Analysis of “Foundations and Retaining Structures - Research and Practice”

Poulos begins the “Bearing Capacity of Shallow Foundations” section of his paper with a discussion of failure mechanisms. A crucial component of foundation design is understanding that the choice of mechanism significantly alters capacity calculations for shallow foundations. Poulos introduces punching and general bearing shear failure, stating that soil fails with “either a general failure mechanism or punching shear failure [mechanism].” General shear failure is brittle, representative of plastic failure. Punching shear failure is elastic and involves gradual settlement without an easily-identifiable strength limit state. Poulos does not provide a plot to assist in his description of these failure mechanisms, but figure 1 displays the footing pressure-settlement relationship of foundations with different failure mechanisms. Poulos states that for general shear, analysis is based on the theory of plasticity [Poulos *et al.,* 2002].

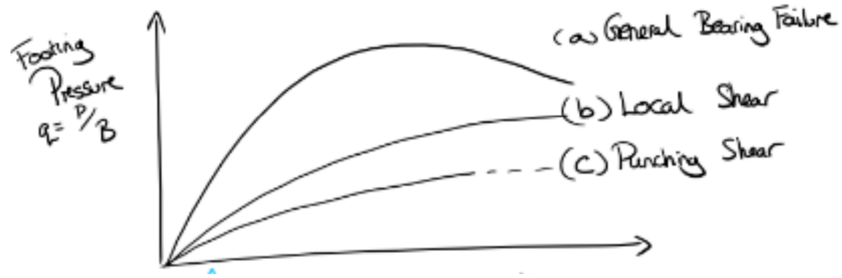

Figure 1. Footing pressure vs. settlement for different mechanisms

Poulos then discusses existing conventional bearing capacity calculation methods, focusing on Vesic and Terzaghi. Vesic’s in particular is widely used in design, but its empirical factors, particularly its self-weight correction factor N_γ, are inaccurate and unconservative. Poulos suggests the use of Davis and Booker’s N_γ value, which was solved using plasticity theory. In class, we conducted a small investigation into the behavior of Vesic’s factors, revealing that they increase exponentially with an increase in effective friction angle (as seen in Figure 2). After reading Poulos’s work, it is clear that this exponential increase is not necessarily indicative of true soil behavior, but just rather the nature of the function chosen to represent the correction factor [Poulos *et al.,* 2002].

However, correcting the self-weight factor of Vesic’s equation is only a first step in generalizing equation 3.1 to better represent the behavior of foundations in 3 dimensions under different loading combinations. Bearing capacity depends largely on the loading combination, and to understand the interaction between three-dimensional horizontal, vertical, and moment loads requires developing a failure envelope of the soil rather than just applying correction factors. In Poulos’s words, “there is a surface in load space, independent of load path,

$$q_u = \frac{Q_u}{BL} = cN_c\zeta_{cr}\zeta_{cs}\zeta_{ci}\zeta_{ct}\zeta_{cg}\zeta_{cd} + \frac{1}{2}B\gamma N_\gamma\zeta_{\gamma r}\zeta_{\gamma s}\zeta_{\gamma i}\zeta_{\gamma t}\zeta_{\gamma g}\zeta_{\gamma d} + qN_q\zeta_{qr}\zeta_{qs}\zeta_{qi}\zeta_{qt}\zeta_{qg}\zeta_{qd} \qquad (3.1)$$

Figure 3. Vesic’s bearing capacity equation

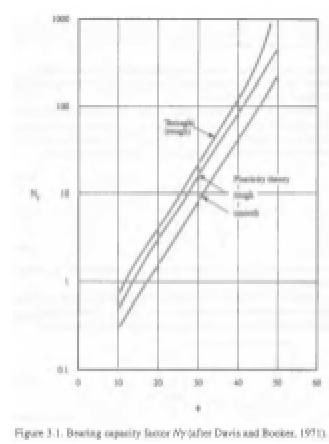

Figure 2. Terzaghi vs. Davis and Booker Factor

containing all combinations of loads . . . that cause failure of the foundation. This surface defines a failure envelope for the foundation," (Poulos, 2535). Many engineers have developed various models of envelopes. All of the analyses discussed focus on undrained soil and are a function of the vertical, horizontal, and moment loads on the foundation [Poulos *et al.,* 2002].

