Earthwork 101

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- Responsible for internal training of field representatives at Schnabel.

Learning Objectives

- Understand the purpose of compaction and why it is important.
- Understand the compaction process.
- Understand the QC process during compaction.
- Learn the keys to evaluating results.

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What is Earthwork?

- Moving earth materials from one place to another.

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Why Earthwork?

- Shape the ground surface.
- Build earth structures.
  - Embankments
  - Dams and Levees

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Earthwork

- Excavation destroys the natural soil structure.
- The soil becomes loose.
- Loose soils are weak.
- Loose soils are compressible.
- Weak, compressible soils are not desirable for civil engineering applications.
- Therefore, we need to remedy this condition.

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Earthwork

- Compact soils
  - Improve Strength
  - Improve Compressibility
- Once compacted the soils have suitable strength and compressibility to support civil engineering structures.

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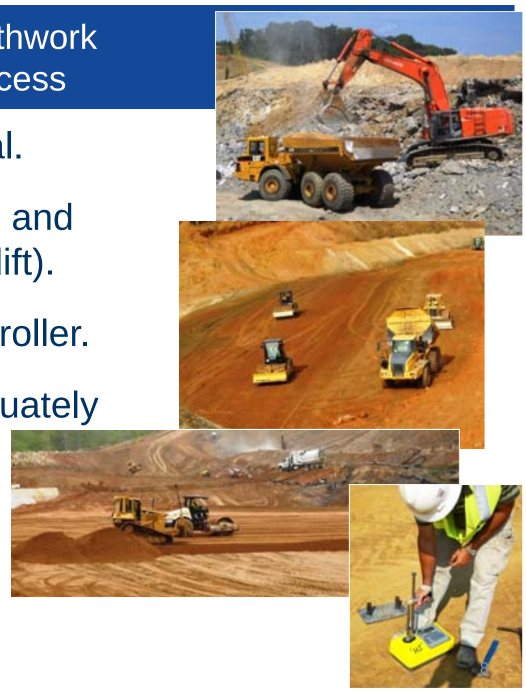
Earthwork Process



- Excavate earth material.
- Move it to new location and place it in a thin layer (lift).
- Compact the lift with a roller.
- Check if we have adequately compacted the soil.
- Repeat.
- How do we check the compaction?

Compaction Theory

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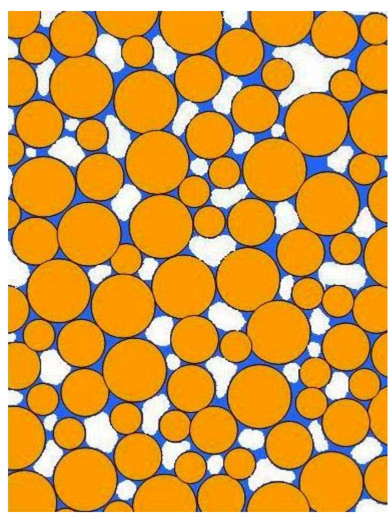
Soil Phases

- Soils phases
  - Soil grains (solids)
  - Water
  - Air
- Air and Water combine to fill the voids between the soil particles.



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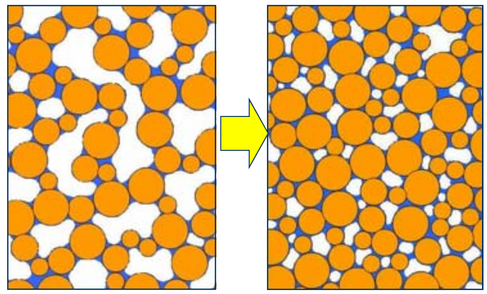
Improving Strength & Compressibility

- Push the soil particles closer together …
  - The soil becomes stronger
  - The soil becomes less compressible
- Therefore, our objective is to pack the particles closer together.



