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REPRESENTATIVE MODULUS OF SUBGRADE REACTION FOR STRUCTURAL DESIGN OF INDUSTRIAL FLOOR SLABS – A CALIBRATION-BASED APPROACH

Summary: The Winkler model is the most widely used approach for the structural design of industrial floor slabs because of its simplicity and implementation in commercial software. However, selecting a representative modulus of subgrade reaction remains a major source of uncertainty. Conventional methods usually derive this parameter from predicted settlements or empirical correlations, although the primary objective of structural analysis is the determination of bending moments. This paper proposes a calibration-based methodology in which the modulus of subgrade reaction is treated as an equivalent numerical parameter rather than an intrinsic soil property. The representative value is obtained by calibrating the Winkler model against a continuum finite element model using bending moments as the calibration criterion. The methodology is illustrated through the redesign of an industrial floor slab and provides a practical and reliable basis for structural design.

Keywords: industrial floor slabs, soil-structure interaction, Winkler model, modulus of subgrade reaction, finite element analysis, calibration

ODREĐIVANJE REPREZENTATIVNOG KOEFICIJENTA KRUTOSTI POSTELJICE ZA STATIČKU ANALIZU I DIMENZIONISANJE INDUSTRIJSKIH PODNIH PLOČA

Rezime: Winklerov model predstavlja najčešće primenjivani pristup za dimenzionisanje industrijskih podnih ploča zahvaljujući jednostavnosti i primeni u komercijalnim softverskim paketima. Međutim, izbor reprezentativne vrednosti koeficijenta krutosti posteljice i dalje predstavlja jedan od najvećih izvora nepouzdanosti u projektovanju. U radu je predložena metodologija zasnovana na kalibraciji, u kojoj se koeficijent krutosti posteljice tretira kao ekvivalentni numerički parametar, a ne kao fizička karakteristika tla. Reprezentativna vrednost određuje se kalibracijom Winklerovog modela prema kontinuum modelu, pri čemu su momenti savijanja usvojeni kao osnovni kriterijum kalibracije. Metodologija je prikazana na primeru dimenzionisanja industrijske podne ploče velikog distributivnog centra i predstavlja praktičnu osnovu za pouzdanije projektovanje.

Ključne reči: industrijske podne ploče, interakcija konstrukcije i tla, Winklerov model, koeficijent krutosti posteljice, metoda konačnih elemenata, kalibracija

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1. INTRODUCTION

Industrial floor slabs represent a specific class of foundation structures whose structural behaviour is governed by soil–structure interaction. Owing to their large plan dimensions, relatively small thickness and highly non-uniform loading conditions, their response depends simultaneously on the stiffness of the slab, the deformation characteristics of the supporting soil and the load distribution. Consequently, an appropriate representation of the foundation soil is essential for reliable structural design.

Despite the widespread availability of advanced continuum-based numerical methods, industrial floor slabs are still predominantly designed using the Winkler hypothesis [1]. Within this approach, the supporting soil is represented by a system of independent springs characterized by the modulus of subgrade reaction. Owing to its simplicity and implementation in virtually all commercial structural software, the Winkler model remains the standard engineering tool for slab design. The principal source of uncertainty is not the structural analysis itself, but the selection of a representative modulus of subgrade reaction. Existing design recommendations usually estimate this parameter from laboratory or in-situ test results through empirical correlations involving deformation modulus, plate load tests, CBR, SPT and other geotechnical parameters [2]. However, these approaches frequently lead to significantly different values even for similar soil conditions.

A fundamental reason for this inconsistency is that the modulus of subgrade reaction is commonly interpreted as an intrinsic soil property. In reality, it is a parameter of an equivalent mechanical model whose representative value depends not only on soil properties but also on the stiffness of the slab, foundation geometry, loading configuration and soil stratification.

