Soil Development, Engineering Properties, and Hazards

From Weathering to Soils



Rain picks up CO₂ from the atmosphere and becomes acidic

Water percolating through the ground picks up more CO_2 from the upper part of the soil, becoming more acidic

A rock particle containing a feldspar crystal, loosened from the rock below, slowly alters to a clay mineral as it reacts with the acidic water

The water carries away soluble ions and SiO_2 to the ground-water supply or to a stream

Soil Horizons: O (organics = humus), A, B, C. Boundaries usually transitional rather than sharp.





Arid = larger A and B horizons.
Humid = smaller A and B horizons.
Loam: equal amounts of sand, silt, & clay.
Topsoil: fertile area.
Sub-soil: more stony & less fertile, lacks organics.

Soil Horizons

O-Horizon: thin, few cms, organic matter, lower part is decayed to humus.

A-Horizon: groundwater percolates down and removes solubles, contains more organic matter than B and C. Dark humus layer at top. May be light and sandy with clays, Fe-oxides, and carbonates at the base.

E-Horizon: Transition between A and B horizons.

O+A = Topsoil; O+A+E = *Zone of leaching*.

B-Horizon: Sub-soil, *Zone of Accumulation* of material leached down from A. Red/brown/grey. May contain soluble minerals, but little organic material.

C-Horizon: mixture of soil and bedrock. Bedrock attacked by acids, frost action, roots from above. Transitional.

Factors Controlling Soil Formation

ORGANIC ACTIVITY: Required to develop humus. Vegetation type also - different kinds of plants extract different nutrients and have different root systems.

DRAINAGE: Soils formed from saturated sediment tend to have more organic material. Depends on depth to water table and slope.

CLIMATE: Most important.

Tropics = thick soils, heavily leached, intense chemical weathering.

Arctic + desert: thin soils that contain soluble material & large component of mechanically weathered debris.

PARENT MATERIAL: Same rock type = different soils depending upon climate. Granite = deep soils; Quartzite thin soil; Basalt = dark soil, rich in Fe oxides.

LATITUDE: Soil thickness varies with latitude, because of variations in temperature, rainfall, and vegetation.

TOPOGRAPHY: Soil development is difficult when topography is steep. **TIME:** Typical development = 2.5 cm/100 yrs. to 2.5 cm/1,000 yrs.

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Engineering Properties of Soils

From an engineering perspective –

Study of soil focuses on characteristics of soils as *construction materials*.

And suitability of soils to withstand the *load applied by structures of various types*.

- > Earth materials are considered *three-phase systems*.
- Most applications this includes solid particles, water and air.
- > Water & air occupy the voids between the solid particles.

Engineering Properties of Soils

Three-phase system: solid, water, air

Total Volume: $V_T = V_s + V_w + V_a$ Total Weight: $W_T = W_s + W_w$ Weight of Solids: $W_s = V_s \cdot G_s \cdot \gamma_w$ - V = volume - G = specific gravity - $\gamma_W = unit weight$ of water (62.4 pounds/cubic foot) Weight of Water: $W_w = V_w G_w \gamma_w = V_w \gamma_w$ ($G_w = 1$)

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Engineering Properties of Soils

• $\gamma_{wet} = W_T/V_T$ unit wet weight • $\gamma_{dry} = W_s/V_T$ unit dry weight • $w = W_w/W_s \ge 100\%$ water content of the soil • $e = V_v/V_s$ void ratio (void vol./ solid vol.) • $n = V_v/V_T \ge 100\%$ porosity • $S = V_w/V_v \ge 100\%$ degree of saturation

Engineering Classification of Soils -Index Properties and Classification

- Characteristics of the particles within the soil
- Factors such as.
 - Size and type of particles and density relate to shear strength and compressibility
 - These INDEX PROPERTIES are the basis of engineering CLASSIFICATION of soils
- Index properties of soils listed in Table 10.5
- Important division of soils (for engineering purposes)
 - > COARSE-GRAINED (COHESIONLESS) SOILS
 - ≻ FINE-GRAINED (COHESIVE) SOILS
 - Contain silt and clay
 - Attractive forces between individual clay particles

Soil Type	Index Property
Coarse-grained (cohesionless)	Particle-size distribution
	Clay content
	In-place density
	Relative density
Fine-grained (cohesive)	Consistency
	Water content
	Atterberg limits
	Type and amount of clay
	Sensitivity

Index Properties of Cohesionless Soils

Index properties of *cohesionless* soils (Table 10.5)

- Particle-size distribution
- · Shape of particles
- Clay content
- · In-place density and relative density

