Design of excavation support using apparent earth pressure diagrams: consistent design or consistent problem?

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ABSTRACT: Over the past 40 years owner agencies in North America have commonly specified minimum earth pressures for design of excavation support systems with detailed design assigned to the contractor. Minimum pressures are typically specified using "apparent earth pressure" diagrams. For urban excavations, the owner's objective is for the support systems to be safe and to limit displacements that might damage properties. The contractor seeks to design the most economical support. These two objectives can be in conflict and the specified design pressures can be at the root of many disputes. This paper summarizes the basis of apparent earth pressure distribution diagrams, their failings, proposes a new semi-empirical method for determining appropriate design pressures, and proposes an alternative approach to contract specification.

1 INTRODUCTION & HISTORICAL BACKGROUND

During the early 20th century, it was observed that the upper supports of temporary excavation support walls experienced relatively high loads and that the distribution of earth pressures on the walls bore "··· little resemblance to the theoretical distribution" (Terzaghi 1936). Based on a number of theoretical and practical considerations, Terzaghi and Peck (1947), developed the notion of "apparent earth pressures". Apparent earth pressures were so called because, having measured the support loads, these loads were then used to back-calculate pressures by distributing the loads over some assumed contributing area of the soil mass (i.e., the pressures were not directly measured). Through the 1960's, data was gathered from subway projects in Berlin, Chicago, New York, Oslo, and Toronto from which apparent earth pressure diagrams were developed for generalized soil types as illustrated in Figure 1.

Observed loads on struts and earth pressures on flexible walls are highly variable, confounding attempts at true prediction, though many back analyses have can resemble field measurements. Measurements of earth pressures on full-scale walls, model tests, and computer simulations also demonstrate that earth pressures are typically more concentrated near wall supports, depending on soil type and wall type as illustrated in Figure 2. This phenomenon has been termed "arching" or ascribed to the stiff supports "attracting" higher loads. To account for this load variation and to permit design optimization, design loads or moments are often based on theoretical earth pressure distributions or application of empirical load reduction factors to the apparent earth pressure diagram. More than 40 years after apparent earth pressure diagrams were first proposed, they are still in use and many issues associated with shoring design and specification remain unresolved.

2 PROBLEMS IN DESIGN & SPECIFICATION

2.1 *Contract issues*

Using apparent earth pressure diagrams, while attractive for their simplicity and generally conservative results with respect to overall shoring stability, can be problematic, particularly in the context of contract requirements or control of displacements.

Underground construction projects in North America often use design-bid-build contracts awarded on the basis of the lowest bid. This practice can lead to several fundamental conflicts related to shoring design. The owner must be concerned about the effects of construction on properties owned by others. This should encourage owners to be both proactive and conservative. At the same time, owners ask for the lowest possible cost within the framework of the contract. Often, detailed shoring design is left to the contractor to encourage use of readily available materials and ingenuity and to avoid interfering with construction operations. The contractor, trying to achieve the lowest possible bid, seeks to design the least costly system. The most economical system is, however, not necessarily one that will maintain displacements within tolerable limits. Therefore, owners or their representatives set requirements that are believed to protect the owner's

