NOTES ON IMPROVEMENT AND UNDERPINNING OF FOUNDATIONS OF HISTORIC STRUCTURES WITH RETICULATED MICROPILES

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ABSTRACT. This paper illustrates the benefit of using micropiles for underpinning historic structures. First, traditional underpinning of structures is reviewed, noting the negative effects to the structure caused by excavation and unloading of the original foundation and then reloading the structure. Second, micropiles are presented as a rational alternative with the advantages of at-grade installation and efficient load transfer with minimal displacement.

INTRODUCTION

The need to improve the foundations of structures has spawned many solutions throughout history. The most simple is the direct excavation of support soils immediately under the structure and widening the footing or base of the wall. If the soil can not support the structure adequately with the widened footing or wall, then subsequent construction of deep foundation elements would proceed, typically installed in a staggered construction sequence. This has been the basic historic methodology for underpinning and retrofit. As structural materials and connections evolved and improved, they were incorporated into this basic process. These methods unload the foundation soil and change the load path through the soil and structure during construction of the new foundation elements, as shown in Figure 1. Alteration of the load path with induced shear stresses occurs at each stage of excavation and foundation construction and can cause additional distress to the structure.

An alternative to these traditional methods is the use of micropiles for underpinning and retrofitting. Lizzi (1982) realized the negative effects of unloading the foundations of historic structures while designing and constructing retrofits during the 1950s in Italy and throughout Europe. Lizzi developed the micropile, the reticulated micropile group, and the reticulated internal reinforcement for strengthening non-reinforced stone or masonry superstructures. With these systems, the strengthening is accomplished without unloading the structure or foundation.

In this paper, the evolution of these methods is described briefly. A more detailed evaluation will be presented at the Transportation Research Board meeting in January 2000.

EARLY METHODS OF UNDERPINNING

In the United States, the rational development of underpinning for structures is often credited to the New York engineering firm of Spencer, White and Prentis. Their text, first published in 1917 and updated in 1931 (Prentis and White, 1931), set the course of underpinning for many years. However, earlier work by Sooysmith (1896) and Breuchaud (1896) also was instrumental in evol-ving these methods from purely empirical to semi-rational. These engineers were working on heavy buildings in New York and Chicago during the mid to late 1800s, and they influenced the development and implementation of deep foundation design, construction, and underpinning. However, the techniques that they developed for underpinning required the excavation of the existing foundation system to construct the new system.

Jacoby and Davis (1925) published a text on "Foundations of Bridges and Buildings" in 1917, which was updated in 1925. In this text was a section on underpinning. They developed methods that would not disrupt the normal traffic and pedestrian flow into a building that was being retrofitted, which was a typical problem for many other methods of underpinning. Their development was the "needle-beam" method of temporary support.

All of these methods consist of externally propping and supporting the structure with a temporary system so that subsequent excavation and underpinning could progress. The rationale for these techniques was that external systems were necessary to stabilize the structure-foundation system. Non-reinforced masonry and stone structures were contained delicately to allow a "fix" to be implemented.

LIZZI AND THE DEVELOPMENT OF MICROPILES

The typical scheme for underpinning, with respect to the wall of a structure, was to install piles either some distance outside of the face of the wall or in the plane of the wall. Both methods necessarily cause soil and structure relaxation - a negative condition in both cases. Lizzi realized that, for an effective foundation and structure retrofit, both of these conditions must be overcome. He explored the concept of internal reinforcement that would not disrupt the original aesthetic intended by the designer. The result is what we now know as micropiles and internal strengthening of the structure.

In the traditional Lizzi (1982) design method, the micropile is a cast-in-place concrete pile, approximately 300 mm in diameter, with a central steel reinforcing bar. The typical service capacities can range from 40 to 1000 kN, depending on need and and soil type. Most designers use a variation of the Lizzi type and use it as a conventional pile element. A distinct advantage of the micropile is that the installation method causes minimal disturbance to both the supporting soils and the historic structure. However, current designers unfamiliar with the history of the technology are missing important aspects of micropile technology. Installation of the foundation elements, without excavation and without any additional pilecap, induces minimal distress to the soil, to the foundation, and to the structure. The traditional underpinning methods induce stresses because of change of gravity loading or by the location of the pile reaction. These changes are manifested in the rotation of the principal stresses, leading to bending moments in the structure because of non-aligned reactions and induced shear stresses.

DESIGN CONCEPTS FOR MICROPILES

Lizzi's original micropiles, the pali radice, are installed from the exterior ground or interior floor surface, as shown in Figure 2. There is no general need to excavate for temporary support, except for exploratory holes to confirm the size of existing foundation components. This type of micropile is constructed by drilling a hole to depth, inserting a centralized reinforcing bar, and gravity grouting the pile. For historic structures, the micropile is installed (i.e., drilled and grouted) through the existing wall. By using this methodology, the foundation system is engaged fully with the structure. The limitation that Lizzi imposed on the axial load of the pali radice is the crushing strength of the grout at the pile top. As the diameter of the cross-section is increased, a proportional increase of side resistance per unit length of pile is developed with increased capacity. As the soil becomes stronger and stiffer, the pile length can be shortened to develop the same ultimate capacity. The service loading will dictate the pile length and spacing, based on this limit. For most of Lizzi's designs, it is apparent that he is using a service level capacity about one-half of the ultimate capacity. This value is linked to the very linear elastic load shed performance of the pali radice.

