Validating a new design method for piled embankments with PLAXIS 2D and 3D
3D Modelling of Train Induced Moving Loads on an Embankment
Preliminary 3D Modelling of Structural Behaviour of Face Bolting and Umbrella Arch in Tunneling
The Plaxis Bulletin is the combined magazine of Plaxis bv and the Plaxis users association (NL). The bulletin focuses on the use of the finite element method in geotechnical engineering practice and includes articles on the practical application of the PLAXIS programs, case studies and backgrounds on the models implemented in PLAXIS.

The bulletin offers a platform where users of PLAXIS can share ideas and experiences with each other. The editors welcome submission of papers for the Plaxis bulletin that fall in any of these categories.

The manuscript should preferably be submitted in an electronic format, formatted as plain text without formatting. It should include the title of the paper, the name(s) of the authors and contact information (preferably e-mail) for the corresponding author(s). The main body of the article should be divided into appropriate sections and, if necessary, subsections. If any references are used, they should be listed at the end of the article.

The author should ensure that the article is written clearly for ease of reading.

In case figures are used in the text, it should be indicated where they should be placed approximately in the text. The figures themselves have to be supplied separately from the text in a vector based format (eps, ai). If photographs or 'scanned' figures are used the author should ensure that they have a resolution of at least 300 dpi or a minimum of 3 mega pixels. The use of colour in figures and photographs is encouraged, as the Plaxis bulletin is printed in full-colour.

Colophon

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Editorial board:
Ronald Brinkgreve
Erwin Beernink
Martin de Kant
Arny Lengkeek

Design:
Judi Godvliet

Any correspondence regarding the Plaxis Bulletin can be sent by e-mail to:
bulletin@plaxis.com

or by regular mail to:
Plaxis Bulletin
c/o Annelies Vogelezang
PO Box 572
2600 AN Delft
The Netherlands

For information about PLAXIS software contact your local agent or Plaxis main office:

Plaxis bv
PO. Box 572
2600 AN Delft
The Netherlands

info@plaxis.com
www.plaxis.com
Tel.: +31 (0)15 251 7720
Fax: +31 (0)15 257 3107
We are pleased to present you the new edition of the PLAXIS bulletin, including three very diverse user articles. With the PLAXIS 2D AE release behind us and its positive reception by our user base, we have since then focused our efforts back into developing new features for the upcoming 3D and 2D releases. We are proud to already reveal a snippet in this Autumn edition, which brings us closer to another milestone in the long history of Plaxis.

The New Developments column focuses on the new Thermal module which is due for release in 2015. With the gradual change of the climate felt worldwide, engineers come across new geotechnical challenges like buildings founded on now thawing permafrost, which they seek to take into account in their modelling. The Thermal module will fulfill their needs and will also open possibilities for some of the more conventional applications like modelling soil freezing or temperature effects of buried pipelines. With the new module we meet our customers’ demands to perform these types of analyses with the PLAXIS program, with the user friendliness that you have come to know.

The first user’s article discusses the validation for a new design method for piled embankments in PLAXIS 2D and 3D. The article expands on earlier works, where a proposed concentric arches model is validated via finite element analyses against earlier measurements from laboratory scaled test and field tests. New insights into previously uncertain factors led to an improved match between model and measurements.

In the second user’s contribution, work on 3D modelling of train induced moving loads on an embankment is presented. The authors propose a method on how to model dynamic loads simulating high-speed trains, which pass over the embankment. Furthermore different constitutive models were used to approximate and compare the dynamic behaviour of the embankment. The authors comment that with more details in the load system, PLAXIS 3D can successfully model interaction between two trains. In the future Plaxis will add facilities to ease the modelling of moving loads.

The third user’s article describes preliminary 3D modelling of structural behaviour of face bolting and umbrella arch in tunneling. Through parametric studies on a base model for the South tube of the Toulon tunnel in France, the author investigates and discusses the effects of face bolting density on surface settlements and on tunnel face displacements. In a second study the effect of the density of the umbrella arch on surface settlements is investigated, finding agreement with an earlier study on the Toulon tunnel.

For the Expert Services update, we review an in-house training that Plaxis delivered in the USA, where the customer required a broad education on the PLAXIS 2D and 3D programs and a day entirely focused on their needs with respect to Dynamic analysis.

For our worldwide presence on events or hosted courses we refer you to the upcoming events on the backside of the bulletin.

We hope to have created another interesting reading for our readers and we look forward to receiving your comments on the autumn 2014 edition of the bulletin.

The Editors
Before considering the details of this new PLAXIS module, let’s first consider some particular applications that require thermal analysis or THM coupling:

- Calculating strut forces and wall forces as a result of thermal expansion of the strut (due to sunlight absorption and temperature changes) in excavation projects.
- Calculating the forces on walls and other structures in the ground as a result of (cyclic) movements due to daily temperature changes.
- Calculating the temperature distribution around freeze pipes in excavation projects involving ground freezing.
- Calculating ground movement and stability considering thermal expansion of underground pipelines.
- Calculate the influence of a changing climate on the temperature distribution in the ground (for example in permafrost areas) to evaluate the corresponding change of soil properties.
- Calculate the efficiency and sustainability of borehole heat exchangers in aquifer layers.
- Calculate the change of temperature in the underground as a result of nuclear waste storage.

Several of such applications are driven by societal issues (global warming, renewable energy, care for the environment). The fact is that more and more PLAXIS users are working on such projects and therefore require thermal calculation capabilities in the software. The new 2D module involves thermal conduction, diffusion and convection in the soil mass as well as advection with groundwater flow. The latter may also lead to density flows due to differences in groundwater temperature. Also air-soil interaction at the ground surface is included, as well as thermal conduction in structural elements and thermal insulation in interface elements.

Just like Plaxflow, the Thermal module will be fully integrated with the existing PLAXIS user-interface. Thermal properties are added to material data sets, and thermal boundary conditions and cluster-related conditions are added to the geometry; all in the same manner as for groundwater flow calculations. In the calculations window, you can specify whether or not you want to consider temperature. If so, the initial temperature distribution can easily be defined based on the earth’s gradient.

In subsequent calculations you can adopt the temperature distribution from the previous phase, or define a new steady-state condition for the current phase, or define a fully coupled transient analysis. The latter also allows for functions for temperature or heat flux to be defined in the attributes library and assigned to certain boundaries; again, very similar as the definition of groundwater flow functions.