The capacity of a shallow foundation under a given combination of loading (horizontal and vertical, vertical and moment, etc.) varies in a non-linear manner with a change in the loads. For example, when a vertical and horizontal load (inclined load) is applied to a foundation, its vertical and horizontal capacities are interdependent. The vertical capacity for a given horizontal load is different from the vertical capacity with a different horizontal load. It is insufficient to simply calculate load types separately. Geotechnical engineers Bolton, Murff, Bransby, and Randolph developed models of these failure envelopes for strip and circular foundations. These were checked using a numerical analysis to determine the failure envelopes' efficacy. Poulos presents the pros and cons of the different solutions in his paper, but an important take-away is the choice of mechanism vastly alters the success of the model. For example, Bransby and Randolph determined that shallow foundation failure depends on the "scoop" and "wedge" mechanism, but only by fitting their model to a particular "scoop-wedge" failure plane do their results match the numerical analysis. This matches with content covered in class, as changing the failure mechanism for undrained analyses can vastly alter the upper-bound capacity prediction. In fact, determining an exact general failure equation for foundations subjected to combined and eccentric loading is practically impossible given all of the possible mechanisms and loading conditions. Even the somewhat accurate 3-D general failure model developed by Taiebet and Carter relies on empiricism in its factors (empiricism was part of the problem with Vesic's and Terzaghi's that these analyses were trying to fix in the first place), which highlights the difficulty of deriving an accurate model using theory [Poulos *et al.,* 2002].

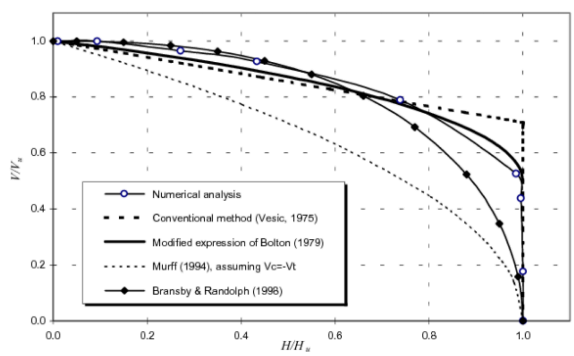

Figure 3. Vertical versus horizontal normalized with ultimate loads

Next, Poulos examines the efficacy of the "effective width method" to analyze capacity of a shallow foundation under eccentric loading. In this method, only the portion of the foundation in which the load is central to is considered in the capacity calculation. Poulos concludes that this is a somewhat accurate and conservative estimate for capacity under eccentric loading and is acceptable for design codes. Some pushback against this conclusion is found in work by Michalowski, which states that "The effective width rule significantly underestimates the bearing capacity for clays (ϕ≈0) only when the footing is bonded with the soil and the eccentricity is relatively large (e/B>0.25). For cohesive–frictional soils this underestimation decreases with an increase in the internal friction angle." While Poulos applauds this method for its conservatism, its simplicity means that it can sometimes be an underestimation to the point of inaccuracy [Poulos *et al.,* 2002].

To dive further into factors affecting bearing capacity, Poulos speaks on three major categories of soil configurations beneath shallow foundations; clays with undrained shear strength increasing linearly with depth, two soil layers with different strengths parameters, and multiple layers with different strength parameters (3 or more layers). There are two studies on linearly increasing undrained shear strength with depth done by Davis and Booker (1973) and Tani and Craig (1995) that Poulos notes in this paper. In both studies, equations for bearing capacity were developed that have proved to be reliable in the field. Davis and Booker assumed the soil obeyed the Tresca Yield Criterion. For rectangular shallow foundations, they derived that bearing capacity is a function of the change in shear strength as well as the soil-structure interaction (see equation 1). The parameter ρ is the strength gradient, which measures the undrained shear strength fluctuates as depth increases. Figure 5, which is seen below, is a figure from Davis and Bookers' study relating the bearing capacity function to those parameters. Tani and Craig later expanded upon this study. They approached the problem through the Theory of Plasticity and found very similar findings to those of Davis and Booker. They also analyzed the bearing capacity of circular foundations, and shallow foundations embedded into the soil. They found that the undrained shear strength directly beneath the embedded pile toe governed the bearing capacity compared to the undrained shear strength at the soil surface. [Poulos *et al.,* 2002].

$$q_u = \frac{Q_u}{B} = F\left[(2 + \pi)c_0 + \frac{\rho B}{4}\right] \qquad \text{Eq 1 (Davis and Booker, 1973)}$$

