MIDDLEWARE-BASED MODELLING AND SIMULATION OF GEOTECHNICAL STRUCTURES

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SUMMARY

Modern large scaled buildings are erected on rather complex foundations. The design and analysis of these geotechnical systems requires a high quality of computer modelling and simulation. Therefore, it is necessary to model all geotechnical structural elements in a realistic and practice-oriented way. Due to the complexity of geotechnical structures object-oriented models are most appropriate. To solve large problems by means of the finite element method using a multi-component-continua theory for partially saturated porous media, it is necessary to parallelize the discretization and the simulation of the soil models. Furthermore, new communication methods permit the distribution of discretization and simulation processes by accessing computer clusters through the Internet.

INTRODUCTION

A network based concept for the co-operative work with finite element models to simulate soil-structure interactions in civil engineering has been developed in a distributed environment. The application and processing of "simulation-objects", which contain model descriptive and numerical data, were developed and tested in this context. The objects are persistently stored in object-oriented databases to assure the consistence of the models. The communication between applications, developed with the programming languages JAVA and C++, was realized using the Internet technology *Common Object Request Broker Architecture* (CORBA). Thereby, the previous approaches for distributed processes with numerical models, particularly the application of the finite element method including the pre- and post-processes using parallel computer architectures, were extended to a platform-independent communication network. In addition to the model description of a pure STEP-data exchange, an integrated system concept has been developed for the distributed processing of simulation objects; the object-oriented paradigm was extended by parallelism and concurrency. The focus of this contribution is on the distributed system architecture and the finite element pre-process.

SYSTEM ARCHITECTURE

The main focus of the system architecture is the distribution of soil-structure objects and numerical objects. In addition to the technical semantics these objects provide mechanisms for distributed processing and network communication. They are stored in object-oriented databases (OODB). The system architecture takes the whole finite element method analysis process into consideration. Thereby, all applications access the same distributed objects through the Internet. By this approach for distributed processes the numerical models are advanced to a platform-independent communication network. To integrate all applications for the geotechnical modelling with CAD-methods, for the definition of boundary conditions and external loads, for the parallel discretization and simulation in a distributed computer environment, the specification of interfaces for distributed objects was necessary. The CORBA-standard was deployed as a communication layer. In the sense of future system extensions the interoperability of the different CORBA-implementations was analyzed. The object exchange between JAVA-applets was realized by RMI (Remote Method Invocation) and the communication between CORBA and RMI by using the network RMI over IIOP (Internet Inter-ORB Protocol). The system architecture of the distributed application is shown in figure 1 including information about programming languages and operating systems.
Concerning the over all behaviour of the distributed application the main objective was to realize the less computational expensive tasks as JAVA- applications. Whereas the expensive discretization and

simulation were developed in C++ and executed on a parallel computer respectively on a workstation cluster. Thus, a maximum efficiency of the available resources was gained. The server-side processes were integrated into a suitable intuitive user interface as JAVA-applet and can be accessed from every workstation connected to the Internet. Therewith, the administration of the applications can be carried out centrally on the servers and all planning participants can access the current versions of the models from the object oriented database located on the server automatically.

