PLAXIS Monopile Designer CONNECT Edition V21

Introduction to the PISA design method with PLAXIS Monopile Designer

Bentley
Advancing Infrastructure

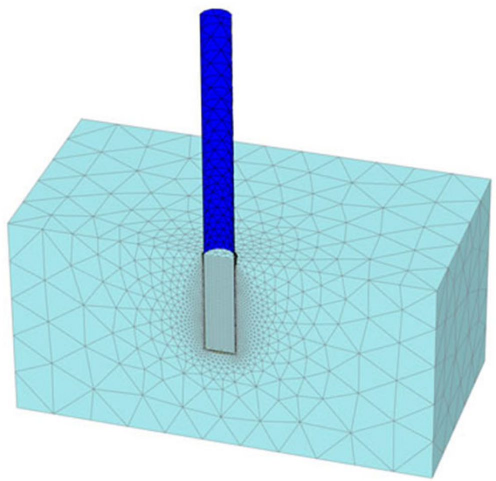
PLAXIS Monopile Designer

- Challenge
  - Need to reduce the cost of OW foundations (~25-30% of CAPEX)
  - Traditional design method adapted from O&G not well-suited for monopiles
- Solution
  - PISA Design Method, optimized for monopile foundations
- Benefits
  - Up to 35% reduction in embedded length (Byrne et al., 2017, 2019)
    - Cost reduction in materials, fabrication, transport, installation, risk, and environmental impact
    - Estimated savings up to ~300,000 GBP (~400,000 USD) **per monopile**
  - Perform more analyses in less time: optimize each foundation in the OWF

Monopile Design | State of the art

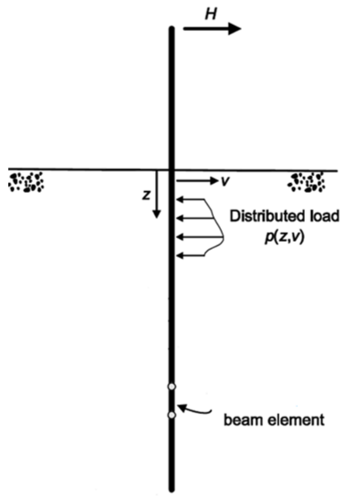
3D FEM analysis

- Good representation of soil-pile interaction
- Time-consuming
  - ~ Hours for a single load case
  - Not practical for structural coupling
- Mostly used for analysis and validation

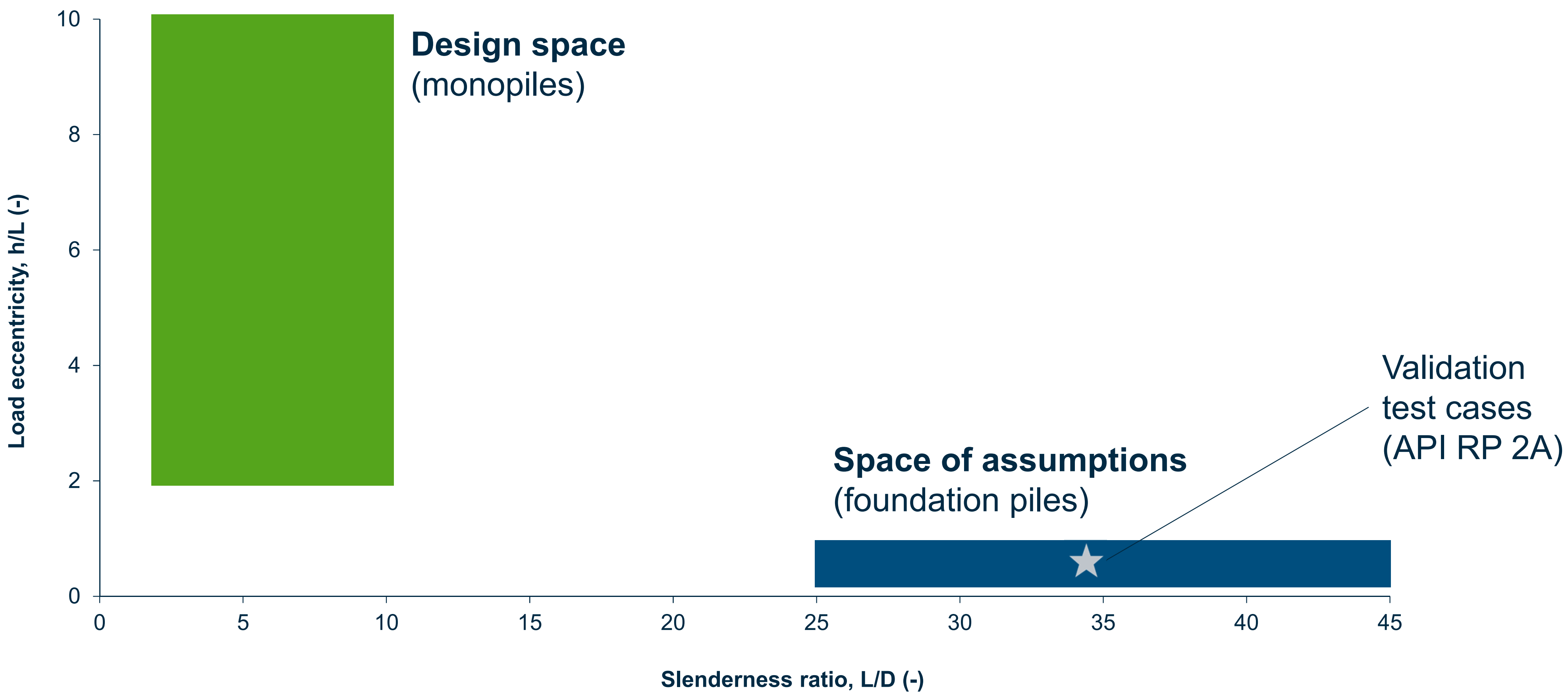


Distributed springs (P-Y method)

- Simplified (1D) approach
- Developed for foundation piles in O&G
- Assumptions
  - Slender pile (Euler-Bernoulli)
  - Independent horizontal springs (Winkler)



