LESSON 8

TOPIC 1

Deep Foundation Design – Load Capacity

Structural Foundation Topics

- ***Shallow Foundations (Spread Footings)***
  - ***Bearing Capacity***
  - ***Settlement***
- ***Deep Foundations***
  - ***Load Capacity***
  - ***Settlement***
  - ***Negative Skin Friction***

Slide 8-1-1

Re-show structural topic slide. Point out that the first step in a deep foundation design is to make sure that you cannot use spread footings, as these are cheaper and more reliable than deep- foundations.

DEEP FOUNDATION DESIGN

Lesson 8 - Topic 1
Load Capacity

Slide 8-1-2

Header

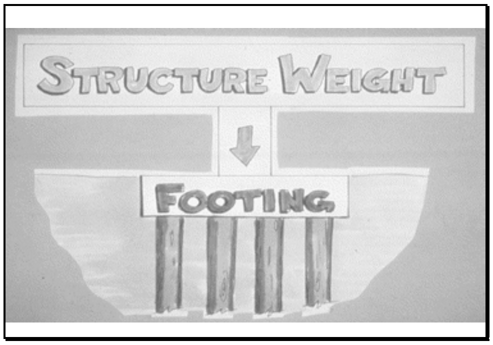
DEEP FOUNDATION DESIGN
Load Capacity

1. Describe Properties of the Pile and the Ground Which Affect Bearing Capacity

ACTIVITY: Static Analysis & Interpretation

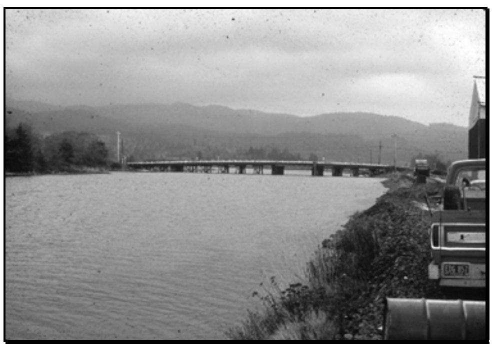
Slide 8-1-3

Objectives



Slide 8-1-4

Schematic of deep foundation. Stress that piles or drilled shafts are structural elements that are used to transfer load through unsuitable to suitable soils. Engineers who specify deep foundations in every situation have forgot this definition in the past. Remind the group of the problems associated with using deep foundations in areas of dense, competent soil conditions (excellent example is case where piles were specified in a surface glacial till deposit that had to pre-augered with a rock auger to achieve the minimum 10' length). However then transition to situation where non-geotechnical factors may require deep foundations; even in competent soils.



Slide 8-1-5

Show a series of situations where non-soil related conditions could make soils at some locations unsuited to carry foundation loads; generally these conditions are related to water or ice. This picture is of a bridge located in a flood plain. Emphasize that the hydraulics engineer should be involved in foundation designs in the vicinity or water crossings.

Slide 8-1-6

This abutment was affected by scour forces that eroded the end fill to a point where the footing was undermined. The point is that embankment material is not sufficient protection against scour forces.

Slide 8-1-7

Note that even abutments that are protected by riprap can be subjected to scour forces. The foundation design must account for future removal of soil by water and extended sufficiently below the scour depth to mobilize the required resistance for the foundation loads.

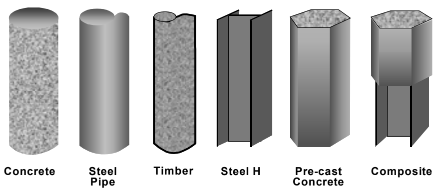
Slide 8-1-8

The presence of ice can cause both lateral and uplift forces on a structure. Deep foundations may be needed to resist those loads.

Slide 8-1-9

This case history demonstrates how pier footings, even those on piles, can fail if scour is not accounted for. This bridge was founded on short timber piles. A 50-year storm caused scour around the pier to about half the length of the piles. The remaining pile embedment was inadequate to resist the applied structure and water forces. The downstream piles plunged and the pier rotated, broke the upstream piles and fell in to the scour hole. The point to make is that rational design needs to accounts for all factors that influence the foundation.

Types of Piling



Slide 8-1-10

At this point inform students that only pile foundations will be dealt with in this course. Other deep foundations types such as micropiles or drilled shafts will not be covered. However the basic concepts discussed here are applicable to all deep foundation types. Show pile types; stress differences in materials, shapes and available dimensions make selection of optimum difficult. Ask students how they select the pile type for their projects.

Individual Piles

Method of Estimating Load Capacity
- ***Load Test***
- ***Dynamic Formula***
- ***Static Analysis***

Slide 8-1-11

Methods of load capacity determination

Slide 8-1-12

Note load testing requires extensive field mobilization and is not commonly done prior to design except on major projects. Even in those cases, useful soil design values are not obtained unless the test elements are instrumented for load transfer.

Slide 8-1-13

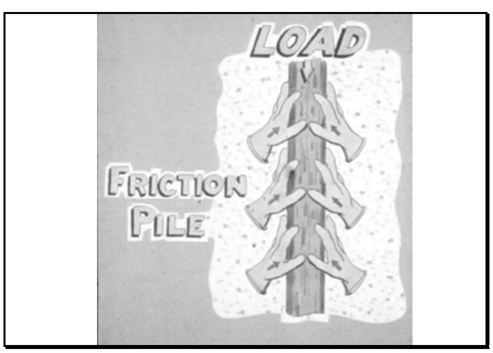
Same for driving test piles prior to design. As in the case of load tests, the mobilization of equipment to install foundation elements is not commonly done in design.

Steps in Rational Pile Selection

- ***Adequate Subsurface Investigation***
- ***Soil Profile Development***
- ***Appropriate Lab/Field Testing***
- ***Selection of Soil Design Parameters***
- ***Static Analysis***
- ***Applied Experience***

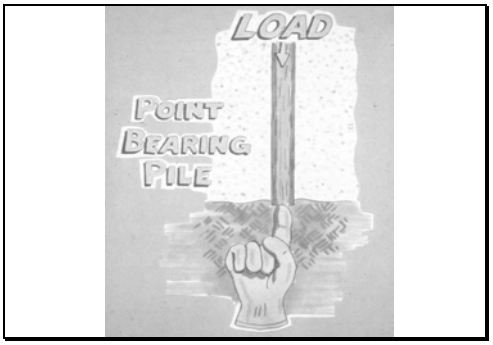
Slide 8-1-14

Bottom line is that the designer usually relies on the soil data to predict the load capacity of deep foundations during the design phase. Advise the students that the computational process is much more difficult than for spread footings and several factors influence capacity. Ask students what factors they think influence pile capacity.