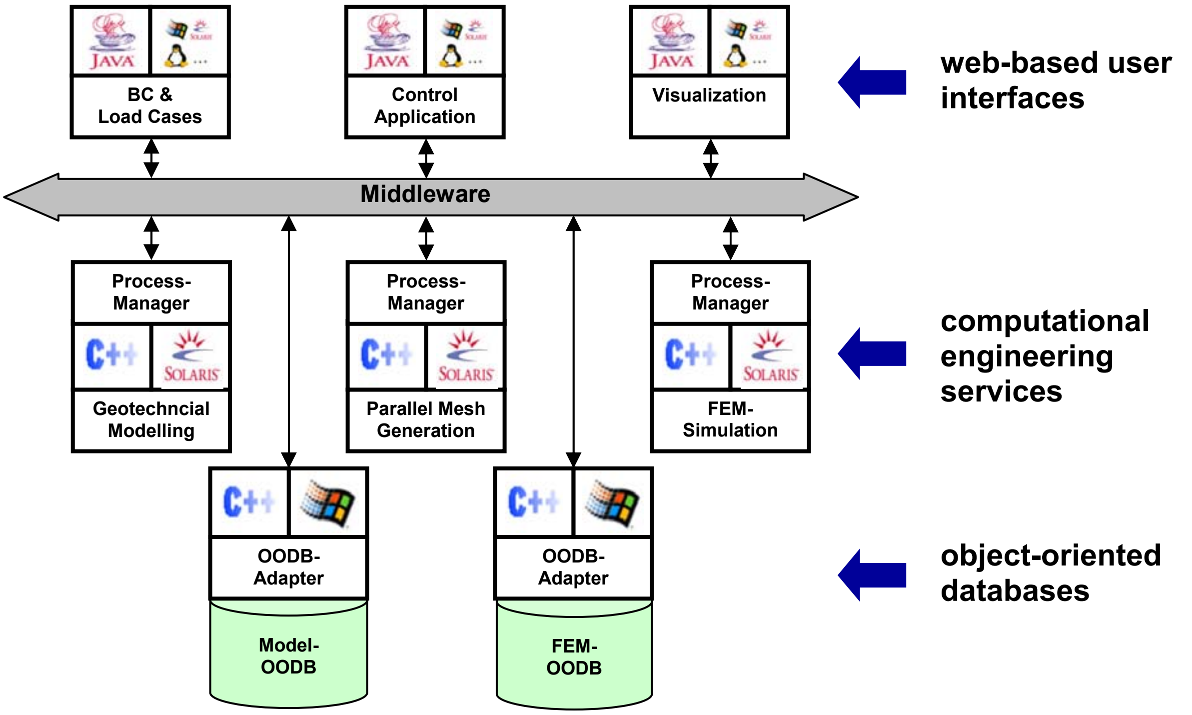


Figure 1 Distributed System Architecture

GEOTECHNICAL APPLICATION

The complex foundation of the Treptower Building (figure 3) in Berlin is a suitable example to demonstrate the results and the individual components of the distributed finite element system. The Treptower rises on a combined pile-plate-foundation [Katzenbach 1993] on 49 piles with a length up to 20 meters. The plate with a size of 37.10 x 37.10 meters is up to 5.00 meters thick [Reul 2000].
Starting from a JAVA-applet (figure 2) that provides an intuitive user interface to perform the pre-process, the simulation and the post-process, the user is able to carry out a complete simulation of soil-structures platform-independently. Thereby, he is assisted by a workflow management with regard to the modelling steps. Additionally, the most important data of the different processes are displayed in combination with a tree view representation of the geotechnical model.

