Dept. of Civil & Environ. Engineering
The University of Iowa
53:139 FOUNDATION ENGINEERING
Final Exam (2.0 Hours -- 200 points)

Spring 2009 Instructor: C.C. Swan

Question 1: (25 points) Slope Stability

a) Without using any formulas, provide a clear concise definition of the factor of safety against slope failure.

The factor of safety against slope failure is the factor by which the strength of the soil would need to be reduced in order to create a condition of incipient failure along the critical mechanism surface passing through the slope system.

Sometimes the factor of safety is computed as the ratio of the ultimate resisting capacity along the critical mechanism to the driving forces along the same mechanism.

b) Does the existence of seeping groundwater in an earthen slope system tend to increase or decrease the stability? Explain briefly.

Seeping groundwater invariably reduces the stability of earthen slopes in two ways: First, a saturated soil is always heavier than a dryer soil. Secondly, and more importantly, positive pore pressures in the soil reduce compressive effective stresses and thus reduce the shear strength of soils.

c) When can methods for "infinite" slopes be used to assess stability?

Stability analysis formulae for infinite slopes generally yield a critical depth D_{cr} beneath the slope face at which the factor of safety is minimal. So long as $D_{cr} \ll H$ the height of the slope, infinite methods can be used.

d) When is it appropriate to use Culmann's method of slope stability analysis?

Generally it best to use Culmann's method for relatively steep slopes with the angle of repose $\beta > 65°$.

e) Explain the major steps that would be involved in using one of the methods slices to analyze the stability of a slope system.

First, one is searching over all possible mechanisms for the one that yields the minimum factor of safety. This involves trying numerous different candidate mechanisms. For each trial mechanism, the following procedure is used:

- **Draw the slope and mechanism to scale;**
- **Partition the soil within the mechanism into vertical slices;**
- **For each slice compute the weight/volume, moment arm about the centroid of the mechanism, and the orientation of the bottom slice surface;**
- **Compute the total driving moment as the cumulative moment of each slices weight about the mechanism centroid;**
- **Compute the normal stress, shear stress, pore pressure, and shear strength at the bottom of each slice;**
- **Compute the cumulative ultimate resisting moment by integrating the moment of the shear strength about the mechanism centroid;**
- **Factor of safety is ratio of ultimate resisting moment to driving moment.**

Question 2: (25 points) Subsurface Site Explorations

a) To what type of sites can a seismic refraction survey be applied, and what information does it yield?

The method yields information on the stratification of a site, specifically layer thicknesses and wave speeds in each layer. The method can only be applied when the wave speeds increase with depth.

b) In words (no formulas), what is the difference between disturbed and undisturbed soil samples collected from the field?

Undisturbed soil samples have the same structure, and void ratio as the in-situ soil, whereas disturbed sample have an altered structure and void ratio due to the sample collection process.

c) If you had a disturbed soil sample and an undisturbed soil sample in a soils laboratory what properties could you obtain from the undisturbed soil sample that you could not get from a disturbed sample?

Void ratio, pre-consolidation stress, compression index, swelling index, undisturbed permeabilities, cohesion.

d) List five different soil properties or parameters that can be estimated from the Standard Penetration Test with empirical formulas.

Relative density; Young’s modulus; friction angle; undrained cohesion; OCR.

e) At a building sight you have encountered what appears to be a deep layer normally of consolidated clay with a very high plasticity index. What tests would you perform to confirm that the soil layer is indeed a high-plasticity clay soil?
Atterberg limit tests.

Question 3: (25 points) Shallow Foundations

The field plate load test is sometimes used to estimate both the expected settlements and bearing stress capacity q_u of full scale shallow spread footings. While the field plate load test uses a plate having a dimension of approximately one foot square or round, the actual foundation dimensions can be on the order of many meters. The bearing stress capacity of the full scale foundation $(q_u)_{foundation}$ can be considerably different than that of a small plate foundation $(q_u)_{plate}$. Also, for the same bearing stress, full-scale foundations will experience much larger settlements. Please explain briefly why these scale effects exist for both

a. ultimate bearing stress capacities; and
b. settlements.

Do not just write the scaling equations. Instead, discuss in words and sketches the physical reasons why the scaling equations are needed.

For Bearing Capacities: In homogeneous soils, shear strength generally increases with depth. The plate test only sees the soil of relatively low shear strength in close proximity to the test. A full-scale foundation sees soil shear strengths from deeper down into the soil, hence the scale effect with bearing capacity.

