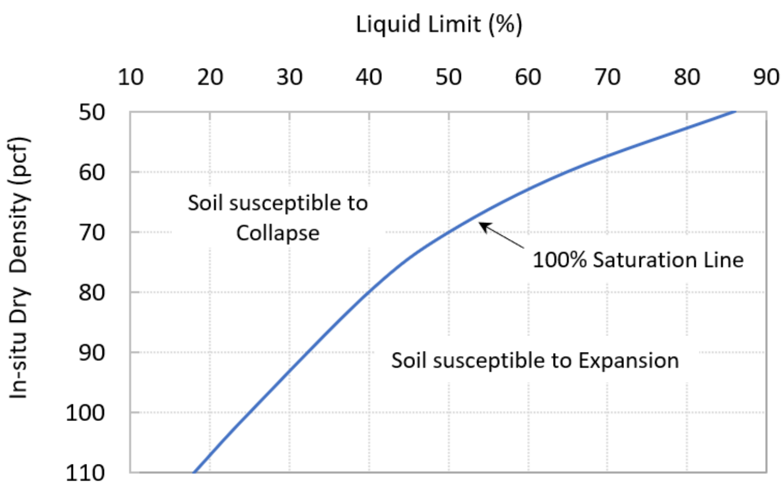

Figure 2: Criterion for collapsible soil (after Gibbs and Bara, 1967).

Direct Identification Methods

Direct identification methods include quantitative criteria based on laboratory testing using an oedometer apparatus.

Collapse Potential (CP) is a measure of the amount of volumetric change that soil undergo when they experience both loading and water infiltration. The most common approach to directly measure the collapse potential is to conduct laboratory tests using an oedometer apparatus (i.e., ASTM D4546), which can control and measure three major CP factors: degree of saturation, dry density, and overburden stress (ASTM D5333 is no longer active).

The laboratory test consists of three test methods. Method A (i.e., the wetting-after-loading test) entails a procedure for measuring wetting-induced collapse of reconstituted samples reflecting compacted fill conditions. Method B (i.e., single-point wetting-after-loading test) is a procedure for measuring wetting-induced collapse of intact samples from a natural deposit or existing fill. Method C (i.e., the loading-after-wetting test) is a procedure for measuring load-strains data of intact (or reconstituted) samples that has previously gone through wetting-induced collapse. Please see the following table for minimum requirements:

Table 2: ASTM D4546 Minimum Testing Requirements with Relevant Test Methods

Type	Samples	Minimum No. of Samples	Inundation Load (Determined by GP)
Method A	Reconstituted	Four identical	Vary
Method B	Undisturbed	One	Overburden pressures plus stresses due to fill and/or structural loads
Method C	Undisturbed	One	First phase: Same as Method B Second phase: Same as ASTM D2435

Note: ASTM D2435 Standard Test Methods for One-Dimensional Consolidation Properties of Soil Using Incremental Loading.

Table 3 provides a summary of the degree of collapse based on the collapse strain from ASTM D4546.

Table 3: Summary of Degree of Collapsed Based on Oedometer Testing

Collapse Strain (%)	Degree of Collapse
0	None
0 < CP ≤ 2	Slight
2 < CP ≤ 6	Moderate
6 < CP ≤ 10	Moderately Severe
10.0 < CP	Severe

Evaluation

Determine if collapsible soil may impact settlement sensitive improvements using the following steps:

1. Based on the results of the geotechnical investigation, estimate the depth and lateral extent of collapsible soil at the site with respect to proposed settlement sensitive improvements.
2. Evaluate the potential for future wetting. Note that full saturation is not required for collapse.
3. Estimate the potential collapse settlement based on the anticipated loading. The collapse strain from ASTM D4546 may be applied to layer thicknesses.
4. Compare estimated collapse settlement with project requirements. The collapse settlement must be added to other calculated settlements before comparing to the project requirements.
5. If the estimated settlement is larger than the project requirements, then discuss mitigation strategies with the client.