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Soil Phases

- Volume of Voids (V_v) = Volume of Water + Volume of Air
- Total Volume (V) = Volume of Voids + Volume of Solids
- Total Weight (W) = Weight of Solids + Weight of Water

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Soil Phases

- Total Density (γ_t) = Total Weight / Total Volume
- Moisture Content (w) = Weight of Water / Weight of Solids

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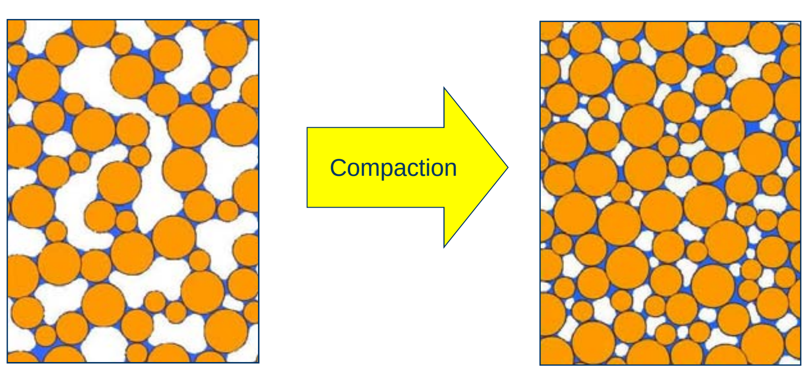
Compaction

- When we compact a soil, we push the soil particles closer together, reducing the volume of the voids.
- Air is forced out



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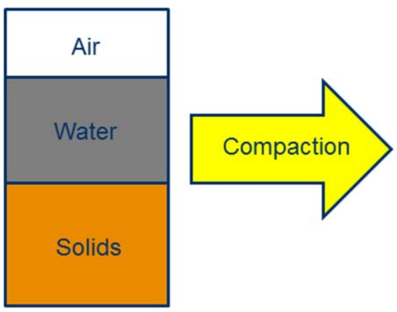
Compaction

- In a given volume, we displace air (no weight) and replace it with solids and water.
- Total weight increases.
- Total density increases.



Density, Strength, Compressibility

- Pack soil particles closer together …
  - Soil strength increases
  - Soil compressibility decreases.
- Pack soil particles closer, total density increases.
- As total density increases, strength and compressibility improve.
- Right?
- Not necessarily.

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What about the water?

- Add water to a soil …
  - Increases total weight
  - Increases total density.
- Soil particles are not packed any tighter.
  - Strength is not improved.
  - Compressibility is not improved.
- Therefore, total density is not a good measure of soil improvement.

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What Now?

- Our goal is to pack the particles tighter.
- We need a measurement that only increases when this happens.
- Therefore, we define *dry density*, γ_d as the weight of solids / total volume.
- Dry density is independent of the moisture content.
- We use dry density to measure the compaction of soils in the field.

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Relationship Between Dry and Total Densities

- Total density (γ_t) and moisture content (w) are easy to measure.
- Measuring dry density (γ_d) is more difficult.
- We can show γ_d , γ_t and w are related as follows:

$$\gamma_d = \gamma_t / (1 + w)$$

- Therefore, we can measure γ_t and w, and then calculate the γ_d.

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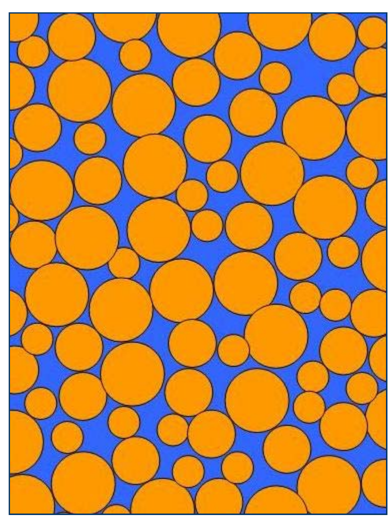
Zero Air Voids

- As we compact a soil, we reduce the amount of air in the voids
- When air void volume becomes zero, what happens?
- The voids will be completely filled with water.



