Determination of distribution of modulus of subgrade reaction

Détermination de la distribution du module de réaction d'un sol de fondation

Larkela A., Mengelt M., Stapelfeldt T.
Ramboll Finland Oy

ABSTRACT: In this investigation, three dimensional finite element soil modeling was used to model the behavior of a rectangular foundation block for on-grade cases in which the foundation experiences uniform loading. Modeling was completed using the commercially available three-dimensional finite element software Plaxis 3D Foundation, Version 2.2. Based on analyzing results, distribution of modulus of subgrade reaction was determined.

RÉSUMÉ : Lors de cette étude à éléments finis tridimensionnels, on a analysé le comportement d'une fondation rectangulaire de taille variable qui a été soumise à différentes sollicitations uniformes. La modélisation a été effectuée à l'aide du logiciel commercial aux éléments finis Plaxis 3D Foundation, version 2.2. A l'aide des résultats obtenus, le module de réaction a été terminé.

KEYWORDS: Modulus of subgrade reaction, soil structure interaction, foundation design, three dimensional finite element modeling.

1 GENERAL

The modulus of subgrade reaction is a parameter expressing the pseudo-elastic behavior of subgrade soil beneath the foundation, and is used for structural analysis of soil-structure interaction. The subgrade modulus concept models the behavior of soil as a series of single springs, and is commonly called Winkler's spring model. The method allows estimation of settlement beneath a loaded shallow foundation member, and thereby facilitates calculation of shear stresses and bending moment magnitudes within the foundation. These calculated values are used for example to dimension the reinforcements for a concrete footing.

The basis of the extensive usage of Winkler's soil model is in its simplicity to the differential equations which have been used to develop the method. However, it is commonly acknowledged that the assumption of soil units acting as separate, elastic springs of uniform stiffness below a footing does not model realistic foundation behavior. Results are unconservative for example in cases when the foundation is loaded with uniform loading.

In this investigation, three dimensional finite element soil modeling was used to model the behavior of a foundation block on grade cases in which the foundation experiences uniform loading. Modeling was completed using the commercially available three-dimensional finite element software Plaxis Foundation 3D, Version 2.2.

The modeling program was completed for Wärtsilä Finland, a major northern European supplier of integrated power generation solutions. The foundations considered in this program were foundation blocks for large diesel engines. A variety of engine foundations were considered for the study, representing the foundation blocks of a variety of diesel engine sizes and weights.

2 NATURE OF MODULUS OF SUBGRADE REACTION

Modulus of subgrade reaction is a spring constant describing the relationship between applied pressure and resulting deflection (settlement) below a structural element founded on grade. In the structural analysis the soil is modeled as an elastic half space, and local supporting pressure is assumed to be directly proportional to settlements. The subgrade modulus is not a fundamental soil property and its magnitude depends on many factors, among them shape of the foundation, stiffness of foundation slab, shape of loading on the foundation, depth of the loaded area below the ground surface, and time. As such, it is not constant for a given type of soil, which makes the estimation of a single general value for design a challenging task.

Modeling work performed in this study demonstrates that the theoretical springs of the subgrade reaction modulus also vary below a foundation. The variation of the subgrade reaction modulus arises especially when a foundation slab is loaded with uniform loading, because vertical pressure near the edges and corners of the foundation are significantly higher while the settlements at the same locations are smallest due to bending of the foundation slab, producing high spring constant. Conversely, at the center of the foundation the pressure is smaller and the settlement higher; thus, the spring constant is smaller at that location. The variation in the calculated subgrade reaction modulus causes the foundation to bend even under uniformly distributed loading.

Further, plastification of soil plays an important role in the determination of modulus of subgrade reaction. If the soil is modeled as purely elastic, pressure concentrations are observed at foundation edges and corners, leading to over conservative reinforcement design of the concrete foundation.

3 METHOD OF CALCULATION

3.1 *General*

The Finite Element Program PLAXIS 3D Foundation 2.2 was used for the analyses. PLAXIS 3D is programmed and built specifically for analysis of interaction between soil and structures.

3.2 *Foundation Model*

The foundation type used to support the engines is a rectangular block of reinforced concrete. The analyses considered the behavior of a variety of different engine types/sizes, and the various engine foundation blocks associated with each engine. Depending on the engine type and size, the thickness of an individual engine foundation varies between 0.6m and 1.2m. The length of a foundation block varies between 10.4m and 20.9m and width between 3.3m and 4.8m. The analysis also considered groups of engines, ranging from one to six engines in a row placed along their short axes. During the usage period, the engine is founded on a spring packet on top of the foundation slab. The purpose of the packets is to damp vibration induced by the engine to the foundation. Each engine is founded on a packet of 20 springs; modeling work by others indicates that the load transmitted through the foundation slab and into the subgrade is evenly distributed. Pressure below each engine type varies between 24kPa and 50kPa. Due to relatively thick foundation slab and heavy reinforcement within the slab, the engine foundations were modeled as linearly elastic; this design assumption was discussed and agreed with the structural engineer to be a valid assumption.