For Settlements: Assume that the bearing stress beneath a plate and a full-scale foundation have the same magnitude. The stress- and strain-field under the foundation exists over a much larger area/volume than those under the plate. Since displacements are found by integrating strains over volumes (or areas in 2D) the displacement under the full-scale foundation will be larger (roughly in proportion to B_F/B_P).

Question 4: (25 points) Mat/Raft Foundations

a) List four reasons why mat foundations are sometimes used as opposed to individual spread footings.

- **Can be more economical than spread footings when cumulative area of footings exceeds half of the buildings footprint area;**
- **Help to minimize differential settlements between different columns;**
- **Using compensation, the net bearing stress can be made very small, helping to reduce overall settlements and increasing the bearing capacity factor of safety.**
- **Can better resist upward lift on some columns using the flexural capacity of the mat.**

b) What is the depth of a fully compensated mat foundation?

$$D_f = \frac{\text{Total Weight of Structure}}{\gamma \text{A}}$$

c) What is a subgrade modulus, and what are its units?

Subgrade moduli are springs that represent the stiffness of the soil during interaction computations between the mat and the soil. Their units are F/L^3.

d) When and how is the subgrade modulus used in the analysis/design of mat foundations?

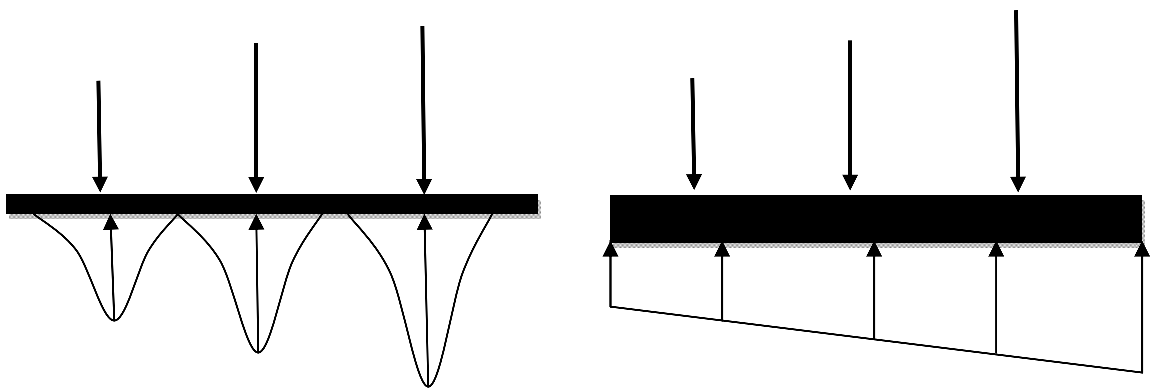
The subgrade modulus is used to represent the stiffness of the soil beneath a mat foundation in response to differential deflections of the mat. Together with the flexural rigidity of the mat itself, they are used in analysis of flexible mat systems to compute the deflection, slope, moment, and shear distributions in the mat around column loads.

e) Using a sketch, explain how the bearing stress distribution beneath a flexible mat foundation differs from that beneath a rigid mat foundation.

Flexible and Rigid are relative terms. A flexible mat is one with a relatively low flexural stiffness relative to the stiffness of the soil. A rigid mat is one in which the flexural stiffness is very large relative to the soil stiffness.

Bearing stresses beneath flexible mat.

Bearing stresses beneath rigid mat.



Question 5: (25 points) Retaining Structures

Assume that you are designing a cantilever retaining wall:

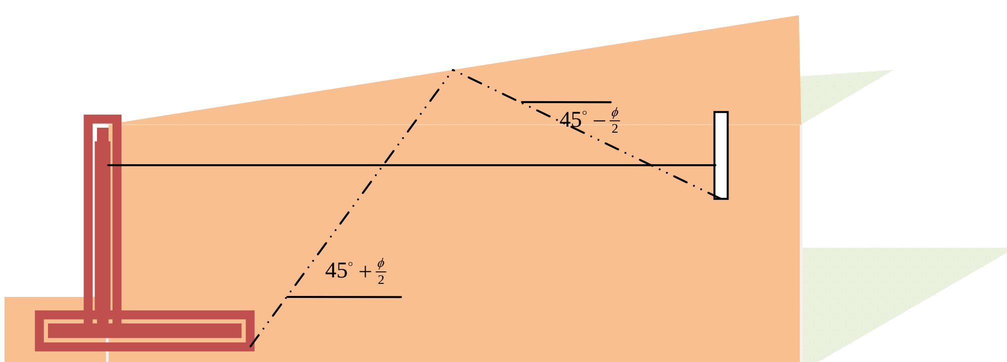
a) List five of the standard checks would you perform to assure that your design is adequate in terms of stability, serviceability, and strength. **(5 points)**

- **Overturning, sliding, bearing capacity, settlements, strength of the wall, and overall stability (like slope stability).**

b) Assume that in performing these design checks, you find that the wall you've designed has <u>inadequate</u> factors of safety. Provide two specific design measures you could take to improve the adequacy of your design with respect to each of the five checked categories.