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Zero Air Voids

- If we try to compact beyond the point where all air voids are gone, one of two things happens.
  - Water leaves the soil, the moisture content is reduced.
  - The water prevents further compaction.
- For each moisture content, there is a unique density where all of the voids are filled with water.
- Further compaction (increase in dry density) ***is not possible*** without removing water.
- This density is *Zero Air Voids Density* (ZAVD).

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Evaluating Compaction in the Field

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Evaluating Compaction

- We need a criteria for adequate compaction.
- We measure the dry density of the fill to evaluate its compaction.
- What dry density is good enough?
- We need a benchmark to which we can compare our measurements.

Compaction Standards

- Project specifications typically require compaction to some percentage of a *maximum dry density* (often 95%) – referred to as *relative compaction*
- However, the maximum dry density will not be the same for all soils.
- Therefore, we need a method to determine the maximum dry density value for each soil.

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Laboratory Compaction Tests

- Compaction or Proctor Tests establish the maximum dry density for a particular soil.
- They accomplish this by compacting soils in a mold using a drop hammer.
- The dry density of the resulting sample is obtained.

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How Much Compaction Energy?

- Not only will the maximum dry density be different for each soil, but it will also depend on the amount of energy we use to compact the soil.
- We solve this dilemma with a laboratory test using a standard amount of compaction energy.
- The amount of energy is based on the weight of the hammer, the height of drop, the number of hammer blows per layer, and the number of layers.
- These tests are typically called *compaction tests* or *proctor tests*.

Does the Moisture Content Matter?

- Now we have a standard energy for establishing a maximum dry density.
- Does the moisture content at which the sample is compacted matter?

Yes!

- What moisture content do we use for the standard?

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Yes, Moisture Content Matters

- Moisture in a soil acts as a lubricant; it allows the soil particles to be more easily pushed into a denser state.
- Can there be too much moisture?

Yes!

- As the percentage of voids filled with water increases, additional compaction becomes more difficult (approaching ZAVD).

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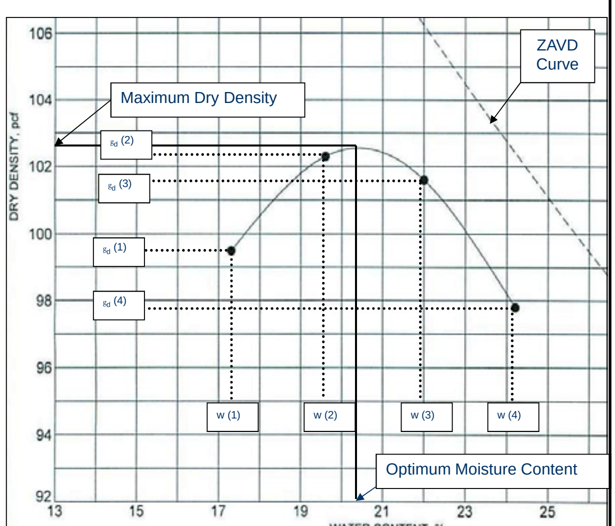
Compaction Curves

- We compact a series of samples with different moisture contents.
- The same energy is used for each sample.
- We plot the resulting dry density for each sample as a function of compaction moisture content.
- The result is a *moisture density relation.*
- More commonly referred to as a Proctor curve or compaction curve.

Moisture Density Relation

- Peak density is the *maximum dry density*.
- Moisture content at the peak is the *optimum moisture content*
- Also plot the ZAVD curve



Two Compaction Standards

- The maximum dry density for a given soil depends on the amount of energy to compact each point on the curve.
- Two common standards:
  - ASTM D698 *Laboratory Compaction Characteristics of Soil Using Standard Effort*
  - ASTM D1557 *Laboratory Compaction Characteristics of Soil Using Modified Effort*
- AASHTO and many DOTs also have standards.

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Two Compaction Standards

- ASTM D698 - Standard Proctor test.
- ASTM D1557 - Modified Proctor test.
- Standards define hammer weight, hammer drop, blows per layer, and number of layers (i.e. the amount of energy).
  - Standard Proctor – 5.5 lbs, 12 inches, 3 layers
  - Modified Proctor - 10 lbs, 18 inches, 5 layers
- Modified energy is about five times Standard energy.