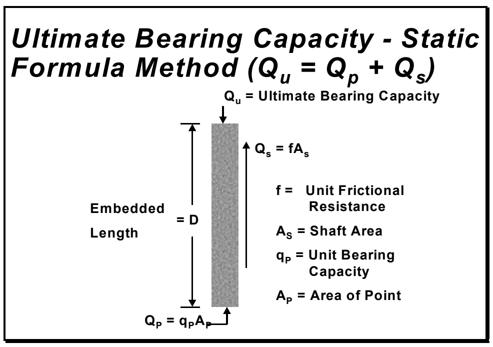
Slide 8-1-15

Next 2 slides describe mechanism of load transfer. Relate skin friction to a person trying to hold a rod when someone is pushing on the rod. If the rod is smooth, the rod slips through your hands more easily then if the rod is rough. The same concept will apply to mobilization of skin resistance by deep foundation elements.



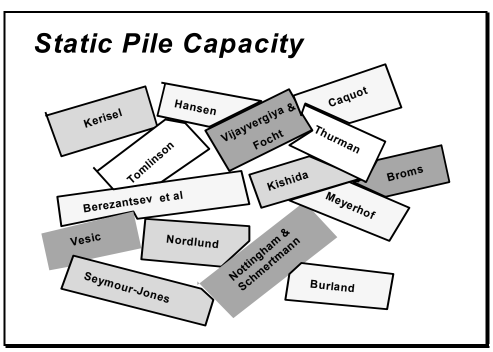
Slide 8-1-16

Describe mechanism of load transfer for end bearing. Relate the tip resistance developed to the resistance developed by a spread footing.



Slide 8-1-17

Overview the concept of static analysis for pile capacity prediction.



Slide 8-1-18

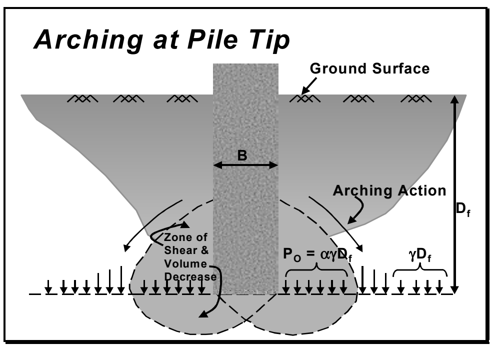
Note that many efforts have been made to refine predictive accuracy but no one method is completely accurate. Also all methods do not apply to all soil types; so we will recommend a different method for cohesive and granular soils.

ALLOWABLE LOAD ON PILES IN COHESIONLESS SOILS

- ***General failure mechanism understood***
- ***Some uncertainty in effects of pile installation on load transfer in both skin friction and end bearing***

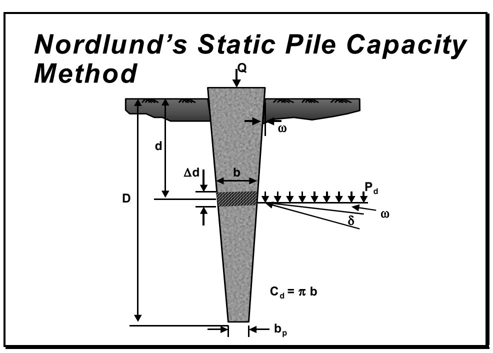
Slide 8-1-19

Introduce cohesionless soil bearing capacity for pile foundations. Mention that FHWA has developed a database of load test information to assist in quantifying load transfer variables and to permit assessment of different methods of static analysis.



Slide 8-1-20

Explain how simple spread footing concepts apply until the pile tip reaches a distance below ground where ground uplift can no longer occur (about 20 to 40 diameters). Explain how capacity is affected by both the densification around the shaft and the pressure reduction at the tip due to arching. Admit that this concept is difficult for non-geotechnical engineers to grasp. The following slides will overview the method of computation of capacity of piles in granular soils. Students should be told to watch the lecture and then the instructor will cover the material again in the reference manual.



Slide 8-1-21

Overview Nordlund's equation, which is, based on load test results.

Ultimate Capacity of Non-Tapered Piles in Granular Soils

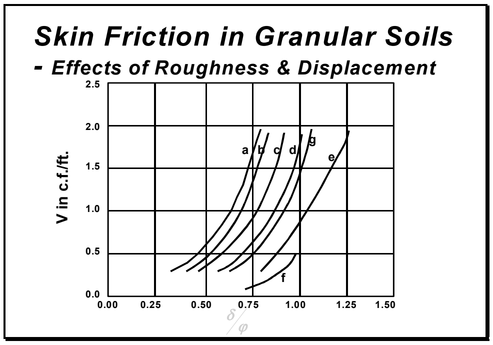
$Q_u = Q_S + Q_P$

$Q_u = K_\delta \, C_F \, P_d \sin\delta \; C_d \, D + A_P \, \alpha \, P_D \, N'_q$

Unknowns are K_δ, C_F, δ, α, N'_q

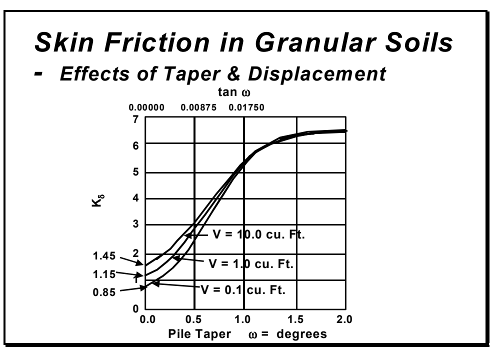
Slide 8-1-22

First explain that the equation shown above is divided into skin friction and end bearing. The terms in each section are composed of soil and pile properties. Each property affects the capacity. The first step in the application of the equation is to assume a particular pile type and a particular soil profile. Then half of the terms are known in the equation. The following slides contain a breakdown the components of the computation of skin friction. Then we deal with end bearing.