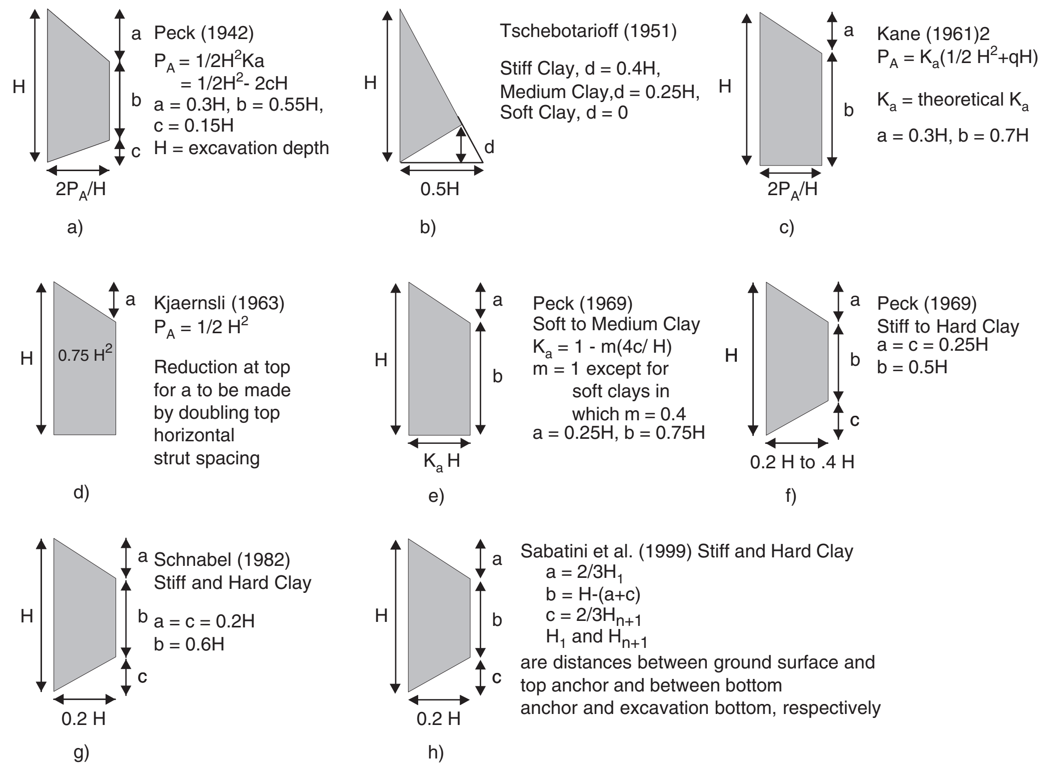

Figure 1. Apparent earth pressure diagrams.

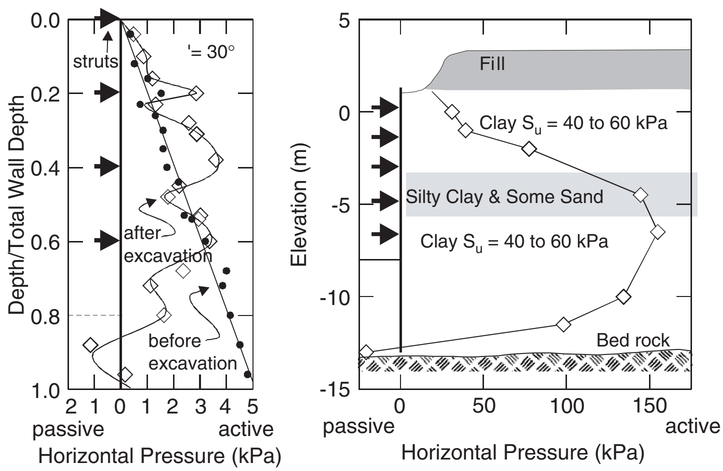

Figure 2. Measured variation of earth pressure distribution for flexible walls. Left: scale model wall in granular soil, $\phi' = 30°$, $S_r = 5.7$ (Rowe and Briggs 1964); Right: field measurements on wall in soft clay, $S_r = 10$ (NGI 1962).

interest while permitting the most freedom for the contractor. Minimum shoring design and construction requirements are often set out in a performance specification. To assure safety, a minimum design load is specified, often through using an apparent earth pressure diagram (e.g. MHD 1993, NYCTA 1994). To limit damage to adjacent facilities, displacement performance limitations are also established. Once having been awarded a bid, it is in the contractor's interest to further limit the cost of the shoring. Thus, the owner's "minimum" prescribed earth pressure becomes the contractor's "maximum" cost earth pressure. Given the imprecise nature of shoring design, technical issues often become avenues of conflict.