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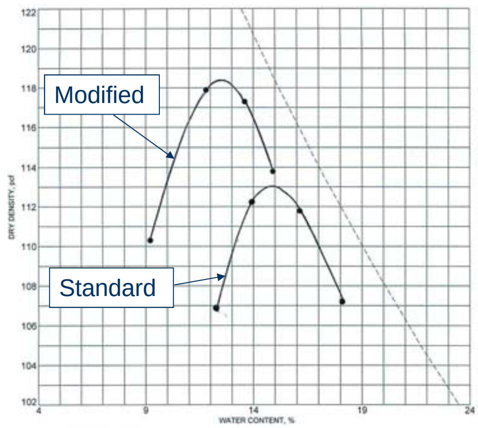
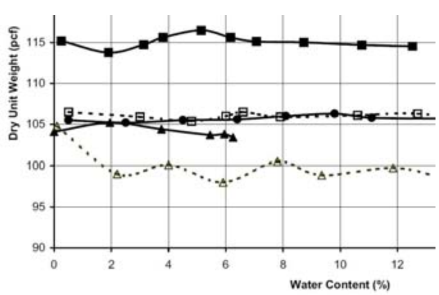
Two Compaction Standards

- The Modified maximum dry density will be higher than the Standard.
- The Modified optimum moisture content will be lower than the Standard curve.
- Increasing compaction energy shifts results up and left.



Clean Granular Soils

- Compaction tests on clean granular soils often do not produce good results.
- Measured MC not MC during compaction
- An alternative method is needed for these soils.
- We use the concept of *relative density*.



Relative Density

- Relative density is based on the premise that there is a minimum density and a maximum density for a soil.
- Project specifications require compaction to some percentage of the range between the minimum and maximum densities.
- ASTM D4253 and D4254 are procedures for determining the maximum and minimum densities, respectively.
- Applicable to soils with up to 15% non-plastic fines.

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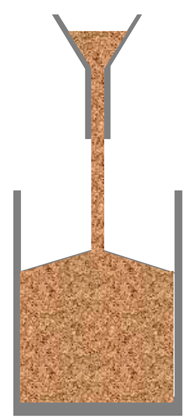
Minimum Density (ASTM D4254)

- Pour oven dried soil into a compaction mold in a manner to achieve a minimum density.
- Strike of the top of the mold, minimizing disturbance (compaction) of the soil.
- Weigh the mold and soil.
- Calculate the minimum density.



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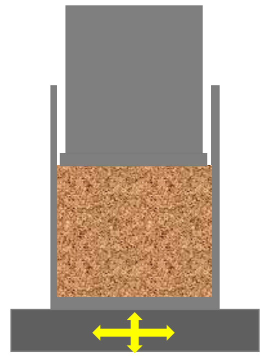
Maximum Density (ASTM D4253)

- Soil placed in mold.
- Surcharge on soil.
- Mold is shaken on a vibratory table for a specified time.
- Measure height of sample and weight of sample.
- Calculate maximum density.



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Use of Relative Density in the Field

- Relative Density, DR

$$DR = [(\gamma_d - \gamma_{dmin}) / (\gamma_{dmax} - \gamma_{dmin})] \times (\gamma_{dmax} / \gamma_d) \times 100$$

- Various correlations with Proctor values
  - 95% RC (standard proctor) y 70% DR (USBR Earth Manual)