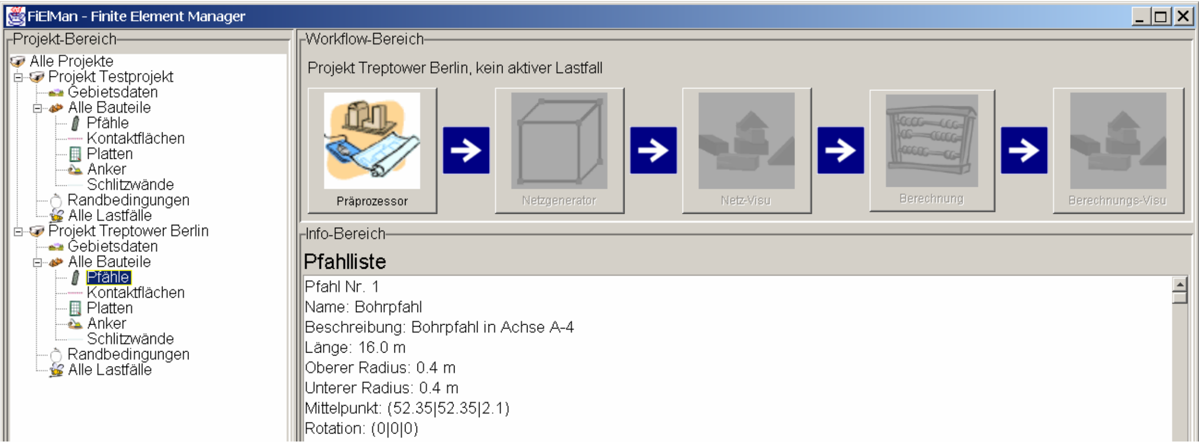


Figure 2 Control Application representing the Treptower Building model

PRE-PROCESS

The basic problem in conjunction with geotechnical engineering is the multi-dimensionality in space and time [Diaz 1998] [Schoenenborn 1999]. Planning work is carried out in several individual phases which differ in their degree of complexity, and generally rely on information obtained from preceding phases:

Phase 1: Prior exploration of geotechnical conditions for a project by site investigations etc.,
Phase 2: Soil investigation for the foundation by determination of soil parameters etc.,
Phase 3: Detailed investigation of the construction (design computation, dimensioning and proof of structured elements etc.),
Phase 4: Additional inspection and supervising of the construction work (e.g. control of the actual foundation soil based on the excavated material).

The order of the individual planning steps prescribes the specific sequence of engineering models. In phase 1, the preliminary site investigation is conducted based on two-dimensional layout plans and geological information. Once the site investigation has been completed, further information concerning soil composition, neighbouring structures etc. are added in phase 2. By combining the information obtained from Phases 1 and 2, a new level of detail is required for the dimensioning of construction elements, which may then be represented in layout plans, sectional drawings and three-dimensional models. Once the dimensioning stage has been reached (phase 3), decisions have to be made concerning the geotechnical construction based on the available planning information. The necessary parameters and dimensions (e.g. material, structural elements etc.) have to be specified or assumed for this purpose. The parameters obtained during the preliminary design stages subsequently serve as input for the final decision making. In order to ensure the necessary structural safety verifications for the selected construction, suitable models are required in the first instance. These models include all relevant information and basic planning data. For this reason, both simplified one- and two-dimensional models as well as complex three-dimensional models are applied. For verification purposes, it is necessary to set up and analyse all these models for the critical construction stages.
For this type of application the GeoTechnical Information System (GTIS) has been developed, implemented and tested. Essential requirements resulting from the described scenario are presented as follows:

- The ground model requires a time-dependent structure to represent all the critical states. This is possible with an object-oriented software design using a dynamic structure.
- A dynamic data structure must be suitable to manage the complexity within the ground model. Therefore, an octree-data-structure was used [Schneiders, Schindler, Weiler 1996].
- Direct relations between the ground model objects and the geotechnical construction elements are necessary.
- A model manager is required for the management of different construction stages.

- Due to the three-dimensional complexity of the ground and the geotechnical construction, a three-dimensional finite element analysis is required for all building states. For this purpose a multi-component-model was developed and implemented [Terlinden, Meissner 2001]

The object-oriented approach for an integrated model design is described in [Diaz 1998] [Schoenenborn 1999].
To simulate different scenarios of the construction state and to design the ground structure object-oriented CAD-methods (figure 3) were developed for a prototype of the GeoTechnical Information System (GTIS). Using these methods three-dimensional time-dependent soil-structure models can be generated and managed. All objects designed by the user are stored in an object-oriented GTIS-database on the server using CORBA.

