Integrating Nonlinear Pile Behavior with Standard Structural Engineering Software

Analyse non linéaire de fondations par pieux à l'aide d'un code industriel

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ABSTRACT: It is common in the practice of bridge design to analyze the superstructure, substructure, and foundation components separately. Applying this kind of modeling, soil-structure interaction effects can only be approximated with moderate accuracy. The foundation stiffness can greatly influence the internal forces, stresses, and displacements of superstructure. This is especially true for portal frame and integral bridges. Better modeling of soil-structure interaction can use three-dimensional geotechnical FEM programs, where the true soil-stucture environment can be analyzed. It is possible to use nonlinear constitutive models; capable of modeling soil behavior accurately, however it is difficult, time consuming, and costly in day-to-day practice.

RÉSUMÉ : Dans la pratique, le dimensionnement des structures et des fondations se fait dans des notes de calcul séparées. En conséquence les interactions sols-structures ne sont décrites qu'approximativement. Par exemple, la rigidité de la fondation peut affectée la répartition des charges et les déplacements de la structure. Cela est d'autant plus vraie dans le cas de fondations par pieux réparties sur une ou deux rangées. Le recourt à des codes de calcul tridimentionnel permet une approche plus réaliste des interactions sols-structures et la prise en compte de lois de comportement non linéaire pour le sol. La presente étude vise à comparer les rigidités des fondations par pieux réparties sur une ou deux rangées à l'aide d'un code de calcul industriel.

KEYWORDS: piles, nonlinear, structural, software

1 INTRODUCTION-DESIGN TRANSITIONS

Geotechnical and structural engineering software has evolved to where most common design tasks are performed on the computer. However, the levels of sophistication of these software packages are somewhat divergent. Geotechnical engineers prefer to consider soils as nonlinear materials with properties that vary throughout a site. These properties may also vary over time and loading conditions, yielding a highly complex set of behaviors. While this is an encouraging trend, structural engineers are often required to take a step back from such a sophisticated and time-consuming approach. The need for a timely and straightforward design that meets all aspects of building code requirements as well as budget and time constraints often forces structural designers to simplify geotechnical solutions. This is often reflected in structural design software that use beam elements and elasto-plastic spring elements to represent soil support behavior. This paper examines the methods to achieve these simplifications without creating an overly conservative or incorrect design.

Representing the full spectrum of three-dimensional soils-foundation-structure interaction is a laudable goal, but rarely achievable within the present design environment, hardware, and software. As a reasonable approximation, one may model the foundation system via sophisticated geotechnical software (Plaxis, Midas, Flac) and produce a family of foundation response curves which can then be approximated in the structural design model with simpler elements and material behaviors (Strom and Ebeling 2001).

2 SPECIFIC FOUNDATIONS CONSIDERED

This paper examines several simple examples of single piles and pile groups that support a bridge abutment. The structural concept of the foundation is rather simple: vertical loading due to structural loads, traffic, and other factors is generally small. Lateral loading due to wind, braking forces, temperature, and seismic contributions may control design. However, the geotechnical loading requirements can be quite demanding: approach embankments add lateral stresses to the piles; soft layers may exist in widely different thicknesses; and effects of consolidation may need to be considered (Szép et al 2009).

Additionally, the determining design quantity may be limiting lateral displacements. At the foundation, this will mean both lateral translation and rotation are important. Such deformations play an important role in the determination of global stiffness, hence deformations and moment/stress distribution throughout the structure. This is especially true for types of bridges (portal bridges, integrated bridges) where the connection between the foundation and the superstructure is moment-resistant (Hetényi 1964). In this paper we limit our investigation to determining how the stiffness of single row and double row pile foundations compare. In other words, what is the meaning of the common design approach, expressed in numbers, that the double row pile foundation is much more rigid than the single row one.

To accomplish this task we used several methods; all commonly used by structural and geotechnical designers. However we try to specifically address the problem of moving across the "structural-geotechnical divide" in the analysis/design process. We combine the results of structural analysis and geotechnical modeling software of varying levels of sophistication, especially when it comes to the treatment of piles and pile groups.

2.1 *Pile and Pile Cap Arrangements*

Figure 1 shows the basic pile configurations studied here. A series of progressively more complex pile foundations were examined: one, two, three, and five piles in a single row, then two, four, six and ten piles in a double row. Pile lengths and center-to-center spacing were identical.

