53:139 Foundation Engineering
The University of Iowa
Spring Semester, 2002
Foundations on Difficult Soils

The difficult soil cases to be discussed involve foundations on:

I. Weak/Compressible Soils;
II. Collapsible Soils; and
III. Expansive Soils.

For each of these cases, an attempt will be made to identify the problem and its nature, and then to discuss possible solutions when working with these difficult soils.

1. WEAK/COMPRESSIBLE SOILS

1.1 Clays/Silts/Peats

These types of soil deposits are often found near the mouths of rivers, along the perimeters of bays, and beneath swamps or lagoons. Soil deposits with high organic content are often found in these low-lying types of locations and can be especially troublesome. Since land features in which these troublesome soils are typically found are low-lying, they are prone to flooding. Hence before buildings or roadways can be constructed on such soil deposits, the grade level must be raised by adding compacted fill. However, adding significant amounts of compacted fill puts significant loads on the soil which can cause significant settlements.

As an example, the New Jersey Meadowlands complex was constructed in the 1980's in marshlands in central New Jersey, just outside of New York City. Settlements observed in the soft soil due to placement of fill were:

a. 0.25m during placement of the fill;
b. 0.12m during the construction phase; and
c. 0.10m over the ten following years.

1.2 Loose Saturated Sands

Loose saturated sand deposits that are located in seismically active regions are prone to liquefaction and settlements during strong ground motion. A classic example occurred in the 1964 Niigata Earthquake in Japan. In this case, many buildings situated on loose saturated sand deposits settled more than 1m during the earthquake, and others (in particular an apartment building) tipped over on their sides. (Apartment buildings are not hydrodynamically stable structures, and when the soil liquefies, they will "capsize.")

1.3 Strategies

1.3.1 Deep Foundations

One option is to support structures on deep foundations (piles or caissons) which penetrate through the weak/ compressible soils. Even when deep foundations are employed, however, it is still generally necessary to import fill to raise the grade level above the flooding level. Thus deep foundations must be used in combination with fill placed on the weak/ compressible soils. This is a delicate situation which the geotechnical engineer must recognize. (Figure 1)

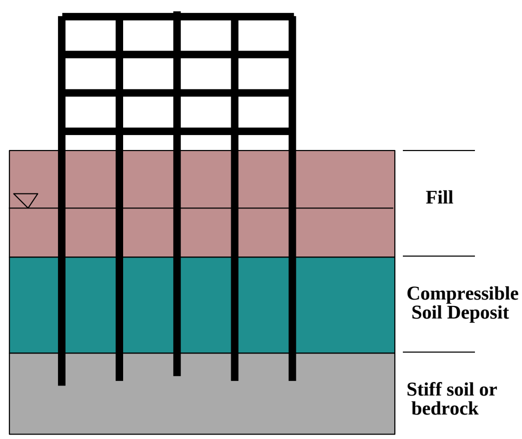

Figure 1: Deep foundations through weak and/or compressible soil deposits.

The potential difficulty is that after the deep foundations are constructed, the weak/ compressible soil with fill placed upon will continue to undergo significant settlement. As the soil settles, it tends to pull down on the deep foundations through "negative skin friction" or "downdrag." This can lead to significant settlement of the deep foundations, and the possibility of significant differential settlements. If pile caps are used this can result in some piles being pulled out of the cap.

If this potential problem is anticipated, numerous steps can be taken to avoid it.

1. The piles (if used) can be coated with a lubricating agent to reduce friction with the soil. (This would not work with pier or caisson foundations).
2. Piles can be driven in large-diameter pre-drilled shafts, but this assumes that the soil will not cave in.
3. Large diameter low displacement pipe piles can be driven through the weak/ compressible soils. The interior soil plug can then be removed and smaller diameter end-bearing piles driven inside of the open pipe piles into the lower strata. This isolates the interior piles from the settling soil.
4. Wait until soils have consolidated before constructing the deep foundations.

1.3.2 Shallow Foundations

If shallow foundations are constructed on fills over weak/ compressible soils, the primary problem will be large settlements. This problem can be mitigated by pre-loading the weak/ compressible deposit before construction. Due to the low permeability of the clay deposits, however, this could take many years. To speed this process up, sand drains are commonly used.

Alternatively, one can build settlement tolerant structures to accommodate potentially large settlements. An example of a settlement tolerant building on fill overlying a weak/ compressible deposit is the Eastern Airlines (now defunct) Terminal built at the LaGuardia Airport in New York City (Figure 2). This structure was built in 1979 on 9m of incinerated refuse fill which overlies a 24m deposit of soft organic clay. During construction, the soft clay deposit settled approximately 2m, and an additional 0.45m of settlement is expected to have occurred by 1999. The building was designed to accommodate these settlements, however, using leveling jacks between floors and in the footings.