These limitations become particularly pronounced in the design of industrial floor slabs founded on layered deposits. Such systems usually consist of a relatively stiff engineered bearing layer overlying considerably more compressible natural soils [3]. When conventional settlement-based procedures are applied, the predicted settlements are largely governed by the deformation of deeper soil layers, whereas the stiffness contribution of the engineered bearing layer becomes insufficiently represented in the equivalent Winkler springs. As a consequence, numerical models calibrated solely on the basis of settlements frequently provide unrealistic distributions of contact pressures and bending moments, leading to inefficient structural design.

The primary objective of the Winkler model in structural engineering is not the prediction of settlements but the determination of internal forces governing reinforcement design. Therefore, the calibration criterion should be directly related to the structural response of the slab rather than to its absolute settlement. The objective of this paper is therefore to propose a practical methodology for determining a representative modulus of subgrade reaction through calibration of the Winkler model against a higher-order continuum finite element model. The proposed procedure uses bending moments as the governing calibration criterion and is demonstrated through the redesign of an industrial floor slab for a logistics distribution centre.

2. LIMITATIONS OF CONVENTIONAL PROCEDURES FOR DETERMINING THE MODULUS OF SUBGRADE REACTION

The modulus of subgrade reaction is conventionally defined as the ratio between contact pressure and the corresponding foundation settlement. Although this definition suggests that it is a soil parameter, the modulus of subgrade reaction does not represent a constitutive property of the soil but the stiffness of an equivalent spring replacing a complex soil continuum [4]. Consequently, its representative value cannot be uniquely defined independently of the adopted structural model.

For relatively small shallow foundations resting on homogeneous soil deposits, this simplification generally provides satisfactory results. However, industrial floor slabs typically cover several thousand square metres and are founded on layered soil profiles consisting of stiff engineered bearing layers overlying considerably more compressible natural deposits. Under such conditions, predicted settlements are dominated by the deformation of deeper strata, whereas bending moments are governed primarily by the stiffness of the upper support layers.

As a consequence, settlement-based procedures usually produce unrealistically low values of the modulus of subgrade reaction. While such values may reproduce the average settlement of the slab, they fail to represent the local soil restraint responsible for the development of bending moments and therefore cannot ensure a realistic prediction of reinforcement demand.

An additional limitation follows directly from the Winkler hypothesis. Since the springs act independently, a uniform modulus of subgrade reaction cannot simultaneously reproduce the bending moment distribution throughout the slab. Satisfactory agreement may be achieved only locally, while significant discrepancies remain elsewhere. This indicates that the equivalent spring system should be calibrated with respect to structural response and, where necessary, represented by a rational distribution of spring stiffness rather than by a single uniform value.

These shortcomings become particularly important in the design of industrial floor slabs subjected to concentrated rack loads, where local bending moments govern reinforcement design. Under such conditions, the representative modulus of subgrade reaction should be selected so that the simplified Winkler model reproduces the bending moments obtained from a more realistic continuum analysis rather than the predicted settlements.

3. NUMERICAL FRAMEWORK AND CALIBRATION PROCEDURE

3.1. FLOOR SYSTEM AND LOADING SCENARIOS

The proposed methodology was developed during the redesign of the reinforced concrete industrial floor slab for the Lidl Distribution Centre in Kumanovo, North Macedonia. The floor system consists of a large number of reinforced concrete panels separated by construction joints. Individual panels have plan dimensions ranging from approximately 25 to 30 m, while the slab is founded on a multilayer soil profile comprising a crushed stone bearing layer, a compacted subgrade layer and natural cohesive deposits.

Unlike conventional foundation slabs subjected predominantly to column loads, industrial floor slabs are exposed to highly non-uniform loading conditions produced by storage racks, forklift traffic and operational activities. Preliminary analyses showed that storage loads have a significantly greater influence on the equivalent spring stiffness than traffic loads or local imperfections.

Owing to the large panel dimensions and the localized nature of rack loads, soil–structure interaction has a governing influence on the distribution of bending moments within the slab. Since the representative modulus of subgrade reaction depends not only on the supporting soil but also on the loading configuration, three characteristic loading scenarios representative of the warehouse operation were considered during the calibration procedure:

- storage areas with static pallet racks,
- storage areas with dynamic pallet racks,
- IN/OUT areas without permanent rack loads.