The design of a reticulated pali radice structure is discussed by Lizzi (1985). There are several ways to visualize the reticulated micropile group: first as an in-situ soil reinforcement and second as an in-situ retaining wall. Either way, there is one important component of the reticulated soil-structure system that Lizzi emphasizes and utilizes in design, and that is the gravity resistance of the encased soil mass within the reticulated structure. The first part of the analysis for a reticulated micropile group is the model of an in-situ retaining wall. Then the analysis investigates the combined stresses because of gravity and active pressure that will load the retaining structure, as though there were no micropiles in the structure. Summaries of available design methodologies are given by Schlosser (1991) and Bruce and Juran (1997).

The utilization of reticulated micropile groups for the underpinning of historic structures can be of two general geometric types: linear or closed, as discussed by Kulhawy and Mason (1996). The linear configuration is an alternating installation of battered piles, which when viewed on end shows that the cross-over (i.e., the node) is centered under the wall being underpinned. Kulhawy and Mason (1996) developed the notation to describe the closed-form reticulated micropile group, that a "quilted" soil arch develops from pile to pile, with "soil diamonds" integrating around the complete surface to form the "quilt". This system also can be thought of as a boundary surface and be designed as such, as shown in Figure 3.

The design of micropiles should follow a rational design methodology, similar to that for drilled shaft foundations (e.g., Kulhawy, 1991). Critical to the design process is the evaluation of the operative horizontal stress after installation. Gravity grouting is similar to a drilled shaft, but pressure grouting will increase this stress. If the grouting effect is not included, the capacity could be underestimated by 50 to 200% or thereabout. Preliminary work by Kulhawy and Jeon (1999) illustrates this effect well. Therefore, it is usually recommended to perform on-site full-scale load tests of individual micropiles, as well as any group configuration, if possible.

SUMMARY

In this paper, an examination of early underpinning techniques showed that current methods are an outgrowth of previous techniques. However, underpinning methods that utilize excavation can actually add further damage to the existing structure. The micropile technique that was developed by Lizzi is a viable alternative for underpinning and strengthening historic structures, primarily because it minimizes distress during construction of the additional foundation elements.

REFERENCES

1. Breuchaud, J, "Underpinning of Heavy Buildings", Transactions, ASCE, Dec 1896, 629-638.
2. Bruce, DA & Juran I, "Drilled and Grouted Micropiles: State-of-Practice Review, Vol. II: Design", Report FHWA-RD-96-017, Federal Highway Administration, McLean, 1997, 204 p.
3. Hool, GA & Kinne, SW, Foundations, Abutments & Footings, 2/E, McGraw-Hill, New York, 1943, 417p.
4. Jacoby, HS & Davis, RP, Foundations of Bridges & Buildings, 2/E, McGraw-Hill, New York, 1925, 665 p.
5. Kulhawy, FH & Mason, JA, "Use of Reticulated Micropile Groups for Bridge Foundations", Proc., 4th Natl. Workshop on Bridge Research, Buffalo, Jun 1996, 101-106.
6. Kulhawy, FH, "Drilled Shaft Foundations", Chap. 14 in Foundation Engineering Handbook, 2/E, Ed. HY Fang, Van Nostrand Reinhold, New York, 1991, 537-552.
7. Kulhawy, FH & Jeon, SS, "Some Observations on Axial Compression Capacity of Micropiles", This Workshop Proceedings, 1999.
8. Lizzi, F, The Static Restoration of Monuments, Sagep Publishers, Genoa, 1982, 142 p.
9. Lizzi, F, "Pali Radice (Root Piles) and Reticulated Pali Radice", Underpinning, Ed. S Thorburn & JFHutchison, Surrey University Press, Glasgow, 1985, 84-158.
10. Prentis, EA & White L, Underpinning, Its Practice & Applications, Columbia University Press, New York, 1931, 318 p.
11. Schlosser, F (Ed.), "Recommendations Clouterre 1991 (EnglishTranslation)", Report FHWA-SA-93-026, Federal Highway Administration, McLean, 1991, 302 p.
12. Sooysmith, C, "Concerning Foundations for Heavy Buildings in New York City", Transactions, ASCE, Mar 1896, 189-199.