P-Y method | The hard truth



P-Y method | The hard truth

- Monopiles are **not** slender
  - Unrealistic failure mechanism
  - Unrealistic soil reactions

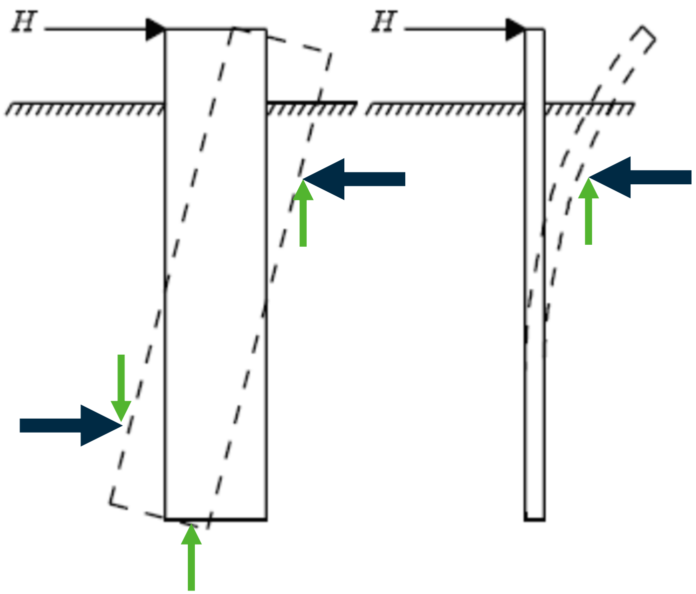
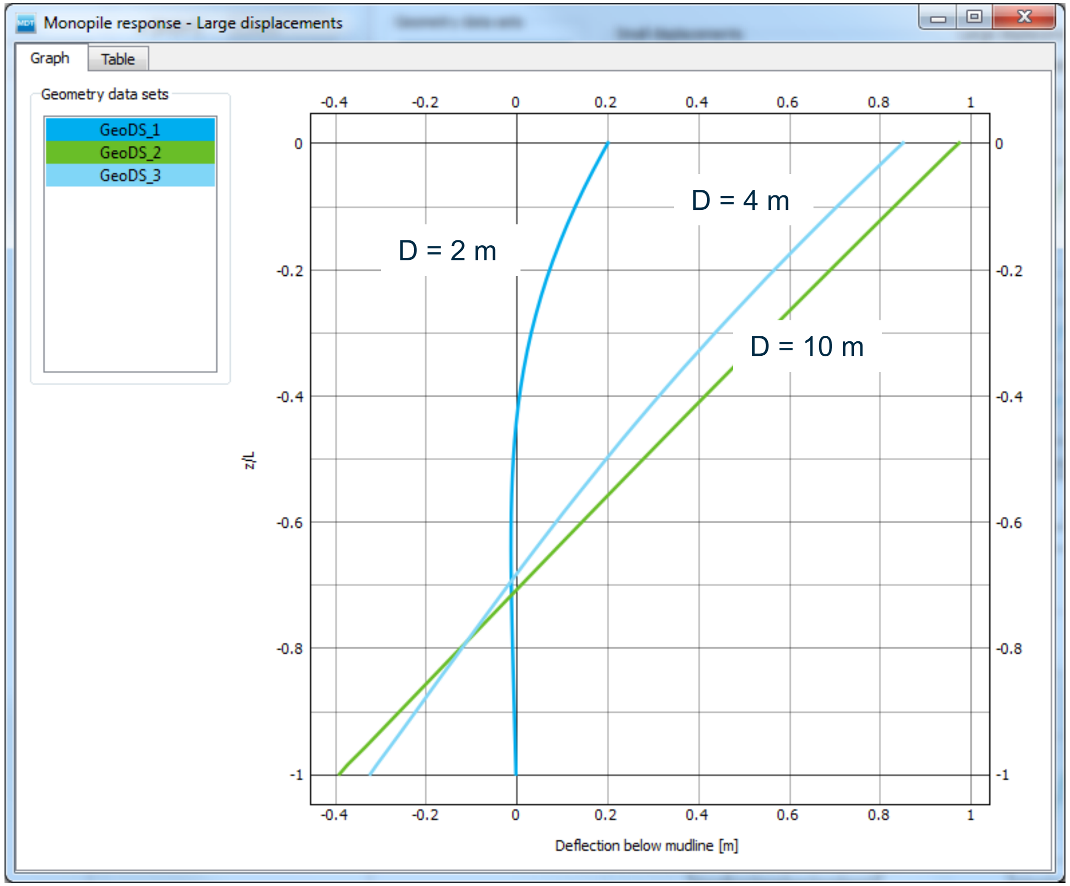


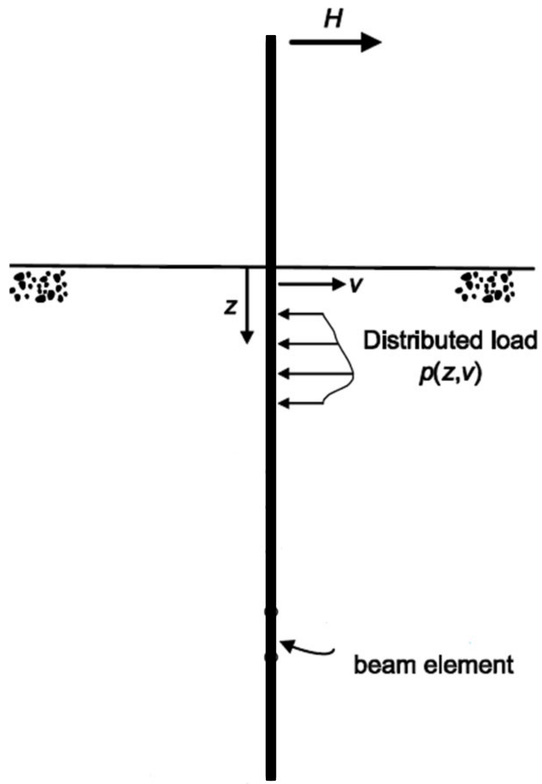
Image: modified from Sorensen et al. (2012)



