PLAXIS

3D FOUNDATION

Version 2

Edited by

R.B.J. Brinkgreve

Delft University of Technology & PLAXIS bv, The Netherlands

W.M. Swolfs

PLAXIS bv, The Netherlands

With co-operation of

L. Beuth

W. Broere

P.G. Bonnier

E. Hartman

Y. El-Mossallamy

M. van der Sloot

D. Waterman

P.-A. von Wolffersdorff

.DOC Den Haag

PLAXIS bv P.O. Box 572, 2600 AN DELFT, Netherlands

Fax: + 31.15.257 3107; E-mail: info@plaxis.nl; Internet site: http://www.plaxis.nl

ISBN-13: 978-90-76016-04-7

Printed in the Netherlands

PREFACE

PLAXIS 3D FOUNDATION is a three-dimensional PLAXIS program, developed for the analysis of foundation constructions including (piled) raft foundations and offshore structures. It is part of the PLAXIS product range, a suite of finite element programs that is used worldwide for geotechnical engineering and design. The development of PLAXIS began in 1987 at Delft University of Technology as an initiative of the Dutch Ministry of Public Works and Water Management (Rijkswaterstaat). The initial purpose was to develop an easy-to-use 2D finite element code for the analysis of river embankments on the soft soils of the lowlands of Holland. In subsequent years, PLAXIS was extended to cover most other areas of geotechnical engineering. Because of continuously growing activities, the PLAXIS company (PLAXIS bv) was formed in 1993. In 1998, the first PLAXIS 2D deformation and stress analysis program for Windows was released. In the meantime a calculation kernel for 3D finite element calculations was developed which resulted in the release of the PLAXIS 3D TUNNEL program in 2001. PLAXIS 3D FOUNDATION is the second three-dimensional PLAXIS program and was developed in cooperation with TNO. The PLAXIS 3D FOUNDATION program was released in 2004.

Goals and objectives: In 1999, the PLAXIS company and the Numerical Mechanics group of TNO decided to start a research cooperation project on foundations. Main cause to start such a project was the increasing interest for pile-raft foundations. This type of foundation may lead to significant economical benefits compared to classical pile or raft foundations. Pile-raft foundations require advanced deformation-based tools to analyse the individual contributions of the piles and the raft in the total bearing capacity of the full foundation. The complementary competences of TNO (structural mechanics and numerical methods) and PLAXIS bv (soil modelling and numerical methods for geotechnical engineering) were essential for such a project, since foundations form the interaction between buildings (structures) and the soil. As a part of the research project a special purpose finite element computer program was developed. The current PLAXIS 3D FOUNDATION program is the result of further elaboration and operationalisation of this research program.

Support: The research required to develop the PLAXIS 3D FOUNDATION program was performed in the framework of a BTS cooperation project, with financial support from the Dutch Ministry of Economic Affairs.

CUR consortium / PDC: Research and development of the PLAXIS software is supported by the Centre for Civil Engineering Research and Codes (CUR), in which a consortium of more than 30 companies participate. This consortium is currently known as the PLAXIS Development Community (PDC). The consortium contributes financially to the PLAXIS developments and the CUR committee checks the efficiency and quality of the resulting software products. The consortium provides a valuable link with engineering practice. Future developments are discussed within the consortium and feedback is provided after new releases.

Scientific network: The development of PLAXIS and PLAXIS 3D FOUNDATION would not be possible without world-wide research at universities and research institutes. To ensure that the high technical standard of PLAXIS is maintained, the development team is

in contact with a large network of researchers in the field of geo-mechanics and numerical methods. Direct support is obtained from a series of research centres:

