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Managing Impacts Of Ground Movement In Urban Tunneling

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Summary

This paper reviews technical and management issues associated with construction- induced ground movement during tunnel construction in urban areas.

1.0 Introduction

This paper discusses effects caused by excavation of the Massachusetts Highway Department Central Artery tunnels in downtown Boston. Designers and contractors must tread a fine line between satisfying owners of adjacent properties and various organizations, who wish construction to proceed without any effects on the surroundings, and the construction realities of the project, in which it is impossible to build without any disturbance at all. The discussion includes:

- Methods used to predict excavation soil movement and effects on nearby structures.
- Construction methods for mitigation of soil movement.
- Issues related to management of excavation soil movement and its effects.

2.0 Causes Of Ground Movement During Excavation

Sources of ground movements beyond the limits of an excavation can be placed in two general categories:

(1.) Deformations of the excavation support system components.
(2.) Ground deformations as influenced by the response of surrounding soils and groundwater to excavation activities.

For simplicity, these categories are referred to as internal and external deformations, respectively.

Internal sources of deformation largely concern the structural response of the excavation wall system. During excavation, the wall deforms in bending between bracing points and as a cantilever above the top bracing point. The tiebacks extend in tension, or the struts deform in compression. External sources of deformation are related to the behavior of the soil mass as a whole. External sources of deformation include the overall global behavior of the soil mass and effects of consolidation.

2.1 Internal Sources of Deformation

2.1.1 Lateral Pressures.
Numerous methods have been developed for prediction of earth pressures. However, no single method can be considered precise due to the non-uniformity of the soil mass (actual versus modeled conditions) and the fact that actual earth pressures cannot be measured with adequate precision during construction. Also, the geologic conditions relating to seepage of groundwater, and the resulting magnitude of hydrostatic pressure, present similar challenges in modeling of the soil/structure behavior.

The magnitude of earth pressures is generally inversely proportional to the strength of the soil, particularly when Coulomb and Rankine parameters are utilized. The stress history also influences the magnitude of lateral earth pressure coefficients, particularly in clays.

The magnitude of earth pressure is further proportional to the amount of yielding of the wall support system. For a support system which is theoretically non-yielding, the at-rest, or K_o, parameter applies for calculation of lateral pressure. However, as the support system yields, the coefficient of lateral earth pressure approaches the active, or K_a condition. It is generally unrealistic to design a temporary support system which is non-yielding. Design for the at-rest condition is therefore most frequently applied to the design of permanent structures. However, when in fact a relatively rigid temporary support system is desired, it may become necessary to apply an earth pressure coefficient which falls between the at rest and active condition. The determination of the magnitude of such a coefficient generally requires considerable judgement.

In cases where impervious walls are installed, the hydrostatic pressures can be greater than those induced by earth pressures. The distribution of hydrostatic pressures along the length of the walls thus has considerable influence on the total forces acting on the support system. The shape of the hydrostatic pressure diagram is governed by the permeability of the support wall and seepage conditions which are mobilized as a result of dewatering within the excavation. The combination of an impermeable wall and the assumption of no seepage into the excavation represents the case of maximum hydrostatic pressures acting on the wall. The associated pressure increases linearly with depth, from the design groundwater level to the bottom of the wall. In the case where seepage is assumed, the magnitude of pressure distribution, particularly at the lower reaches of the excavation, can decrease considerably from the no seepage case. A seepage analysis can be preformed to establish the steady state pressure distribution along the length of the wall.

When lateral loads are imposed on a support system, elastic deformations of structural elements are induced. The walls move inward, resulting in a field of horizontal and vertical soil movements induced in the soil mass beyond the excavation. The initial stage of most cut-and-cover excavation usually results in a cantilever condition of the wall. Such a condition is present both prior to and after installation of the first level of bracing. In the initial state, the soil at the interim subgrade represents the cantilever reaction point. The effective length of the cantilever exceeds the depth of the excavation since the point fixity cannot occur at the excavated surface. The depth of fixity is governed by soil strength and wall stiffness. Once the first bracing member is installed, the cantilever length is effectively decreased. However, the settlement outside the excavation which occurred in the prior stage is not recovered. This is to say that during the staged excavation, the magnitudes of soil settlement are cumulative.