PISA method

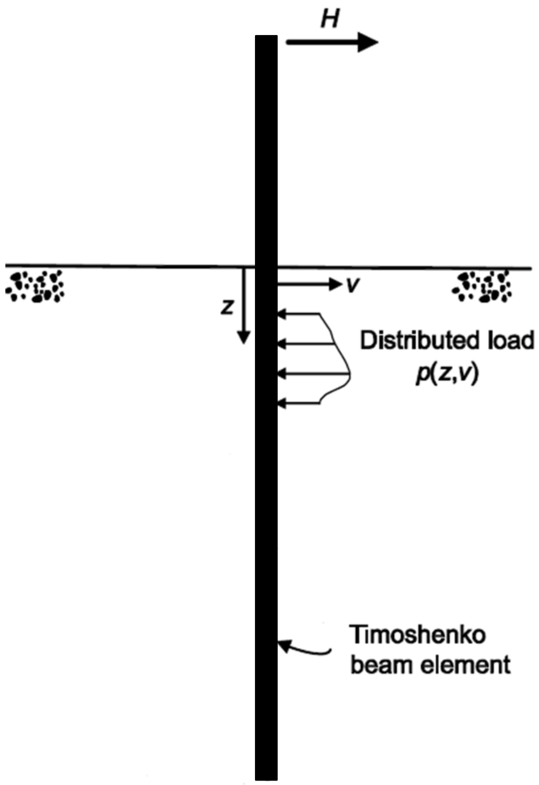
P-Y Method

Pile model	Slender pile (Euler-Bernoulli)
Soil reaction curves	Distributed load: p-y (Winkler)
Design space	Individual geometry



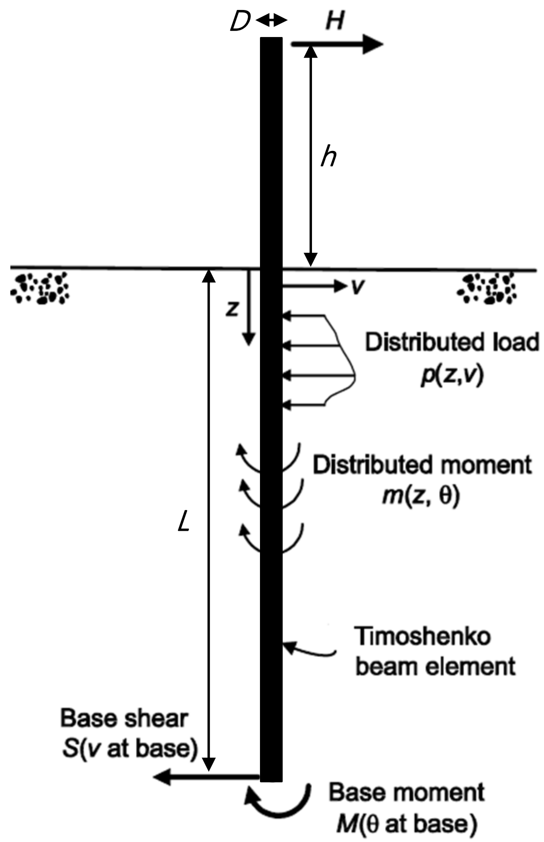
PISA method

	P-Y Method		PISA Method
Pile model	Slender pile (Euler-Bernoulli)	→	Any pile (Timoshenko)
Soil reaction curves	Distributed load: p-y (Winkler)		
Design space	Individual geometry		

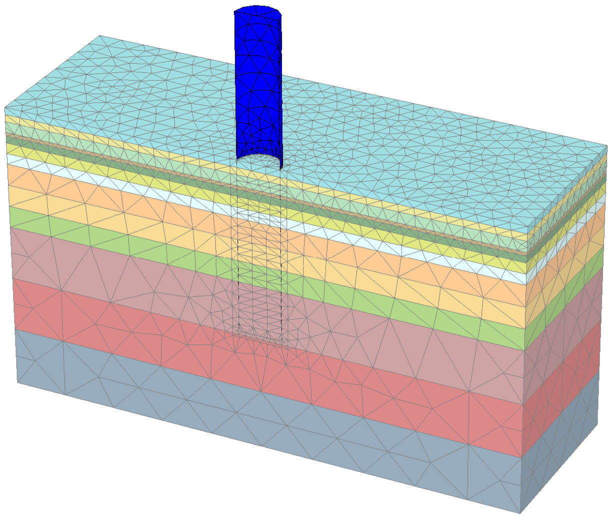


PISA method

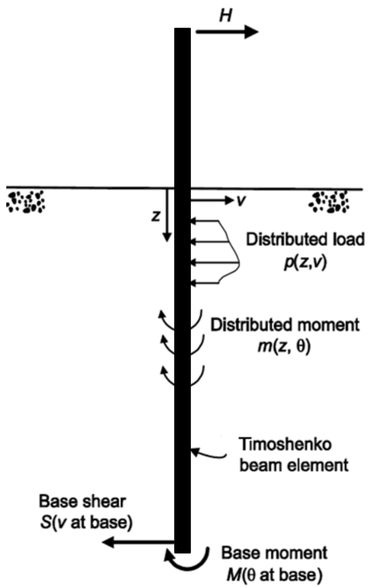
	P-Y Method		PISA Method
Pile model	Slender pile (Euler-Bernoulli)	→	Any pile (Timoshenko)
Soil reaction curves	Distributed load: p-y (Winkler)	→	Distributed load: p-v Distributed moment: m-ψ Base shear: H_B-v_B Base moment: M_B-ψ_B
Design space	Individual geometry	→	Parametric