Although the Thermal module will first be released as a 2D module only, we are confident to provide many users with thermal calculation facilities that are very useful in several applications. We are looking forward to welcome you as a user of this new module as of the first quarter of 2015, and we are very interested to receive your feedback.

In addition to the facilities for rock engineering, as mentioned in the previous Bulletin, PLAXIS is now coming with new facilities for thermal analysis and thermo-hydro-mechanical (THM) coupling. This major extension will again broaden the range of applications in civil, environmental, energy, mining and polar engineering. The first release of the Thermal module will become available with the new 2D 2015 version.

Ronald Brinkgreve, Plaxis bv

Figure 1: Temperature distribution around a nuclear waste canister after 100 days
The group of geotechnical engineers to be trained at Hart Crowser Inc. consisted of 3 different levels of engineers:

1. Principle engineers, responsible for project acquisition and marketing;
2. Associate engineers, responsible for project management and project review;
3. Geotechnical engineers, responsible for Plaxis calculations.

The purpose of the training was to provide the different attendees with the specific knowledge for their daily work. In consultation with the Client a stepwise approach was chosen.

The first part of the training concentrated on the Principle engineers and explained the basics of Finite Element (FE) modelling with Plaxis 2D and 3D. With this knowledge the Principle engineers are better able to judge when the use of a Plaxis model in a project is suitable.

The second part concentrated on the Associate engineers and explained more theoretical aspects of FE modelling and also a number of hands on exercises were made. Finally some important aspects of FE model review were discussed. With this knowledge the Associate engineers are better able to review the Plaxis models set up for their projects.

The third part was only for the level 3 Geotechnical engineers who work with Plaxis on a regular basis and focused in detail on working with PLAXIS 3D and dynamic modelling with PLAXIS 2D.

With this knowledge the engineers are better able to set up and run their Plaxis models.

Course schedule
First day, part 1 (level 1, 2 and 3 engineers):
• Introduction to PLAXIS 2D and 3D
• Possibilities and limitations of PLAXIS 2D and 3D
• Demonstration of 2D and 3D models

First day, part 2 (level 2 and 3 engineers):
• Background of the MC and HS(model)
• Exercise: simulation with SoilTest

Second day (level 2 and 3 engineers):
• Focus on excavations and embankments with a.o.:
  • Background and modelling of undrained behavior
  • Exercise: modelling tied-back excavation with MC and HS model
• Important aspects of FE model review

Third day (level 3 engineers):
• Focus on modelling using PLAXIS 3D, with a.o.:
  • Tips on modelling and meshing in Plaxis 3D
  • Exercise: Piled raft foundation
• Discussion on common modelling problems

Fourth day (level 3 engineers):
• Focus on dynamic analysis using Plaxis 2D, with a.o.:
  • Modelling liquefaction using the UBCsand model
  • Exercise: Quay wall in Kobe

Customer quotes
"Plaxis worked with us to create a unique training schedule that allowed us to maximize the time spent in training. The trainer was excellent and was comfortable working with some of the unusual problems we proposed to him."
-Brice Exley, Hart Crowser, Inc. 2014

About Hart Crowser Inc.
Founded in 1974, Hart Crowser is a 110-person consulting firm specializing in natural resources, environmental, and geotechnical services. The firm's offices are in Seattle (headquarters), Edmonds, and Vancouver, Washington, and Portland, Oregon, and Honolulu, Hawaii. Hart Crowser has been the geotechnical engineer of record on significant projects including the world's longest floating bridge, largest diameter bored tunnel, and many deep excavations.
Validating a new design method for piled embankments with PLAXIS 2D and 3D

T.C. van der Peet, Witteveen + Bos consulting engineers - P.G. van Duijnen, Huesker Synthetic BV - S.J.M. van Eekelen, Deltares

Infrastructural projects such as roads and railway tracks are usually built on an embankment of sand or granular material. When building on soft soils, the prevention of differential settlements and resulting damage is traditionally done by including a long settlement period in the construction process. One method to decrease construction time is to use a pile foundation beneath the embankment. If a geosynthetic reinforcement (GR) is used in the base of the embankment, the construction is called a basal reinforced piled embankment.

In September 2013, Van Eekelen et al. published a new design model for basal reinforced piled embankments. This Concentric Arches model specifically focuses on determining the load distribution within the embankment.

Additional to the validation given in the publication itself, numerical calculations were used to determine the validity of the Concentric Arches model. This was done within the MSc thesis of Van der Peet (2014), also reported in Van der Peet and Van Eekelen (2014) and included two steps of validation. First, a numerical model was designed and its results compared to field and laboratory measurements. Then, the numerical model was used for a parameter variation study to validate the Concentric Arches model. This was done by comparing the numerical results to predictions of the Concentric Arches model as well as two other models that are currently in use. The Zaeske (2001) model is used in guidelines in Germany and the Netherlands and the Hewlett & Randolph (1988) model is used in guidelines in the UK and France.

Definitions of arching and load distribution

Three load parts are defined as shown in Figure 1, each in kN/pile. Load part A is the part that is directly transferred to the piles by arching (this load part increases when using a GR). The residual load is partly redirected to the piles by the GR (load part B) and partly carried by the subsoil (load part C). When designing piled embankments, the (relative) amount of arching, $A\% = A/(A+B+C)$ needs to be determined. This is the objective of the Concentric Arches model or other arching models.

Lessons learned

As described before, the validation of the Concentric Arches model was done in two steps. The first step was to create a numerical model with results that are similar to measurements. These measurements were drawn from scaled laboratory tests (Van Eekelen et al., 2012a and 2012b) and full-scale field tests (Van Eekelen et al., 2012c). The laboratory test was modelled first. It became clear that the test set-up included a number of complexities that greatly influenced the performance of the numerical model.
Some of these issues could not be solved within the limited time available. Other issues were solved and led to a model that produced similar results as the field test measurements. The solved issues are:

- In practice, a sand layer is often placed between the piles and the GR. In the numerical model, punching failure occurs in this layer at the edges of the piles. This punching failure can be prevented by modelling the sand layer as a linear-elastic material with low stiffness. By using a Poisson’s ratio close to 0.5, the stiffness of the layer as a whole is included. However, the actual modelled stiffness cannot straightforwardly be compared to measured parameters. Therefore, in the final model of the field test, the sand layer was removed.
- To correctly model the friction between the GR and the surrounding soils, interfaces were added around the GR. Because the linear-elastic material of the piles cannot behave plastically, slip of the GR over the soil is very small. This slip reaches more realistic values if a separate material set is used for the interface. This material set uses the Mohr-Coulomb model with low strength parameters. The stiffness is kept high, to prevent overlap of the GR over the piles or sand layer.
- When subsoil with low stiffness is used, the water inside has an unrealistic low stiffness, leading to unrealistically low water overpressures for undrained conditions. By increasing the Skempton-B parameter of the subsoil the ratio between the stiffness of the soil and the water can be increased so that the water overpressure matches measurements.