Mitigation

When evaluating mitigation options, consider the following (Coduto et al., 2016):

- Can project components be relocated to avoid collapsible soil? Avoidance may be the most practical method for mitigating collapsible soil.
- How deep does the collapsible soil extend? What is the lateral extent of the collapsible soil relative to project components? Consider the wetting front for site conditions and potential sources of wetting.
- How much total and differential settlement is likely to occur if the collapsible soil is accidentally wetted? Would project components be able to tolerate the potential total and differential settlements? Designing project components for the potential settlements may be the most practical method for mitigating collapsible soil.
- What portion of the total stress is due to total overburden stress and what portion is due to applied loads?
- Has any artificial wetting already occurred?
- What are the potential impacts of mitigating collapsible soil to existing and/or adjacent improvements and properties?
- Do new improvements have the potential to inadvertently wet collapsible soil that could impact settlement sensitive improvements at the site or adjacent sites (e.g., sheet flow run-off, infiltration BMPs, distressed culverts, etc.). Avoid infiltration at sites with collapsible soil.

Earthwork Methods

Removal and Replacement

Partially or fully remove collapsible soil and replace with properly placed and compacted materials. This alternative is more practical when collapsible soil is shallow and accessible by typical earthwork equipment.

Prewetting with Surcharging

Artificially saturating collapsible soil using ponding, trenching, or wells followed by surcharging. This alternative may be feasible for both shallow and deep collapsible soil. Surcharging is not appropriate for improvements where collapsible soil will be loaded by shallow foundations with bearing pressures greater than surcharge loads. Settlement monitoring should be implemented using pipe riser or fluid level settlement devices. The GP and PDT should consider the risks of introducing water into subgrade soil as this could result in distress or impacts to surrounding existing improvements and properties.

Compaction of New Fills

Settlements from collapse in new fills may be reduced by compacting deeper portions of new fills wet of optimum moisture content and to a higher degree of compaction. For fills more than 30 feet in height, consider providing project specific compaction requirements in the project's Special Provisions.

Ground Modification Methods

There are several ground modification methods available for mitigation of collapsible soil:

- Blast Densification
- Chemical Grouting/Injection Systems
- Compaction Grouting
- Deep Dynamic Compaction
- Deep Mixing Methods
- Vibrocompaction

Refer to the *Ground Modification* module for additional information.

Deep Foundation Methods

Cast-In-Drilled Hole (CIDH) piles, driven piles, etc. may be used to extend foundation loads below collapsible soil to competent bearing materials. Consider potential future strength reduction/loss within collapsible soil layers and downdrag loads from collapse settlement.

Reporting

The potential for, or presence of, collapsible soil must be discussed in all geotechnical reports per the applicable reporting module.

Planning Phase

- Discuss the potential for collapsible soil at the project site based on existing information such as geology, soil type, site history, etc.
- Discuss the proposed field investigation and laboratory testing to determine the extent and depth of collapsible soil.
- Discuss preliminary mitigation options to address the potential presence of collapsible soil at the project site.

Design Phase

- Present the results of field investigation and lab testing including the extent (lateral and vertical) of collapsible soil. Present the results of collapse tests in a tabular format:

Borehole ID	Structure ID (or Roadway Project Type)	Sample Elevation (Depth)	USCS Soil Type	Applied Load (or Pressures)	Collapse Strain (%)	Degree of Collapse

- Present a summary table of total collapse and differential settlements.

Structure ID (or Roadway Project Type)	Location (Beg Station, or Lat/Long)	Location (End Station, or Lat/Long)	Maximum Collapse Settlement (in)	Estimated Potential Differential Settlement[1]	Meeting Differential Criteria[2] (Yes, or No)

1. Ratio of maximum collapse settlement to longitudinal distance.
2. Applicable standards criteria or project specific criteria.

- Provide justification for the recommended mitigation method(s) considering the subsurface conditions, project requirements, cost, constructability, and effectiveness.
- Provide layout and cross sections of the mitigation area showing extent (lateral and vertical) of the mitigation area and supporting engineering evaluations.
- Refer to corresponding modules in the Geotechnical Manual (e.g., Ground Modification, Grouting) for required recommendations.
- Provide instrumentation and monitoring plans, and specifications.

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