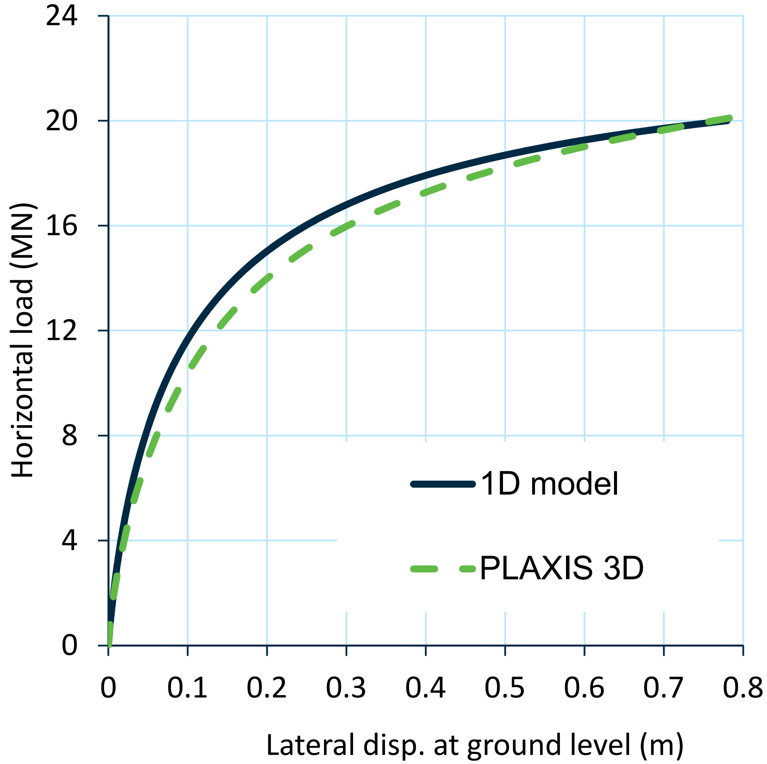
Fast analysis with 1D pile solver



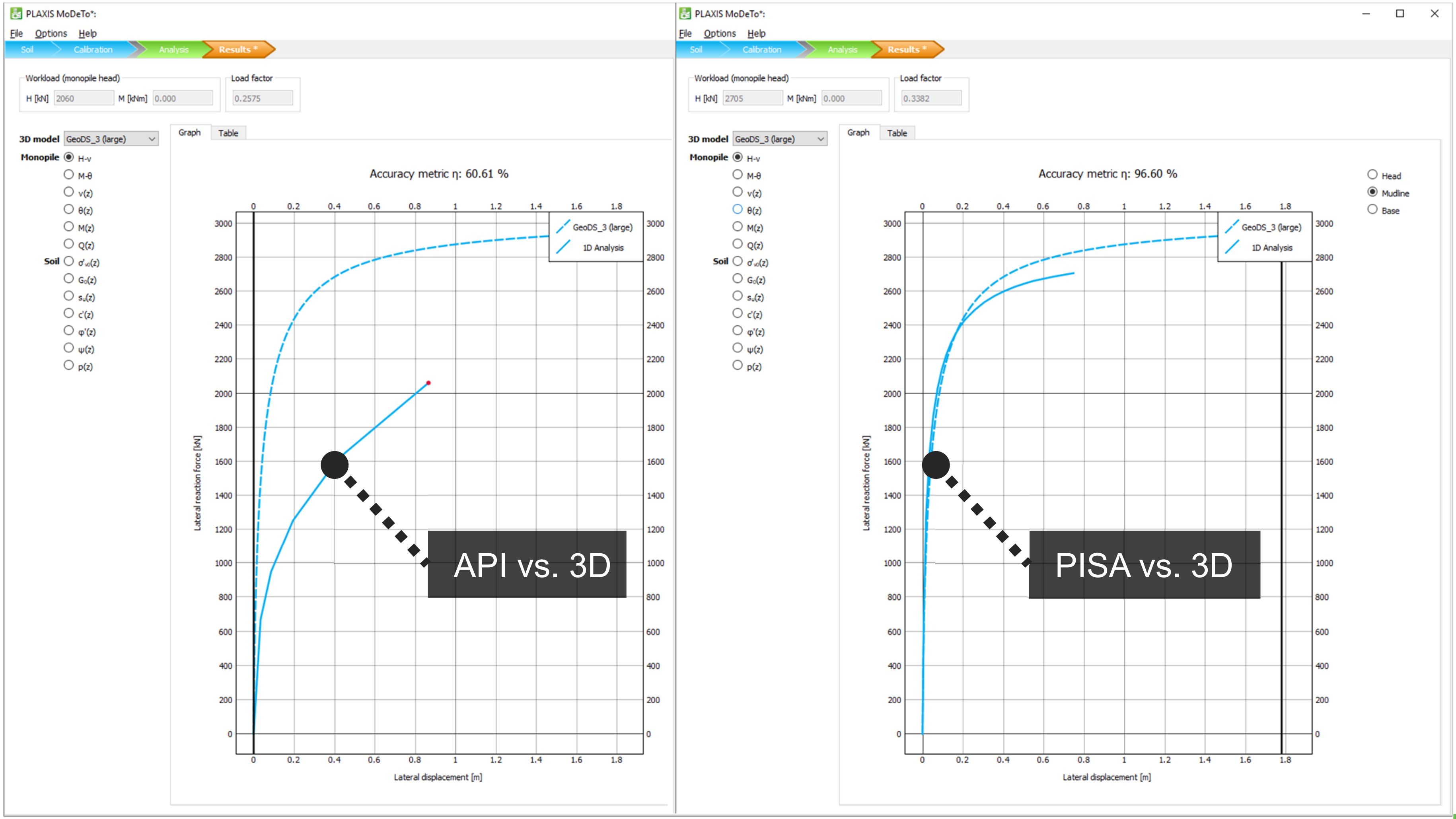
~ 10.000 elements
~ hours



~ 100 elements
~ seconds



Comparison with API p-y curves



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Parametric design space | Geometry

- Cylindric shape enables easy parameterisation
  - 3 major variables to play with: *L, D, t*
  - 4th variable, *h*, is a function of **both geometry and load case**