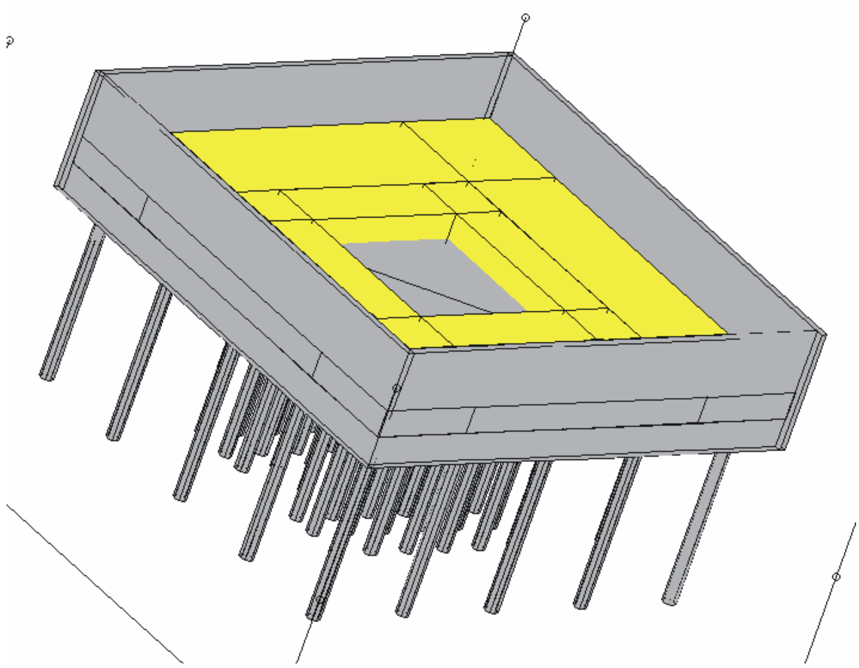


Figure 3 Foundation of the Treptower Building modelled with GTIS

Definition of Boundary Conditions and Load Cases

To simulate the system behaviour of the soil-structure with the finite element method boundary conditions and external loads have to be defined. To prepare such complex three-dimensional foundation models for a numerical simulation it is necessary to provide suitable software tools to specify these conditions. This has been realized by implementing a JAVA-applet which accesses the geotechnical objects of the GTIS-database in a project-specific manner to ensure the consistency of the model. After the graphical interactive definition of boundary conditions and external loads arranged in load cases these additional objects are persistently stored in the GTIS-database.

Mesh Generation

For the automatic generation of three-dimensional finite element meshes to represent the ground and the construction components a detailed description of the geotechnical system is essential. Therefore, the complex structure of ground and construction elements is modelled by CAD-methods within GTIS. Hexahedron and tetrahedron elements were used for the discretization of the soil-structure. The finite element software implements a 20-node hexahedron element for the simulation of the multi-component continuum. To ensure the accuracy of the finite element analysis mesh refinements are necessary. An error estimator based on a variational energy principal [Meissner, Wibbeler 1990] was included in the system. Boundary conditions and loads are assigned automatically to the finite element model when it is derived from GTIS.

Due to the complexity of the ground and the construction, unstructured hexahedron meshes are used to represent the discretized geometry. They are generated by a projection method [Burghardt 2001], comprising the following three steps (figure 4):

- Projection: The geometrical information of the ground topography and of the geotechnical construction elements is projected on a horizontal layer.
- 2D-Mesh: The projection is triangulated and the triangles are converted to a smoothed quadrangle mesh.
- Hexahedron Elements: Providing additional information in depth about the ground layers and construction elements, columns of hexahedron elements are generated for each quadrangle.