Delft University of Technology (NL)	Prof. F. Molenkamp, Prof. L.J. Sluys
Institut für Geotechnik, Uni Stuttgart (DE)	Prof. P.A. Vermeer, Dr. T. Benz
BundesAnstalt für Wasserbau (DE)	Dr. M. Heibaum, Dr. R. Schwab
Geodelft (NL)	J.M. van Esch, M. Visschedijk
TNO (NL)	Dr. G.J. Schreppers
Technical University of Graz (AT)	Prof. H.F. Schweiger
Laboratoire 3S, Univ. of Grenoble (FR)	Prof. M. Boulon, Prof. C. Viggiani
University of Oxford (UK)	Dr. H.J. Burd
University of Glasgow (UK)	Prof. S. Wheeler
University of Strathclyde (UK)	Prof. M. Karstunen
University of Colorado at Boulder (US)	Prof. S. Sture
Massachusetts Institute of Technology (US)	Prof. A.J. Whittle
University of California at Berkeley (US)	Prof. J.M. Pestana
Norwegian Univ. of Science and Tech (NO)	Prof. S. Nordal
Norwegian Geotechnical Institute (NO)	Dr. L. Andresen, Dr. H.P. Jostad
National University of Singapore (SG)	Prof. H. Tan
Parahyangan Catholic University (ID)	Prof. P. Rahardjo
Ain Shams University, Cairo (EG)	Dr. Y. El-Mossallamy
California Department of Transportation (US)	Dr. A. Shamsabadi
University of Lille (FR)	Prof. I. Shahrour
Technical University of Catalunya (ES)	Prof. A. Gens
Middle East Technical University (TR)	H.K. Engin

This support is gratefully acknowledged.

The editors

OVERVIEW OF THE FULL MANUAL

General information

IMPORTANT WARNING AND DISCLAIMER

PLAXIS is a finite element program for geotechnical applications in which soil models are used to simulate the soil behaviour. The PLAXIS code and its soil models have been developed with great care. Although a lot of testing and validation have been performed, it cannot be guaranteed that the PLAXIS code is free of errors. Moreover, the simulation of geotechnical problems by means of the finite element method implicitly involves some inevitable numerical and modelling errors. The accuracy at which reality is approximated depends highly on the expertise of the user regarding the modelling of the problem, the understanding of the soil models and their limitations, the selection of model parameters, and the ability to judge the reliability of the computational results. Hence, PLAXIS may only be used by professionals that possess the aforementioned expertise. The user must be aware of his/her responsibility when he/she uses the computational results for geotechnical design purposes. The PLAXIS organization cannot be held responsible or liable for design errors that are based on the output of PLAXIS calculations.

PLAXIS VERSIONS, COURSES AND USER SERVICES

Update Versions and new releases of PLAXIS, containing various new features, are released frequently. In addition, courses and user meetings are organised on a regular basis. Registered users receive detailed information about new developments and other PLAXIS activities. Valuable user information is provided by means of the PLAXIS bulletin and the Internet site *www.plaxis.nl*.

2D Professional Version: A large range of geotechnical problems may be analysed using this high capacity version. It is possible to use extensive 2D finite element meshes. The Professional Version is supplied as an extended package, including static elastoplastic deformation, advanced soil models, stability analysis, consolidation, safety analysis, updated mesh and steady-state groundwater flow.

2D Dynamics module: The PLAXIS Dynamics module is an add-on module to the PLAXIS 2D Professional Version. This module may be used to analyse vibrations in the soil and their influence on nearby structures. Excess pore pressures can be analysed. Liquefaction, however, is not yet included in this version, but is intended to become available in future versions.

PLAXFLOW: The PLAXIS Groundwater flow program is an independent program for the analysis of steady-state and transient groundwater flow. PLAXFLOW incorporates sophisticated models for saturated/unsaturated groundwater flow, using the well-known "Van Genuchten" relations between pore pressure, saturation and permeability. PLAXFLOW provides state-of-the-art facilities to incorporate time-dependent boundary conditions. It also enables the user to combine results with the PLAXIS 2D Professional Version for deformation and stability analysis.

3D Tunnel Program: This program is designed for the analysis of tunnel projects, but it also enables the analysis of a large range of other geotechnical problems. Large 3D finite element meshes can be generated. The 3D TUNNEL program is supplied as an extended package, including static elastoplastic deformation, advanced soil models, stability analysis, consolidation, safety analysis, updated mesh and steady-state groundwater flow.

3D Foundation Program: This program is designed for the analysis of raft foundations, but it also enables the analysis of piled raft foundations and offshore foundations. Large 3D finite element meshes can be generated. The 3D FOUNDATION program is supplied as an extended package, including static elastoplastic deformation, advanced soil models, stability analysis, consolidation and safety analysis.