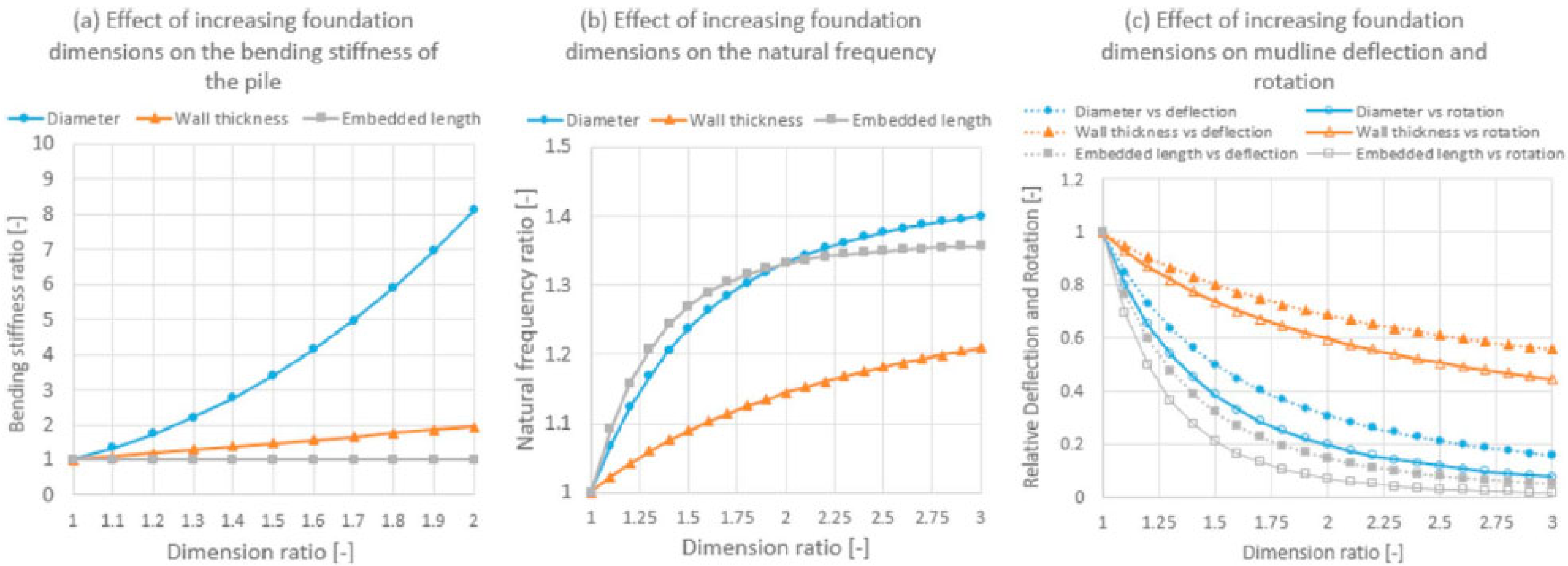
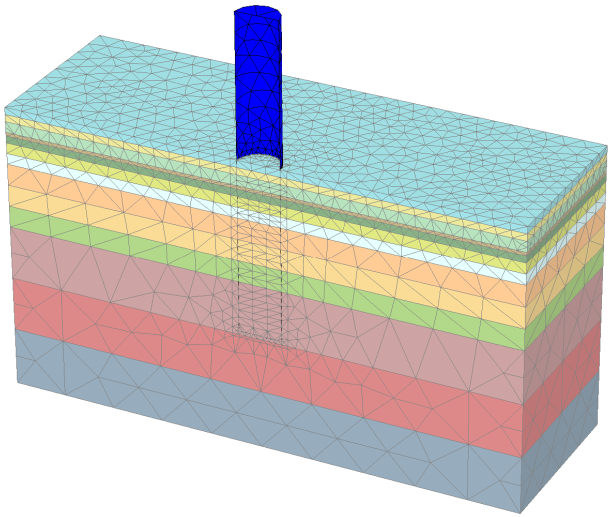
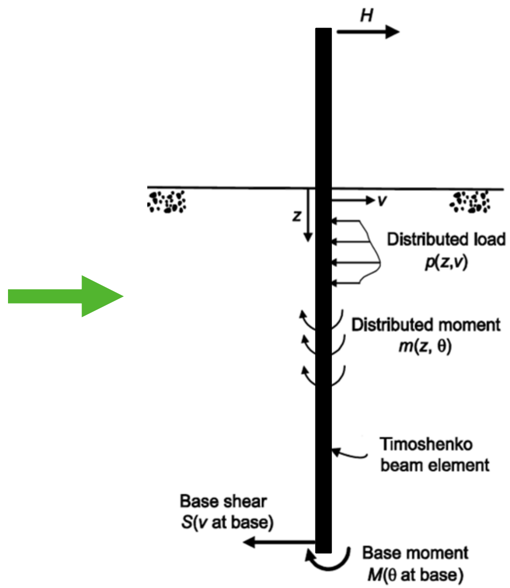


Image: Arany et al. (2017)