Since the proposed methodology is identical for all loading scenarios, only the results corresponding to the static pallet rack area are presented in this paper. Loading scheme for static pallet racks is given in Figure 1. The given loading scheme is repeated in given pattern all over the panels.

Two characteristic operating scenarios were considered. In the first scenario, the analysed panel was fully loaded, while the adjacent panels remained unloaded. This configuration represents the most unfavourable condition for bending moments developing in the bottom zone beneath the rack columns. The second scenario represents the normal operating condition of the warehouse, in which the analysed panel and all adjacent panels are simultaneously loaded. In this case, the surrounding panels participate in the deformation of the supporting soil, resulting in a significantly different distribution of contact pressures and bending moments within the analysed slab. Since these two loading scenarios produce fundamentally different structural responses, both were included in the calibration procedure. When no reliable information on the future loading sequence is available, the envelope of the two analyses may be adopted for structural design.

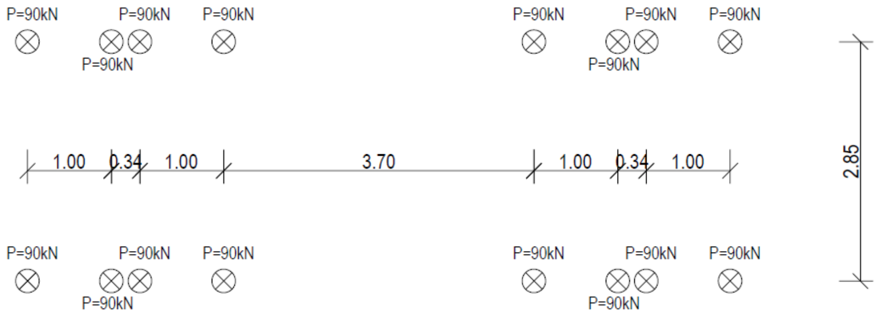

Figure 1: Loading scheme for static pallet racks

3.2. GROUND MODEL

The geological profile consists of three principal components relevant for the structural behaviour of the slab: engineered crushed stone bearing layer, compacted subgrade, natural cohesive deposits extending beneath the influence zone CL/CI/SF (USCS classification of soil). The stiffness of the natural soil profile was determined from laboratory oedometer testing, whereas the deformation characteristics of the compacted subgrade were evaluated using plate load tests performed after compaction. The stiffness of the crushed stone bearing layer was estimated from project specifications and verified through sensitivity analyses.

Because excavation depth varies throughout the building footprint, several representative ground models were considered in order to investigate the influence of stress history on the calibrated modulus of subgrade reaction.

Since the objective of the present study is the evaluation of the calibration methodology rather than the characterization of the investigated site, only representative material properties were adopted in the numerical analyses. Table 1 summarises the representative deformation parameters adopted for the reference continuum model.

Table 1: Representative values of the elasticity moduli and shear strength parameters

Layer	**Depth below the slab (m)**	**Representative values of the elasticity moduli E (MPa)**				**Poisson's ratio ν**	**Unit weight γ (kN/m³)**	**φ′ (°)**	**c′ (kPa)**
		Excavation depth							
		0.0 m	**1.0 m**	**2.0 m**	**≥ 3.0 m**				
Bearing layer	0-1.0	See Table 2.				0.30	22.3	38	1
Compacted subgrade	1.0-1.5	24.0	24.0	24.0	24.0	0.30	20.0	24	10
CL/SF	1.5-4.5	2.1	4.1	6.1	8.2	0.30	18.7		
CL/CI/SF	4.5-13.0	3.8	5.2	6.7	8.2	0.30	19.2	24	10
CI/SF	13.0-20.0	8.7	10.0	11.0	12.0	0.30	20.5		

The reference continuum model explicitly accounts for the multilayer soil profile, whereas the equivalent Winkler model replaces the complete soil domain by an equivalent system of vertical springs.