**Description of numerical models**

Using the lessons learned above, a numerical model was set up that gives acceptably similar results to the field test measurements. Both in PLAXIS 2D (2012) and PLAXIS 3D (2012.02). Its geometry incorporates two fields. After slight adaption of the basic geometry of the 3D model, as shown in Figure 2, uses a pile width \( b = 0.75 \text{ m} \) and a centre-to-centre distance \( s = 2.25 \text{ m} \). The embankment height was chosen \( H = 2.0 \text{ m} \), the subsoil height \( H_{\text{sub}} = 1.0 \text{ m} \) and the top load \( p = 5.0 \text{ kN/m}^2 \). These are realistic values in practice. In the 2D model, the piles in y-direction were combined into beams using the same parameters. All boundary conditions are standard conditions (bottom fixed in all directions, sides fixed in lateral direction). Vertical interfaces were added between the beams/piles and the subsoil, including an extension of 0.10 meter up into the embankment fill. Horizontal interfaces were used around the GR, both above towards the fill and below towards the beams/piles and the subsoil. The constitutive models and their parameters are given in Table 1. The piles are modelled as a linear elastic (LE) and Non- porous material.

**Table 1. Soil material sets in the basic models**

The soft subsoil is modelled using the Mohr-Coulomb (MC) model. The embankment fill, consisting of crushed granular material, is modelled by the hardening soil (HS) model, using the drainage type Drained. The fill property set is copied with \( R_{\text{ur}} \) set to 1.0, to be used specifically for the interface extensions of the subsoil-beam interfaces. The geogrid is modelled as a Linear-Elastic material. In 2D, the material is isotropic, using axial stiffnesses \( E_0 \) and \( K_0 \). In 3D however, in order to correctly model the biaxial material behaviour, the stiffness is set to anisotropic and the stiffness in shear loading, \( G \), is set to zero.

Construction was modelled in four phases aside from the initial phase, which are summarized in Table 2. In phase 2, when the embankment is built...
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by activating the GR and fill, the displacements are set to zero. In the last phase (Phase 4), the subsoil cluster is turned off to simulate a situation where subsoil support is lost. This is realistic when a sand layer is included between the piles and the GR, which makes the subsoil settle below the GR leaving a gap from which no support is possible.

All calculation phases (not counting the initial situation) use a plastic drained analysis, which means the effect of consolidation is not included, but only the final situation of equilibrium. It is necessary to account for large deformation effects, so the updated mesh (UM) option is turned on.

During the parameter variation study, the basic model was adapted one parameter at a time. The parameters included in this study were the GR stiffness $E_A1$ and $E_A2$, the top load $p$, the fill’s friction angle $\phi$ and the embankment height $H$.

Interpreting the results

The arching models under consideration are limit state models, attempting to find the lightest construction that will remain stable. This implies that throughout the (arches of the) models the ultimate limit state (ULS) is reached and the full strength profile of the embankment has been mobilised. This can be analysed using the relative shear stress output of PLAXIS. In both 2D and 3D, the last phase, without subsoil support, results in a relative shear value of 1.0 throughout the embankment.

This means the shear strength is fully mobilized and ULS has been reached. In the earlier stages however, ULS is not reached, not even when the top load is increased to unrealistically high values. Therefore, only the last phase is comparable to the results of the analytical models.

Van der Peet (2014) and Van der Peet and Van Eekelen (2014) extensively analysed different aspects of the numerical results, such as the shape of the arches, the stress distribution above the GR (Figure 3), the deflection of the GR and the load distribution over arching (A), GR (B) and subsoil (C). In the 3D model, the analysis of the shape of the arches and GR deflection was done for three separate areas, see Figure 4, to include 3D effects.

The principal stress directions output of Plaxis was used to determine the arch shape (Figure 5 and figure 6). For the 2D model, the distribution of the load (over A, B and C) could be analysed using the forces view option of the Output program. However, more accurate results were acquired by integrating the closest stress points over the surface under consideration. This is a method that can be extended to the 3D situation as well.

The stress points used were selected using their material type and location. This introduces a slight inaccuracy because the updated mesh analysis results in coordinate values for the stress points that change each phase. The stresses in the stress points under consideration were then averaged using a weighing factor equal to the volume of the stress point’s element.

By creating a thin soil layer both above and below the GR, the elements are enforced to have similar heights. Therefore, this method should closely approximate the exact result. An overview of the results of the analysis of the basic model and parameter study can be found in table 3. These results are presented extensively in Van der Peet and Van Eekelen (2014).
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Conclusions
The numerical calculations and the predictions of the Concentric Arches method show strong similarities, both in shape of the arches and the amount of arching A%. Especially for higher top loads and when the influence of the fill’s friction angle is of importance, the Concentric Arches model performs better than the other analytical models under consideration.

References
Increasing traffic intensity and train speed in modern railway tracks require complex analysis with focus on dynamic soil behavior. Proper modelling of the dynamic behavior of the railway track system (railway track, trainload, embankment materials and subsoil) is essential to obtain realistic results. This paper presents preliminary results of numerical modelling in PLAXIS 3D for simulating moving loads on a typical soil embankment, which is designed for high-speed railway trains. For this purpose, several static point loads were applied along the railway track. The amount of load is equal to the axle load of the train. For each point load, a dynamic multiplier is assigned as a time-shear force signal. A beam under unit loads on the elastic foundation was modeled for calculation of shear forces. The resulting shear forces in the beam were applied to the 3D model as factors of the dynamic multiplier. In addition, different constitutive soil models such as Linear Elastic (LE), Mohr-Coulomb (MC) and Hardening Soil small-strain (HS-small) were used to approximate the dynamic behavior of the soil embankment.

In terms of structural dynamics, a moving load changes its place during the time and compared to a static load, it can significantly increase displacements in the structure. Moreover, it causes different soil behavior, which has not been fully investigated so far. The dynamic deformation that is caused by trains is normally inelastic. The cumulative plastic deAerations during track’s lifetime increase progressively and its amount depends on several factors, among them on the subsoil parameters. Irregularities in the track level are common phenomena due to the spatial variation of subsoil and, to some extent the embankment. This degradation of the track is known as differential track settlement [1].