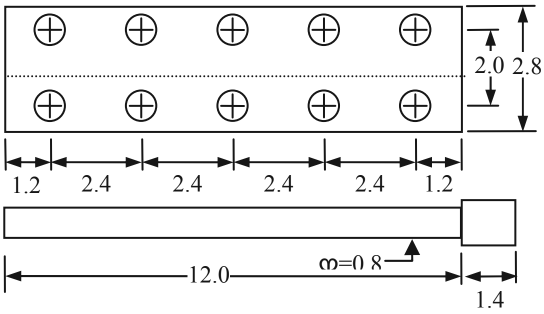

Figure 1. Model dimensions for pile study.

Single-line piles have become a favorite design alternative for bridge foundations in Hungary. Based on construction methods and materials, it is usually the most economic alternative. Pile type is the Continuous Flight Auger (CFA). There is some debate about how to model the pile structurally since its diameter is variable and difficult to estimate. The choice of diameter=0.8m seems to work best when compared to past pile load test data and examination of excavated prototypes.

With the new, advanced geotechnical packages more realistic modeling of soil-structure interaction becomes possible. For some critical problems, calculations show more favorable mechanical behavior than it was assumed based on routine bridge design calculations. Calculations show that the piles in the abutment have significantly lower loads on them than suggested by the Winkler-style models (Reese and Wang 1997) while the piles of the intermediate supports suffer more significant horizontal displacements and are subject to greater loads than previously assumed (Szép 2011).

2.2 *Analysis Methods*

As a first step, a single laterally loaded pile (*Fig. 1*) was analyzed using three different numerical methods. Results of bending moment distribution and displacements were then compared. The three numerical methods are:

- AXIS 10VM, the fundamental structural design tool in Hungary;
- GEO4 (and GEO5), an increasingly popular geotechnical design code;
- PLAXIS and MIDAS GTS, 2D and 3D geotechnical FEM packages that provide more realistic modeling for soil-structure interaction.

The AXIS and GEO software use similar subgrade reaction approaches to determine lateral pile behavior. The GEO software allows the user to calculate subgrade reactions as they are distributed down the pile and can allow for different backfill levels on either side as well as adjusting for passive and active conditions. AXIS uses a more direct approach in placing the subgrade reaction springs along the pile at discreet points. Both software packages will model the soil response as elastic or elasto-plastic with a specified strength limit.

3 2-D ANALYSIS AND RESULTS

The first level of analysis was a 2-D simplification of the actual geometry. This is a common design and analysis simplification that allows the engineer to evaluate the effects of 1-row or 2-row pile group as well as estimating the deflections, rotations, and bending moments generated within the model. Due to the relative ease of analysis, many design alternatives can be considered on a trial basis, and decisions made to further refine the design alternative or discard it. The two candidates for analysis are shown above (Figure 2) with element meshes generated by Plaxis. Material properties used in the analyses are presented in Table 1. Pile dimensions are identical to those presented in Figure 1. Interface elements were also used to better represent soil/pile interaction. Results from the analysis are summarized in Figure 3. Lines most closely paired in the figure are one- and two-pile geometries indicating that doubling the number of piles has less effect than doubling, or halving the applied load. While the group-effect for this configuration has been studied before (Bak et al, 2010), the structural design implications can be more difficult to assess. The altered flexibility of the substructure now comes into play when dimensioning structural elements for the superstructure.

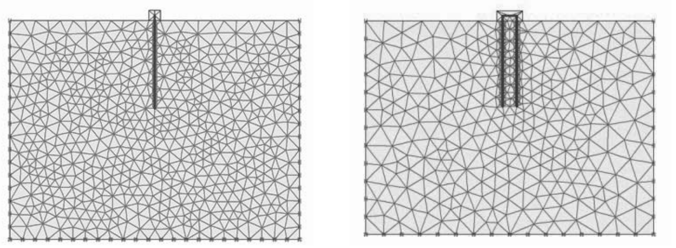

Figure 2. Two dimensional model for 1-row and 2-row pile groups.

Table 1. Material properties for analysis

			Sand	Clay	Concrete
Young's Modulus	E	kN/m^2	20 000	5 000	20 000 000
Poisson's-Ratio	ν	–	0.3	0.3	0.15
Dry unit weight	γ_d	kN/m^3	20.0	20.0	24.0
Wet unit weight	γ_t	kN/m^3	20.0	20.0	–
Cohesion	c	kN/m^2	0	20	–
Angle of Friction	φ	°	30	20	–

From Figure 3 one may also see that the rotation of the pile head for single-row groups is far greater, leading to greater deflections above the foundation. Most noticeable is the degree of rotation for sand where the soil is relatively much weaker near the surface than at depth, causing a very pronounced curvature in the pile. Comparing the Plaxis results with AXIS and GEO4 is a challenge. One may choose a wide variety of subgrade reaction values for AXIS and GEO4 and produce a corresponding wide variety of answers. In this study, a great deal of effort was spent trying to follow recommendations of the software providers and base subgrade reaction values on formulae and soil properties consistent with the other analyses.