All of these properties can be measured

Grain-Size Distribution

- Pass soil through a series of sieves and plot the cumulative weight percent vs. particle size.
- Well-graded = contains a variety of sizes (similar to poorly-sorted)
- Poorly-graded = narrow range of sizes (similar to well-sorted)



A, C = well-graded

Index Properties of Cohesionless Soils

- > Particle shape roundness and angularity
- In-place density measured by weighing an oven-dried sample of a known volume
- Relative density D_R ratio of actual density to the max density
 - $D_R = (e_{max} e_0)/(e_{max} e_{min}) \times 100\%$
 - *e*_{max} = void ratio in loosest condition
 - e_{min} = void ratio in densest condition
 - e₀ = void ratio in natural state

 D_R is a good indication of possible increases in density or compaction, if load is applied to soil. Compaction of soil under load is referred to as SETTLEMENT.

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Index Properties of <u>Cohesive</u> Soils

- > Type and amount of <u>clay minerals</u> are very significant
- Consistency strength and resistance to penetration of the soil in its in-place condition (Table 10.6)

Consistency	Shear Strength (kg/cm ²)	Unconfined Compressive Strength (kg/cm ²)	Feel or Touch
Soft	< 0.25	<0.5	Blunt end of a pencil-size item makes deep penetration easily
Medium (medium stiff or medium firm)	0.25-0.50	0.50-1.0	Blunt end of a pencil-size object makes 1.25-cm penetration with moderate effort
Stiff (firm)	0.50-1.0	1.0-2.0	Blunt end of a pencil-size object can make moderate penetration (about 0.6 cm)
Very stiff (very firm)	1.0-2.0	2.0-4.0	Blunt end of a pencil-size object makes slight indentation; fingernail easily penetrates
Hard .	>2.0	>4.0	Blunt end of a pencil-size object makes no indentation; fingernail barely penetrates

Index Properties of Cohesive Soils

Consistency determined by

Fabric - arrangement of soil particles, particularly clays

- Flocculated lots of edge to edge, non-ordered contact of clay particles
- Dispersed parallel arrangement of clay particles
- Flocculated much stronger than dispersed
- Change from flocculated to dispersed = remolding

Clay Fabric



Flocculated

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Dispersed

Index Properties of Cohesive Soils

- Sensitivity ratio of unconfined compressive strength in undisturbed state to strength in remolded state.
 - *S_t* = strength in undisturbed condition/strength in remolded state

Table 10.7 Ser	ensitivity of Clays		
Туре	Sensitivity Value		
Nonsensitive	2–4		
Sensitive	4-8		
Highly sensitive	8-16		
Quick	>16		

• High sensitivity = highly unstable and dangerous

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Index Properties of Cohesive Soils

Water content and Atterberg Limits

- Water content exerts important influence upon properties and behavior of cohesive soil
- Water content values that delimit changes in consistency of cohesive soils are referred to as Atterberg Limits

Index Properties of Cohesive Soils

> Atterberg Limits

- Liquid Limit water content level at which the soil passes from a liquid to a plastic state
- <u>Plastic Limit</u> decreasing water content;
 Limit at which the soil passes into a semisolid state
- <u>Shrinkage Limit</u> continued decreasing water content;

Limit at which soil becomes a solid and no longer shrinks in volume with decreasing water content

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Atterberg Limits

Unified Soil Classification System

Most useful classification of soils for engineering purposes

Major division		Group symbols	Typical names	
Coarse-grained soils More than 50% retained on No. 200 sieve	Gravels carse 50% or more of coarse sieve fraction retained on No. 4 sieve	Clean gravels	GW	Well-graded gravels and gravel-sand mixtures, little or no fines
			GP	Poorly graded gravels and gravel-sand mixtures, little or no fines
		Gravels with fines	GM	Silty gravels, gravel-sand- silt mixture
			GC	Clayey gravels, gravel- sand-clay mixtures
		nds 0% of coarse es No. 4 sieve fri Clean sands	SW	Well-graded sands and gravelly sands, little or no fines
	nds 0% of c es No. 4		SP	Poorly graded gravels and gravel-sand mixtures, little or no fines
	Sa More than 5 fraction pass	fines	SM	Silty sands, sand-silt mixtures
		San with	SC	Clayey sands, sand-clay mixtures
Fine-grained soils 50% or more passes No. 200 sieve	Silts and clays Liquid limit 50% or less		ML	Inorganic silts, very fine sands, rock flour, silty or clayey fine sands
			CL	Inorganic clays of low to medium plasticity, gravelly clays, sandy clays, silty clays, lean clays
	and clays uid limit than 50%		OL	Organic silts and organic silty clays of low plasticity
			мн	Inorganic silts, micaceous, or diatomaceous fine sand or silts, elastic silts
	Silts a Liqu greater	СН	Inorganic clays of high plasticity, fat clays	
			он	Organic clays of medium to high plasticity
Highly organic soils		Pt .	Peat, muck, and other highly organic soils	

Unified Soil Classification System (ASTM Designation D-2487)

Fig. 10.15: Each soil type is given a two-letter designation.