High train speeds demand smaller differential settlement, which must be considered in the modelling of the rail-embankment-subsoil-system by reducing the model error. Another important problem to address is that, after a critical speed, the moving-loads-induced reactions at the track differ significantly depending on trainloads and speed. When the loads travel on a beam, they do not affect only under the impact points; these loads have also effect on the adjacent parts (away from the impact points of the loads) of the beam. In case of the numerical simulation, Vogel et al. (2011) carried out a study about dynamic stability of railway tracks on soft soils. They have modeled a train railway embankment in PLAXIS 2D and the numerical results have been compared to experimental data [5]. Correia et al. (2007) also accomplished a preliminary study of comparative suitability of 2D modelling with different numerical tools such as PLAXIS 2D and other finite element software [6]. In recent studies, the effect of the third dimension is considered by some assumptions, for example, Yang and Hung (2001) suggested a so called 2.5 D model for moving loads [7].

The reliability of the models depends largely on the accuracy of the model, the input data and the choice of an appropriate underlying theory. In this respect, the presented results are based on 3D modelling and a first contribution to provide a method for modelling of moving loads.

Simulation Approach
The moving-loads-induced reactions at the track differ significantly depending on trainloads and speed. When the loads travel on a beam, they do not affect only under the impact points; these loads have also effect on the adjacent parts (away from the impact points of the loads) of the beam. To consider the effect of the moving loads, the authors have statically analyzed the beam to approximate the length of the shear force distribution in the rail and then those distances are taken into account to extend the length of the model. To estimate shear forces in the rail, a static analysis based on the theory of ‘beam on the elastic foundation’ has been computed by using PROKON (Structural Analysis and Design software). PROKON performs a linear analysis in which the beam is modeled as a 2D frame on a series of springs with very short distances [8]. The shear forces that were obtained from this analysis have been used as the dynamic multipliers for each point load in PLAXIS 3D.

It has been assumed that the distance between two supports are too small and contacted support along the beam has been provided by the underlying soil. Furthermore, the beam is significantly thin; hence, the external loads are transferred to the support directly (See Figure 1).

The length of the train axles ‘L’ controls the length of the model. Moreover, this length has been extended ‘0.18L’ on both sides of the beam for considering the effect of the shear force on the adjacent parts of the impact points of the loads.
It has been supposed that the dynamic loads have effect over a greater length of the beam than static loads, and the effect of each axle is felt further away, hence, another length of ‘0.12L’ is added to each side of the beam, to consider the dynamic impact of the loads. Therefore, the optimal length of model could be suggested as ‘L_m = L+2(0.12+0.18)L’ (see Table 1).

To approximate the shear forces in a standard railway track, a beam with length ‘L_m’ and pin supports in every 60 cm (a = 60) laying on soil was considered. A dynamic multiplier is defined as a time-shear force signal in PLAXIS 3D. In the model, every single dynamic point load has its own multiplier. In other words, the dynamic point load is multiplied with the value of signal in every time step. These load multipliers represent the shear forces in the beam due to the static load along the rail in the specific time. The time interval of the multiplier signal has to be considered sufficiently small to prevent miscalculation in FE simulations. The time step is constant because the train speed and the distance between dynamic point loads are constant. For example, a train with speed 180 km/h passes every 30 cm in 0.006 sec, hence, the time interval must be chosen 0.006 sec for the fixed dynamic point loads [9].

The dynamic point loads are located in distances of ‘a/2’, to consider the maximum shear forces in the middle of the spans. The distance between the dynamic point loads can be reduced to minimize the model error, but it increases the calculation time. A total number of ‘4(L_m/a)’ dynamic point loads for two rails are defined (Figure 2 & Table 1).

Example
In Figure 2 and Table 1 the relevant information for the model can be found. In the example simulation, the train speed is 180 km/h, and the distance between each dynamic point load is 30 cm. The train passes every 30 cm in 0.006 sec (time step). Consequently, the first axle of the train needs 0.702 sec to pass all 117 dynamic point loads.

<table>
<thead>
<tr>
<th>Distance between the first and the last wagon axles [m]</th>
<th>L</th>
<th>21.7</th>
</tr>
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<tr>
<td>Additional length for model [m]</td>
<td>L_a = 0.3L</td>
<td>6.5</td>
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<tr>
<td>Total additional length (right and left) [m]</td>
<td>L_a,total = 2*0.3L</td>
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<tr>
<td>Model length [m]</td>
<td>L_m = L+0.6L</td>
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<tr>
<td>Sleepers distance [m]</td>
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<tr>
<td>Dynamic loads distance [m]</td>
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</tr>
<tr>
<td>Number of dynamic loads for one rail [-]</td>
<td>(2L_m)/a</td>
<td>117</td>
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<tr>
<td>Number of dynamic loads for whole model (two rails) [-]</td>
<td>(4L_m)/a</td>
<td>234</td>
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</table>

Table 1: Model parameters for modelling the moving loads
For each time step all of the point loads acquire their values based on the PROKON outputs. In this way, the point loads will be activated continuously and they reach the maximum values when the train axles pass over them (see Table 2).

The distance between the first and the last axle for an ICE is 21.7 m, which in terms of time is 0.434 sec for a train with speed of 180 km/h. The total time that the last axle of the train needs to pass the length of the model is 1.136 sec. In this time, the effect of the train before entering and after leaving the model was also considered.

An additional time of 0.112 sec, which denotes eighteen added rows to the multiplier was considered for relaxing and preventing of miscalculations in the model to the effect of stress wave reflection in dynamic calculations. Various methods are used for modelling boundaries that decrease the effect of wave reflection. Nine multiplier rows with values (shear forces) equal to zero are inserted in the beginning and the end of the multiplier. A small part of the multipliers’ sequence is shown in Table 2 and schematic view of multipliers change during the time is illustrated in Figure 3.

The static analysis for the calculation of shear forces was performed by applying four unit point loads on the beam to simulate four axle’s forces. Because the last axle of the train needs to pass the length of the model used in PROKON was rescaled to the model length used in the PLAXIS model.

**Geometry of 3D-model**

The length of the model for X and Y direction is 35 meters. Due to the geological conditions a model with the depth of 11 m has been considered. Standard fixities and absorbent boundaries were applied in the model to reduce wave reflection at the boundaries. A typical railway track includes rails, rail clips (rail fastening system), and sleepers while all these track elements rest on ballast and subsoil with different soil layers.