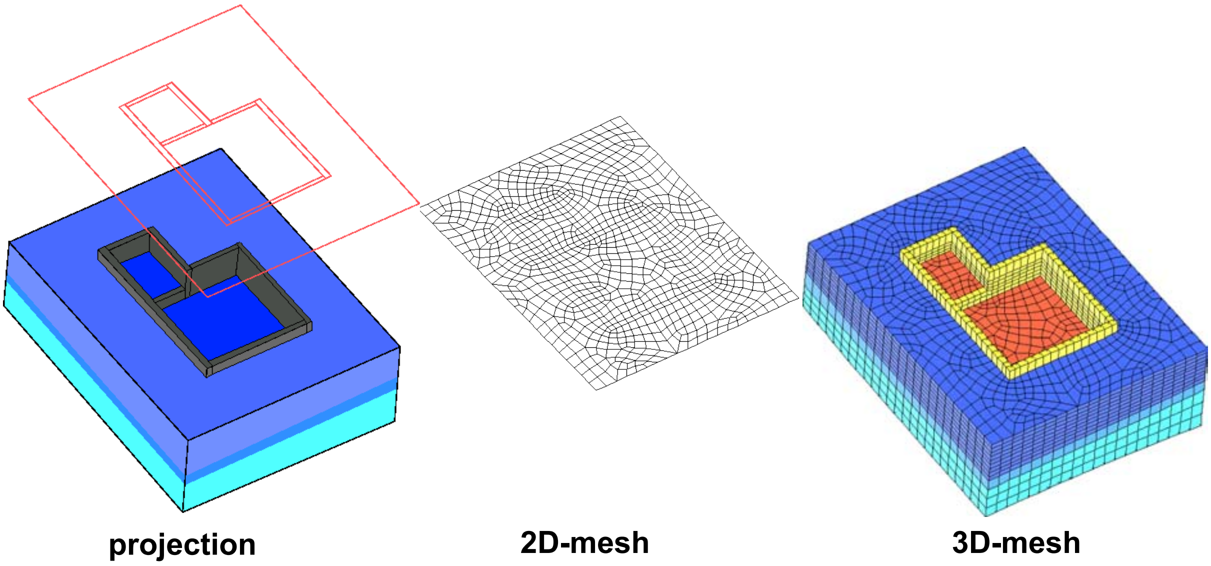
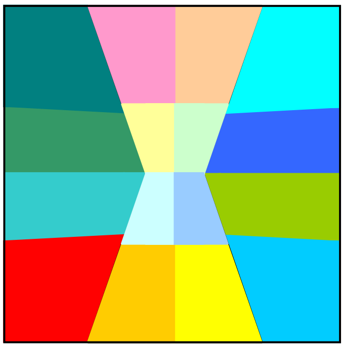


Figure 4 Projection Model

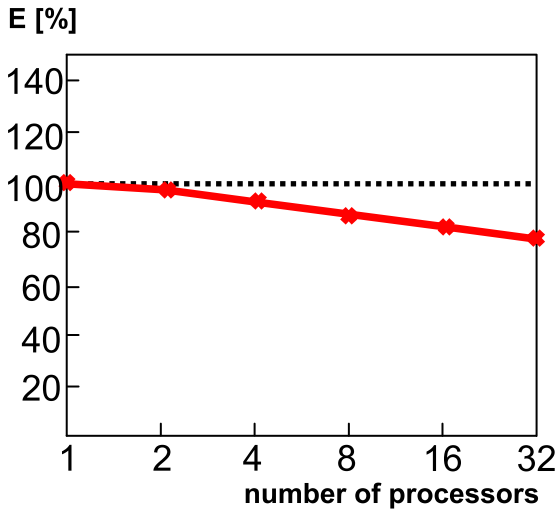
Local mesh refinements are necessary to ensure accuracy of the finite element analysis. While using the projection technique, the initial mesh is generated with a unique mesh density and refinements are achieved in subsequent steps. For the refinement of hexahedron elements of any region 22 different interface-meshes are useful [Burghardt 2001]. Some of these interface meshes can not be generated automatically. To refine a convex region only 5 of those interface-meshes are necessary. Recursive refinements are suitable in order to achieve locally higher density [Burghardt 2001].
An efficient parallelization of the finite element method is achieved by a non-overlapping partitioning of the soil-structure system into an appropriate number of sub-domains. The problem size required for an accurate FEM-application is considerably large. Therefore, the problem description in terms of finite element data is difficult to handle within the memory of a single workstation [Laemmer, Burghardt 1997]. The parallel mesh generation presented herein avoids this bottleneck using a workstation cluster.
The geometry of the projected geotechnical model is split into partial-domains in a recursive way by using the principal axis method [Burghardt 2001]. This method splits the projection geometry into sub-domains of approximately equal problem size within three steps:

1. The centre of gravity of the projected geotechnical model is calculated.
2. The coordinate-system is rotated due to the direction of the principal axes.
3. The geometry is split along the calculated axes.

These steps are repeated recursively until each processor possesses its own partial geometry to be discretized as illustrated in figure 5. This parallel approach for the mesh generation process provides an efficient use of a workstation cluster.