Plaxis 3D Foundation 2.2 allows modeling of structural plate units as two dimensional floor elements. This simplification from three dimensional elements was employed, because using this method the program provides bending moments, shear stresses and settlements of plate units in an easily-usable format.

For the purposes of brevity a single engine type is discussed in this report. The results of this engine analysis are reflective of the results obtained for other engine foundation types. Foundation dimensions of this example engine model are 11.9m by 4.1m by 0.6m, with uniformly distributed pressure on a foundation slab of 28.5kPa. Group affects of engines placed closely in rows was found to influence the results obtained; as such, the results provided in this article are representative for the two middle engines in 6 engine foundation group. This arrangement produces the largest estimated foundation settlements, bending of foundations and therefore the largest bending moments within the foundation blocks. Free distance between each engine foundation was 1.1m, reflecting the distance between the engines after installation in a typical facility.

The analysis results reveal that with these rectangular foundation dimensions, the variation of the subgrade modulus is more significant over the length of the foundation as compared with the width of the foundation. Thus the distribution of modulus of subgrade reaction was determined only in longitudinal direction of foundation. This assumption was confirmed by investigating the bending moments and settlements in the diagonal direction across the foundation.

3.3 *Soil Model*

Plaxis 3D Foundation offers various soil models for different purposes and applications. In this particular case, application of the hardening soil model was considered to be the most suitable model because it is formulated in an elasto-plastic framework.

The soil model considers hardening of the soil by shear hardening and isotropic compression hardening. The isotropic compression hardening can be simplified as hardening of soil, when the soil is placed under isotropic pressure and the pore pressure within the soil is allowed to dissipate. The shear hardening of soil is the increased shear strength of soil, as the pore pressure between the soil particles decreases.

Yielding of the soil occurs if the shear strength of the soil is exceeded in any element node point, because the soil is modeled as elasto-plastic. Yielding of soil below the edges and corners of foundation slab is considered to be very important in determination of naturalistic bending of the foundation and especially in determination of bending moments and shear stresses within the foundation slab. If the yielding of soil would be neglected from the analyses, unrealistically high bending moments and shear stresses would occur at the edges and corners of foundation slab.

The three dimensional model of the soil space below and around the foundation slab allowed more realistic distributions of stresses. Modeling of the soil space as three dimensional around and below the foundation slab, was the key element in resolving the bending of the foundation slab even with evenly distributed loading in top of the foundation slab. As the pressure is distributed on a wider area around the corners of the foundation slab, the corners and edges of the foundation settle less than the center portion of the foundation even when the loading on the foundation slab is evenly distributed.

These considerations allowed more realistic analyses of the soil especially when compared to conventional Winkler's spring model, even though simplifications were made.

The dimensions of the model were chosen to be 200m x 200m; depth was chosen to be 50m. Given these dimensions, no boundary effects were observed due to induced stresses during calculation stages.

3.4 *Procedure and Order of Analysis*

Due to the reason that modulus of subgrade reaction is specifically used for structural analyses the modeling work with PLAXIS was performed in close co-operation with structural engineers. Therefore the following work flow net of work was used in order to determine distribution of modulus of subgrade reaction:

1. Dimensions and elastic modulus of foundation were determined by the structural engineer.
2. Load acting on the foundation was determined by structural engineer.
3. Soil parameters were defined by geotechnical engineer.
4. Soil – structure interaction was determined by geotechnical engineer using PLAXIS 3D finite element modeling program.
5. Results from soil-structure interaction modeling, including bending of slab, settlement of slab, and bending moments with in the slab were provided for the structural engineer. Example settlement and bending moment distribution maps are presented in Figure 1 of this article.
6. Structural engineer evaluated whether assumption of elastic behavior of foundation was valid.
7. The structural engineer used the modeled values and a finite element model of a beam on Winkler's springs to determine subgrade reaction modulus (spring constant) distribution below the foundation, to obtain a match between results from the Plaxis model and the model of the beam on springs. Match between both foundation settlements and bending moments within the foundation slab were required to approve the spring model.
8. The varying spring constants calculated in Step 7 were used for design of the foundation reinforcements. Using this method, no unique value of subgrade modulus was found, and the actual soil-structural interaction was reflected by the non-uniform values calculated from the modeling and analysis program.