The rail is modeled with a beam element along 35 m of profile in Y direction with rectangular cross section. The properties of the beam section are considered in such a way that it has the same properties as a rail (UIC 60). The rail clips are modeled as node to node anchor elements. Each of the sleepers is connected to the rail with two rail clips with 30 cm thickness. The standard sleeper B70 is modeled as a beam element by providing the moment of inertia and area. 68 sleepers are placed in the model with a center-to-center distance of 60 cm. Figure 6 shows the model in PLAXIS 3D. Active dynamic point loads are defined for a train (one wagon) speed of 180 km/h with 4 fixed axles and 8 moving axles.

**Calculation Phases and Results**

The calculation consists of three phases. The first phase is common for generating the initial stresses with active groundwater table. A plastic drained calculation type is chosen in phase two. In this phase, all elements of the railway track (sleepers, rails and rail clips) should be active. The dynamic option should be selected in phase three to consider stress waves and vibrations in the soil. In this phase, all dynamic point loads on the rails are active.

The simulations (SIM1 and SIM2) are performed with active groundwater table. A plastic drained calculation type is chosen in phase two. In this phase, all elements of the railway track (sleepers, rails and rail clips) should be active. The dynamic option should be selected in phase three to consider stress waves and vibrations in the soil. In this phase, all dynamic point loads on the rails are active.
Table 2: Sequence of multipliers for all point loads

<table>
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<tr>
<th>Time steps</th>
<th>Distance [m]</th>
<th>Time [s]</th>
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<td>-0.001</td>
<td>-0.001</td>
<td>0</td>
<td>0.0001</td>
<td>0</td>
<td>0.0001</td>
</tr>
<tr>
<td>5</td>
<td>229</td>
<td>66.3</td>
<td>1.326</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>6</td>
<td>239</td>
<td>66.6</td>
<td>1.332</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

Table 3: Basic material properties of the soil layers for LE and MC models

<table>
<thead>
<tr>
<th>No.</th>
<th>Soil layers</th>
<th>γsat [kN/m³]</th>
<th>γunsat [kN/m³]</th>
<th>υ</th>
<th>φ’</th>
<th>c’</th>
<th>Ψ</th>
<th>E’ [kN/m²]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Ballast</td>
<td>21</td>
<td>19</td>
<td>0.30</td>
<td>35</td>
<td>30</td>
<td>5</td>
<td>30000</td>
</tr>
<tr>
<td>2</td>
<td>Protective layer</td>
<td>23</td>
<td>22</td>
<td>0.25</td>
<td>40</td>
<td>30</td>
<td>15</td>
<td>55000</td>
</tr>
<tr>
<td>3</td>
<td>Backfill, SE, SU, loose</td>
<td>19</td>
<td>18</td>
<td>0.35</td>
<td>28</td>
<td>10</td>
<td>0</td>
<td>25000</td>
</tr>
<tr>
<td>4</td>
<td>Backfill, SE, SU, semidense</td>
<td>20</td>
<td>19</td>
<td>0.35</td>
<td>28</td>
<td>10</td>
<td>0</td>
<td>35000</td>
</tr>
<tr>
<td>5</td>
<td>Backfill, SE, SU, dense</td>
<td>20</td>
<td>19.5</td>
<td>0.35</td>
<td>28</td>
<td>10</td>
<td>0</td>
<td>43000</td>
</tr>
<tr>
<td>6</td>
<td>Peat, HN, HZ</td>
<td>11</td>
<td>11</td>
<td>0.35</td>
<td>26</td>
<td>15</td>
<td>0</td>
<td>2000</td>
</tr>
<tr>
<td>7</td>
<td>Organic silt</td>
<td>13</td>
<td>13</td>
<td>0.35</td>
<td>25</td>
<td>10</td>
<td>0</td>
<td>4000</td>
</tr>
<tr>
<td>8</td>
<td>Sand</td>
<td>20</td>
<td>19</td>
<td>0.35</td>
<td>40</td>
<td>5</td>
<td>10</td>
<td>80000</td>
</tr>
</tbody>
</table>

Table 4: Advanced material properties of the soil layers for HS-small model

<table>
<thead>
<tr>
<th>No.</th>
<th>Soil layers</th>
<th>m</th>
<th>E_mod [kN/m²]</th>
<th>E_ref [kN/m²]</th>
<th>f ur [kN/m²]</th>
<th>f ref [kN/m²]</th>
<th>G [kN/m²]</th>
<th>γ ref 0.7 %</th>
</tr>
</thead>
<tbody>
<tr>
<td>6</td>
<td>Peat, HN, HZ</td>
<td>0.7</td>
<td>2000</td>
<td>2000</td>
<td>6000</td>
<td>8100</td>
<td>3000</td>
<td>6.29×10⁻⁴</td>
</tr>
<tr>
<td>7</td>
<td>Organic silt</td>
<td>0.7</td>
<td>4000</td>
<td>4000</td>
<td>12000</td>
<td>16200</td>
<td>6000</td>
<td>2.79×10⁻⁴</td>
</tr>
<tr>
<td>8</td>
<td>Sand</td>
<td>0.5</td>
<td>80000</td>
<td>80000</td>
<td>240000</td>
<td>270000</td>
<td>100000</td>
<td>1.81×10⁻⁴</td>
</tr>
</tbody>
</table>

Table 5: Input properties in PLAXIS 3D for rail and sleeper

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>Rail</th>
<th>Sleeper</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cross section area (A)</td>
<td>[m²]</td>
<td>7.7×10⁻⁴</td>
<td>5.13×10⁻⁵</td>
</tr>
<tr>
<td>Unit weight (γ)</td>
<td>[kN/m³]</td>
<td>78</td>
<td>25</td>
</tr>
<tr>
<td>Young’s modulus (E)</td>
<td>[kN/m²]</td>
<td>200×10⁴</td>
<td>36×10⁵</td>
</tr>
<tr>
<td>Moment of inertia around the second axis (I₂)</td>
<td>[m⁴]</td>
<td>3.055×10⁻⁸</td>
<td>0.0253</td>
</tr>
<tr>
<td>Moment of inertia around the third axis (I₃)</td>
<td>[m⁴]</td>
<td>5.13×10⁻⁸</td>
<td>2.45×10⁻⁸</td>
</tr>
</tbody>
</table>

In consideration of three different constitutive soil models. In SIM1, for all soil layers the Linear Elastic (LE) model was used. SIM2 was simulated using a combination of Mohr-Coulomb (MC) and Hardening Soil small-strain model (HS-small). Here, upper soil layers are modeled with the MC model and the deepest three soil layers are modeled with the HS-small model [12].