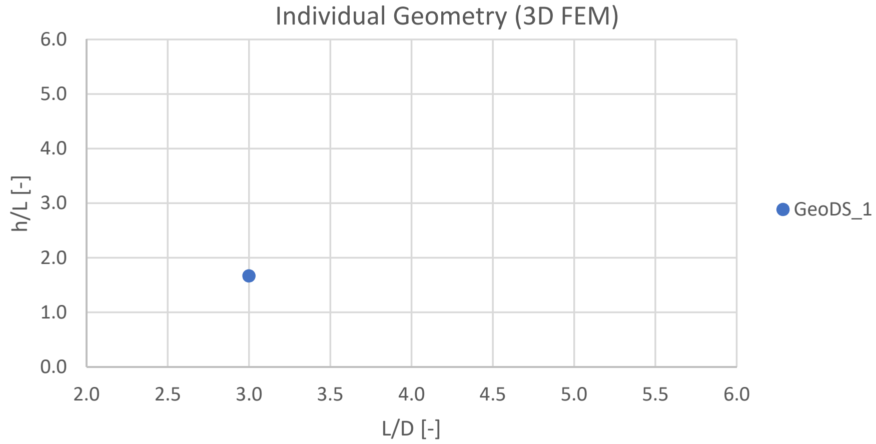
Parametric design space | Geometry

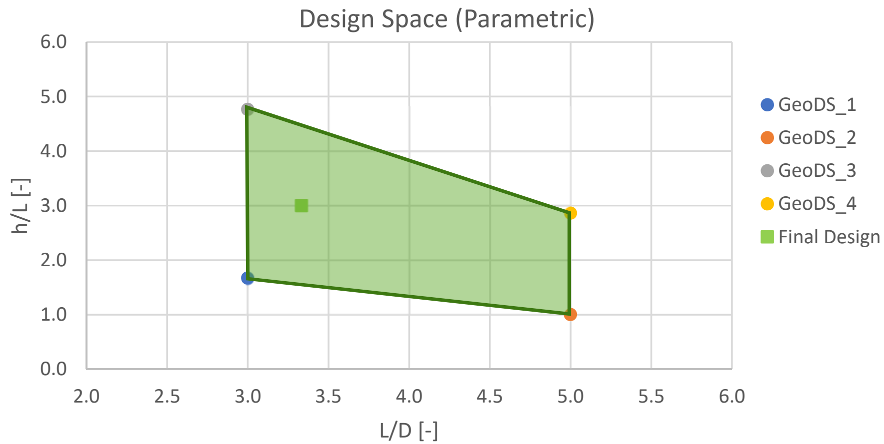


~ 10.000 elements
~ hours



~ 100 elements
~ seconds





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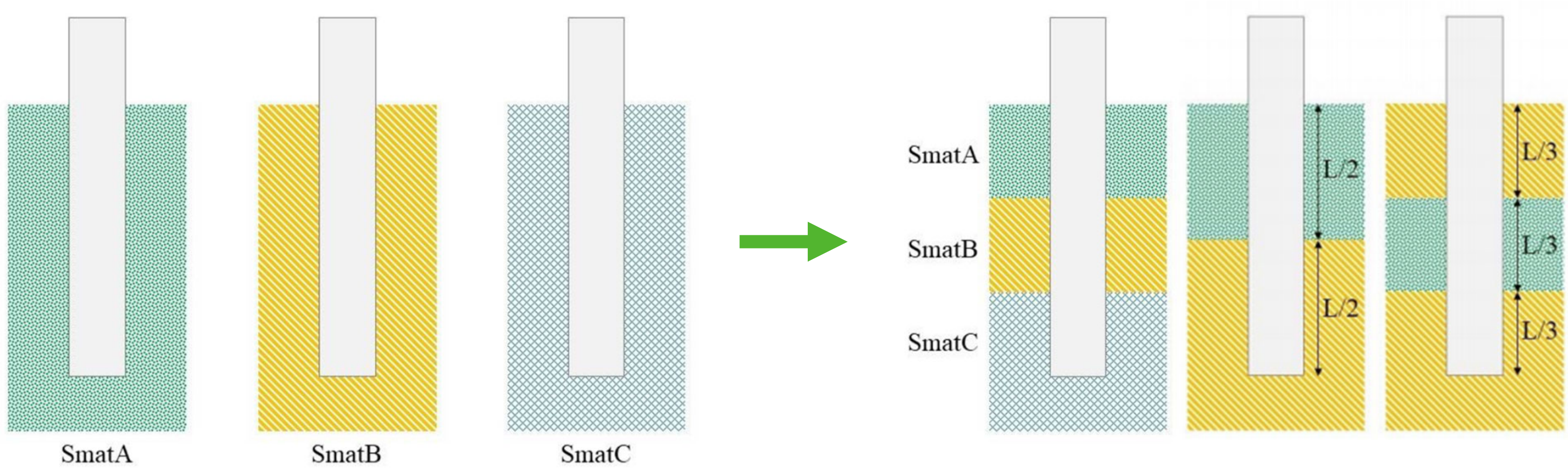
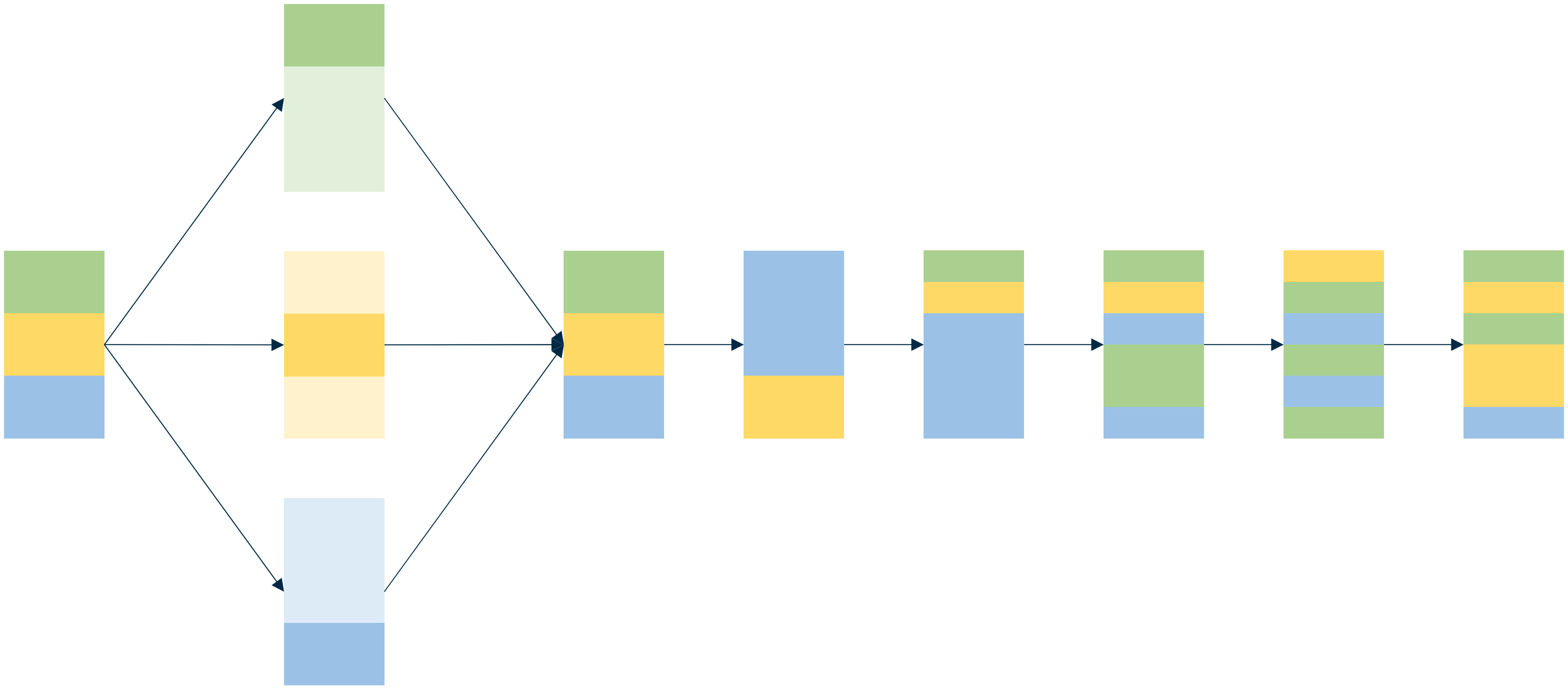
Parametric design space | Stratigraphy