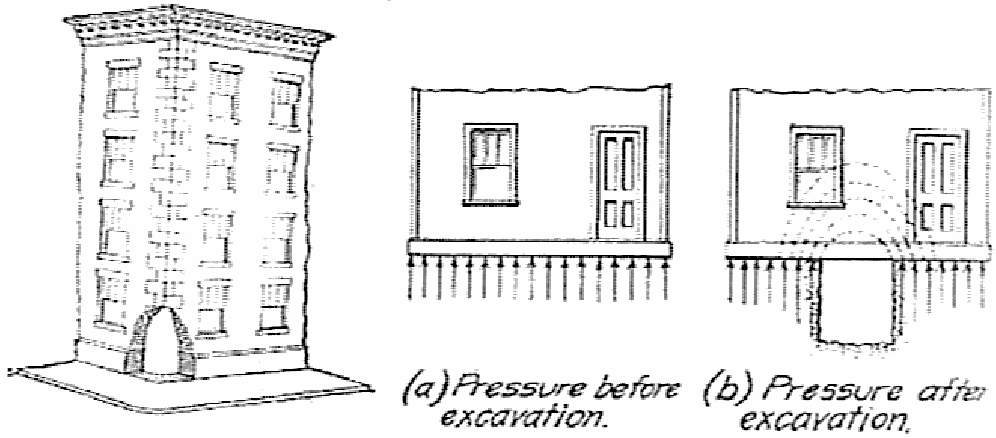

FIG. 1. —Building with portion of wall removed showing arching action developed.

FIG. 2.—Length of arrows indicates relative intensities of soil loads.

Figure 1. Arching and Load Re-Distribution Because of Excavation (Hool and Kinne, 1943, p. 268)

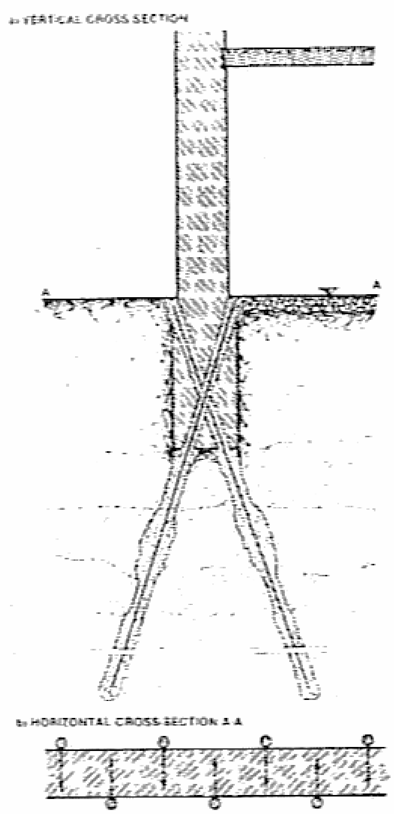

Figure 2. Basic Underpinning Configuration with Micropiles - The Node (Lizzi, 1982, p. 88)

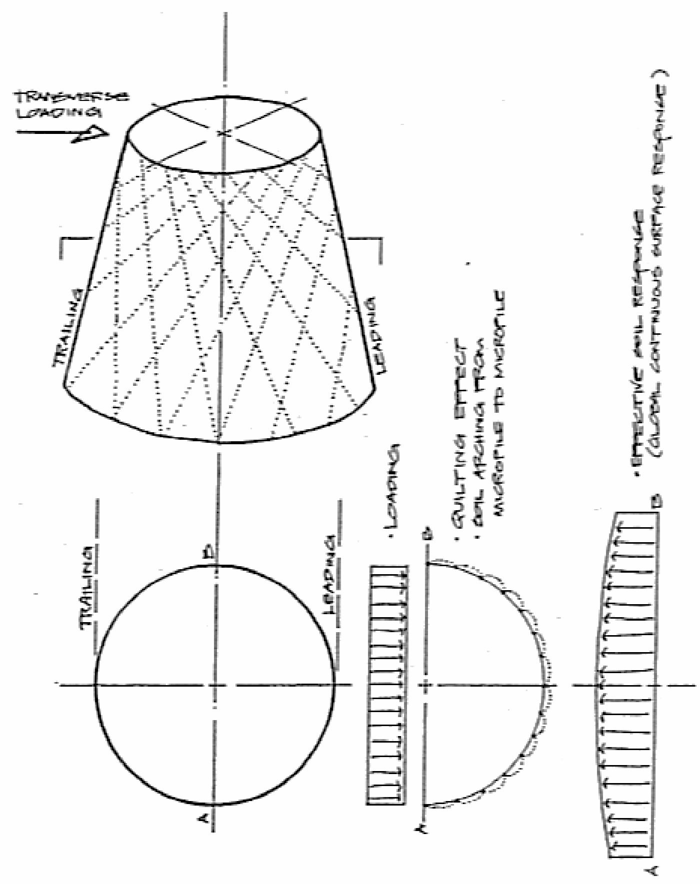

Figure 3. Global Continuous Surface Response of Reticulated Micropile Group Showing "Quilted" Soil Arching Effect (Kulhawy & Mason, 1996, p.106)