V.I.P*laxis* Service Program: The V.I.P*laxis* Service Program is an additional subscription system on top of the traditional perpetual licenses. V.I.P*laxis* members benefit from the latest releases of their PLAXIS software and support from PLAXIS technical experts. In addition, some features of PLAXIS programs are only available for V.I.P*laxis* members. An overview of these features and more information about V.I.P*laxis* are available at the Internet site *www.plaxis.nl*.

Educational Version: For universities and education centres, an Educational Version of the listed PLAXIS programs for non-commercial use is available at a reduced price.

PLAXIS Introductory: An introductory version of PLAXIS Version 8, PLAXIS 3D FOUNDATION and PLAXIS 3D TUNNEL is available for interested persons who wish to learn about the program features and capabilities before ordering the Educational Version or the Professional Version. PLAXIS Introductory is based on the Professional Version, but there is a limited number of material sets, groundwater flow calculations are not available and the number of calculation phases is limited. In addition, it is not possible to copy or print. A Tutorial Manual with examples specifically generated for the PLAXIS Introductory is included.

Courses on Computational Geotechnics: Courses dealing with both theoretical and practical aspects of computer modelling in geotechnical engineering are given on a regular basis in several countries, with support from the scientific network. In these courses, application exercises and case studies are included during which participants have the opportunity to carry out various types of computer analyses. Although PLAXIS is intensively used, the courses are not primarily intended to teach the details of the computer programs. The main aim of these courses is to teach finite element modelling in geotechnical engineering, with direct applications to practical problems.

Bulletin: An international bulletin, issued twice a year, is provided to all registered PLAXIS users. This bulletin contains descriptions of practical projects in which PLAXIS has been used, backgrounds on the use of advanced soil models, information on new developments, hints for optimised usage of the program and a diary of activities. Ideas and experiences with the PLAXIS programs are highly appreciated.

Internet site: In addition to the information provided in the bulletin, the internet site *http://www.plaxis.nl* contains more general information about PLAXIS, including information on courses and user meetings, answers to frequently asked questions and a discussion group for users. Registered users can download the latest PLAXIS updates.

User support: Unlimited priority technical support is provided by e-mail for members of V.I.P*laxis* Service Program. A professional helpdesk is available for clients who wish to obtain prompt and extensive technical and scientific support.

For more information on products and user's services, contact:

PLAXIS bv

P.O. Box 572

NL-2600 AN Delft

The Netherlands

E-mail: info@plaxis.nl

Internet: www.plaxis.nl

SHORT REVIEW OF FEATURES

PLAXIS 3D FOUNDATION is a finite element package intended for the three-dimensional deformation analysis of foundation structures. Foundations form the interaction between an upper structure and the soil. Settlements depend on local soil conditions and on the construction method. Especially for pile-raft foundations there is an important interplay between the pile, the raft and the soil to support the forces from the upper structure. In this interplay deformations are a key factor. Such a situation can only be analysed effectively by means of three-dimensional finite element calculations in which proper models are incorporated to simulate soil behaviour, soil-structure interaction and structural behaviour. The PLAXIS 3D FOUNDATION program offers these facilities. A brief summary of the most important features is presented below.

New features: Version 2 of the PLAXIS 3D FOUNDATION program offers additional functionality compared to previous releases. New features include embedded piles, ground anchors, the Hardening Soil model with small-strain stiffness (HSsmall), support for user-defined soil models, soil tests, vertical mesh refinement, user-defined boundary conditions for consolidation and Phi/c reduction. Further features include multi-select and grouping, hardware accelerated display of graphical output data and the possibility to create animations of the results.

Graphical input of projects: A project geometry is modelled using a top view approach. The input of soil data, structures, construction stages, loads and boundary conditions is based on convenient CAD drawing procedures, which allows for a detailed and accurate modelling of the major geometry. From this geometry a 3D finite element mesh is generated.

Boreholes: Soil layers are defined by means of boreholes. Multiple boreholes can be placed in the geometry to define a non-horizontal soil stratigraphy or an inclined ground surface. PLAXIS automatically interpolates layer and ground surface positions in between the boreholes.

Work planes: Structures and loads are defined in horizontal work planes. Multiple work planes can be defined to create complex foundations, multi-storey basements and relevant parts of the upper structure.