- DVFs from homogeneous soil profiles can be directly used to model layered profiles containing those same soil units



Panagoulias, S.; Hosseini, S.; Brinkgreve, R.B.J.; Burd, H.J. (2019). **Design of laterally-loaded monopiles in layered soils**. In: 2nd International Conference on Natural Hazards & Infrastructure (ICONHIC), Chania, Greece.

Parametric design space | Stratigraphy



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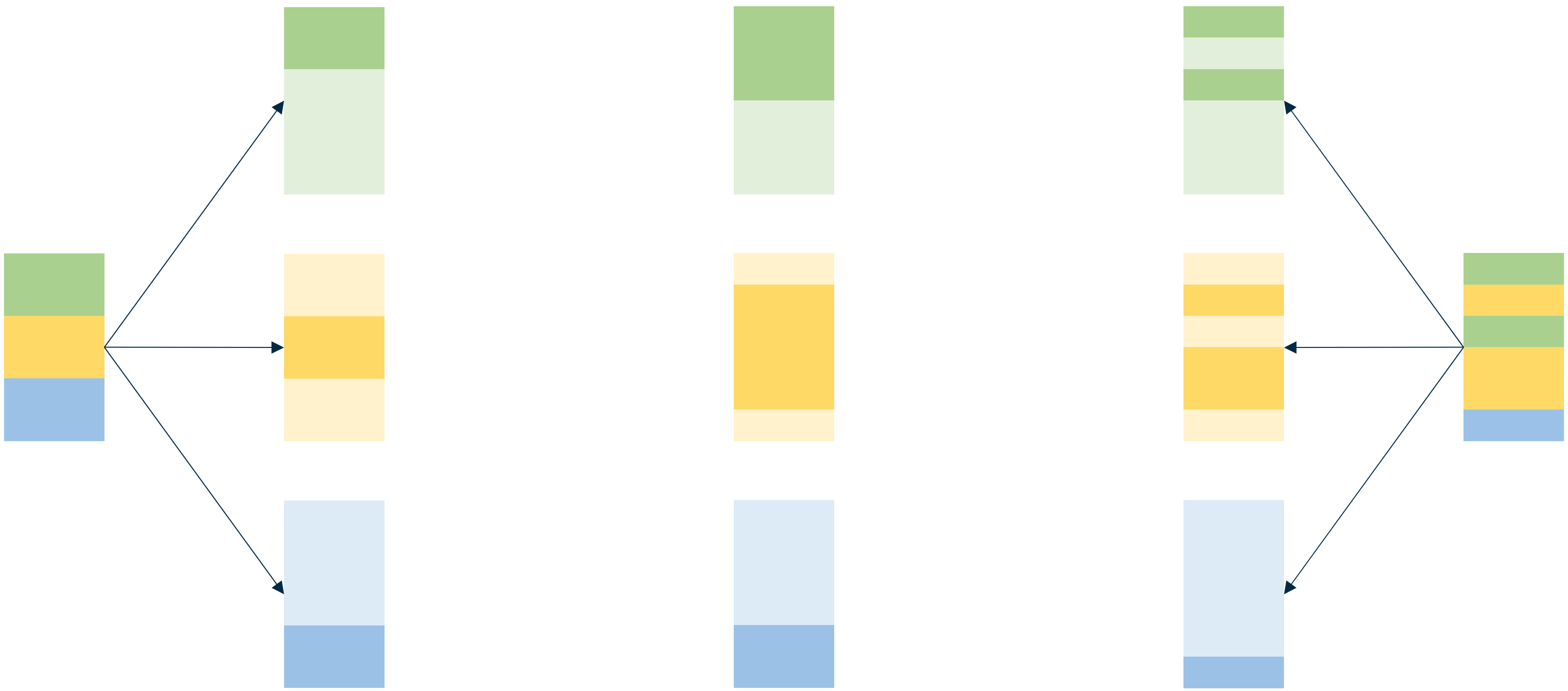
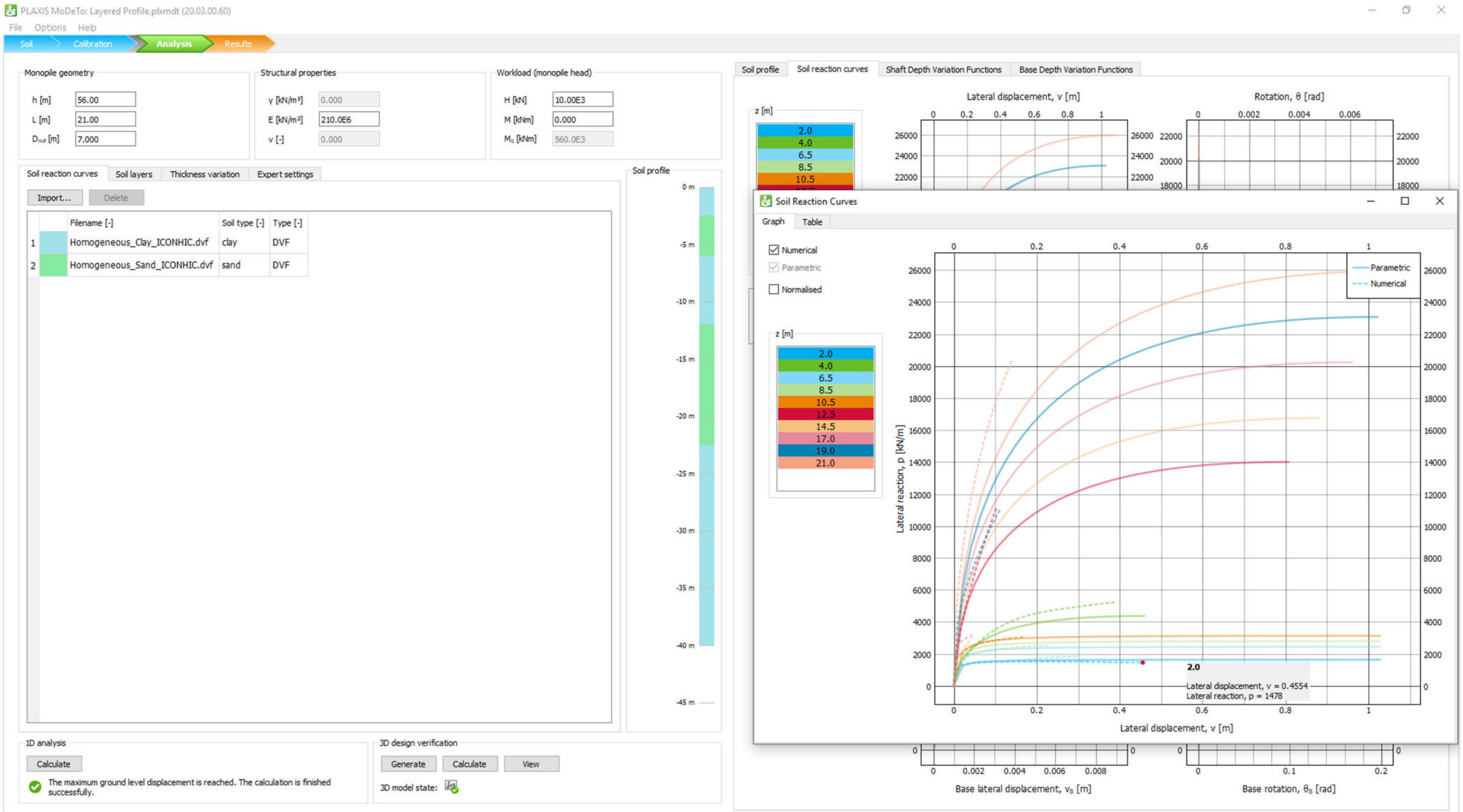
Parametric design space | Stratigraphy