1st Letter: G = gravel

S = sand

2nd Letter: W = well graded **P** = poorly graded **M** = >12% silt **C** = >12% clay

1st Letter:

M = silt C = clay

2nd Letter: H = high (plasticity) L = low (plasticity)

Plasticity of Soil



◄ FIGURE 10.16

Chart for determining classification of fine-grained soils by the Unified Soil Classification System. *Source:* From D. F. McCarthy, *Essentials of Soil Mechanics and Foundations*, 4th ed., © 1993 by Prentice Hall, Inc., Upper Saddle River, N.J.

- Fig. 10.16
- *PI* = *LL PL*
- PI = plasticity index
- LL = liquid limit
- PL = plastic limit

Shear Strength of a Soil

- Determines the soil's ability to support a load or to remain stable on a hillslope.
- > Mohr-Coulomb Failure Theory:

Cohesionless soils - no interparticle bonding, friction determines shear strength.

Cohesive soils - both interparticle bonding and friction contribute to overall shear strength.

- How to determine shear strength?
 - Direct Shear Test, Triaxial Shear Test

Shear Strength of a Soil



For <u>unconsolidated materials (e.g. dry sand)</u> relationship between <u>normal stress (σ_n) and <u>shear</u></u> strength (S) is linear and passes through the origin (Fig. 7.19):

$$S = \sigma_n \tan \phi$$

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Shear Strength of Cohesionless Soils



Angle of internal friction - determined by material

- Sand-gravel 33-36 degrees
- Well-graded sand 32-35 ٠

Shear Strength of a Soil

For <u>consolidated materials or cohesive soils</u> relationship is also linear, but there is inherent shear strength due to interparticle bonding (cohesion - C, Fig. 7.20):



DIRECT SHEAR TEST

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Shear Strength of Cohesive Soils

- More complicated than cohesionless soils.
- Presence of interparticle bonding and friction may suggest that cohesive soils always have greater shear strength -NOT always the case.
- Water plays an important role
 - Cohesive soils usually saturated increased load forces pore water out of the soil.
 - As water is forced out, density and shear strength increase.
 - Time is also important as water loss is not instantaneous.
 - Controlling the drainage of the sample during the shear strength test is critical.

Shear Strength of Cohesive Soils

- No drainage pore water keeps particles from being forced closer together - no increase in shear strength with increasing load.
 - The shear strength value is COHESION, which is related to CONSISTENCY of the soil
 - The higher consistency the higher cohesion
- Drainage during load shear strength increases with increasing load - similar to that of a cohesionless soil.
- Failure stress exceeds the shear strength of the soil.
 - Building loads are rarely great enough to exceed the shear strength of the soil.

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Settlement and Consolidation

- Settlement vertical subsidence of the building as soil compresses under load.
- Uneven settlement
 - Potentially serious problem
- Compressibility tendency for the soil to decrease in volume under load
 - Consolidation test
 - Soil sample is under a compressive load void space is measured at various loads
 - Compression Index (C_c) used to predict the amount of settlement

Consolidation

Consolidation - process of soil compression

- Very slow in saturated clay-rich soils due to very low permeability and high water content.
- Takes long time (years) for water to leave void spaces and for compression of soil to occur.
- Total decrease in void ratio can be quite high in clay-rich soils, but takes many years to reach equilibrium.

Nonuniform consolidation in clay layer





Soil Hazards

Expansive Soil

- Most costly natural hazard in United States on average.
- 37 states have expansive soil provinces in most cases difficult, expensive or impossible to avoid building on these soils.
- Repair of damage runs into billions of dollars annually.



Soil Hazards

Factors causing swelling of Expansive Soils:

- Clay particles attract water molecules force apart sheet structure of clay.
- Cations are bound in the clay intersheet voids water moves into intersheet void to reduce cation concentration forces sheets apart.
- During dry periods the water can leave the clay particles causing shrinkage.
- Only occurs above the *soil-moisture active zone* below this zone water content is constant

Soil Hazards

Expansive Soils

- Uneven volume change most damaging.
- *End-lift* soil around edge of building swells while center remains constant.
- **Center-lift** soil around edge of building shrinks due to vegetation (e.g. trees).
- Can be alleviated by use of special foundation building techniques e.g., Belled Pier and grad beam foundation.