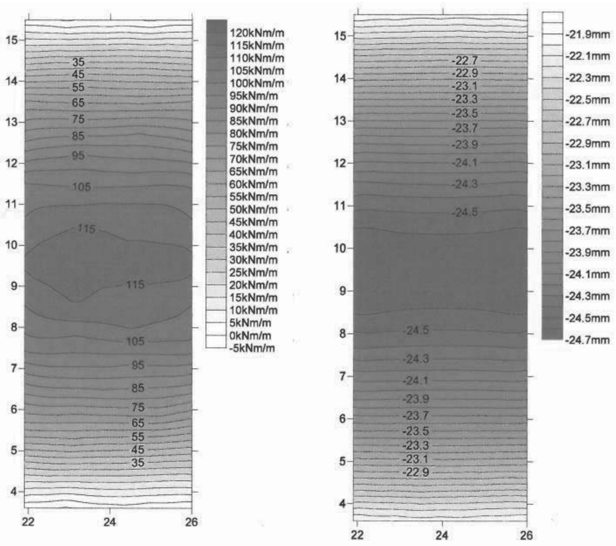

Figure 1: Longitudinal bending moment and settlement map of example engine foundation.

4 RESULTS OF ANALYSES

The investigations and models performed for this study agree with the observation that subgrade reaction modulus is not a fundamental soil property and, for a single soil, varies not only with the foundation dimensions, but also beneath a given foundation. Significant variability in calculated subgrade modulus was observed beneath a single foundation.

A close match was found between computed foundation slab settlements and bending moments within the foundation slab using the Plaxis model and the model using Winkler's Spring Model. The subgrade modulus is observed to be lowest in the middle and highest at the ends of the foundation slab. Between these two points the subgrade modulus variation correlates well with a second-degree parabolic distribution.

In the example engine foundation case presented in this article, from which the settlement and bending moment distributions are presented in Figure 1, the best correlation between the modeled foundation settlements and bending moments were found with subgrade modulus being 1190kN/m^3 at the center and 3160kN/m^3 at the ends of the foundation and being parabolically distributed between these peak values.

Due to good correlation between results from parabolic subgrade modulus distribution used in Winkler's soil model and 3D soil-structure model, parabolic distribution of subgrade modulus was considered to provide sufficiently accurate results. Therefore, more detailed analysis on which the peak subgrade modulus would be located somewhere near the edge of the foundation, due to yielding of soil, were not considered to be required.

5 DISCUSSION OF COMPUTATION METHODS

The method which was used to determine distribution of modulus of subgrade reaction below a foundation was time consuming, but the results were considered positive and logical.

The method allowed definition of subgrade modulus in such a way that reinforcement quantity in the engine blocks could be reduced significantly; resulting in large cost savings for the customer. The designs have since been employed in the field and the engine foundations exhibit acceptable performance in operation.

In common structural design programs Winkler's soil spring method is often used to model the behavior of soil below a foundation, even though this method is widely found to be inaccurate and not reflective of reality. The usage of soil spring method of Winkler was justified in the past, when only structural computation methods based on differential equations have been available. However the structural design programs based on finite element methods commonly use Winkler's soil model for analysis as well in modern engineering practice, even though modern computation methods (e.g. FE modeling) is capable of modeling the soil in much greater detail and more accurately. Use of more sophisticated soil models can be expected to increase the accuracy of design significantly.

As improvements to the current situation, the authors propose the following:

Clause 1: Three dimensional finite element soil space shall be modeled below and around footings.
Clause 2: Soil shall be modeled as elasto-plastic.

Clause 1 would lead to more correct stress distribution within soil. Using this method a foundation slab would bend even when being loaded with uniformly distributed loading. Clause 1 would also take into consideration settlements due to closely spaced foundations, as was the case with the modeled 6 engine foundations, presented in this article.

The plasticization requirement set in Cause 2 would result in more realistic pressure distribution below foundation and problems of extremely high peak pressures occurring at the corners of foundation would not be observed. This will result in more realistic bending moments and shear stresses within foundation slabs.

When the yielding stress of soil is being determined, it should be noted that if the yielding pressure is set to be too low, the region of yielded soil will become too large and the analyzed foundation may not bend as much as it should. This will result into too small bending moments within the analyzed foundation slab, resulting into under reinforcement. Conversely, if the yield strength of soil is set too high, the total displacements may become too small.

In the conducted analysis, it is found to be very time consuming for structural engineer to determine distribution of subgrade reaction below foundation manually. This is due to the reason that distribution of spring stiffness varies significantly below footing and different spring variation shall be determined separately for each load condition. As such it is recommended that in structural design programs using finite element methods, the soil would be modeled using more sophisticated soil models than Winkler's soil model.

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