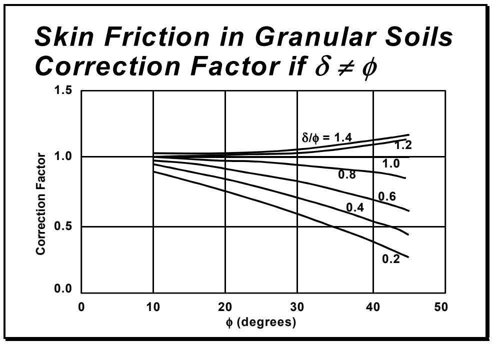
Slide 8-1-23

Explain that the skin resistance is dependent on the load transfer between the pile and the soil. Both the roughness of the pile and the soil displaced by the pile affect the angle of friction developed between the pile and the soil. The volume of soil displaced by the pile has a profound effect on skin friction. This chart is entered with the volume of the soil displaced per foot. The chart has been developed for piles of different roughness and shape. If the volume displaced per foot and the pile type are known, the ratio between the friction angle and the angle of friction between the soil and the pile can be found.



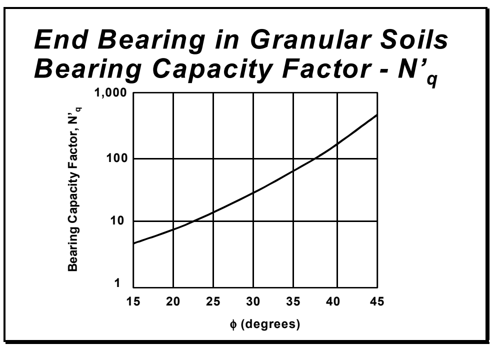
Slide 8-1-24

Taper and soil displacement also affect the lateral pressure against the side of the pile; much as the lateral pressure against a retaining wall is affected by the angle of the backwall and the compaction of the soil. The lateral pressure is needed to find the normal force against the side of the pile.



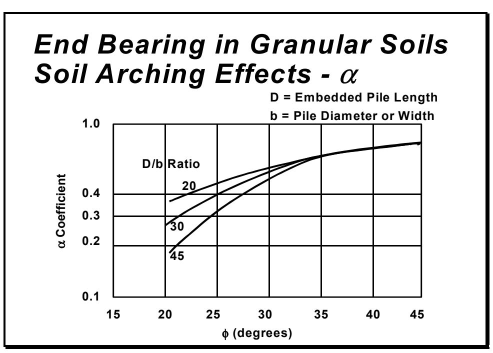
Slide 8-1-25

Finally a correction factor is applied to situations where the angle of friction does not equal the friction angle between the pile and the soil. This correction is needed to account for the theoretical simplification of equality of both angles that was used to develop the initial equation. At this point all the unknowns have been found to find the skin friction.



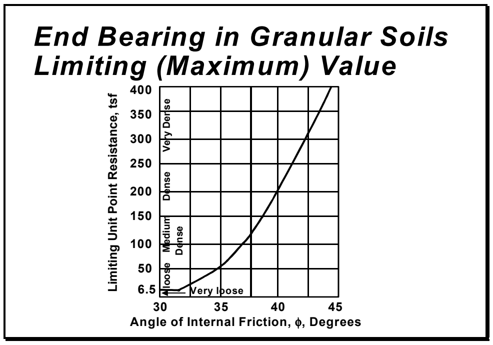
Slide 8-1-26

The end bearing computation contains two unknowns. The first is the bearing capacity factor. However we explained the concept of bearing capacity in the previous lesson. Then ask who can tell me the bearing capacity factors that were used for spread footing bearing capacity (answer is N_c, N_γ, N_q. Then ask why is only N_q used to pile design… answer is that embedments is the overriding factor for deep foundation… ask students to remember the effect of embedding the footing in the granular soil example of the previous lesson).



Slide 8-1-27

The end bearing will also be affected by the amount of arching that occurs when soil displacement occurs. The arching is depending on the angle of friction of the soil and the number of diameters that the tip is located below ground.



Slide 8-1-28

Finally introduce the concept of limiting end bearing. Explain that the results of load tests confirmed that the original Nordlund equation over predicted end-bearing resistance. This separate computation is done and compared to the original end bearing resistance. The smaller of the two values is chosen to prevent over prediction of the end bearing.

Slide 8-1-29

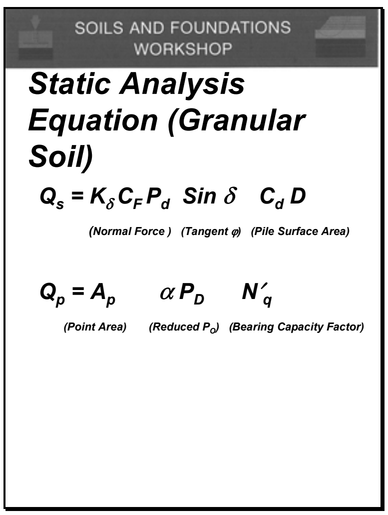
Ask, which end treatment procedures the highest end bearing; first is this flat plate treatment.

Slide 8-1-30

Second is this conical point treatment.

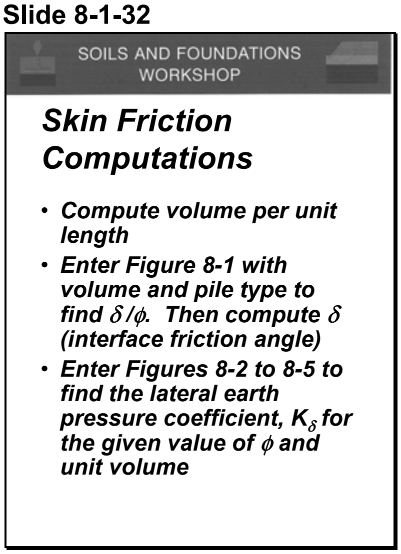
Slide 8-1-31

Third is this open-end pipe pile. Before giving the answer, go to the flip chart and draw the flat plate and show the failure occurs by the formation of a shear wedge in the soil below the plate (soil to soil shear). Then draw the conical point and show where the failure occurs, (along the point face in a steel to soil shear). The answer is the flat plate or a plugged open-end pile as these are soil-to-soil shear.



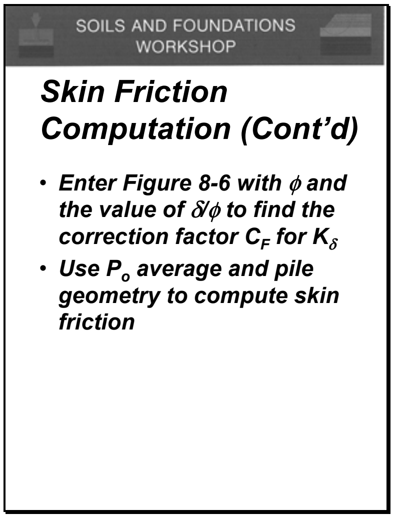
Slide 8-1-32

Ask students to open reference manual to the deep foundation section. Overview the information in the manual up to the static analysis section. Then ask students to follow along in their reference manual as the computation process is explained. Mention that an example will follow the lecture and a student exercise will be done after cohesive soils are explained in the next session. Encourage students to ask questions about the process. Then the instructor begins the discussion by relating the equations for skin friction and end bearing to practical aspects.