2.2 *Design issues*

The effects of and methods to account for high in situ horizontal stresses are not well established, though some apparent earth pressure diagrams imply some effect of this; e.g. for stiff to hard clay (Peck 1969). Depending on the chosen apparent earth pressure diagram, the total "apparent" load on the temporary excavation support system can be greater than the design load for the permanent structure – an apparent conflict of purpose. Opinions on the appropriateness of different diagrams differ widely and selection of a particular apparent earth pressure diagram for design is often highly subjective.

Reducing wall design bending moments, where the maximum bending moment is calculated using theoretical active earth pressures, has been proposed and demonstrated to be valid for anchored flexible bulkhead walls (e.g. Rowe 1952, Rowe and Briggs 1961). Peck et al. (1973) suggest that the earth loads on the vertical components of braced excavation support walls could be reduced by applying a multiplying factor as low as 0.67 to the apparent earth pressure diagram, but the applicability of such reductions is subject to dispute (e.g. Goldberg et al. 1976).

"Stiff walls", such as concrete diaphragm walls, are often designed using active or "at-rest" earth pressures rather than apparent earth pressure diagrams. Thus, there is a discrepancy between the shape of the assumed earth pressure distribution that depends on the retaining structure stiffness but the definitions of and transitions from "flexible" to "stiff" wall systems are not well established.

Design practices for anchored flexible bulkheads are markedly different than for braced excavations, yet many of the same fundamental soil mechanics principles likely prevail in their performance. Apparent earth pressure diagrams typically terminate at the base of the excavation – in this case, the principles used to design the embedment depth of the wall are primarily empirical or judgment-based in nature. The shoring engineer has several tools available for solving such design problems including:

- relatively simple structural beam calculations based directly on the apparent earth pressures or some reduction thereof;
- use of beam-on-elastic-foundation computer programs with soil pressures and assumed "spring" responses; or
- sophisticated numerical modeling.

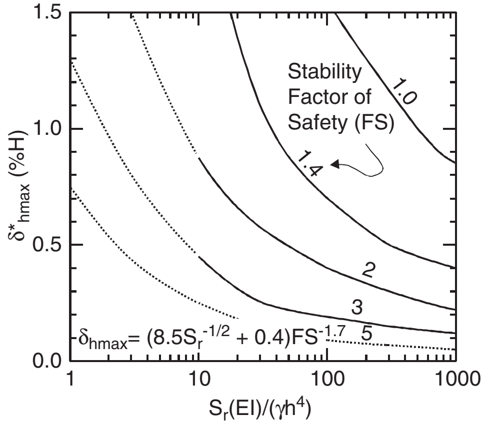

Figure 3. Maximum lateral displacement, factor of safety for overall stability, and relative shoring system stiffness (after Boone and Westland 2005).

Beam-on-elastic foundation models, while providing a more rigorous structural analysis, still rely on simplified earth pressure assumptions. Numerical modeling, while a powerful tool, can produce inadequate or misleading results depending on the choices for soil parameters and constitutive equations, model discretisation, interfaces, assumptions for construction sequences, and the training of the personnel using modeling software.

The net result is that any one particular shoring design can be relatively arbitrary – and the differences between practicing engineers can vary considerably. Most importantly for urban projects, the relationship between wall displacement and design earth pressure can sometimes be neglected.

For design of excavation support systems in soft clay soils, studies have been completed that, using parametric numerical modeling and field data, demonstrate the relationship between support system stiffness, excavation stability factor of safety, and displacement. These concepts have also been extended to granular soils and very flexible retaining systems (see Figure 3). It is clear in Figure 2 that the distribution of earth pressure depends on its stiffness and ground conditions. All of these characteristics of shoring systems therefore should be related and considered during design and specification.