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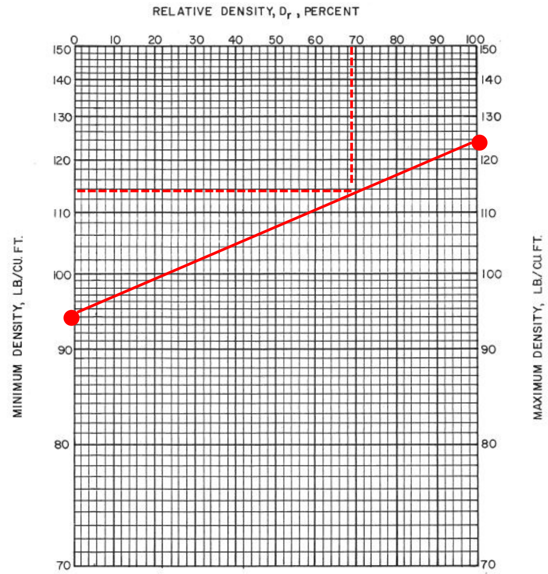
Use of Relative Density in the Field



Alternatives to ASTM Methods

- Vibrating tables are problematic.
- USACE – Modified Providence Method: Similar to ASTM, except for maximum density, vibrate sample by striking mold with a mallet.
- ASTM D7382 –Maximum Dry Unit Density with Vibratory Hammer. Develops a maximum dry density using commercial vibrating hammer

Earthwork Operations

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Earthwork Placement

- Fill is placed on an approved subgrade.
- Fill is placed in thin lifts.
- Each lift is compacted.
- Measure dry density and compare to maximum dry density determined in the laboratory.
- When the specified relative compaction is achieved, another lift is placed.

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Earthwork Placement

- Typical lift thickness: 8 to 12 inches.
- Thicker lifts may result in low densities at the bottom of the lift.
- Each lift is compact by a number of roller passes.
- The number of roller passes required depends on …
  - Roller size
  - Lift thickness
  - Compaction moisture content

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Suitable Compaction Moistures

- Range of moistures at which we can easily achieve compaction.
- Compaction on the dry side of this range can be achieved by applying more compaction energy.
- The range of moisture content on the wet side of the curve where we can compact the soil is limited by the ZAVD curve.

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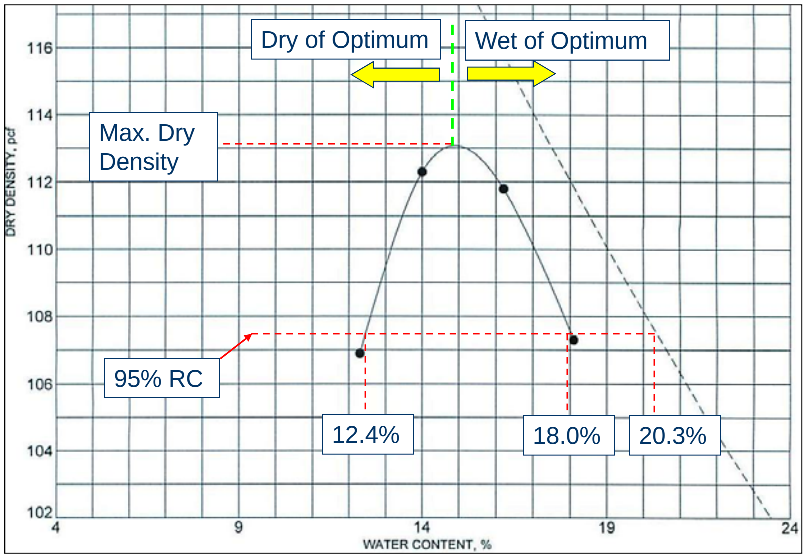
Suitable Moisture Contents



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Types of Rollers

- Two basic types
  - Smooth drum
  - Sheepsfoot
- Smooth drum used for granular soils
- Sheepsfoot used for fine-grained, cohesive soil
- Rollers often include drum vibrators

Earthwork Observation and Testing

Observation and Testing

- Earthwork is typically observed and tested by testing agency retained by the owner or contractor.
- The testing agency evaluates whether the contractor is meeting the earthwork specs.

Observing Earthwork Operations

- The testing agency should …
  - Classify the soil being placed. Confirm it meets the project specifications.
  - Visually evaluate the moisture content. Does it appear wet or dry of optimum.
  - Check the lift thickness is in accordance with the specs.
  - Observe the compaction of each lift. Note the roller pattern and number of passes.
  - Observe the behavior of the fill during compaction.