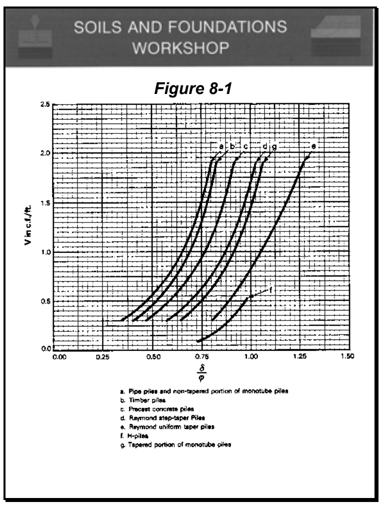
Slide 8-1-33

Instructor walks students through computational process for granular soils in the next two overheads. Note that this process may be difficult for non-geotechnical engineers to understand. The concepts must be clearly and slowly stated. Read each bullet. If a figure is referred to on the bullet, go to that figure and explain where to enter the figure and what value is to be determined.



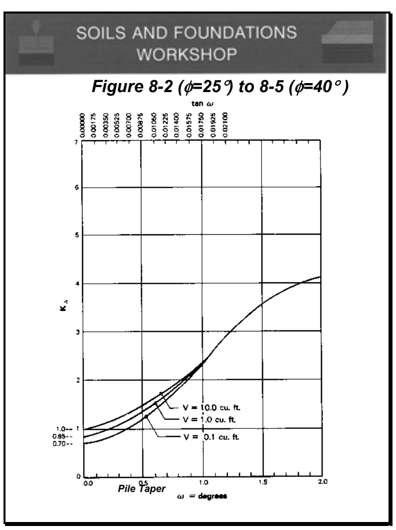
Slide 8-1-34

Instructor walks students through computational process for granular soils. Note that this process will be difficult for non-geotechnical engineers to understand. The concepts must be clearly and slowly stated.



Slide 8-1-35

Instructor walks students through computational process for granular soils. Note that this process will be difficult for non-geotechnical engineers to understand. The concepts must be clearly and slowly stated.

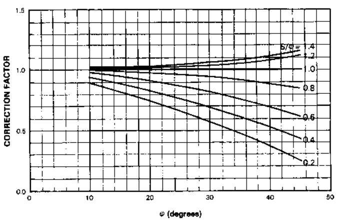


Slide 8-1-36

Instructor walks students through computational process for granular soils. Note that this process will be difficult for non-geotechnical engineers to understand. The concepts must be clearly and slowly stated. In this chart, note that different figures are used for different F̣ values.

SOILS AND FOUNDATIONS WORKSHOP

Figure 8-6



Slide 8-1-37

Instructor walks students through computational process for granular soils. Note that this process will be difficult for non-geotechnical engineers to understand. The concepts must be clearly and slowly stated.

SOILS AND FOUNDATIONS WORKSHOP

End Bearing Rules Granular Soils

- ***P_D should not exceed 3000 psf for end bearing computations***
- ***Q_p must be compared to the limiting maximum end bearing for the soil friction angle selected.***

Slide 8-1-38

Instructor walks students through computational process for granular soils. Note that this process will be difficult for non-geotechnical engineers to understand. The concepts must be clearly and slowly stated.

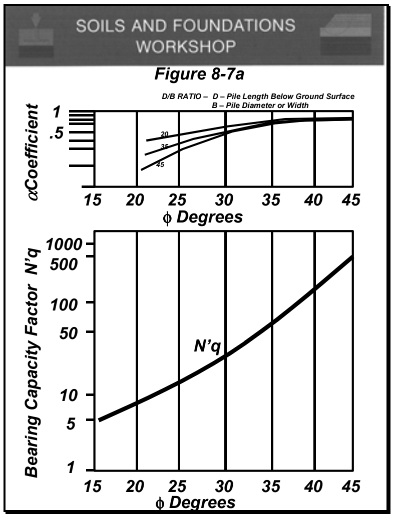
SOILS AND FOUNDATIONS WORKSHOP

End Bearing Rules Granular Soils (Cont'd)

- ***Q_{LIM} = (Unit Point Resistance from figure 8-7B)(Pile End Area)***
- ***The lesser of Q_{LIM} or Q_p is used as the end bearing value***

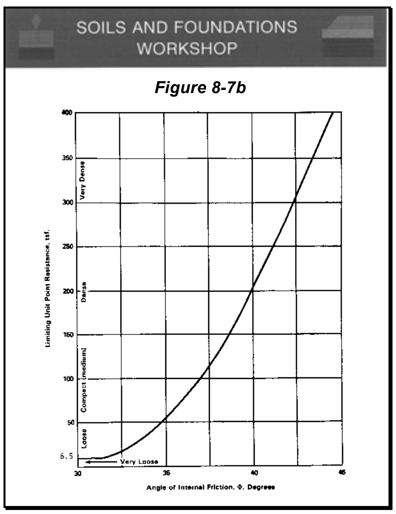
Slide 8-1-39

Instructor walks students through computational process for granular soils. Note that this process will be difficult for non-geotechnical engineers to understand. The concepts must be clearly and slowly stated.



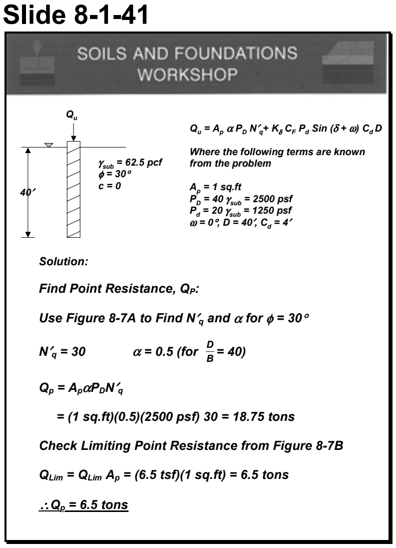
Slide 8-1-40

Instructor walks students through computational process for granular soils. Note that this process will be difficult for non-geotechnical engineers to understand. The concepts must be clearly and slowly stated.