In dynamics, velocities rather than displacements are presented to avoid second integration leading to increasing errors in low frequency domain [14]. The velocity amplitude decreases by propagation of the wave to the deeper soil layers. Material and geometric damping are the main reasons for the decreasing velocity amplitude in deep layers. In this model, both types of damping are considered by applying Rayleigh damping coefficients. The lowest and highest relevant frequencies
Table 7: Estimated velocities for train with speed of 180 km/h

<table>
<thead>
<tr>
<th>Constitutive model</th>
<th>Wagon No.</th>
<th>Vertical velocity (mm/s) in different checkpoints</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>BP1</td>
</tr>
<tr>
<td>SIM 1</td>
<td>1</td>
<td>27.15</td>
</tr>
<tr>
<td>SIM 2</td>
<td>1</td>
<td>28.90</td>
</tr>
</tbody>
</table>

Figure 7: Vertical velocity, LE-Model, 180 Km/h

Figure 8: Vertical velocity, HS-small & MC-Model, 180Km/h
3D Modelling of Train Induced Moving Loads on an Embankment

depend upon the model properties and train speed. In this study, the lowest and highest frequencies for estimation of the Rayleigh damping coefficients are assumed to be between 10 and 100 Hertz.

Table 7 summarizes the results of the simulations in terms of velocity (mm/s) for four checkpoints in different soil layers. Moreover, velocity amplitudes are decreased by going to the depth, which is matched to the engineering expectation. The checkpoints BP5 and BP6 show smaller velocities as the wave goes deeper in Z-direction. Velocity changes in each checkpoint by passing the train for both models are shown in Figure 7 and 8. Figure 9 shows a comparison between the calculated maximum velocities in checkpoints of two simulations (SIM1 and SIM2). The highest velocity belongs to the checkpoint BP1 that is located in shallowest depth under the railway. SIM2 estimated smaller values for deeper checkpoints than SIM1, while in shallow depth, it points out higher velocity compared to the SIM1. However, both simulations show a similar trend in the results.

Conclusion
Moving loads can be modeled in PLAXIS 3D by applying the proposed approach and the help of auxiliary software. This proposed approach has also a big limitation. For defining the moving loads, all multipliers have to be assigned manually to each dynamic point load. For getting more accurate results, one could divide the distance between the sleepers in four or even eight parts. By adding more point loads, it is possible to get more detailed results. With this method, one could also model the break effect as well as the interaction of two trains, which are moving in opposite directions. This approach provides a way for investigating moving loads in PLAXIS. Real 3D modelling of moving loads in PLAXIS 3D was done here successfully. These models have to be evaluated through comparison with results from experiments and theoretical analysis. The validation of these models will be accomplished in next phase of this project. Geotechnical applications require advanced constitutive models for the simulation of the non-linear and time-dependent behavior of soils. Although the modelling of the soil itself is an important issue, many geotechnical engineering projects involve the modelling of complex geotechnical problems such as the moving loads. Therefore, future versions of the PLAXIS software will be equipped with special features to deal with the moving loads.

References

Figure 9: Estimated velocities for train with speed of 180 km/h in checkpoints
Preliminary 3D Modelling of Structural behaviour of Face Bolting and Umbrella Arch in Tunneling

Antoine Monnet - Emad Jahangir, emad.jahangir@mines-paristech.fr, Mines ParisTech

Umbrella arch and face bolting are two reinforcement technics used in tunnelling (NATM conventional tunnelling), especially for low-depth tunnels (H/D=1 to 5) in poorly consolidated soils. The arch is built by setting pipes around the contour line of the tunnel face prior to excavation, while bolting consists in setting and sealing long fiberglass or metallic rods at the tunnel face. The bolts provide improved mechanical properties to the ground that is to be excavated and they are gradually destroyed as the excavation progresses, whereas the arch brings stability to the whole face area and is left as a permanent reinforcement. In this context, 3D modelling of these tunnels and their reinforcement is essential to predict surface settlements and an important tool to validate appropriate tunnel designs.

Face bolts act essentially in tension but they may also be subjected to bending depending on the bolting density and the location of bolts in the tunnel cross section. They are designed to ensure the face stability and reduce the extrusion. In the literature the effect of an umbrella arch in tunnel stabilization has not been as well documented as face bolting. Most studies agree on the improvements brought by the face bolts regarding surface settlements and face stability. Though, some authors point out that the umbrella arch may only provide better global stability. This may depend on the surrounding ground characteristics (hard or soft rocks, etc.), on the applied arch tilt and on the connection type used to hang the arch pipes to the tunnel steel ribs. Through a numerical analysis, Prountzopoulos (2011) showed how the umbrella arch could provide a good protection against local instabilities which are rather common in soft grounds or fractured rocks. Similar concluding
remarks were highlighted by Janin (2012): while the face bolting undergoes tension loads to improve face stability and reduce settlements, the umbrella arch mainly absorbs bending moments but does not affect surface settlements significantly.

AKSOY and ONARGAN (2010) concluded that an umbrella arch could be more efficient in grounds with poor mechanical properties. Figure 1 shows the efficiency of the combined system of both face bolting and umbrella arch in soft rocks (Ankara argillite, RQD<10%).

In order to verify above-mentioned findings and to examine the mechanical behaviour of each reinforcement element a parametric study was performed using the PLAXIS 3D software. In the context of face bolting and the umbrella arch reinforcement, it is obvious that a realistic numerical modelling should be done in 3D configuration. PLAXIS 3D software was chosen because it includes in its library firstly, the Hardening Soil constitutive model (HSM) adapted to the rheology of studied soils (normally-consolidated soils due to small depth of tunnelling), and secondly an appropriate structural element to model the used bolts. The latter one is a beam element entitled "embedded pile" which is able to take into account the soil-bolt interface to study closely the behaviour of reinforcement. This software also has a quick and easy automatic mesh generation tool.