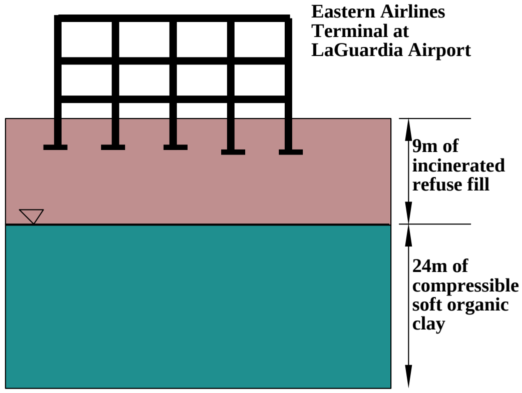

Figure 2: Settlement tolerant structure on highly compressible soils.

1.3.3 Soil Improvement

The various strategies used here include:

- Removal and replacement. This method can be employed when: the poor soil deposit is relatively small; the groundwater level is relatively deep; and good fill soil is readily available.
- Temporary Surcharge Fills. The idea here is to pre-load the weak/ compressible soil with a temporary surcharge. The underlying weak/ compressible soil is allowed to consolidate under the surcharge (again sand drains accelerate the process). The surcharge is removed before the proposed building construction occurs. Since the building is constructed on overconsolidate soil the displacements are considerably reduced.
- Vibro-compaction. This is particularly effective for loose sandy soils.
- Chemical stabilization. In the past, the weak clays and silts were often mixed with lime and the existing soil pore fluid to cement the soil grains together, making the soil stronger and less compressible. Presently, the trend in geotechnical engineering is away from using lime and toward using pulverized fly ash (pfa), which is a processed waste product from coal fired electric power generating plants. Again, the effect is to cement the soil grains together, increasing the soil strength and reducing both its compressibility potential expansivity.
- Reinforcement using Geotextiles.

2. COLLAPSIBLE SOILS

2.1 General Characteristics

Collapsible soils are those that appear to be strong and stable in their natural (dry) state, but which rapidly consolidate under wetting, generating large and often unexpected settlements. This can yield disastrous consequences for structures unwittingly built on such deposits. Such soils are often termed “collapsible” or “metastable” and the process of their collapsing is often called any of “hydroconsolidation”, “hydrocompression”, or “hydrocollapse.” As Iowans, you should be particularly well aware of this problem, since Iowa (along with Nebraska, Illinois, Colorado, and Missouri) has extensive deposits of “loess” which is recognized as potentially collapsible.

Collapsible soil deposits share two main features:

i. they are loose, cemented deposits; and

ii. they are naturally quite dry.

Loess soils consist primarily of silt-sized particles loosely arranged in a cemented honeycombed structure (Fig. 3). The loose structure is held together by small amounts of water softening or water soluble cementing agents such as clay minerals and $CaCO_3$. The introduction of water dissolves or softens the bonds between the silt particles and allows them to take a denser packing under any type of compressive loading.

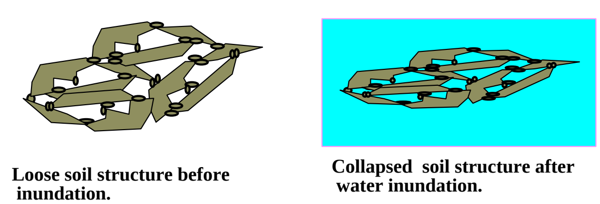

Figure 3. Collapsible soil before and after inundation by water.

2.2 Deposit Mechanisms

Since collapsible soil deposits are necessarily "loose", they are generally created by deposition mechanisms that yield loose deposits. For example, alluvial (water deposited) and colluvial (gravity deposited) soils are usually deposited loosely and in a saturated state. As the water eventually drains from these soils, the last amounts of moisture are drawn by capillarity to the contact points between grains. As the water evaporates, minerals are left behind at the soil contact points, cementing them together. Collapsible colluvial and alluvial soil deposits are common in desert portions of the southwestern U.S. Deposits can range from depths of a few meters to tens of meters. Collapses of 2-3 feet are common, and up to 15 feet have been reported.

Wind deposited (aeolian) soils are fine sands, volcanic ash tuffs, and loess. In particular, loess consists of clay-coated or bonded silt-sized particles. Collapsible loess deposits are characterized by high porosity $n > 50\%$ and low dry unit weights ($\gamma_d \simeq$ 70-90 pcf or 11-14 kN/m^3. Thick loess deposits of up to 60m are not unusual.

Other soil deposits that are potentially collapsible are residual soils formed by extensive weathering of parent materials. For example, weathering of granite can yield loose collapsible soil deposits.