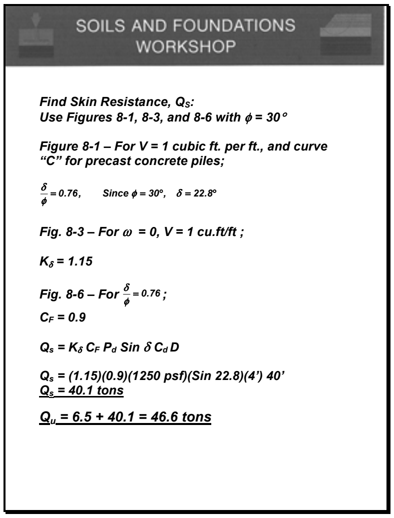
Slide 8-1-41

Note to the group that this figure is in tons per square foot.



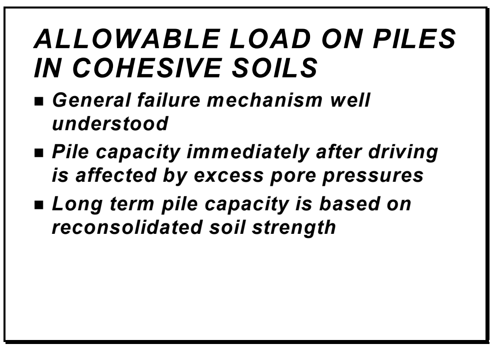
Slide 8-1-42

Instructor uses all previous information in example solution for a pile in a granular soil. The example will initially pull together all the concepts into a defined computation. The instructor should show where all values are obtain by asking students to go to appropriate charts and directing them to enter with the known value to find the desired value.



Slide 8-1-43

After completing the solution, ask if the value computed was in the ballpark of what the students expected. Usually the students think the value is too low but point out the water table is at the ground surface and has a large effect on the results. Mention that the group will get a chance to do a student exercise after the next session on cohesive soils is explained.



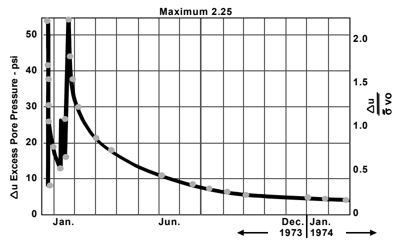
Slide 8-1-44

Introduce cohesive soil capacity determination.

Slide 8-1-45

Case history to demonstrate affects of pore pressure increase on pile capacity with time in clay. These closely spaced, closed end pipe piles were driven into a soft clay layer that was over 200' thick. The piles were designed to mobilize all resistance in skin friction at an estimated length of about 140'. When each pile was driven, a conical pile of liquefied clay was squeezed out of the ground and formed around the pile. While driving the third pile, the first pile heaved a short distance out of the ground. Efforts to redrive that pile resulted in heave of adjacent piles. This was due to the lack of skin friction to hold the piles in place as high pore pressures caused both reduced friction and increased pressures under closed end plates. The solution to prevent the heave was to wait until set-up occurred before installing adjacent piles. In this case the contractor drove every other pile with out any heaving and then returned to drive out the remainder after skin friction was mobilized.

Pore Pressure – South Bay Bridge
Pier No. 3, Piezometer Nos. 1 & 2



Slide 8-1-46

Case history to demonstrate the magnitude and time for dissipation of pore pressures. Piezometers were installed about three diameters away from friction piles driven into a 400' thick clay deposit to measure the excess pore pressure. The readings were used to determine the length of the waiting period prior to beginning a load test. Note the initial pressures exceeded 50 psi and took about 10 days to return to normal when the test pile was driven. Also note the time after driving the group of 60 piles for the pressure to return to normal was very large, i.e., months

Ultimate Capacity of Piles in Cohesive Soils

$$Q_{ult} = C_a\, C_d\, D + 9\, C_u\, A_P$$

Slide 8-1-47

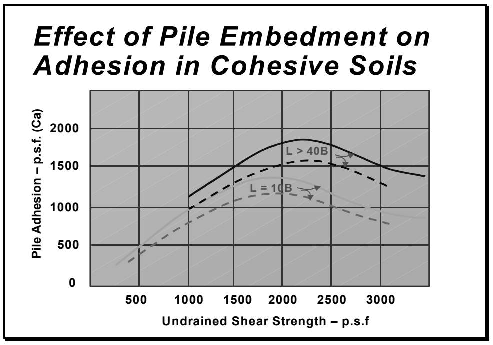
Introduce basic concept of capacity in clays and explain factor influencing capacity.

Adhesion on Piles in Saturated Clay (Circa 1960)

Material	Cohesion (psf)	Adhesion (psf)
Concrete and Timber	Soft 0 – 750 Firm 750 – 1500 Stiff 1500 - 3000	Soft 0 – 750 Firm 750 – 1250 Stiff 1250 – 1400
Steel	Soft 0 – 750 Firm 750 – 1500 Stiff 1500 – 3000	Soft 0 – 600 Firm 600 – 1050 Stiff 1050 – 1200

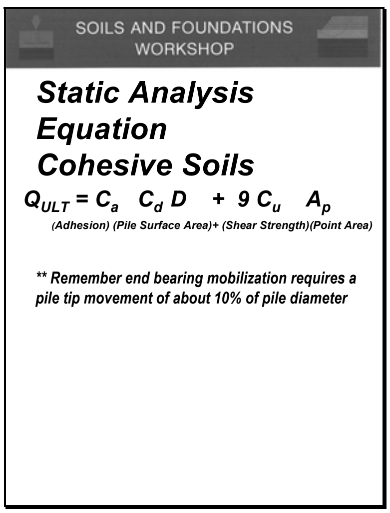
Slide 8-1-48

In the early 1960's tables were developed to find adhesion between clay soils and piles. Begin by explaining the impact of roughness on the pile capacity. Rough piles mobilize more skin friction than smooth piles. Then explain why soft clays will reconsolidate back to their original strength while overconsolidated clays will suffer a permanent reduction in strength. Note that this table is based only on early historical data for relatively short piles and has since been improved.



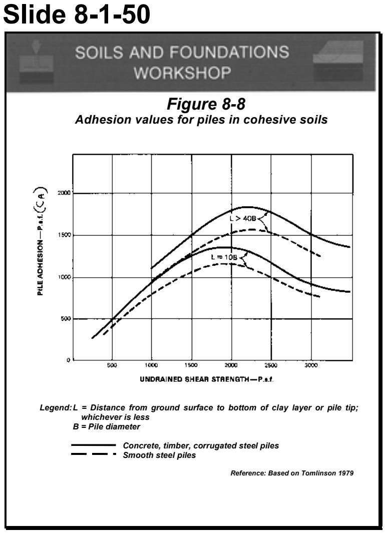
Slide 8-1-49

First note that this graph contains the relations between roughness and soil strength that were just explained. These facts have been well known for many years. However a third factor has been found to also be important; the severe disturbance to the clay that occurs near the ground surface due to unsupported pile vibrations during driving. Research has indicated that the reductions in strength are the greatest generally within about 10 diameters of the ground surface and no strength reduction is considered below a depth of 40 diameters.