Automatic mesh generation: The PLAXIS 3D FOUNDATION program allows for an automatic generation of unstructured 2D finite element meshes based on the top view. The 2D mesh generator is a special version of the Triangle generator, which was developed by Sepra[1]. A 3D mesh is automatically generated, taking into account the soil stratigraphy and structure levels as defined in the boreholes and work planes. There are options for global and local mesh refinement. Global mesh refinement can affect the horizontal element distribution as well as the vertical element distribution.

Volume elements: Quadratic 15-node wedge elements are available to model the deformations and stresses in the soil. Due to non-horizontal soil stratigraphy, these

[1] Ingenieursbureau Sepra, Park Nabij 3, 2267 AX Leidschendam (NL)

elements may degenerate once to 13-node volume elements or twice to 10-node tetrahedral elements.

Beams: PLAXIS 3D FOUNDATION may involve structural objects like springs, beams, embedded piles, ground anchors, walls and floors. Horizontal or vertical beam elements can be used to model slender one-dimensional objects with a significant flexural rigidity. The stiffness of these elements is defined using elastic stiffness properties or non-linear deformation curves.

Walls and floors: Plate elements can be used to model raft foundations, basements, walls and floors of buildings, as well as other parts of structures. The behaviour of these elements is defined using elastic stiffness properties or non-linear deformation curves (N-ε, Q-γ and M-κ diagrams).

Interfaces: These joint elements are added to walls to allow for a proper modelling of soil-structure interaction. Interfaces may be used to simulate, for example, the thin zone of intensely shearing material at the contact between a wall and the surrounding soil. Values of interface friction angle and adhesion that are not necessarily the same as the friction angle and cohesion of the surrounding soil may be assigned to these elements.

Piles: Circular and square piles can be defined using a pile designer. Massive piles are composed of volume elements whereas hollow piles are composed of wall elements. Pile-soil interaction can be modelled using interfaces around the pile.

Embedded piles: These special elements consist of beam elements with embedded interface elements to describe the interaction of the pile with the soil at the skin and the foot of the pile. The beam element is considered to be linear elastic and its behaviour is defined using elastic stiffness properties. The embedded interface elements are considered to be elasto-plastic. The failure behaviour of the embedded pile elements is defined by their bearing capacity.

Ground anchors: These special elements consist of embedded pile elements (representing the grout body) and an anchor. The behaviour of the anchor is defined using a normal stiffness and a maximum force. The embedded pile elements consist of beam elements with embedded interface elements to describe the interaction of the ground anchor with the soil. The beam element is considered to be linear elastic and its behaviour is defined using elastic stiffness properties. The embedded interface elements are considered to be elasto-plastic. The failure behaviour of the ground anchors is defined by their bearing capacity. During calculations, a ground anchor may be pre-stressed.

Springs: Springs can be used to simulate anchors or props to support retaining walls. Alternatively, springs can be used to simulate piles in a simplified way, i.e. without taking into account pile-soil interaction. The behaviour of spring elements is defined using a normal stiffness or a non-linear deformation curve.

Loads: The program allows for various types of loads (point loads, line loads, distributed loads) that could be applied in the model. Different loads and load levels can be activated independently in each construction stage.

Mohr-Coulomb model: This robust and simple non-linear model is based on soil parameters that are known in most practical situations. Not all non-linear features of soil behaviour are included in this model, however. The Mohr-Coulomb model may be used to compute realistic bearing capacities and collapse loads of footings, as well as other applications in which the failure behaviour of the soil plays a dominant role. It may also be used to calculate a safety factor using a 'phi-c reduction' approach.

Advanced soil models: As a general second-order model, an elastoplastic type of hyperbolic model is available, which is called the Hardening Soil model. This model allows for plastic compaction (cap hardening) as well as plastic shearing due to deviatoric loading (friction hardening). To account for the increased stiffness of soils at small strains, the Hardening Soil model with small-strain stiffness is available. To analyse accurately the time-dependent and logarithmic compression behaviour of normally consolidated soft soils, a Creep model is available, which is referred to as the Soft Soil Creep Model. More detailed information on these models can be found in the Material Models Manual.

User-defined soil models: A special feature in PLAXIS 3D FOUNDATION is the user-defined soil models option. This feature enables users to include self-programmed soil models in the calculations. This option is primarily of interest for researchers and scientists at universities and research institutes, but it may also be useful for practising engineers. An overview of existing user-defined soil models is available on the PLAXIS website.

