Foundations of Engineering Mechanics

Spatial Contact Problems in Geotechnics

Boundary-Element Method

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Preface

The studies of contact interaction in the mechanics of deformable solids have been carried out since late 19th century, starting from the works of Winkler (1867), Hertz (1881), and Boussinesq (1885). These studies have been further developed by specialists in the mechanics of deformable solids as well as in structural mechanics, bases and foundations. Thousands of papers on this topic have been published, most of their authors using simplifying assumptions of theoretical modeling on a flat or axially symmetrical stressed state of a base under a punch (a foundation model). It is seen from the detailed analysis of references found in literature that mathematical modeling of essentially spatial contact interaction is in its early stage.

The existing methods for the calculation of complex-shaped foundations are, as a rule, based on a bed coefficient hypothesis. This results in the introduction of empirical coefficients into the calculation methods, thus restricting the range of their application. In the recent years more attention is paid to finite-element approach to mathematical modeling of spatial contact interaction of foundations with bases. However, in such studies the dimensionality of the algebraic analogue of the contact problem sharply increases and the problem must be restricted to a number of partial problems – for example, by imposing restrictions to shape and size of both the foundations themselves and the soil massifs around the foundations, by considering loads in assumption of existence of symmetry axes or planes in the calculation scheme etc. Such studies are rather rare and lack proper consideration of loads of general spatial type (horizontal, vertical forces and moments) and the possibility of their combined action. And extremely rare are studies where the complex shape of various foundations, applied in industrial and civil engineering, is fully taken into account and theoretically based calculations are made.

Creation of new progressive foundation structures and solution of current problems of geotechnical engineering result in more complicated problems to be solved and in the increasing accuracy of the calculation results. The mathematical description of the problems has become so complicated that traditional methods are no longer suitable for their solution. The lack of reliable mathematical methods to a certain extent retards elaboration and implementation of new foundation structures in engineering. Hence, the development of boundary element method (BEM), a relatively new trend in structural mechanics, based on boundary integral equations, seems to be quite promising from the point of view of both theory and application as an efficient tool for solving 3-D problems. The BEM advantages over other methods of numeric modeling consist in lowering the problem dimensionality (not the whole calculation domain is subject to discretization, but only the boundary surface), in the possibility of a detailed analysis of separate stressed areas, in the simplified data preparation stage etc. This determines the broad application of BEM for solving various problems of structural mechanics, especially the unlimited domains. Simultaneously, by the present time numerical implementation of BEM to the spatial problems of structural mechanics in the field of interaction of foundations and bases has not been sufficiently elaborated yet and appropriate boundary element algorithms and software are still unavailable. Therefore, there is an urgent need to develop efficient numeric approaches using the BEM to solve spatial contact problems of interaction of complex-shaped volumetric punches with deformed bases.

The present book is devoted to one of the BEM application areas – numerical modeling of contact interaction of rigid foundation structures with soil. The main attention is paid to the specific features of stress-strained states of elastic bases at spatial conditions. Contrary to the finite element method, special literature for the BEM application in mechanics of spatial contact interactions between bases and foundations is at present unavailable. In recent publications, devoted to the calculation of bases and foundations, BEM is merely mentioned. On the other hand, well-known books, describing theory and application of BEM, do not appropriately cover the issues of creating calculation models and numerical algorithms for analyzing spatial contact interaction of foundation structures with soil bases.

The whole material is set in six chapters. The first chapter presents some introductive data while reviewing spatial contact models in geotechnics. Classical fundamental solutions for the spatial theory of elasticity obtained by Boussinesq, Cerruti, Mindlin are quoted as well as their generalizations, suitable for calculating constructions on elastic nonclassical bases. The properties of the influence functions are analyzed, required for characterizing elastic bases with nonhomogeneous deformation properties (connected half-spaces, elastic layers of constant and variable thickness).

In the same chapter a numerical-and-analytical procedure is developed for construction of fundamental solutions of spatial elasticity theory for multilayer bases without restrictions on the layer thickness and elastic parameters. Using the two-dimensional Fourier transform, the formulae have been derived, enabling three-dimensional contact problems for complex-shaped structures deepened into spatially nonhomogeneous (layered) soils to be solved in the framework of the BEM numerical algorithm. The final part of the first chapter contains the results on the formulation of influence functions for elastic bases with variable deformation properties. The Boussinesq problem is solved for an elastic half-space when the deformation modulus increases with depth according to a most general law. Proper relations, enabling adequate description of the experimental data, are considered. An efficient numerical-and-analytical procedure is developed for construction of the influence functions, taking into account the soil deformation modulus variation with depth. All the theoretical results for the influence functions were obtained within a unique approach enabling all the main types of nonhomogeneities of natural soil bases to be taken into account.

The second chapter is devoted to the mathematical formulation of mixed problems of the elasticity theory for a half-space and to the numerical-and-analytical methods of their solution. The results obtained in this chapter on developing the mathematical means are the reference data for BEM-based numerical modeling of the spatial contact interaction. The boundary integral equations of the spatial contact problem are written for the case when the calculation scheme is accepted in the form of variously deepened punches undergoing the action of the spatial system of forces. It is shown how to reduce the initial integral equation system of the contact problem with respect to the contact stress function and the punch displacement parameters to the appropriate finite-dimensional algebraic analogue. Much attention is paid to calculating the matrix coefficients of the resolving system of algebraic equations. A numerical-and-analytical procedure is given for integrating Mindlin's fundamental solutions over flat triangular and quadrangular boundary elements, arbitrary oriented in the half-space. For convenience, to apply the developed approach in practical calculations, the boundary integral equations of the spatial contact problems for a number of essential special cases are presented. The contact problems at axial loading and torsion of absolutely rigid rotation bodies deepened into the half-space, are considered. Boundary-element formulations of the contact problems for complex-shaped punches with flat and smooth bases (shallow foundations), situated on spatially nonhomogeneous bases of the semi-infinite elastic massif type are presented.