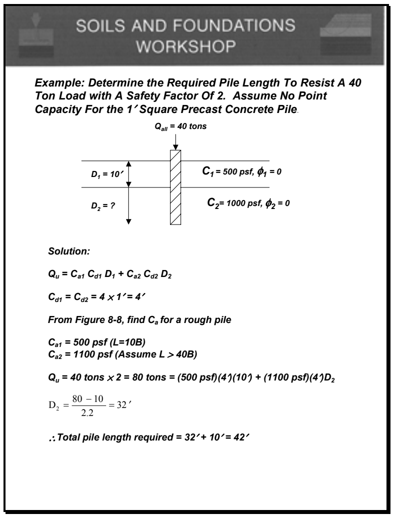
Slide 8-1-50

Relate the factors in the equation to practical terms.



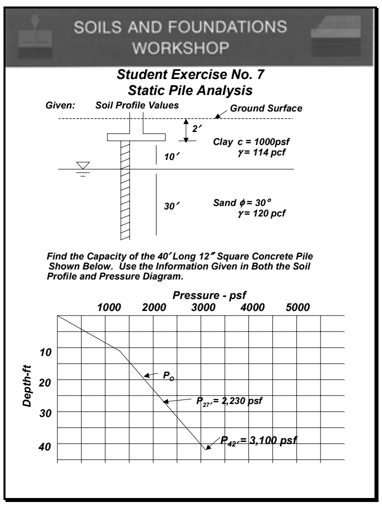
Slide 8-1-51

Demonstrate how to obtain adhesion values for deign.



Slide 8-1-52

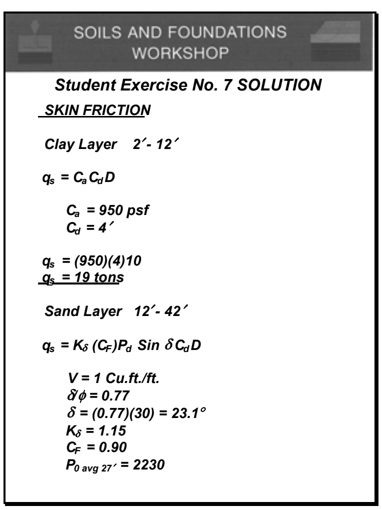
Instructor completes an example computation to summarize the cohesive capacity computational process. This process is similar to the previous granular example but simpler to comprehend. After the example recall the granular example computation process and compare to the cohesive method. Then ask how reliable the answer is? (answer is to ask students how reliably the undrained shear strength was determined…the equation theory is correct but the answer depends on the soil properties to be accurately determined.



Slide 8-1-53

Instructor asks students to do the student exercise. If time is an issue, the instructor can assign different part of the computation to different teams. Student exercise involves computation of static capacity for a pile in both cohesive and cohesionless soils. The purpose of the exercise is to test comprehension of the computational process and to evaluate the students learning of the definition of a pile. Instructor asks team to present solution.

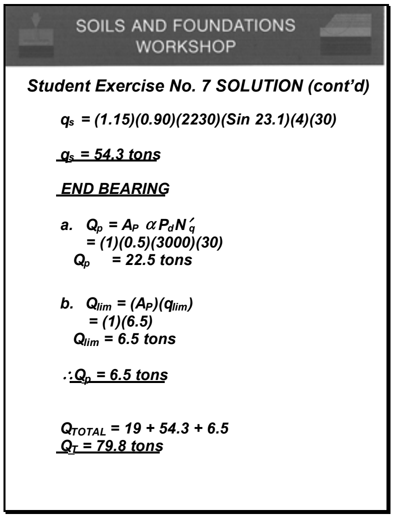
Please refer to the end of the lesson for this exercise.



Slide 8-1-54

Page one of solution to problem.

Please refer to the end of the Participant Workbook for the solution to this exercise.

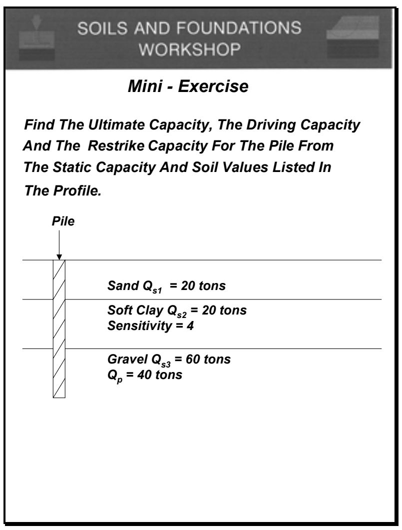


Slide 8-1-55

Page 2 of the solution. After the students have completed the explanation of the computation, ask what ultimate value would be used for the pile design? The answer is the skin friction in the sand and the end bearing or about 61 tons as the clay will consolidate if load is transferred to the deposit. Students should determine that if the clay was suitable for foundation support then a spread footing would have been the best solution. Go to the reference manual and point out the section on practical aspects of pile design.

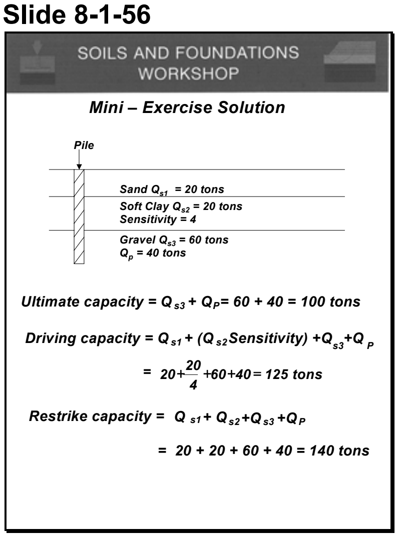
At this point the instructor demonstrates both SPILE and Driven software programs and emphasizes the ability of the programs to compare various pile alternates.

Please refer to the end of the Participant Workbook for the solution to this exercise.