At subsequent stages of excavation the wall acts as a continuous beam, with bracing members behaving as reaction points. Wall deformations now become a factor, in part, of span length between the brace points. As with the cantilever condition, the condition which influences the magnitude of deformation is that which exists immediately prior to bracing installation, wherein the effective span length is greater than the vertical spacing of bracing levels. In effect, the soil deforms below the excavation line before the next brace level can be installed. This phenomenon, where the soil at subgrade deforms with the imposition of wall loads, is termed the "bulge effect".

In cut-and-cover tunneling through compressible soils, the "bulge effect" commonly represents the largest single source of deformations and is the most difficult to control. When the subgrade soil immediately below the excavation acts as a reaction for wall loads, this mass of soil is placed in compression. The wall pushes against it in a passive mode of soil loading. As a result, the soil mass deforms and inward movement of the wall results. The resulting settlements are generally non-recoverable and accumulate as excavation progresses. The condition becomes more problematic when compressible soils extend to depths beyond that of the final excavation. Measures designed to lessen these deformations may have limitations on the depths at which they remain technically and economically feasible to implement.

2.2 External Sources of Deformation

2.2.1 Consolidation Due to Seepage and Dewatering

For excavation through compressible soils, consolidation settlement can be caused by changes in piezometric head. The magnitude of consolidation settlement is primarily a function of the thickness, consolidation or recompression ratios, and stress history of the compressible strata; the magnitude and duration of groundwater drawdown, and the permeability of the drained aquifers.

Dewatering is almost unavoidable when constructing a cut-and-cover tunnel. Dewatering can be done by the installation of pumping wells outside the excavation, sumps and pumps within the excavation, or both. However, in cases where it is necessary to maintain groundwater levels beyond the excavation, external pumping wells cannot be installed.

Pressure relief, a form of dewatering, is required when hydrostatic uplift of the invert is to be prevented. Such a condition can occur when a relatively impervious soil within the limits of excavation is underlain by relatively pervious stratum. If the weight of remaining impervious layer is less than the hydrostatic force acting on the bottom of the stratum, uplift can occur. To avoid this situation, the underlying pervious layer should be penetrated by a series of pressure relief wells designed to effect depressurization. However, if the walls of the excavation do not extend into an impervious stratum below the pervious layer, the depressurization will extend beyond the limits of the excavation, thus resulting in the potential for consolidation settlement.

3.0 Methods Of Predicting Deformation

The magnitude and position of the soil movement outside the excavation is important since it directly affects structures along the right-of-way. Too much deformation or a significant dropping of the water table can lead to serious damage and safety concerns for the existing structures. This is particularly important for older historic buildings.

Methods for predicting soil movement include:

3.1 Previous Experience.
Evaluation based on results from excavation of similar conditions.

3.2 Semi-Empirical Methods.
Recent studies have attempted to correlate past experience with generalized analysis of wall and bracing systems. Clough and O'Rourke (1990) prepared a study in which movement observations from several excavations were tabulated and compared against the stiffness of the wall systems and the factor of safety against basal heave. Figure 1, taken from the paper, illustrates some results from use of the method. For excavation in soft to medium clay, the figure compares normalized maximum lateral wall movement to wall system stiffness, which is defined as:

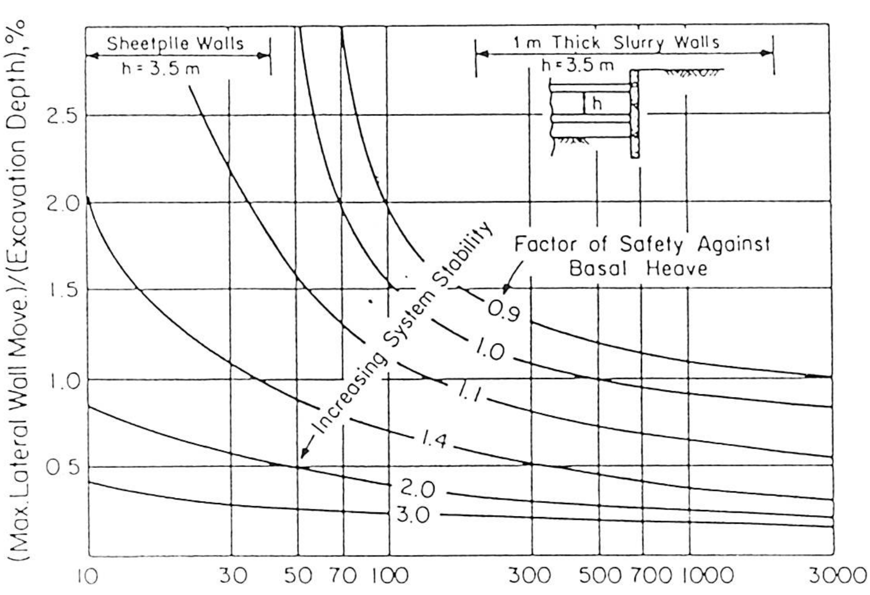
$$EI / \gamma_w h^4$$

where E is the Modulus of Elasticity of the wall, I is the moment of inertia of the wall, γ_w is the unit weight of water, and h is the average spacing between brace levels. Different curves are presented for different factors of safety against basal heave, FS, where FS is defined as:

$$N_c s / (\gamma D + p)$$

and D is the depth of excavation, γ is the density of the clay, s is the undrained shear strength of the clay at the bottom of the excavation, p is a surface surcharge, and Nc is a coefficient depending upon the dimensions of the excavation.

MOVEMENTS OF INSITU WALLS



The figure and accompanying study were prepared by correlating soil-structure interaction analyses to wall movement calculations observed from actual excavations.

3.3 Analysis for Soil-Structure Interaction.

For this analysis, the soil and structure are modeled as a mass. The mass is broken up into discrete elements and assigned elastic or inelastic properties. Using the finite element or finite difference method, stress and strain of each material in the model are related. The model predicts wall and soil movement by simulating the states of stress caused by the construction process.

Application of the program, SOILSTRUCT, serves as an example of this type of analysis. SOILSTRUCT includes available elastic models for wall and bracing elements, hyperbolic stress-strain relationships to model the behavior of the soil mass, and a capability of simulating staged construction. For this last capability, the engineer makes assumptions about the sequence of the excavation, including depth of each cut and installation of bracing. The model sequentially deactivates blocks of soil and adds bracing pre-loads. The soil mass

behind the wall reacts to the modeled construction behavior based on the constitutive material properties input into the program.

The analysis will also need to consider effects due to consolidation. Other factors to be considered include the potential for variable construction practice, such as cross lot braces not installed snugly, or preloading improperly applied.

3.4 Evaluation of existing structures.

The analysis is not complete without an evaluation of the effects of soil movement on existing structures along the right-of-way. The excavation and wall movement analysis will provide estimates for a field of soil movement behind the wall. This movement can be imposed upon models of the existing building structures to estimate effects. For example, for a particular type of building structural frame and foundation system, certain support points can be deflected based on the wall movement analysis. The resulting effects on the building structure can be quantified.

The analysis also needs to consider effects not so easily quantified, such as the condition of the existing building. A distinction can be made between "structural" damage and "architectural" damage. Structural damage due to adjacent excavation involves significant damage or failure to major structural members of the building. Architectural damage is mostly cosmetic: cracked facades, doors out of plumb, etc. Architectural damage can be more easily dealt with after construction is complete. However, for historic buildings, even the imposition of architectural damage may not be acceptable.

Boscardin and Cording (1989) prepared studies analyzing the effects of soil displacement beneath building structures. Their studies attempted to quantify various parameters associates with the soil movement, and they compared applied their method to some tunneling case histories.

4.0 Construction Methods To Reduce Soil Moment

Faced with the challenge of designing and constructing a cut-and-cover tunnel in a densely built area, the designer and contractor need to consider various methods to limit soil movement. The approaches need to consider the two major sources, wall movement and movement due to consolidation. Methods to address the problem include:

- Making the walls stiffer, deeper, or less permeable. For example, concrete slurry walls are stiffer than sheet piling or soldier piles and lagging. Soldier pile tremie concrete (SPTC) walls are stiffer than concrete slurry walls.
- Use of more or stiffer braces
- Preloading cross lot braces
- Methods to control consolidation such as curtain grouting, blanket grouting, and groundwater recharge beyond excavation support walls.
- Construction staging methods, such as limiting the longitudinal extent of excavation to take advantage of "3D" stiffness effects.
- Less conventional methods such as ground freezing
- If soil movement is still too great, underpinning existing building structures. However, underpinning must be done with great care, because the impact on the building can be greater than what would have been imposed by tunnel construction.

Geotechnical exploration and instrumentation during excavation form an important part of the overall program to manage and control construction excavation impacts. An extensive boring program provides the basis for the engineering decisions. Instrumentation for ground movement, water table impacts, and effects to existing buildings, provides checkpoints to monitor the construction and take corrective actions if needed.

Acknowledgments

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