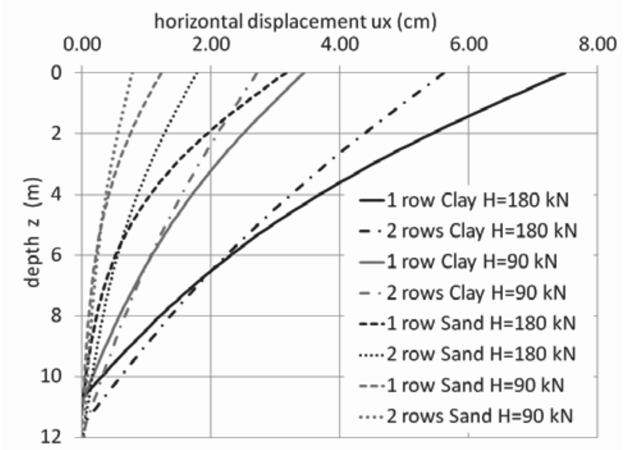

Figure 1. Lateral deflections for 1- and 2-row pile groups.

Table 2 lists the calculated lateral deflections consistent with the loads and soils shown in Figure 3. While the elastic/plastic behavior allowed for nonlinear load-displacement curves, deflections from these two programs were consistently lower than Plaxis-2D. There is also reason to believe that the two subgrade reaction programs may better represent single piles (as in 3D, discussed later) than as a 2D "pile wall" as represented in Figure 1.

Table 2. Summary of reaction coefficients and displacements

Spring Mode	Axis		Geo 4	
	k (MN/m/m)	ux (cm)	Ch (MN/m^3)	ux (cm)
Elastic	15-45	0.66	19-56	0.88
Elas/Plas	15-45	1.35	19-56	1.70
Elas/Plas	30-90	1.09	19-56	0.65

4 COMPARING 3-D ANALYSES

3-D methods highlight the same behavior but to different degrees. Using similar soil properties, one may compare the benefit of a two-pile system. The 3D model also made use of interface elements and a thin pile element placed within the solid element pile in order to determine shear and bending moments (MIDAS 2009). This time, the benefit is more pronounced, due to the more efficient process of spreading reaction loads throughout the soil in three dimensions.

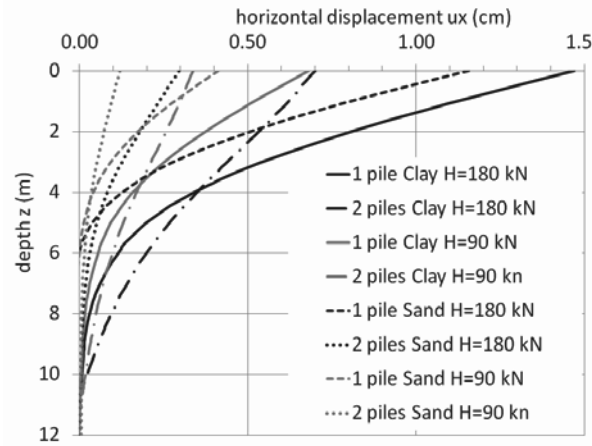

Figure 2. Displacement profiles for 1, 2 piles; Sand, Clay; 90,180 kN.

Displacement magnitude is much less for all combinations of load and soil. Surface displacements are smaller than those in Figure 3 by a factor of about 5-8x. This time the number of piles resisting movement is more influential in reducing displacement than the soil modulus. This is evidenced by the fact that the displacement profiles are grouped by number of piles and load magnitude (1 pile Sand H=180 is most near to 1 pile Clay H=180, etc.) The single piles also show a very pronounced slope at the surface which will again translate to rigid body rotation of the bridge pylons.