Weighted Partitioning



Efficiency diagram

Figure 5 Parallel Mesh Generation – Partitioning and Efficiency

NUMERICAL SIMULATION

Many geotechnical models treat the soil material as a homogeneous isotropic continuum with no consideration of the inner structure of the material or of the fact that most materials consist of a compound of different parts. Especially for the numerical simulation of soil-structure systems the theory of multi-component continua is most useful to predict consolidation phenomena. Based on the theory of porous media [Terlinden, Meissner 2001] the continuum approach was extended to a multiphase system using the mixture theory and the concept of volume shares. The system occupies the solid skeleton as well as liquid and gas phases within the porous medium domain (Figure 6).

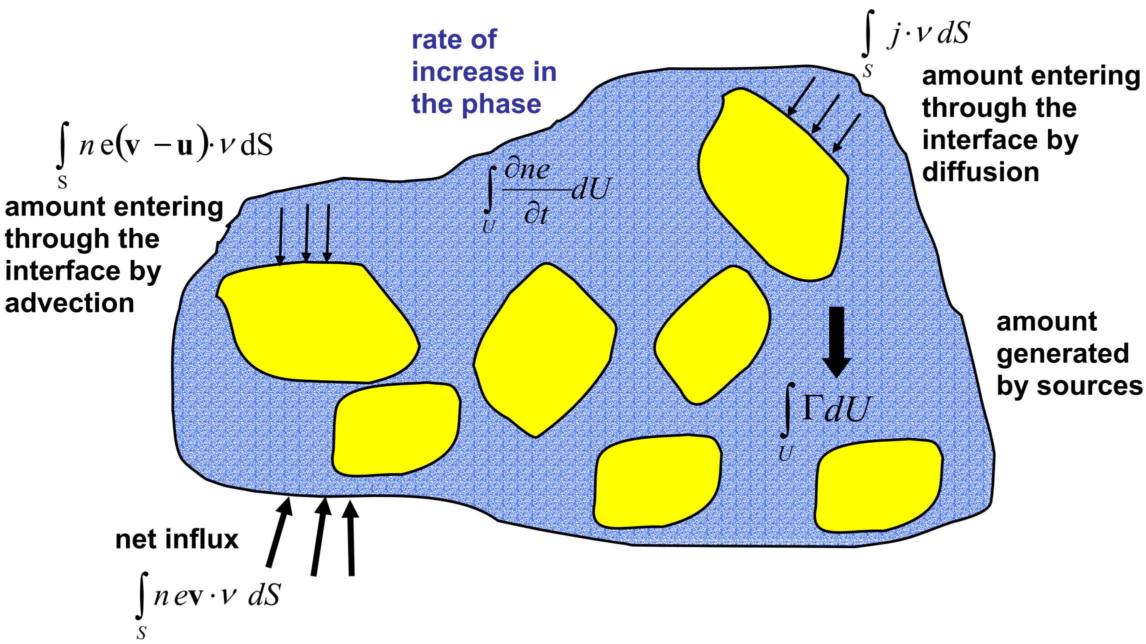


Figure 6 Macroscopic Balance

The multi-component problem cannot be solved at the microscopic level due to the lack of information concerning the microscopic configuration. The continuum approach can be extended to a multiphase system such as a porous medium, where the various phases are separated from each other by interfaces. The real system is replaced by a model in which each of the phases is assumed to be statistically described over the macroscopic space. Figure 6 illustrates the balance equations of mass or momentum, especially with its interaction terms between different phases.

$$\begin{bmatrix} M_S & 0 \\ 0 & M_F \end{bmatrix} \cdot \begin{bmatrix} \ddot{u} \\ \ddot{U} \end{bmatrix} + \begin{bmatrix} C_1 & -C_2 \\ -C_2 & C_3 \end{bmatrix} \cdot \begin{bmatrix} \dot{u} \\ \dot{U} \end{bmatrix} + \begin{bmatrix} K_1 & K_2 \\ K_2 & K_3 \end{bmatrix} \cdot \begin{bmatrix} u \\ U \end{bmatrix} = \begin{bmatrix} R_S \\ R_F \end{bmatrix} \tag{1}$$

The numerical model is derived from the basic physical equations by means of the finite element method adopting a three-dimensional Ritz-Galerkin scheme with regard to the boundary conditions [Terlinden, Meissner 2001]. A system of matrix equations (1) is obtained describing the phenomena which has to be integrated with respect to time by Newmarks method. The stepwise numerical results have to be stored into the object-oriented database.