A parametric study comprising nine numerical models was carried out to investigate the influence of the engineered bearing layer stiffness on the representative modulus of subgrade reaction. Unlike the natural foundation soil, whose mechanical properties can only be marginally modified, the bearing layer represents an engineered material whose stiffness may be controlled during construction through the selection of aggregate grading, mineralogical composition and compaction quality.

Consequently, the deformation modulus of the bearing layer was treated as a design variable. The calibration procedure was therefore repeated for values of the deformation modulus ranging from 35 MPa to 160 MPa, covering the range typically achievable in practical construction. The remaining soil layers were kept unchanged, allowing the influence of the bearing layer stiffness on the representative modulus of subgrade reaction to be evaluated independently. The different considered deformation modulus used in parametric study for bearing layer are summarized in Table 2.

Table 2: Considered ground models for bearing layer

Scenarios label	**Deformation characteristics of bearing layer (d is the thickness of zone within the layer)**
M1	zone 1: d=20 cm E=70 MPa; zone 2: d=20 cm E=50 MPa; zone 3: d=30 cm E=35 MPa; zone 4: d=30 cm E=35 MPa;
M2	zone 1: d=50 cm E=65 MPa; zone 2: d=50 cm E=35 MPa
M3	zone 1: d=100 cm E=60 MPa
M4	zone 1: d=100 cm E=50 MPa
M5	zone 1: d=100 cm E=70 MPa
M6	zone 1: d=100 cm E=80 MPa
M7	zone 1: d=100 cm E=100 MPa
M8	zone 1: d=100 cm E=120 MPa
M9	zone 1: d=100 cm E=160 MPa (value obtained from CBR)

3.3. NUMERICAL MODELS AND CALIBRATION PROCEDURE

Calibration was performed by comparing the structural response obtained from two numerical models. The reference model represents the supporting soil as a three-dimensional continuum discretised by finite elements. The multilayer soil profile, contact conditions and constitutive behaviour of individual geological units are explicitly taken into account. To realistically reproduce stress redistribution beneath the slab, the soil was modelled using the Mohr–Coulomb elastoplastic constitutive model. The reference model is not intended for routine design. Its primary role is to provide reliable values of bending moments against which the equivalent Winkler model can be calibrated.

The structural design model was developed using the conventional Winkler hypothesis, in which the supporting soil is represented by a system of discrete vertical springs characterised by the modulus of subgrade reaction. Both numerical models were created using identical slab geometry, boundary conditions and load combinations. Consequently, the adopted soil representation represents the only significant difference between the analyses.

The representative modulus of subgrade reaction was determined iteratively by modifying the spring stiffness until satisfactory agreement between the bending moments obtained from the continuum and Winkler models was achieved.

Unlike conventional settlement-based procedures, where the modulus of subgrade reaction is selected to reproduce calculated settlements, the proposed methodology adopts bending moments as the governing calibration criterion. Since reinforcement design depends directly on internal forces, matching the bending moment distribution provides a considerably more rational basis for selecting the equivalent spring stiffness. The quality of calibration was evaluated by comparing:

- maximum positive bending moments,
- maximum negative bending moments,
- location of maximum bending moments,
- overall shape of the bending moment diagrams.

3.4. STIFFNESS ZONING

Preliminary analyses demonstrated that a uniform modulus of subgrade reaction cannot simultaneously reproduce the complete bending moment distribution throughout the slab. This behaviour follows directly from the assumptions of the Winkler hypothesis, which neglects interaction between neighbouring springs.

To overcome this limitation while preserving the simplicity required for practical structural design, several geometrically simple stiffness zoning schemes were investigated. Instead of assigning individual stiffness values to every spring, the slab support was divided into a limited number of zones with constant representative values of the modulus of subgrade reaction. The considered zoning schemes are given in Figure 2.

Particular attention was devoted to keeping the adopted zoning sufficiently simple for routine engineering application while still reproducing the dominant mechanisms governing soil restraint. The representative spring stiffnesses for individual zones were obtained through iterative calibration against the continuum model.