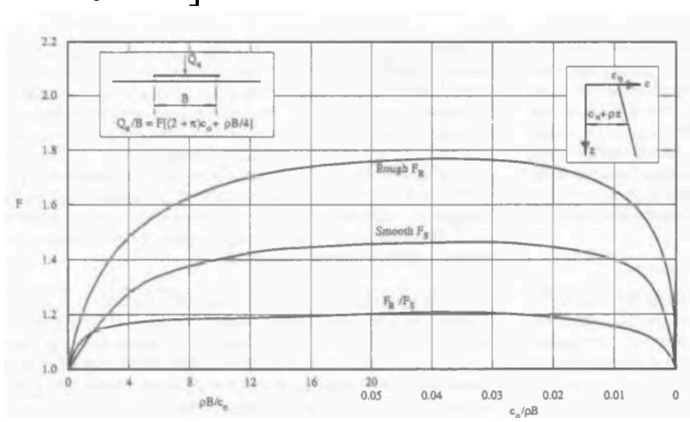

Figure 5. Bearing Capacity of a Strip Footing on Non-homogeneous Clay (after Davis and Booker) [Poulos *et al.,* 2002]

The second soil layout Poulos highlighted was the case of two distinct soil layers below the shallow foundation. There is a certain interest in this scenario because of two specific cases; strong soil overlaying weak soil, and sand overlying clay. These have a high risk of punching failure, so a lot of time has been put into making sure this behavior is predicted accurately and efficiently. To understand how punching shear failure may occur, see Figure 6 below. The mechanism of strong soil over weak soil is similar to that of sand over clay. The top layer will displace directly downwards as a rigid block, displacing the weaker soil beneath. This mechanism is similar to simpler mechanisms that have been seen in this course. There have been many studies done to analyze the bearing capacity of two-layer soils following different methods. Poulos mentioned using average strength parameters (Bowels, 1988), limit equilibrium equilibrium considerations (Button, 1953; Reddy and Srinivasan, 1967; Meyerhof, 1974), and a limit analysis approach (Chen and Davidson, 1973; Florkiewicz, 1989; Michalowski and Shi, 1995; Marfield *et al.,* 1999). However, all of these studies only looked at foundations resting on top of the soil. The bearing capacity analysis was broken further into two types, small deformation analysis and large deformation analysis. The difference between these two methods is that for large deformation analysis, the soil beneath the foundation is weak enough for settlement to occur prior to loading. This settlement is significant enough that the surrounding soil needs to be considered in the bearing capacity equations [Poulos *et al.,* 2002].

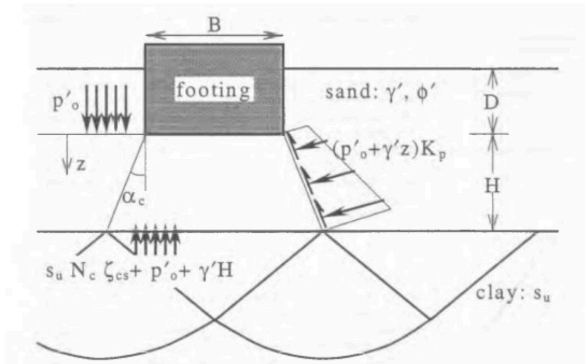

Figure 6. Failure Mechanisms Suggested by Okimura *et al.* (1998) for Estimating the Bearing Capacity of a Layer of Sand Over Clay [Poulos *et al.,* 2002]

Lastly, Poulos spoke on analysis methods for multiple-layered soils. Unlike the other cases, there is not a generic approach. Poulos questions if simple hand calculations can be used to realistically evaluate the bearing capacity. He recommends answering the following questions: Can the bearing capacity be accurately estimated by computing the average bearing capacities over a particular depth? If not, can the strength of the layers be averaged and used in the bearing capacity calculation to get a reliable estimate? If neither are accurate, how can a reliable estimate of bearing capacity be estimated? There has not been a straightforward answer to this last question. Studies have been done looking at six specific cases with only 3 layers. However, it was noted by those performing these studies that there were assumptions that were used in the bearing capacity equations that were specific to each case. Poulos notes these restrictions and comments that they “[...] highlight the necessity of being aware of the limitations of all design methods, if very substantial errors in estimating the bearing capacity are to be avoided” [Poulos *et al.,* 2002]. Because of these limitations, a standard estimate for bearing capacity of multiple-layered soils has not been derived.

Poulos evaluated the reliability of bearing capacity estimations from various studies. With particular emphasis on the methodologies to use in analyzing combined loadings and shallow foundation capacities in heterogeneous soils. His findings included updating the bearing capacity factors in conventional methods, using alternative bearing capacity equations for various soil configurations, and examining failure mechanisms and envelopes. These findings tie to common themes in geotechnical engineering, including the limitations of empiricism, importance of mechanism selection and understanding where equations can be realistically applied.

Sources:

Michalowski, R. L. (1999, February 1). *Effective width rule in calculations of bearing capacity of shallow footings*. Computers and Geotechnics.

Poulos *et al.,* 2002, “Foundations and Retaining Structures - Research and Practice”