3 EARTH PRESSURES ON FLEXIBLE WALLS

Earth pressure on shoring systems can concentrate near support locations, as illustrated in Figure 2. However, curved earth pressure distributions, as may be derived from numerical modelling, would be too difficult to specify for particular projects, as the specific locations of supports and wall stiffness may

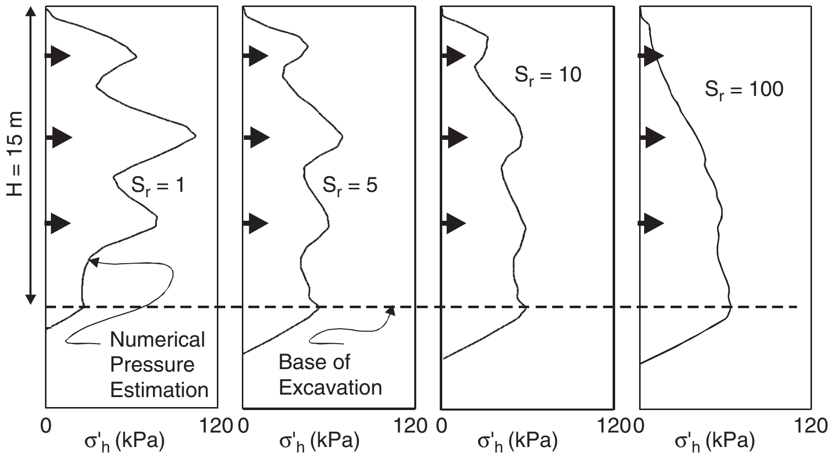

Figure 4. Variation of net horizontal earth pressure related to wall stiffness illustrating the transition from "flexible" to "stiff" retaining structure. Example shown for homogeneous granular soil ($\phi' = 30°$) and three strut supports.

be unknown if detailed design was assigned to the contractor. Alternatively, they could be approximated by an project-specific apparent earth pressure diagram.

The results of non-linear parametric numerical models, in which only the wall stiffness was varied (Boone 2003), illustrate that the shape of the earth pressure distribution evolves from one that can be bound by a trapezoidal envelope to one that is more consistent with a theoretical earth pressure distribution (see Figure 4). The evolution of earth pressure distribution shape depends on the relative stiffness of the wall system in comparison to the strength of the ground. For an equivalent wall stiffness, soils that impose less load on the shoring will exhibit a more triangular stress distribution.

The parametric numerical modeling also indicated that *total* active loads (area of the pressure diagram, "net" of passive pressure below the excavation base) on support walls in granular soils estimated by numerical modeling, closed-form active earth pressure formulae, limit equilibrium analyses, or Peck's (1969) apparent earth pressure diagram were all within about 10% of each other, as shown schematically by Figure 5. This illustrates an important concept: though the in situ construction of a flexible retaining structure may locally change the pattern of load distribution, the total load imposed by the earth mass changes very little.

Complicating these relationships, however, is the sequencing and time of construction. In a cohesive soil, the soil may be relatively selfsupporting for a time near the top of the cut and impart little load on the structure, consistent with the zone of "tension" expressed by the well-known Bell's equation (Bell 1915). Rotation of the wall about the position of the first support, as the excavation is carried to the level of the second support, causes the earth pressure to transition from

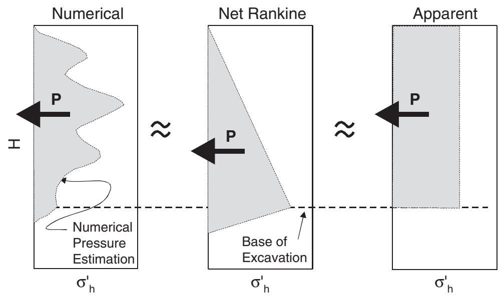

Figure 5. Illustration of approximate equality of total net active loads on flexible retaining structures in granular soils.

active behaviour toward a passive pressure condition. Over time, as the soil and support structure continue to deform, the upper materials again actively load the structure. Drainage conditions may also result in the soil transitioning from undrained to effective stress behaviour.