The third chapter deals with practical implementation of the developed numerical algorithms and substantiation of the reliability of the numerical solutions. It presents the general characteristics and structure of the *Rostwerk* software package for investigating three-dimensional stress-strained states of elastic bases corresponding to the interaction of foundation structures with soil under force factors of general kind. Procedures for creating input databases are described in detail. Algorithms and modules for automatic formation of boundary element grids in plane and in space are presented. An original algorithm for triangulation of flat single- and multiply connected domains, bounded by straight line segments or circle arcs, is described. An algorithm of generation (according to the given triangulation) of dual polygonal boundary element grids of Dirichlet cell type is considered. The created object library of boundary element modules, partitioned into boundary elements, enabling spatial discretization of complex-shaped surfaces of foundation structures, is described. Specific features of solving the systems of linear algebraic equations with asymmetric and close-packed matrices, arising in boundary element analysis, are considered. For solving such systems by direct (Gauss type) methods a special scaling procedure is applied, improving the conditioning of matrices for the finite-dimensional algebraic analogue of a contact problem. The data about the reliability of the numerical solutions are presented. The BEM accuracy and efficiency are demonstrated by the examples of the solved test problems for flat punches of circular, annular and polygonal shapes. Boundary-element solutions for spatial contact problems concerning a rigid spherical inclusion and a cylindrical deepened punch in an elastic half-space are obtained. The final part of the chapter gives the results for numerical-and-analytical solution of the spatial contact problem on impressing a deepened conical punch into an elastic half-space. The method of determination of the deformation modulus from tests for deepened conical indenters with different angles by static loading is substantiated theoretically.

In the fourth chapter the results of the boundary-element solutions of spatial contact problems for complex-shaped punches, located on the surfaces of elastic nonclassical bases, are analyzed. The problems under consideration correspond to the modeling of contact interaction of shallow foundations with elastic nonhomogeneous bases. Contact pressure fields under punches of various shape under an eccentric load (a contact problem on a strongly inclined punch) are obtained. The influence of non-uniform (over the area) compressibility as well as depth-dependent nonhomogeneity of the base deformational properties on the formation and development of detachment zones, settlements and slopes of punches with the increase of the absolute values of overturning moments is shown. An algorithm to calculate the boundaries of the section core for rigid complex-shaped foundation plates from the stress values is described. Some optimization problems are solved for load and shape parameter control in order to provide uniform settlement of rigid foundation. As an example for the application of the developed boundary element method, a contact problem is solved and the elastic base stress-strained state is determined for a rigid strip foundation of variable width. In the same chapter a spatial contact model of the base is built taking into account nonlinear elastic soil properties. A procedure for the model parameter characterization based on the direct punch test data is considered. Finally, the chapter contains the studies of contact problems of bending of orthotropic plates situated on elastic nonclassical bases, performed by BEM combined with finite difference method.

In the fifth chapter BEM is applied to calculate contact interaction of foundation structures with soil, taking into account the deepening factor. The need for spatially-based calculation of bases of deepened foundations is explained. The principles for foundation structure calculations from the base deformations are briefly reviewed as well as the existing problem formulations and solution methods for spatial problems of contact interaction of deepened foundation structures with soil bases. Solutions of spatial contact problems for deepened monolithic-type foundation structures most widely used in the recent years are also considered, namely for (1) pyramidal piles; (2) foundations made of short vertical or inclined bored piles with caps; (3) bored pile foundations with support extensions; (4) slot foundations with the longitudinal cross-section of various shape. Heterogeneous stress-strained states of the base are taken into account as well as the formation of cavities between the soil and the foundation structures. The effect of the foundation shape on its displacement and slope at various spatial loading is estimated quantitatively. Numerous examples show the results of the boundary-element modeling to be in good agreement with the experimental measurements performed for spatial foundation structures, in most cases BEM results being closer to the experiment than those obtained by other known calculation methods.

Finally, the sixth chapter presents solutions of spatial problems of applied geomechanics related to variation of pore pressure in the soil. The influence of the pore pressure decline on the soil settlement and cracking as well as the induced seismicity and other environmental hazards due to pumping out gas and oil deposits or intense removal of underground water at industrial or civil engineering is discussed. The methods for numerical modelling of soil mass deformations due to the reduction of the pore pressure are described. The approach is based on the application of integral representations for displacements in a half-space saturated with liquid (or gas) according to the theory of linear pore-elasticity (filtration consolidation). Spatial deformation of the earth surface due to operating horizontal gas-and-oil wells or water drains is studied with the account of the run-off mode. Finally, the results for boundary-element solutions of the spatial contract interaction of structures with the soil at reduced pore pressure are presented.

The studies, presented in the book, are of applied character and have been initially oriented at geotechnical objects in industrial and civil engineering. The boundary element methods developed are suitable for wide applications to calculate the spatial deformation of soil bases. They provide high reliability and efficiency of design solutions for foundation structures. Moreover, the boundary element approach presented here can be helpful for solving other spatially-based problems of mechanics and mathematical physics.

The book summarizes the studies performed in the recent years in Voronezh State University of Architecture and Civil Engineering. The author is grateful to Prof. Viktor N. Nikolaevskiy for his all-round support as well as to Dr. Sergey V. Ikonin and Dr. Alexandr A. Sedaev for fruitful communications and helpful discussions which have enabled the book to be made more substantial.

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The author hopes that the work presented in the book can be a helpful study for numerical experiments in geotechnical engineering and will be grateful to the readers for their comments.

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