5 COMBINING ANALYSES

Presently the research group is adapting an optimization method to translate pile head displacement and rotations computed from 2D and 3D finite element analyses to a small number of elasto-plastic subgrade springs for use in structural or geotechnical design software (such as GEO and AXIS). The method assumes the pile has identical structural properties as the original (more sophisticated) analysis software. Four to six lateral springs are placed on the pile at various depths. One spring is always placed at the surface, another at the pile tip. The remaining springs will be placed in optimal positions to produce similar responses at the top of the pile.

The procedure seeks to optimize three quantities for each spring: elastic constant, k; plastic limit, c; and depth were the spring is attached to the pile, z. The pile structural element is modeled as a series of beam elements with nodes located at the pile tip, point of application of the middle springs, and the pile top. For a four spring model, the pile will consist of four nodes and three elements (Figure 5).

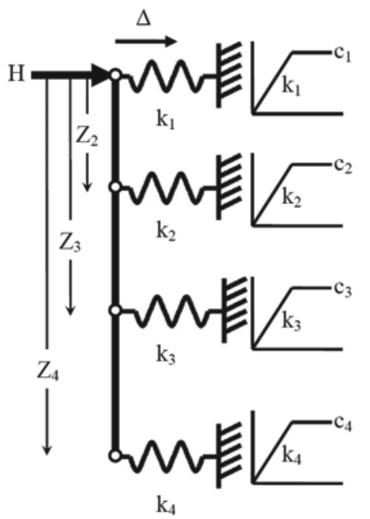

Figure 3. Four element pile with elasto-plastic springs.

The optimization process varies the eight spring parameters and two depths (the other two are the fixed length of the pile and zero) to minimize the least squares error between the deflection, Δ, computed above and the displacement generated from the finite element model for the same load, H. When the sum of least-squares error is minimized, the problem is solved. This is the same process one uses for fitting trend lines to data. The program is written in Visual Basic for Applications (VBA) and runs within an Excel spreadsheet. Computing deflections for the various loads is done with a small, nonlinear matrix structural analysis program that is called as an Excel function and returns the computed deflection value to the spreadsheet. The optimization makes use of the Solver add-in found in Excel. The parameters that are varied in the solver are those discussed above, the target value to minimize is the sum of the squared errors. Sample output for the optimization process is shown in Figure 6.

The optimization process can also be applied to pile load test data or any other method that generates the necessary values. The example here fits only horizontal deflections at the pile top. A better, slightly more complex approach is to fit both deflection and pile head rotation data. Since this involves more statistical degrees of freedom (double the number just demonstrated) more springs would be necessary. Data that is being compared can be assigned weighting (importance) values if some data is more reliable or vital than others.

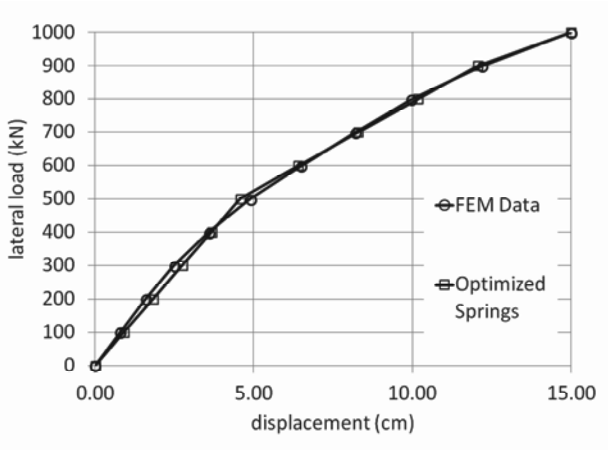

Figure 4. Finite element data with optimized spring response fit.

6 CONCLUSION AND FURTHER STUDY

Harmonizing structural and geotechnical design methods is a worthwhile challenge. Implementing the recently adopted design methods of Eurocode opens the possibility to teach new professionals a more integrated approach to design. However, in order to accomplish this, design methods and software must be better integrated and understood from both the structural and geotechnical perspectives. In this paper several methods were presented that Hungarian designers use for geotechnical and structural projects. Due to the more rigorous demands of modern designs, the substructure and superstructure components must work together seamlessly.

As part of ongoing research at Széchenyi University, the authors have presented several methods for analyzing and designing piles for lateral loads. Ideally the methods would be totally integrated; however this is not always possible due to the nature of design contracts, project timing, and available design software. Ideas and methods to overcome these limitations have been given and it is hoped they will engender further discussion by the engineering community.

Further research will focus on more complex structural and geotechnical systems where the entire construction process is modeled. By understanding the nuances of excavation, earthwork, falsework, concrete placement and finish schedules, further design efficiencies and enhancements can be found.

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