As with apparent earth pressure diagrams and the principles of flexible bulkhead design, the goal of the semi-empirical design pressure is not to replicate the exact pressure distribution but to provide a reasonable basis for design that, through structural analysis, produces bending moments close to those that might occur in the field. The proposed approach to earth pressure distribution approximation follows:

1. Prepare Rankine active earth pressure diagrams or, for cohesive soils use Bell's equations but ignore the tension zone and consider the distribution starting from the surface of the deposit to the maximum earth pressure (e.g. Bowles 1996). Alternatively, total earth mass loads may be determined

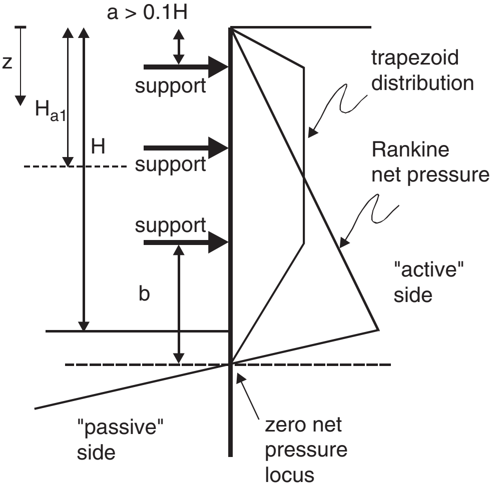

Figure 6. Simplified Rankine "net" pressure diagram and trapezoidal pressure diagram.

using limit equilibrium methods (e.g. Rahardjo and Fredlund 1983).

2. Select a trial relative wall stiffness, S_r, according to the following guidelines:
   - for dense granular soils or hard clay, choose $S_r = 5$;
   - for loose to medium dense granular soils or for medium clay, choose $S_r = 10$; and
   - for soft clay, choose $S_r > 30$.

   where $S_r = EI/(h^4\gamma)$, E = modulus of elasticity of wall, I = internal moment of inertia of wall per unit length of wall, γ = unit weight of soil, and h = average vertical spacing between supports (also see Boone and Westland 2005).
3. Determine the total net active load (to zero net pressure locus, see Figure 6).
4. Prepare a trapezoidal earth pressure diagram using the total load equal to that from the net active earth pressure diagram defined above (see Figure 6). The top transition point (to depth "a" as shown), is defined by the first strut location, provided that the first support is positioned at a point greater than about 10%H from the wall top. Otherwise, the second support position will govern the transition point.
5. Combine the two diagrams according to the following rule:

$$\sigma'_h = \sigma'_{h\,(Rankine)}\,\alpha_\sigma + (1-\alpha_\sigma)\,\sigma'_{h\,(Trapezoid)}$$

where α_σ is defined by Figure 7 and K_{a1} is the initial active earth pressure coefficient over the maximum depth of the excavation supported by a single strut. For example, in an excavation supported by two struts,

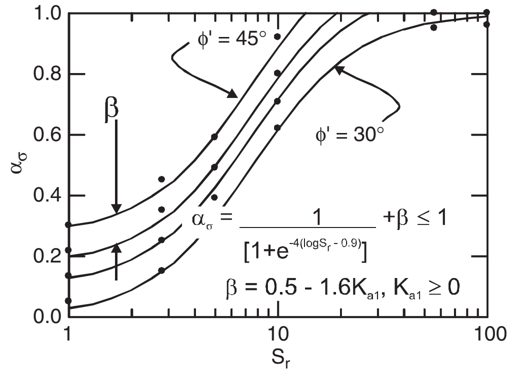

Figure 7. Earth pressure distribution shape factor.

this depth would be equivalent to the depth from the surface to immediately below where the second strut would be installed. In the case of cohesive soils, the active undrained earth pressure coefficient is taken as $K_{a1} = 2P_a/(\gamma H_{a1}^2)$ where P_a is the total active earth load and H_{a1} is the effective depth for the first support level as defined above. The zone of "tension" resulting from using Bell's equation for the active horizontal earth pressure for undrained cohesive soils (S_u = undrained shear strength), where $\sigma_h = \gamma z - 2S_u$, may produce a negative or very small value of K_{a1}. In this case, K_{a1} should be no less than zero and the maximum value of α_σ will result. Several examples are shown in Figure 8.