- **Overturning:**
  - **increase strength of the backfill soil, since this would reduce the active force Pa.**
  - **reduce the height of the wall**
  - **use anchors (tie-backs)**
  - **use tie-down extending beneath the heel**
  - **increase the width (or length) of the heel of the footing**
- **Sliding**
  - **Increase strength of backfill soil, since this would reduce Pa.**
  - **Reduce height of the wall**
  - **Use tie-back anchors**
  - **Increase width of the heel**
- **Bearing capacity**
  - **Increase width B of the wall's footing**
  - **Replace soil beneath footing with stronger soil (least feasible option)**
  - **Under-pinning the footing**
  - **Use a lighter weight backfill soil or material.**
- **Settlements**
  - **Increase width B of the wall's footing**
  - **Replace soil beneath footing with stronger soil (least feasible option)**
  - **Under-pinning the footing**
  - **Use a lighter weight backfill soil or material.**
- **Strength of the Wall**
  - **Take measures that would reduce the soil forces creating bending moments in the wall such as usage of a lighter and stronger backfill soil;**
  - **Increase the thickness and reinforcement in the wall's stem.**
  - **Use tie-back anchors as these reduce the bending moments in the stem.**

c) If you were designing the cantilever wall to retain a sloping, granular, cohesionless backfill soil ($c = 0; \phi = 30^\circ$) making an angle ($\alpha = 20^\circ$) with the horizontal, where could you safely place the anchors? (Assume Rankine's active failure state in a sloping, cohesionless backfill. Use a sketch as necessary.) **(10 points)**



Question 6: (25 points) Deep Foundations

a) Numerous methods exist for estimating the ultimate capacity of driven piles. The methods generally fall into the classes listed below: Briefly (but fully) discuss the advantages and disadvantages unique to each of these general classes of methods. **(15 points)**

1) analytical and/or semi-empirical formulas based on site material properties,
2) full-scale field tests, and
3) pile driving formulas.

Analytical/empirical formulae based on soil properties:

- **Advantages: quick and easy to use**
- **Disadvantages: the scatter or range of pile capacities yielded by these methods is wide creating uncertainty in what the actual capacity is. Requires usage of larger factors of safety.**

Full-scale field load tests:

- **Advantages: most reliable method of ascertaining pile capacity. Can also separate out the skin friction capacity by measuring uplift capacity and the end bearing capacity.**
- **Disadvantages: relatively expensive and time-consuming to perform. When the tests are sped-up to save time/money, rate effects enter and the pile capacity might be over-estimated.**

Pile driving formulae:

- **Advantages: idea is very attractive in principle. Pile advancement per blow is readily available and site-specific.**
- **Disadvantages: rate effects. For dry granular soils, rate effects would tend to overestimate capacity. For saturated cohesive soils, potential liquefaction during pile driving could lead to temporary loss of strength. Accounting for actual energy imparted to the pile and that lost to other mechanisms is hard to do.**

b) Driven piles and drilled pier/shafts are two alternative deep foundation systems. Provide the relative advantages and disadvantages for each of these two alternative systems **(10 points).**

Advantages of driven piles: (1) relatively quick to install; (2)can have very large length due to splicing; (3) no possibility of ground loss due to collapse of unlined shaft; (4) driven in groups and integrated with pile caps.

Disadvantages of driven piles: (1) noise and potentially destructive vibrations from the pile driving process; (2) hard to know what happens to the pile as it goes down into the soil.

Advantages of drilled shaft foundations: (1) quiet with no pile driving vibrations; (2) can go down into the shaft and inspect bedrock; (3) can get greater end-bearing capacity with usage of belled shafts.