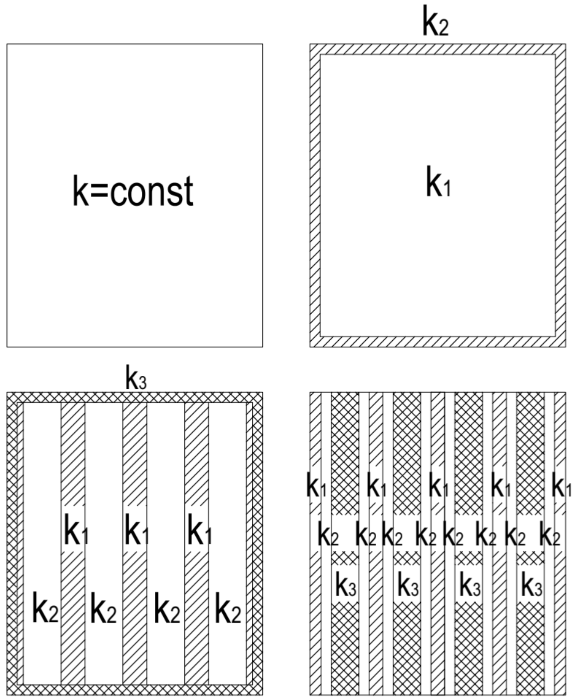

Figure 2: Considered zoning schemes

4. RESULTS AND DISCUSSION

To demonstrate the proposed calibration procedure, one representative design scenario is presented in detail. Figure 3 shows the bending moment distribution in the x-direction obtained from the reference continuum model for a series of floor slabs subjected to static storage rack loading. The bending moments represent average values over a strip width of 2.85 m and correspond to the governing ULS load combination. The presented results were obtained using Ground Model Scenario 1 (M1), corresponding to an excavation depth of H = 0 m, in which the supporting soil was modelled as an elastoplastic continuum.

The equivalent Winkler model was subsequently calibrated using the structural model adopted in the main design, where the analysed panel is supported by vertical springs characterized by a constant modulus of subgrade reaction. Because a uniform modulus of subgrade reaction cannot simultaneously reproduce the bending moments in both the upper and lower reinforcement zones, the calibration was carried out independently for each zone. This approach enabled the determination of representative spring stiffnesses governing the reinforcement design in the corresponding regions of the slab.

Figure 4 and Figure 5 present the bending moment distribution obtained from the equivalent Winkler model. The modulus of subgrade reaction was determined by an iterative trial-and-error procedure until satisfactory agreement with the reference continuum solution was achieved for the lower reinforcement zone. The final calibrated value adopted for structural design is also indicated in Figure 4 and Figure 5.

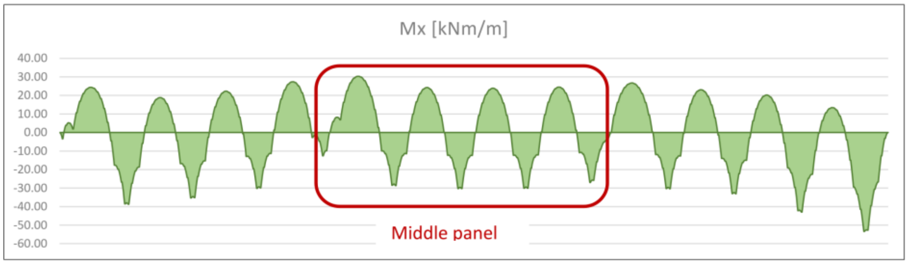

Figure 3: Bending moment diagram for the system of slabs with static racks

The same calibration procedure was subsequently repeated for all analyzed ground models and loading scenarios. Some of the resulting representative values of the modulus of subgrade reaction are given in Figure 6. Their variation clearly demonstrates that the equivalent spring stiffness depends not only on the soil profile but also on excavation depth, stress history and loading configuration. Consequently, the representative modulus of subgrade reaction cannot be regarded as a unique soil parameter, but rather as a calibration parameter of the adopted structural model.