After estimating the pressure distribution the maximum support loads and bending moments can be determined using common indeterminate structural analysis methods. Although the position of zero net pressure may not be coincident with the point of zero moment, the zero net pressure locus may be used as the end point of the equivalent structural beam (and last support) for practical design purposes, following the approach commonly employed for design of flexible bulkheads (e.g. NAVFAC 1986).

Defining earth pressures using these methods produces design moments consistent with the results of Rowe's physical modeling and "moment reduction factors" and, therefore, no further modification of the design loads need be made to arrive at appropriate design moments (Boone 2003).

Although this approach provides a systematic method of determining earth loads and their distribution under "active" loading conditions, introduction of relatively high preloading stresses will alter both the magnitude and distribution of stresses and how these stresses are carried by the supports. The effects of temperature will also affect total loads on the supports (Boone and Crawford, 2000). Preloading of supports up to 100% of the design earth loads would not alter the anticipated earth loading. Greater prestresses, however, would have to be considered separately and

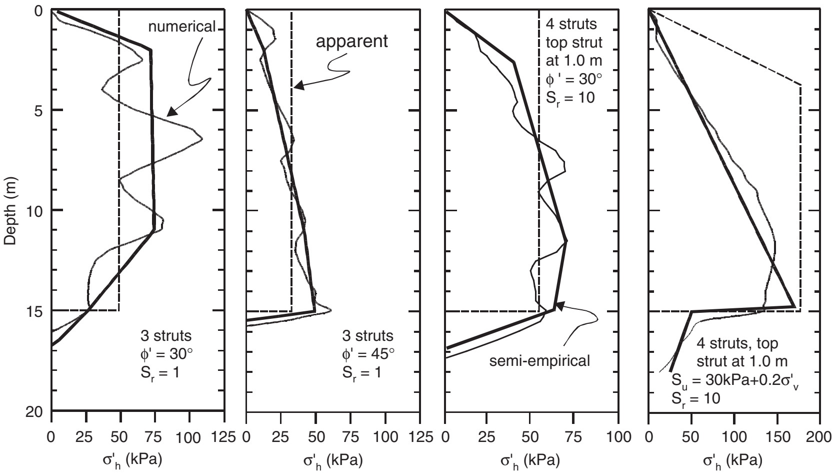

Figure 8. Examples of semi-empirical earth pressure estimation method as compared to numerical modeling (thin lines) and typical apparent earth pressure diagrams (dashed lines) for non-preloaded systems.

will influence the distribution of pressure on the wall system.

4 DISCUSSION & CONCLUSIONS

Design of excavation support systems using apparent earth pressure diagrams requires considerable judgment and local experience. Contractually specifying that design be completed using a specific apparent earth pressure diagram can be a source of technical and contractual conflict. Even if a suitable apparent earth pressure can be agreed upon, designs based solely on an apparent earth pressure diagram may be entirely unrelated to displacement control needs. Alternatively, it is suggested that non-dimensional shoring system stiffness (S_r,) is a relatively unambiguous design criteria that can be directly related to displacement control (e.g. Boone and Westland 2005). Having defined a systematic method by which displacement and design loads are directly related, these and other individual factors may be more rationally taken into account in design or specification.

Prior to specification of excavation support, relatively simple estimations of both displacement and pressure can be made using the methods described in this paper and Boone and Westland (2005) to ascertain whether or not a particular shoring system might perform as desired. Having assessed the minimum performance required for any one particular project, it is concluded that using the non-dimensional relative stiffness results in a more systematic and justifiable design process as well as providing a less contentious approach to shoring specification than the conventional application of apparent earth pressure diagrams.

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