1. Base case
The analysis was conducted on the South tube of Toulon tunnel that is the tunnel on which Janin (2012) based his PhD Thesis. This tunnel was chosen, as it is well documented and appropriate to the study of settlements in low-depth tunnelling. Similar ground properties (c = 20kPa, \(\phi = 30^\circ\)) and dimensions were used in order to compare results with Janin's model. Though the geometry was slightly simplified to a circular and constant tunnel section. The staged construction of Plaxis 3D (staged-step features) was used, with 3m-long processing cuts. The tunnel surface at the most recent cut is modelled by plate elements (with mechanical properties representative of shotcrete of 0.3m thickness). A layer of shotcrete is also sprayed on the face at every stage. The bolts are partially renewed every 3m. These bolts are 18-m long, and their properties are collected in table 1 together with other used reinforcements. Figure 2 shows the geometry of the tunnel and the vertical displacements caused by the excavation.

![Figure 2: Geometry, mesh and vertical displacements of the tunnel surroundings](image)

![Figure 3: Impact of bolt density: partial settlement depression for a 3m-long cut for 0.4 bolt/m², 0.2 bolt/m² and without bolts](image)

<table>
<thead>
<tr>
<th>Reinforcement</th>
<th>E(GPa)</th>
<th>S(m²)</th>
<th>I(m⁴)</th>
<th>L(m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Face bolt</td>
<td>210</td>
<td>0.448×10⁻³</td>
<td>0.0327×10⁻⁶</td>
<td>18</td>
</tr>
<tr>
<td>Umbrella arch</td>
<td>210</td>
<td>2.036×10⁻³</td>
<td>1.689×10⁻⁴</td>
<td>9</td>
</tr>
<tr>
<td>Shotcrete</td>
<td>1.35</td>
<td>-</td>
<td>-</td>
<td>3</td>
</tr>
</tbody>
</table>

Table 1: Characteristics of used reinforcements

2. Modelling of the tunnel face bolting
This study investigated first the impact of bolting density on surface settlements. As shown in figure 3, settlements decrease while increasing bolting density (d = number of bolts per square meter at the tunnel face) even though this effect is less significant if we keep increasing this density. Here, bolts are modelled by "embedded pile" elements, which is discussed in the following.
Figure 4 shows the impact of face bolting on extrusion of the tunnel face. At this stage, the face bolts were modelled by either beam or spring structural elements (fixed-end spring element, is able to consider only the axial forces). Figure 4a shows widely favourable effect of face bolting on extrusion decrease (face stabilization). At a significant bolting density, the results remain the same regardless the sort of element used to model the bolts.

Modelling bolts by “embedded pile” elements (beams with friction interface law) can be very useful to characterize the nature of undergone loads. Figures 5 and 6 show stresses (axial, mobilized friction and shear) and strains (deformed shape) profiles along the bolts, depending on the location of the bolts and the bolting density. For a bolt located at the center of tunnel section, a low bolting density results in an important axial stress, mobilized friction and the shearing stress is significant nearby the face. On the contrary, at a higher bolting density, friction is mobilized on more bolts and then becomes less significant as the axial stress.

For a given bolting density, different profiles were observed, depending on the location of bolts on the tunnel face. Bolts located at the top of the face experience much more bending moments, especially nearby the face.

(a) Horizontal displacements at the face
(b) Modelling bolts with beam elements
(c) Modelling bolts with spring elements
(d) No face reinforcement

Figure 4: Impact of face reinforcement modelling: horizontal (a) and normalized (b, c, d) displacements
Preliminary 3D Modelling of Structural behaviour of Face Bolting and Umbrella Arch in Tunneling

Figure 5: Impact of bolting density on strains and stresses

(a) Density = 0.012 b/m²
(b) Density = 0.2 b/m²
(c) Density = 0.4 b/m²

Figure 6: Impact of bolt positioning on strains and stresses

(a) Middle bolt, density = 0.012 b/m²
(b) Up bolt, density = 0.012 b/m²

(c) Stresses on a bolt depending on its position in the face
Bolts located at the top of the face experience much more bending moments, especially nearby the face.

On the contrary, axial stress is lower at the top as well as the mobilized friction. The central bolt undergoes a high axial stress as well as mobilized friction where lower shear stresses are generated. Regardless the location of the bolts or the bolting density, all the bolts showed a positive axial stress at the face. This seems contradictory with the boundary conditions (pressure inside the tunnel is 1 atm and therefore axial stress at the face should be null). It can actually be explained by the presence of the shotcrete layer covering the face.

3. Modelling of the umbrella arch
The same kind of parametric study was conducted for the umbrella arch. The geometry of the arch and its properties were the same as Janin’s for the Toulon base case. The arch was made of 13 pipes of 18m length. Each pipe was spaced 50 cm from the next and tilted by 6°. All were renewed every 9m. The characteristics of used tubes for the umbrella arch are collected in table1. Figure 7 shows the geometry of the tunnel with the umbrella arch and the vertical displacements generated by the excavation.

Figure 7 shows the geometry of the tunnel with the umbrella arch and the vertical displacements generated by the excavation.

Figure 8 shows the surface settlement for a 60m long tunnel construction. Settlements were reduced by about 5% with the umbrella pipes. This result confirms Janin’s conclusion: the arch does not seem to impact significantly the surface settlements. Increasing the diameter of the pipes does not seem to modify significantly the result either (depicted by D2 on figure 8). It is well known that the pipes of the arch undergo essentially bending moments. Figure 9 confirms this point and locates the highest bending moments close to the pipe heads. This last point is important because it means any inaccuracy in the numerical modelling of that sensitive region could impact the local stability of tunnel. In particular, the hanging point between the pipes and the tunnel steel rib should be modelled carefully.

Conclusion
The study on structural behaviour of the face bolting showed that the bolts work essentially in tension, but may be subject to bending according to their position and density.

A beam element is therefore more appropriate than an anchor element. Yet, the axial load in the bolts remains the most important, suggesting the importance of the bolt-ground interface considered in the numerical analysis. This interface was taken into account using PLAXIS 3D "embedded piles" elements which permitted the estimation of the mobilized friction and the shear stress through the bolts.

The parametric study on the arch umbrella confirmed Janin’s results. However the connection between the pipes and the tunnel wall seems to play an important role.

It should be noted that a circular constant geometry was used to model the tunnel in this study, where a tunnel with a variable section would provide a better rigidity (connection quality) between the pipes and the tunnel, as depicted in figure 1(a).

References
• Aksoy C.O., Onargan T. (2010). The role of umbrella arch and face bolt as deformation preventing support system in preventing building damages, in Tunnelling and underground space technology, 25, pp. 553-559.
Preliminary 3D Modelling of Structural behaviour of Face Bolting and Umbrella Arch in Tunneling

Figure 8: Impact of umbrella-arch reinforcement on cumulative surface settlement

Figure 9: Bending moment in the umbrella arch
Recent activities

Since the release of the PLAXIS 2D Anniversary Edition in the beginning of the year, we have already released two updates.