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Field Density Testing

- After a lift has been compacted, we evaluate the relative compaction by running a field density test.
- Common types of field density tests.
  - Sand Cone Test (ASTM D1556)
  - Nuclear Gauge Test (ASTM D6938)
  - Drive Cylinder Test (ASTM D2937)
- Test results are compared to the laboratory compaction curve.

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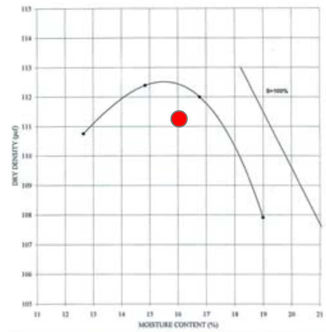
Evaluating Test Results

- Compare the dry density from the FDT to the maximum dry density from the laboratory compaction test.
- Plot the test result (dry density & moisture content) on the compaction curve to check it's reasonableness.



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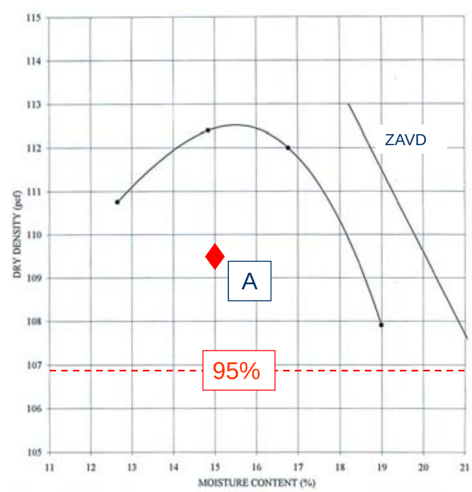
Evaluating Results

- Test A
  - Moisture close to optimum
  - Density greater than 95% of maximum dry density



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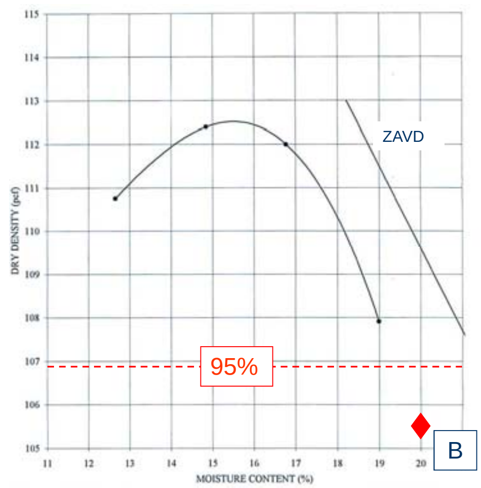
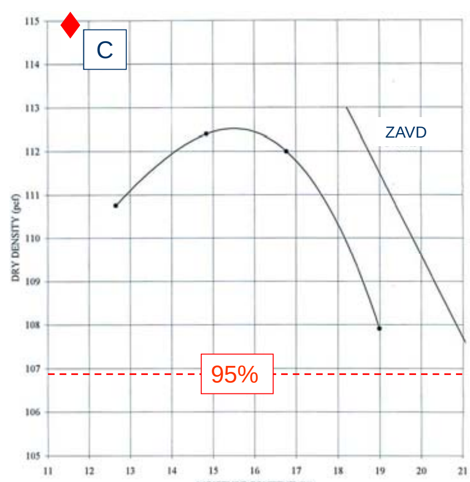
Evaluating Results

- Test B
  - Density is less than 95%
  - Moisture content well above optimum.
  - More energy may help, but difficult to achieve compaction
  - May need to dry the soil