Soil tests: The soil test option in PLAXIS is a convenient procedure to check the behaviour of the selected soil material model with the given material parameters. After entering the model parameters, the user can quickly simulate several standard soil tests and compare the results against the results from actual laboratory tests.

Structural behaviour: Structural behaviour may be defined as linear elastic material orthotropy or as non-linear elastic force-deformation curves. This applies to beams, walls, floors and springs. Geometric orthotropy of plates with a particular profile can also be emulated to a certain extend. Embedded piles and grout bodies of ground anchors are always considered to be linear elastic. The anchor of a ground anchor can be defined either linear elastic or linear elastic perfectly plastic.

Steady-state pore pressure: Complex pore pressure distributions may be generated on the basis of the input of water levels or pore pressure distributions in the bore holes and soil clusters.

Excess pore pressure: PLAXIS distinguishes between drained and undrained soils to model permeable sands as well as almost impermeable clays. Excess pore pressures are computed when undrained soil layers are subjected to loading.

Automatic load stepping: The PLAXIS 3D FOUNDATION program runs in an automatic step-size selection mode. This avoids the need for users to select suitable load increments for non-linear calculations by themselves and it guarantees an efficient and robust calculation process.

Staged construction: This PLAXIS feature enables a realistic simulation of construction and excavation processes by activating and deactivating clusters of elements, application of loads, changing of water pressure distributions, etc. This procedure allows for a realistic assessment of stresses and displacements as caused, for example, by the construction and loading of a foundation.

Consolidation analysis: The decay of excess pore pressures with time can be computed using a consolidation analysis. A consolidation analysis requires the input of permeability coefficients in the various soil layers. Geometry boundaries can be set open or closed for consolidation. Automatic time stepping procedures make the analysis robust and easy-to-use.

Safety factors: The factor of safety is usually defined as the ratio of the failure load to the working load. This definition may be suitable for foundation structures, but not for sheet-pile walls or embankments. For this latter type of structure it is more appropriate to use the soil mechanics definition of a safety factor, which is the ratio of the available shear strength to the minimum shear strength needed for equilibrium. PLAXIS can be used to compute this factor of safety using a 'phi-c reduction' procedure.

Preview option: A convenient preview option is available to check model and calculation settings in a graphical 3D environment. Since 3D calculations can be quite time consuming, it is important to check the model carefully before starting the calculation process.

Presentation of results: The PLAXIS postprocessor has enhanced 3D graphical features for displaying computational results. Exact values of displacements, stresses, strains and structural forces can be obtained from the output tables. Plots and tables can be sent to output devices or to the Windows® clipboard to export them to other software.

Stress paths: A special tool is available for drawing load-displacement curves, stress paths and stress-strain diagrams. Particularly the visualization of stress paths provides a valuable insight into local soil behaviour and enables a detailed analysis of the results of a PLAXIS 3D FOUNDATION calculation.

HARDWARE SPECIFICATIONS

System requirements: The program runs on Pentium PC's using Windows® 2000 Service Pack 6 or Windows® XP Professional 32-bit; Windows® XP is the preferred operating system. Although there is no reason to assume that the program does not run under Windows Vista® business editions, it has not yet been tested sufficiently to guarantee this. Version 1.1 or higher of OpenGL should be installed.

External drives: For installation purposes a CD-ROM drive is required.

USB port: To insert the dongle a USB port is required.

Graphics card: The program requires a graphics card with at least 64 MB RAM. The graphics card should support OpenGL Version 1.1 (or higher).

Processor: A Pentium IV processor or better is recommended.

Hard disk: To install the package, at least 40 MB of hard disk space must be available for the application itself. The provided examples require 110 MB of hard disk space. In addition, a minimum workspace of 500 MB is recommended, but for large projects more disk space may be required.

Random Access Memory (RAM): The minimum recommended amount of free RAM in the computer is 1GB. When more memory is used, a faster operation can be performed or more elements can be used.

Video modes: The PLAXIS 3D FOUNDATION program requires a minimum screen resolution of 1024 x 768 pixels and a 32 bit colour palette.

Mouse: A graphical pointing device (mouse) with two or three buttons is required.

Output devices: Graphical and tabulated output can be printed on all modern types of laser or inkjet printers (including colour printers). Printing is fully controlled by the Windows® operating system. For more information on the installation of output devices reference should be made to the respective manuals.