POST-PROCESS

Within the post-process the user has to access all data, evaluate and interpret the results of the numerical model in order to draw conclusions onto the behaviour and the reliability of the model in relation to the problem [Katz 2000]. A distributed C++-application provides the visualization of the finite element systems. The user is enabled to verify results by a number of different representation possibilities. The direct access to the server database through the Internet permits a complete visual control of the time-variant calculation during run time of the simulation. Figure 7 illustrates a browser-based JAVA-application for the representation of a typical finite element discretization.

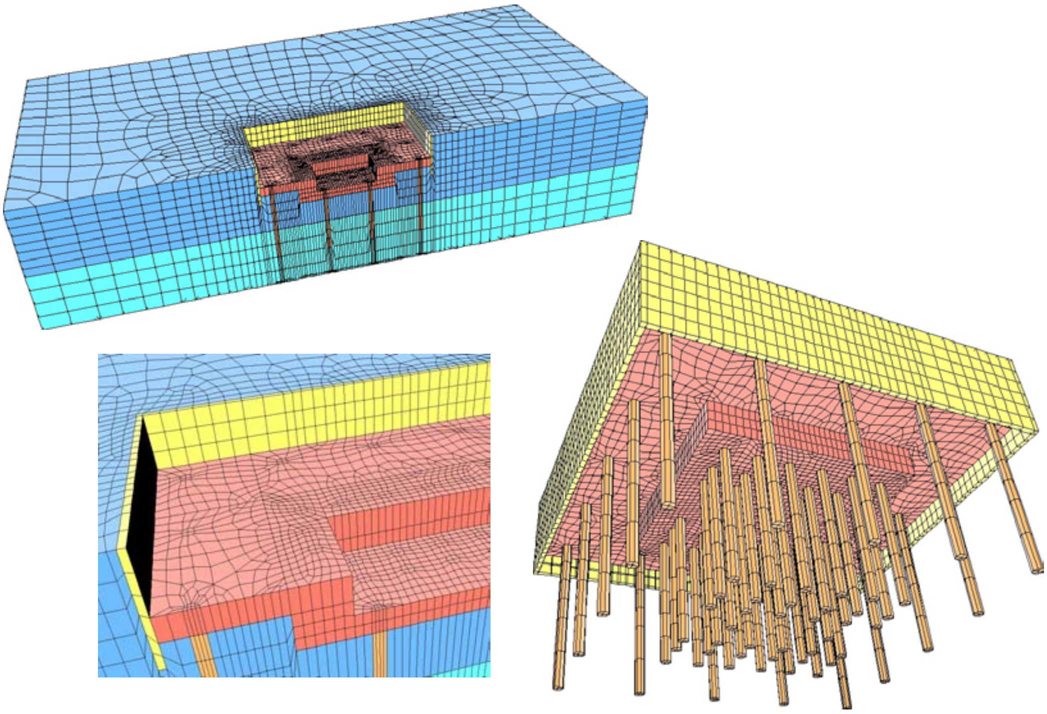


Figure 7 Three-Dimensional Discretization of the Treptower Building

CONCLUSION

The developed system provides an integral concept for the co-operative work with finite element models in a distributed engineering environment. Therefore, the whole finite element analysis process including post- and pre-processes has been integrated to establish a holistic modelling and analysis of soil-structure interactions. Object-oriented applications developed in C++ have been merged and supplemented with JAVA-applications by a middleware solution. Simulation objects have been designed for parallel processing in computer networks. Thus, the computing intensive discretization and numerical simulation can be speed-up by sharing computer resources in the network. Users have access and control to the distributed application (figure 1) by use of Internet-technologies.

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