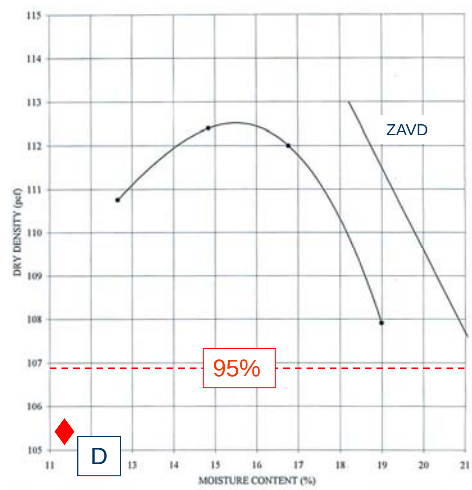
Evaluating Results

- Test C
  - Density > 100%
  - Not necessarily wrong
    - High compaction energy
  - However, check to make sure it's the correct curve



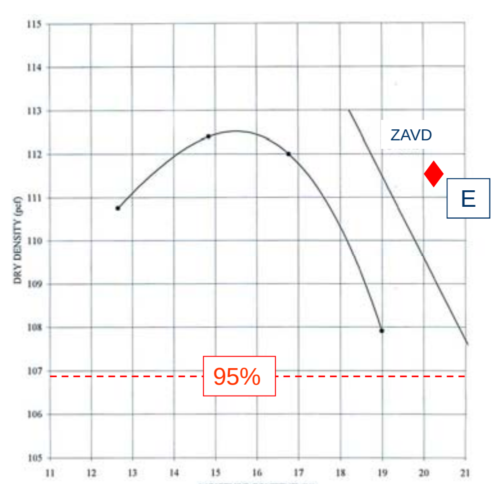
Evaluating Results

- Test D
  - Inadequate density
  - Can achieve density at this moisture by adding more energy
  - Adding moisture will make it easier.



Evaluating Results

- Test E
  - Density is OK
  - Moisture content is high
  - What's wrong with this test?
  - It's an impossible result.



Evaluating Results
It's Not Just About Testing

- Observations during fill placement are as important as the test results.
  - Visual evaluation of moisture content
  - Lift thickness and roller pattern
  - Behavior of fill during compaction

- Consistent placement and compaction procedures will produce consistent results.

Behavior During Compaction

- Behaviors that indicate inadequate compaction:
  - Pumping
  - Rutting
  - Cracking

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Behavior During Compaction

- Behaviors that indicate adequate compaction:
  - Sheepsfoot Roller Walking-out
  - Elimination of ridges

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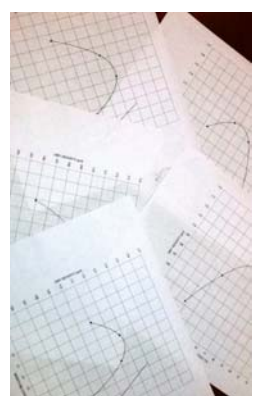
Evaluating Results
Picking the Right Curve

- Laboratory compaction curves are developed for different fill soils used on each project.
- The number of compaction curves for each project may vary from one or two to dozens, depending on the size of the project and the variability of the soils.
- *It is critical to select the correct compaction curve.*



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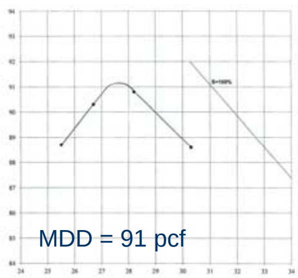
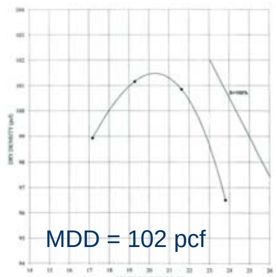
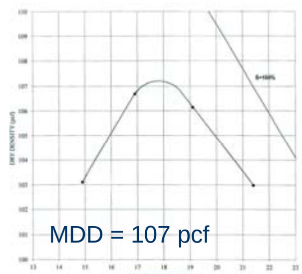
Evaluating Results - Example

- FDT on MH soil. FDT dry density = 96 pcf
- Three curves for MH soils on this project.
- Results very from 90% to 105%
- How do we pick the right curve?







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Picking the Right Curve

- Visually classify the fill soils tested.
- Select a Proctor curve with the same soil classification and similar gradation.
- Your “gut feeling” about the degree of compaction can also guide you on the selection of the curve.
- If you think the soil is near (wet of, dry of) optimum, pick a curve that supports this conclusion.
- One-point compaction test can help.