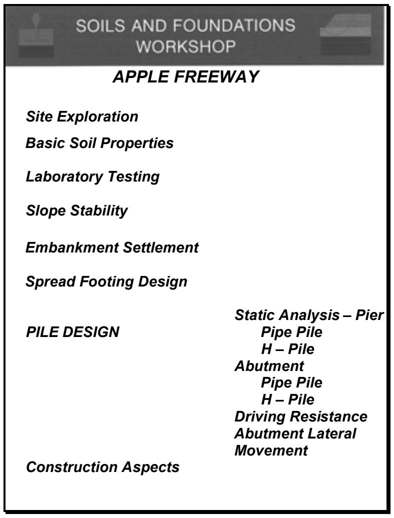
Slide 8-1-56

After introducing the terms; ultimate capacity, initial driving capacity and end of driving capacity in the DRIVEN demo, ask student to compute each in this simple exercise. Do not assign to teams but do as group exercise. Put on flip chart.



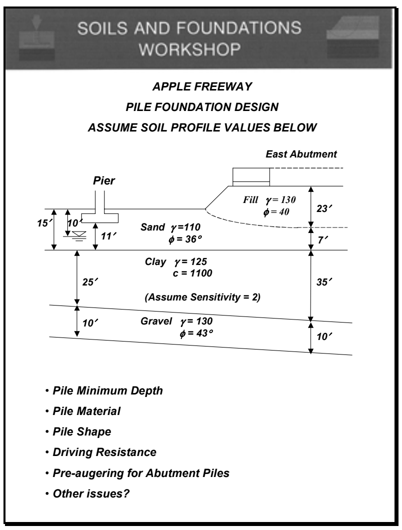
Slide 8-1-57

Please refer to Reference Manual 8-19 for solution, which follows.



Slide 8-1-58

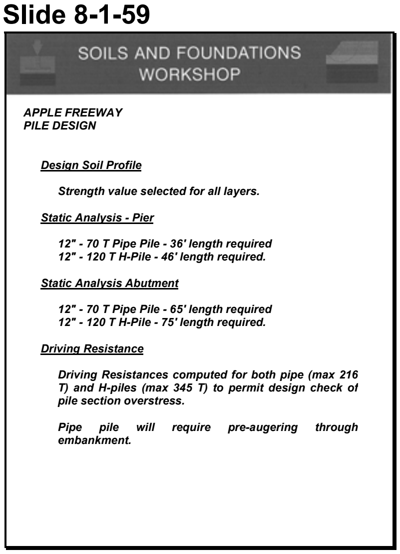
Summarize status of Apple Freeway design.



Slide 8-1-59

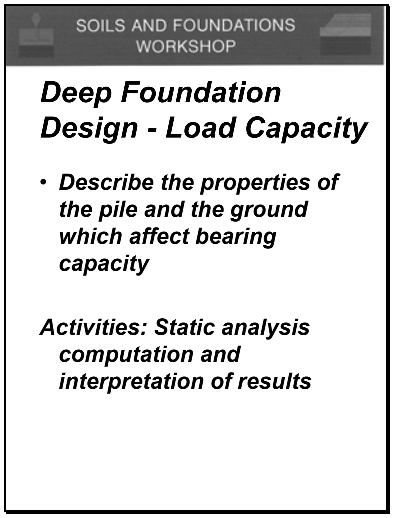
Ask students their opinions on the bullet topics.

Then ask about other issues, which need to be considered in project design that influence the performance of any foundation.



Slide 8-1-60

Summarize design results for Apple Freeway pile design



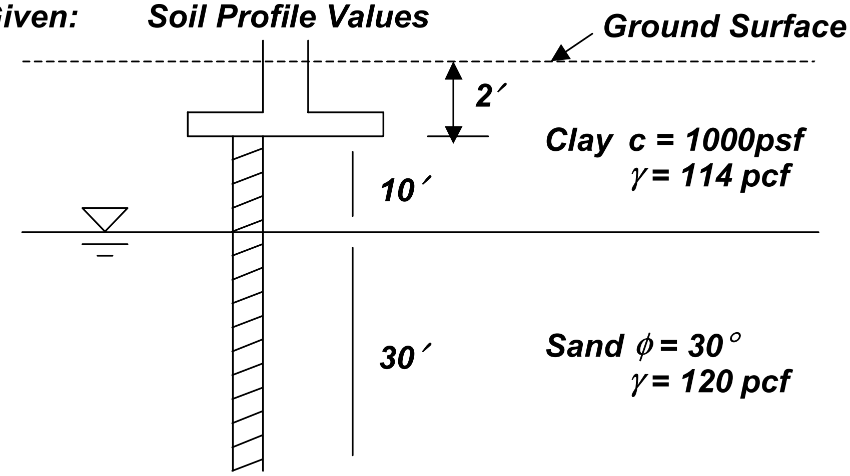
Slide 8-1-61

Repeat objectives for lesson 8 topic 1.

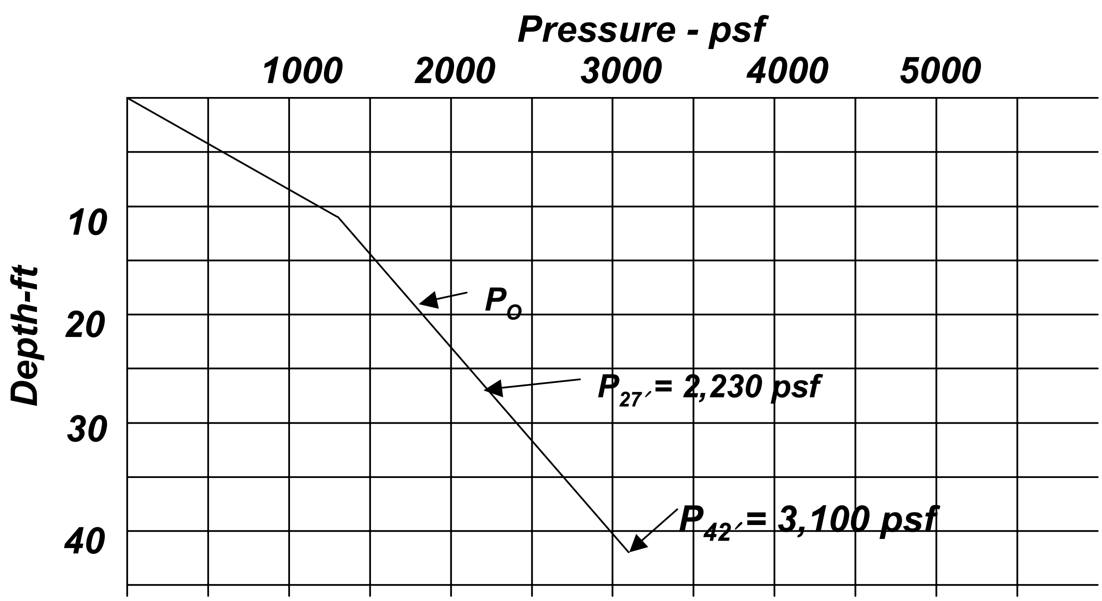
SOILS AND FOUNDATIONS WORKSHOP

Student Exercise No. 7
Static Pile Analysis

Given: ***Soil Profile Values***



Find the Capacity of the 40′ Long 12″ Square Concrete Pile Shown Below. Use the Information Given in Both the Soil Profile and Pressure Diagram.