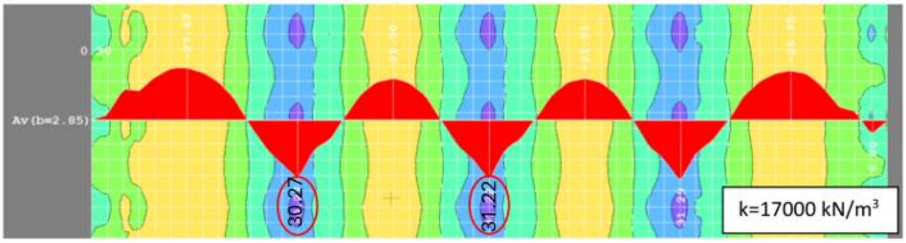

Figure 4: Bending moment diagram – Winkler soil model calibration for the lower zone

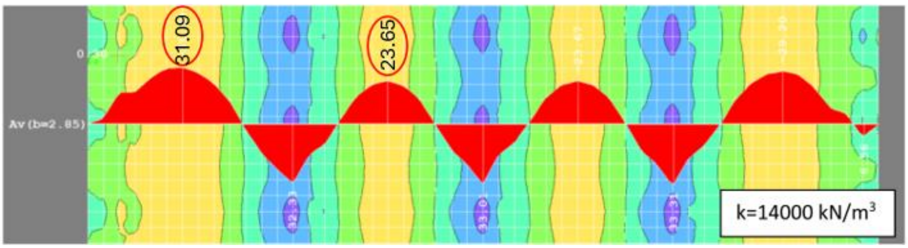

Figure 5: Bending moment diagram – Winkler soil model calibration for the upper zone

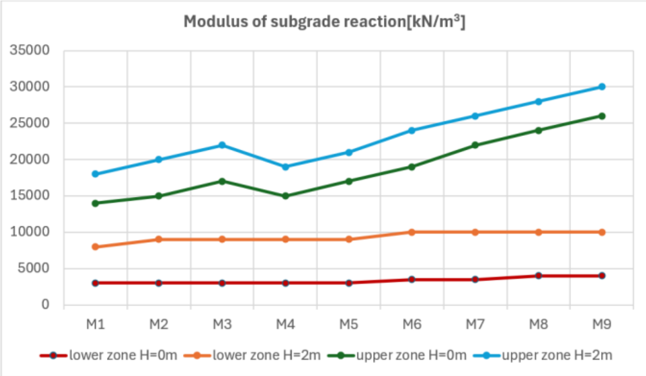

Figure 6: Resulting representative values of modulus of subgrade reaction

5. CONCLUSIONS

A calibration-based methodology for determining the representative modulus of subgrade reaction for the structural analysis of industrial floor slabs has been presented. The proposed procedure treats the modulus of subgrade reaction as an equivalent parameter of the numerical model and determines its representative value by matching the bending moments obtained from a higher-order continuum model.

Based on the performed analyses, the following conclusions can be drawn:

1. The representative modulus of subgrade reaction cannot be regarded as a unique soil property, since its value depends on the adopted structural model, loading configuration and stress conditions within the supporting soil.
2. Calibration based on bending moments provides a more rational basis for structural design of industrial floor slabs than conventional settlement-based procedures, because reinforcement design is governed by internal forces rather than predicted settlements.
3. The calibrated modulus of subgrade reaction is strongly influenced by the stiffness of the engineered bearing layer. Since this layer represents an engineered material, its properties may be controlled during construction and therefore have a direct influence on the equivalent Winkler model.
4. Excavation depth and the corresponding stress history significantly affect the representative modulus of subgrade reaction. Consequently, a single recommended value cannot adequately represent all construction conditions encountered within the same project.
5. Different operational loading scenarios, particularly the interaction between adjacent loaded panels, produce different structural responses and should therefore be considered during the calibration procedure.

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