Hydrocompaction

- Common in arid regions.
- Particles held in a loose arrangement by weak bonds formed by clay, water or soluble precipitants in an UNsaturated state.
- If the soil becomes water saturated, then these bonds are broken and the soil collapses on itself.
- Results in foundation settlement, utility line rupture, etc.

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Soil Hazards

Liquifaction

- Conversion of a saturated soil to a liquid state under rapid or cyclic stress earthquakes, vibrations, explosions.
- Increased stress upon soil (*pore water*) from earthquake can be great enough to suspend soil particles rather than driving pore water from soil (loss of shear strength).
- Result is a total loss of shear strength and a liquid behavior of the soil.
- Once the stress is removed the soil rapidly regains its strength.



Niigata Earthquake and rotated buildings due to liquifaction ⁴⁶



Liquifaction causing building collapse - 1964 Alaska Earthquake 47

Soil Hazards

Land Subsidence

- Sinking of land surface
- Can be localized (sinkhole) or widespread (whole region sinking, e.g. New Orleans)
- Caused by....
 - Removal of subsurface fluids
 - Drainage or oxidation of organic soil
 - Surface collapse into subsurface cavities

Soil Hazards

Removal of Subsurface Fluids

- Removal of groundwater
- Removal of oil and natural gas reserves
- Wilmington Oil Field California
 - 9 m of elevation decrease due to petroleum withdrawal
- Problem in Texas oil field areas
- Aquifer withdrawal has caused land subsidence over 1000's km² in midwest and western US

San Joaquin Valley, CA; ~28 ft of subsidence \rightarrow

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hoto by Richard O. Ireland, U.S. Geological Survey

Soil Hazards

Drainage or oxidation of organic soils

- Everglades drainage has resulted in oxidation of organic component and removal of pore fluid.
- Oxidation leads to degradation and a thus decrease in particle size.
- Oxidation and pore fluid removal lead to compaction and gradual subsidence.
- Dramatic change of Everglades ecosystem due to reversal in slope.



Soil Hazards

Surface Collapse

- Sinkholes roughly circular pits resulting from collapse
- Regions affected by surface collapse
 - Coal mining regions
 - Karst limestone regions
- Winter Park Sinkhole, Florida
- Lake Jackson, Florida
- Seffner, Florida Feb. 28th, 2013



Seffner, Florida – 30 ft. wide x 15 ft. deep hole 2^{nd} sink hole formed two miles away – no injuries or structural damage





Dissolution Sinkholes



Rainfall and surface water percolate through joints in the limestone. Dissolved carbonate rock is carried away from the surface and a small depression gradually forms.



On exposed carbonate surfaces, a depression may focus surface drainage, accelerating the dissolution process. Debris carried into the developing sinkhole may plug the outflow, ponding water and creating wetlands.



Cover Subsidence Sinkholes

Granular sediments spall into secondary openings in the underlying carbonate rocks.



ments settles into the vacated spaces (a process termed "piping").

tinue, forming a noticable depression in the land surface.

A column of overlying sedi- Dissolution and infilling con- The slow downward erosion eventually forms small surface depressions 1 inch to several feet in depth and diameter.



Cover Collapse Sinkholes

Sediments spall into a cavity. As spalling continues, the

As spalling continues, the cohesive covering sediments form a structural arch. The cavity migrates upward by progressive roof collapse.







The cavity eventually breaches the ground surface, creating sudden and dramatic sinkholes.



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Winter Park Sinkhole, Florida (May 1st, 1981)

Hole swallowed up a Porsche dealership and 2-story house



September 16th, 1999 – 8 ft diameter sinkhole (Porter Hole) drained much of the Central portion of Lake Jackson





Case in point 10.2 Land subsidence in New Orleans



Case in point 10.2 Land subsidence in New Orleans



▲ FIGURE 10.51

Subsidence of organic soils in New Orleans after drainage. The photo on the left shows the house built on pilings just after construction in 1941. The photo on the right shows the same house in 1992. Front-porch steps were added over the years as the ground surface subsided. *Source:* Photo courtesy of J. O. Snowden.

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Summary

Formation and Structure of Soils: Weathering, erosion, soil horizons

Factors Controlling Soil Formation.

Engineering Properties of Soils: 3-phase system

Index Properties and Classification: Cohesionless & Cohesive

soils; importance of clay; grain size distribution, compaction, consistency (fabric: flocculated, dispersed); Sensitivity, water content; Atterberg Limits.

Unified Soil Classification Scheme

Plasticity of Soil: Shear strength; Mohr-Coulomb Failure Theory. **Settlement & Consolidation**

Soil Hazards: Expansive soils; Hydrocompaction; Liquefaction; Land subsidence; Removal of subsurface fluids;

Drainage/oxidation of organic soils; Surface Collapse (sinkholes)