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One-point Compaction Test

- Compact a sample in the mold using the appropriate compaction standard.
- Determine its moisture content and dry density.
- This moisture content – dry density pair should plot on the curve for the appropriate compaction curve.

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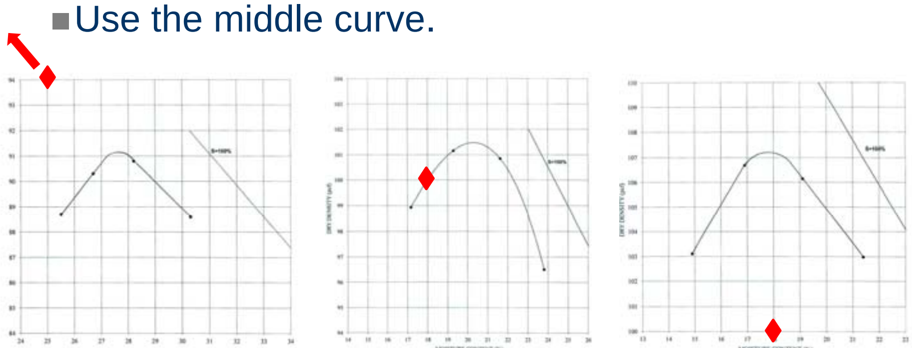
One-point Compaction Example

- One-point results – 100 pcf @18% MC
- Since the same energy is used, the point should plot on the correct curve.
- Use the middle curve.



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Other Testing Issues

- Frequency of testing
- Nuclear gauge check tests
  - Moisture content
  - Density
- Oversize correction.

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Frequency of Testing

- Conduct at least one FDT on each lift of fill.
- Most specs require a test for a certain area of fill or for a certain volume of fill (i.e. one test every 5000 sf or one test every 1000 cy)
- If the specs are silent on the test frequency, conduct a test for every 10,000 sf (100' x 100') of area, or fraction thereof.

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Nuclear Gauge Check Tests

- Moisture content errors in certain soils
  - Hydrogen other than in water
  - Boron, chlorine and cadmium
- ASTM D6938 requires periodic checks of moisture content by a non-nuclear method.
- Some specifications (USACE, FAA), require periodic check tests of the nuclear gauge density results using the sand cone or drive cylinder method.

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Oversize Corrections

- Samples compacted in the laboratory have oversized particles removed.
- If oversize particles are present in the field, they will inflate dry density results (non-conservative).
- When oversize particles are present, an oversize correction must be applied (ASTM D4718)

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What if We Can't Achieve Compaction?

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Corrective Actions

- If continued compaction effort does not achieve compaction …
- Check for test errors.
- Make sure you are using the right compaction curve.
- Adjust the moisture content
- Increase compaction energy

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Test Errors

- Nuclear gauge errors.
  - Moisture / density errors in the gauge.
  - Gauge proximity.
  - Testing in a trench or near some barrier.
- Vibrations during sand cone testing.
  - Will result in low densities

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Adjust Moisture Content

- Wrong moisture content makes compaction difficult (impossible).
- Add water.
- Scarify and dry soil.
- Chemical drying agents.

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Increase Compaction Energy

- Bigger roller.
- More roller passes.
- Thinner lifts.



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Summary

- Compact fill to increase strength and decrease compressibility.
- Compaction process: excavate fill, transport, place, compact, evaluate compaction, repeat.
- Compaction effectiveness depends on the amount of energy applied and the moisture content of the soil at the time of compaction.
  - Soil can be either too wet or too dry for compaction.

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Summary

- Evaluate compaction effectiveness by …
  - Observing the compaction process (lift thickness, number of roller passes, behavior during compaction).
  - Measuring dry density in the field and comparing it to laboratory maximum dry density.
- Selecting the correct lab curve for comparison is critical.
- Be alert for test results that don't look right or are just impossible.

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Questions?

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