SOILS AND FOUNDATIONS WORKSHOP

Student Exercise No. 7 SOLUTION

SKIN FRICTION

Clay Layer 2′- 12′

$q_s = C_a C_d D$

$C_a = 950$ psf
$C_d = 4'$

$q_s = (950)(4)10$
$q_s = 19$ tons

Sand Layer 12′- 42′

$q_s = K_\delta (C_F) P_d \sin \delta C_d D$

$V = 1$ Cu.ft./ft.
$\delta/\phi = 0.77$
$\delta = (0.77)(30) = 23.1^\circ$
$K_\delta = 1.15$
$C_F = 0.90$
$P_{0\ avg\ 27'} = 2230$

SOILS AND FOUNDATIONS WORKSHOP

Student Exercise No. 7 SOLUTION (cont'd)

q_s = (1.15)(0.90)(2230)(Sin 23.1)(4)(30)

<u>q_s = 54.3 tons</u>

<u>END BEARING</u>

a. $Q_p = A_P \, \alpha P_d N'_q$
= (1)(0.5)(3000)(30)
Q_p = 22.5 tons

b. $Q_{lim} = (A_P)(q_{lim})$
= (1)(6.5)
Q_{lim} = 6.5 tons

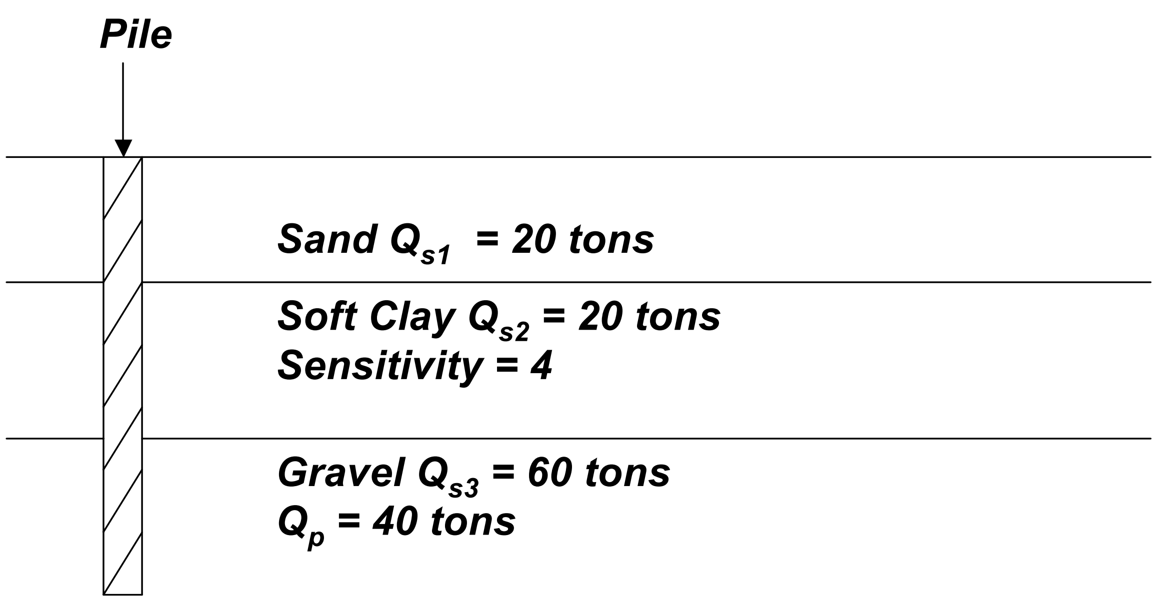
$\therefore$ <u>Q_p = 6.5 tons</u>

Q_{TOTAL} = 19 + 54.3 + 6.5
<u>Q_T = 79.8 tons</u>

SOILS AND FOUNDATIONS WORKSHOP

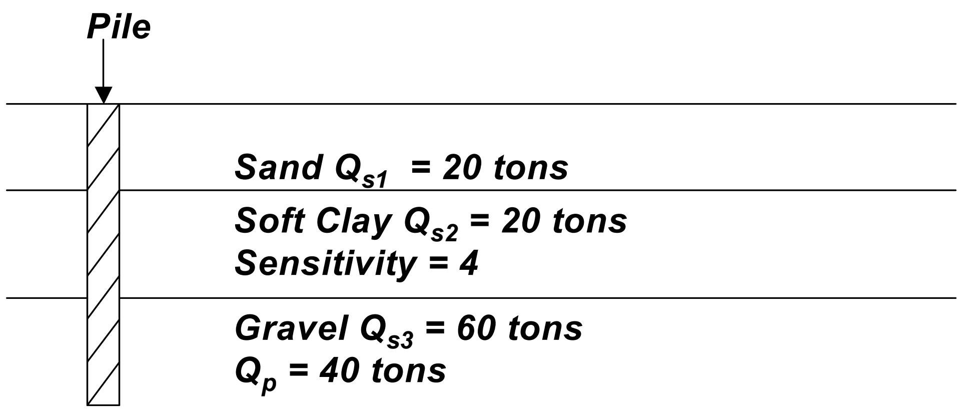
Mini - Exercise

Find The Ultimate Capacity, The Driving Capacity And The Restrike Capacity For The Pile From The Static Capacity And Soil Values Listed In The Profile.



SOILS AND FOUNDATIONS WORKSHOP

Mini – Exercise Solution



Ultimate capacity $= Q_{s3} + Q_P = 60 + 40 = 100$ ***tons***

Driving capacity $= Q_{s1} + (Q_{s2} Sensitivity) + Q_{s3} + Q_P$

$$= 20 + \frac{20}{4} + 60 + 40 = 125 \text{ tons}$$

Restrike capacity $= Q_{s1} + Q_{s2} + Q_{s3} + Q_P$

$$= 20 + 20 + 60 + 40 = 140 \text{ tons}$$