These updates contain some valuable improved features and fixed issues in the program. These are amongst others, improvements regarding groundwater flow calculations. Most notable is the improved visualization of flow boundary conditions and the ability to specify a non-uniform groundwater head along non-vertical lines. It is now also possible to edit Polygon point coordinates directly through the selection and model explorers.

Furthermore in the latest update, PLAXIS 2D AE.02 we have focused some attention on the Dynamics module. Please read some of the new tips-and-tricks on our knowledge base (kb.plaxis.nl) to get the most out of its advanced technical features:

- Compliant base and free field boundaries: check on input signal
- How to setup tied degrees of freedom
- Using an accelerogram for Dynamics
- Drift correction for dynamic input signal from file
- Fixed and Compliant base: what input motion is required?
- On the use of dynamic boundary conditions

Users of PLAXIS 2D AE can update their software through PLAXIS Connect, or download the new software via the software updates page on our website. Prospects for the new PLAXIS 2D AE can request a new introductory version via the demo page on our website: www.plaxis.nl/page/demo_cd/.

XG Geotools

Press Release - April 23, 2014

On April 23, 2014, NGI from Norway and Plaxis from the Netherlands announced the establishment of their joint venture XG Geotools bv. XG Geotools will produce and market cloud based software tools tailored for design tasks in offshore geotechnical engineering. These tools will combine the in-depth subject knowledge and software design skills of both companies.

SPCalc is the first tool that has been launched at OTC in Houston TX, U.S.A. early May - a tailor made application for calculating the capacity of suction anchors and suction piles using the finite element method. XG Geotools plans regular new additions to their ‘toolbox’ in the time to come. SPCalc is a special purpose two-dimensional finite element application used to calculate the factor of safety for the undrained load capacity of suction anchors in offshore geotechnical engineering projects. The calculation is based on robust numerical procedures and the FEM analysis is fully automated – a calculation run takes less than a minute. The computational results are automatically stored and always available online.

The soil, geometry and load data are easily input into the model using clear and intuitive input screens. The finite element model is generated automatically, and the calculation kernel solves for the undrained capacity of the anchor design using a non-linear, anisotropic soil model. 3D effects are approximated in the anchor capacity calculation. The output facilities provide visualization of the stress distributions on the anchor under load.
The summer of 2014 saw yet another course in New York City. This sold-out standard course had a wide range of attendees, with a strong presence of engineers interested in deep foundations and several contracting companies present. The course featured a special day on design and analysis of foundations using PLAXIS 3D.

Plaxis was an exhibitor or visitor at a numerous events in the past months, ranging from one of the largest US trade shows to a small regional geotechnical conference. Modelling suction piles, mudmats and other subsea structures in PLAXIS 3D was further brought under the attention at the Offshore Technology Conference in Houston (with an attendance of over 100,000). Additionally, the first product of the newly formed joint-venture between NGI and Plaxis was revealed at OTC.

Further, in the past months pleasant chats and good discussions took place at the Plaxis booth at Geo-Congress in Atlanta, the Central Pennsylvania Geotechnical Conference in Hershey, the American Rock Mechanics Association conference in Minneapolis, and the North American Tunneling conference in Los Angeles. We’ll continue to visit and exhibit at events across North America in 2015, so be sure to receive our emails or check the list of upcoming events to see when and where you can meet us in person. We look forward to meet you!

In the fall of 2014 another advanced course will be organized, this time in Houston, October 7 through 10. This advanced course will include a special day on offshore geotechnics. We plan to organize several interesting courses throughout North America in 2015 with a variety of topics. These courses will be announced through our e-mailings and on our website.

The first Indonesia Plaxis Users meeting was held on April 17, 2014. The meeting was well received with an attendance of almost 200 users and guests. This event was co-organized by our local counterpart in Jakarta and Plaxis AsiaPac. There were 9 presentations and the topics touched on the use of PLAXIS 2D and PLAXIS 3D on the modelling of Deep Foundations, Embankments, Reinforced Soil Walls and Slope Stabilization.

We look forward in seeing our users from Indonesia in the 2nd edition of PUM-Indo 2015 in Jakarta. Other events this summer organized by or contributed to:

- The HKIE Geotechnical Division Annual Seminar in Hong Kong
- ATC-18 International Workshop on Mega Deep Foundations in Japan
- 49th National Conference in Geotechnics in Japan
Upcoming Events 2014

8 - 11 September
Standard Course on Computational Geotechnics
Zurich, Switzerland

9 - 13 September
Combrasseg 2014
Goiania, Brazil

12 September
Workshop on Foundations and 3D Modelling
Zurich, Switzerland

21 - 25 September
Dam Safety 2014
San Diego CA, U.S.A.

21 - 25 September
10th International Conference on Geosynthetics
Berlin, Germany

23 - 26 September
33. Baugrundtagung
Berlin, Germany

23 September
Workshop on Modelling 2D vs. 3D
Delft, The Netherlands

24 September
Workshop on Advanced Modelling in PLAXIS
Delft, The Netherlands

28 September - 1 October
GeoRegina 2014
Regina, Canada

29 - 30 September
Workshops on PLAXIS 3D and Offshore Applications
Hamburg, Germany

29 September - 2 October
Advanced Course on Computational Geotechnics
Trondheim, Norway

30 September - 3 October
Standard Course on Computational Geotechnics & Undrained Soil Behaviour
Brisbane, Australia

6 - 10 October
Advanced Course On Computational Geotechnics & Dynamics
Wellington, New Zealand

7 - 10 October
Advanced Course on Computational Geotechnics
Houston TX, U.S.A.

13 - 15 October
AFTES 14th International Congress
Lyon, France

14 - 16 October
Advanced Course on Computational Geotechnics
Dubai, U.A.E.

21 - 24 October
DFI 39th Annual Conference on Deep Foundations
Atlanta GA, U.S.A.

29 - 31 October
Advanced Course on Computational Geotechnics
New Delhi, India

10 - 14 November
7th International Congress on Environmental Geotechnics
Melbourne, Australia

19 – 21 November
XXVII Reunión Nacional de Ingeniería Geotécnica
Puerto Vallarta, Mexico

25 – 28 November
Modélisation Numérique des Ouvrages Géotechniques avec PLAXIS 2D
Paris, France