2.3 Testing & Identification

Once the geotechnical engineer recognizes the possibility that collapsible soils are present, tests are sometimes done to quantify the collapse potential of the soils. If lab tests are to be performed, "undisturbed" samples must be obtained using Shelby tubes. Once undisturbed samples are collected, two types of tests are generally performed:

a. double oedometer tests; and

b. single odeometer tests.

The oedometer, as you recall, is the apparatus in which dry or wet stress-controlled confined compression or consolidation tests are performed on soil specimens.

2.3.1 Double Oedometer Test

In this test, two "identical" soil specimens are placed in oedometers and subjected to confined compression tests. One of the specimens is tested at natural in-situ water content, which is generally quite low. The other specimen is fully saturated before the test begins, and then subjected to an identical compression test. Two stress versus strain curves will be generated, one for the "dry" soil and one for the saturated soil. If the soil is strongly hydro collapsible, the stress-strain response for the saturated curve will be significantly different than that of the dry soil (Figure 4). For a given applied stress σ_n, the strain offset ϵ_w between the two curves is called the hydro-collapse strain for that stress level. Generally, for the dry specimen, there will be a critical stress σ_{cr} at which the loose structure breaks down and beyond which the two curves converge.

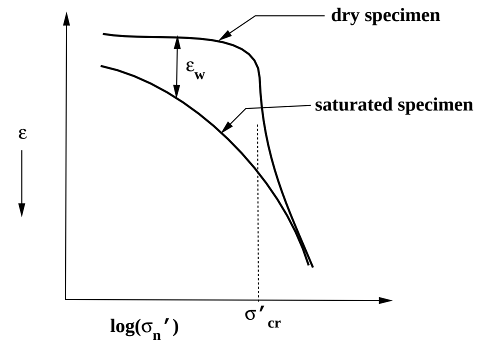

Figure 4: Typical results from a double oedometer test.

2.4 Single Oedometer Test

As the name implies, the single odeometer test uses only a single soil specimen. The procedure is as follows:

1. An undisturbed sample is placed in the oedometer at its natural (dry) moisture content.
2. A small seating load is applied to the specimen.
3. The soil is gradually loaded to the anticipated field loading conditions.
4. At this stress level, the sample is then inundated with water and allowed to saturate. The resulting hydro collapse is then observed.
5. Loading of the specimen is then continued with consolidation permitted.

The characteristic stress versus strain curve generated from such a test is sketched in Figure 5. Clearly, the larger the collapse strain ϵ_w observed, the more collapsible the soil is considered to be. Collapse strains on the order of 1% are considered to be mild, while those on the order of say 30% are considered to be very severe.

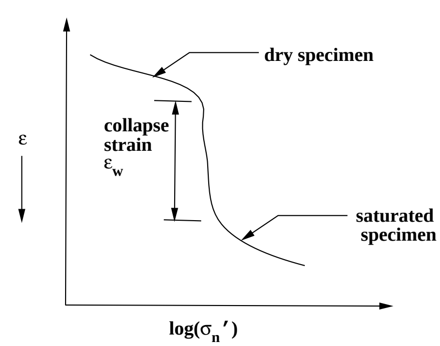

Figure 5: Typical results from a single oedometer test.

2.5 Wetting Processes

Part of the obvious problem with hydro collapsible soils is that they tend to have relatively low natural in-situ water contents. When development occurs on such soil deposits, the soil can be subjected to numerous sources of additional wetting that will lead to an increase of its water content. Among the common artificial sources of wetting associated with development are:

- irrigation of landscaping and/or crops;
- leakage from unlined canals, pipelines, swimming pools, storage tanks, *etc;*
- septic systems; and
- changes in surface drainage of rainwater.

Minor artificial wetting is often confined only to the top few feet of soil. Sustained, long term leaks can lead to soil wetting deep below the surface. This can be quite serious and lead to enormous settlements. As an example, a study was published by an investigator named Curtin in 1973 which involved large scale wetting collapse tests performed on collapsible soils located in California's San Joaquin Valley. After applying continuous wetting to a 75m deep collapsible soil deposit for 484 days, the wetting front advanced to a depth of 45m below the ground level. The resulting hydrocollapse settlement observed was 4.1m!

2.6 Precautions

When dealing with collapsible soils that will be subject to wetting depths of ≤ 2 meters, common measures are to:

a. pre-wet the soil;

b. compact the soil using heavy rollers and heavy tamping.

c. treat the soil with sodium silicate and/or calcium chloride solutions to provide cementing that is not water soluble.

When dealing with collapsible soils subject to large wetting depths, then deep foundations through the collapsible soils are commonly used.