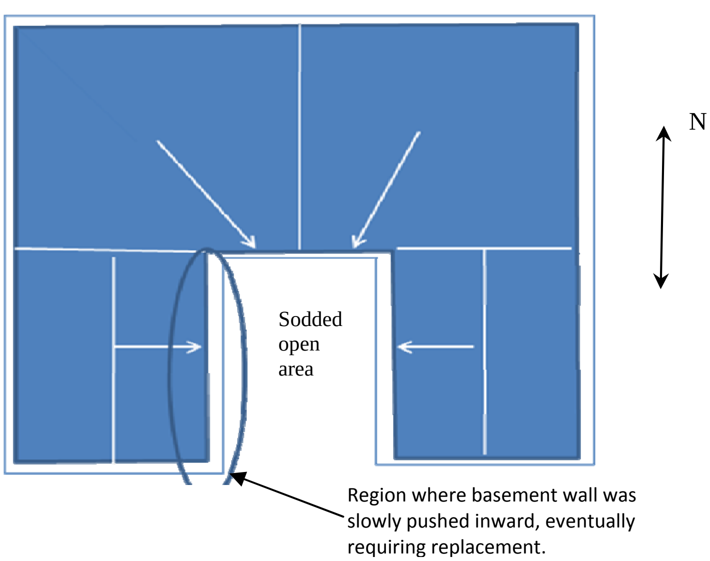
Disadvantages of drilled shafts: (1) potential collapse (ground loss) of unlined shafts; (2) takes time for the concrete shafts to cure.

Question 7: (25 points) Difficult Soils

Consider the following case history. The picture below shows the plan view of a 100 year old multi-story duplex house built on stiff cohesive soils in a region that receives about 40 inches of rainfall per year. The current owners removed the original wooden roof drainage system (gutters and downspouts) which required high maintenance with the intention of installing a new system of aluminum gutters and downspouts. A few years passed without any apparent incidents and the owners began to think the replacement drainage system was unnecessary. Over the same time period, the owners began to notice that the masonry basement wall of the west wing of the house was slowly being pushed inward. There was no apparent moisture, seeping through any of the basement walls, but slowly, year by year, the wall was getting pushed further inward. Eventually the basement wall and strip footing for the west wing of the house had to be completely replaced costing the owners approximately $15,000.

You are a friend of the owners and they shared their story with you. Given your background in foundations of structure, diagnose the problem and make some helpful recommendations to your friends. What soil tests might help to confirm your diagnosis of the problem.

Plan view of a duplex. Arrows indicate rainfall drainage patters from the roof.



The problem is that the soil within the open sodded area is expansive and that lack of proper removal of rainwater with gutters is channeling water into the expansive soil. As the soil expands, it exerts increasing forces on the basement walls until one finally failed. To confirm this one could test Atterberg limits (LL, PL, PI) of the soils in the open sodded area. If they are indeed expansive, they could be excavated and replaced with a granular, non-cohesive soil. Most importantly though is to re-install the rain gutter system so that rainwater from the roof is channeled away from the home.

Question #8 (25 points):
The following are true/false questions. To answer each, just enter ``T'' or ``F'' for each in your test booklet. If you find a question ambiguously worded, you may provide a more extended answer or explanation.

a. Very loose, saturated sands are highly vulnerable to liquefaction during earthquakes since they tend to compact (contract volumetrically) when sheared. **True**
b. Shallow footings for retaining walls and shallow strip footings in general should always be placed as close to the existing ground surface level as possible. **False**
c. When designing deep foundations to resist uplift loads, it is standard practice to use a factor of safety against uplift failure that is larger than the standard factor of safety against downward loading failure. **True**
d. General shear failures tend to occur in dense, well-compacted soils whereas local punching failures are likely to occur in loose soils of low relative density. **True**
e. Three semi-empirical methods of computing the end-bearing capacity of deep foundations bearing on soils are Meyerhoff's, Vesic's, and Janbu's methods. Of these, only Meyerhoff's method accounts for the possibility of local punching failure at the pile or pier tip. **False**
f. H piles are ``high-displacement'' piles. **False**
g. Invariably, the larger the shear capacity between the soil and the pile, the better. **False**
h. Piles are generally driven in groups and structurally integrated through either grade beams or pile caps. **True**
i. Iowa loess is highly expansive. **False**
j. Expansive soils are those which exist in loose ``cemented'', semi-dry states and which expand when the cemented bonds disintegrate in the presence of water. **False**
k. A commonly observed rate effect in dry, granular, cohesionless soils is that they show higher strength when loaded rapidly as opposed to quasi-statically. This means that pile driving formula methods to estimate the ultimate capacity of piles in granular, cohesionless soils systematically *over predict* the quasi-static capacity of the piles. **True**
l. The ``freeze'' behavior of piles driven in clay is related to thixotropic behavior. **True**
m. The friction angle between soil and steel piles is generally less than that of a soil's drained internal angle of friction ϕ'. **True**
n. In general, sheetpile wall anchors can be safely placed a distance of 3.5h away from the wall, where h is the height of the anchor. **False**
o. A high liquid limit(LL) and plasticity index (PI) are strong indicators of a highly expansive soil. **True**