PC network: A single version may be installed on a PC network. However, single versions can only be run on one workstation at a time using a local dongle. A multiple licence network version is available upon special request. A network dongle can only be installed on a computer using a Windows operating system (either workstation or server).

INSTALLATION

The package is installed by using an easy-to-use installation program. The program acts like a wizard and guides the user through the installation settings. During installation the files from the installation CD are decompressed and copied to the appropriate locations on the hard disk. At the end of the installation procedure, a new program group is automatically created in the *Programs* sub-menu of the *Start* menu. The installation does not affect other PLAXIS products. Installation under the various Windows® versions, as mentioned in the system requirements, is similar. Make sure that you have the *Administrator* rights to be able to update the Windows registry and to write all files.

Program installation

- Insert the installation CD in the CD-ROM drive. Within 10-20 seconds an introduction screen should appear. If this is not the case, then:
  - Click the Windows® *Start* button and select *Run...* from the *Start* menu.
  - In the *Open* edit field type "R:\AUTORUN.EXE" (assuming that the installation is executed from CD-ROM drive "R").
  - Click the *OK* button to start the introduction screen.
- Choose the option *Install PLAXIS 3D FOUNDATION Version XX*.
- Follow the instructions on the screen.
- Before starting the program, make sure that the dongle is correctly installed.

Make sure that the latest dongle drivers are installed. These can be downloaded from the PLAXIS website: http://www.plaxis.nl/ in the *Downloads* section.

Local dongle installation

PLAXIS continuously checks for the presence of the dongle that is included in the package. The dongle must be inserted in a USB port of the computer. Normally a device driver for the dongle is installed during the setup. If, for some reason, the installation of the dongle driver fails the user can install it manually as described in the section *Troubleshooting* at page xiv.

Network dongle installation

Alternatively it is possible to use a shared multiple licence dongle over the network. The document “CodeMeterNetworkSetup.pdf” that can be found on the Plaxis 3D Foundation Installation CD describes the procedure to follow.

PROGRAM UNINSTALL AND REINSTALL

Should you wish to uninstall or reinstall the program you can either use the Windows' *Add/Remove* programs utility from the *Control Panel* or re-run the installation from the Installation CD. You can now choose whether to remove the program from your computer, repair a currently installed version or modify the currently installed version.

TROUBLESHOOTING

In exceptional cases the installation program fails to install the PLAXIS package. Some possible error messages during the execution of the program are:

- The program starts with a message and then closes immediately
- Problems with OpenGL

Additionally the following problems may occur:

- Mesh generation fails or calculation hangs directly after starting

The appropriate actions to be taken on the problems are described below. In addition, more solutions to problems can be found on the PLAXIS website: http://www.plaxis.nl/ in the *Product Updates* part of the *Downloads* section.

Program start with a message and then closes immediately

Make sure that the dongle is inserted in a USB port of the computer. In addition, make sure that the latest drivers are installed. These can be found on the PLAXIS website: http://www.plaxis.nl/ in the *Downloads* section. Download the drivers for the right system type (32-bit or 64-bit Operating System).

Problems with OpenGL

In case of problems with OpenGL make sure that the latest drivers for the graphics card have been installed. In addition, the settings of the graphics card can be changed via the windows dialog *Display Properties*, tab sheet *Settings*, button *Advanced*. This way the quality of the display can also be increased.

Mesh generation fails or calculation hangs directly after starting

Both problems are related to the Windows' temporary directory stored in the TEMP environment variable. By default the TEMP variable contains a rather long path ("C:\Documents and Settings\<username>\Local Settings\Temp" for the case where Windows has been installed on drive "C") causing the problem.

The solution is to set the TEMP variable to a shorter, existing, path. To do this:

- Go to the Windows Start Menu and successively select "Settings", "Control Panel" and "System".
- In the "System Properties" window that has now appeared choose the last tab sheet called "Advanced".
- From this tab sheet choose the middle option "Environment variables"
- In the "Environment variables" window choose from the uppermost list the variable called TEMP and select the "Edit" button in order to change its value.
- Set the TEMP variable's value to, for example, "C:\TEMP".
- Close all windows.

- Make sure the newly defined temporary directory exists. If this is not the case, then create the directory using the Windows Explorer.

Note that the above procedure may have to be repeated after installing a Windows Service Pack.