Rule-based design



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Rule-based design | General Dunkirk Sand Model (GDSM)

Burd, H.J.; Taborda, D.M.G.; Zdravković, L.; Abadie, C.N.; Byrne, B.W.; Houlsby, G.T.; Gavin, K.G.; Igoe, D.J.P.; Jardine, R.J.; Martin, C.M.; McAdam, R.A.; Pedro, A.M.G.; Potts, D.M. (2020). **PISA design model for monopiles for offshore wind turbines: application to a marine sand**. *Géotechnique,* Volume 70 Issue 11, November 2020, pp. 1048-1066 [doi:10.1680/jgeot.18.P.277]

Table 6. Relative density functions for the GDSM, calibrated for $2 \leq (L/D) \leq 6$; $5 \leq (h/D) \leq 15$; $45\% \leq D_R \leq 90\%$

Soil reaction component	Soil reaction parameter	Relative density functions
Distributed lateral load, p	Ultimate displacement, $\bar{v}_{pu}$	$\bar{v}_{pu} = 146{\cdot}1 - 92{\cdot}11 D_R$
	Initial stiffness, k_p	$k_{p1} = 8{\cdot}731 - 0{\cdot}6982 D_R$ $k_{p2} = -0{\cdot}9178$
	Curvature, n_p	$n_p = 0{\cdot}917 + 0{\cdot}06193 D_R$
	Ultimate reaction, $\bar{p}_u$	$\bar{p}_{u1} = 0{\cdot}3667 + 25{\cdot}89 D_R$ $\bar{p}_{u2} = 0{\cdot}3375 - 8{\cdot}900 D_R$
Distributed moment, m	Ultimate rotation, $\bar{\psi}_{mu}$	Given by $\bar{m}_u/k_m$
	Initial stiffness, k_m	$k_m = 17{\cdot}00$
	Curvature, n_m	$n_m = 0{\cdot}0$
	Ultimate moment, $\bar{m}_u$	$\bar{m}_{u1} = 0{\cdot}2605$ $\bar{m}_{u2} = -0{\cdot}1989 + 0{\cdot}2019 D_R$
Base horizontal force, H_B	Ultimate displacement, $\bar{v}_{Hu}$	$\bar{v}_{Hu1} = 0{\cdot}5150 + 2{\cdot}883 D_R$ $\bar{v}_{Hu2} = 0{\cdot}1695 - 0{\cdot}7018 D_R$
	Initial stiffness, k_H	$k_{H1} = 6{\cdot}505 - 2{\cdot}985 D_R$ $k_{H2} = -0{\cdot}007969 - 0{\cdot}4299 D_R$
	Curvature, n_H	$n_{H1} = 0{\cdot}09978 + 0{\cdot}7974 D_R$ $n_{H2} = 0{\cdot}004994 - 0{\cdot}07005 D_R$
	Ultimate reaction, $\bar{H}_{Bu}$	$\bar{H}_{Bu1} = 0{\cdot}09952 + 0{\cdot}7996 D_R$ $\bar{H}_{Bu2} = 0{\cdot}03988 - 0{\cdot}1606 D_R$
Base moment, M_B	Ultimate rotation, $\bar{\psi}_{Mu}$	$\bar{\psi}_{Mu} = 44{\cdot}89$
	Initial stiffness, k_M	$k_M = 0{\cdot}3515$
	Curvature, n_M	$n_M = 0{\cdot}300 + 0{\cdot}4986 D_R$
	Ultimate reaction, $\bar{M}_{Bu}$	$\bar{M}_{Bu1} = 0{\cdot}09981 + 0{\cdot}3710 D_R$ $\bar{M}_{Bu2} = 0{\cdot}01998 - 0{\cdot}09041 D_R$

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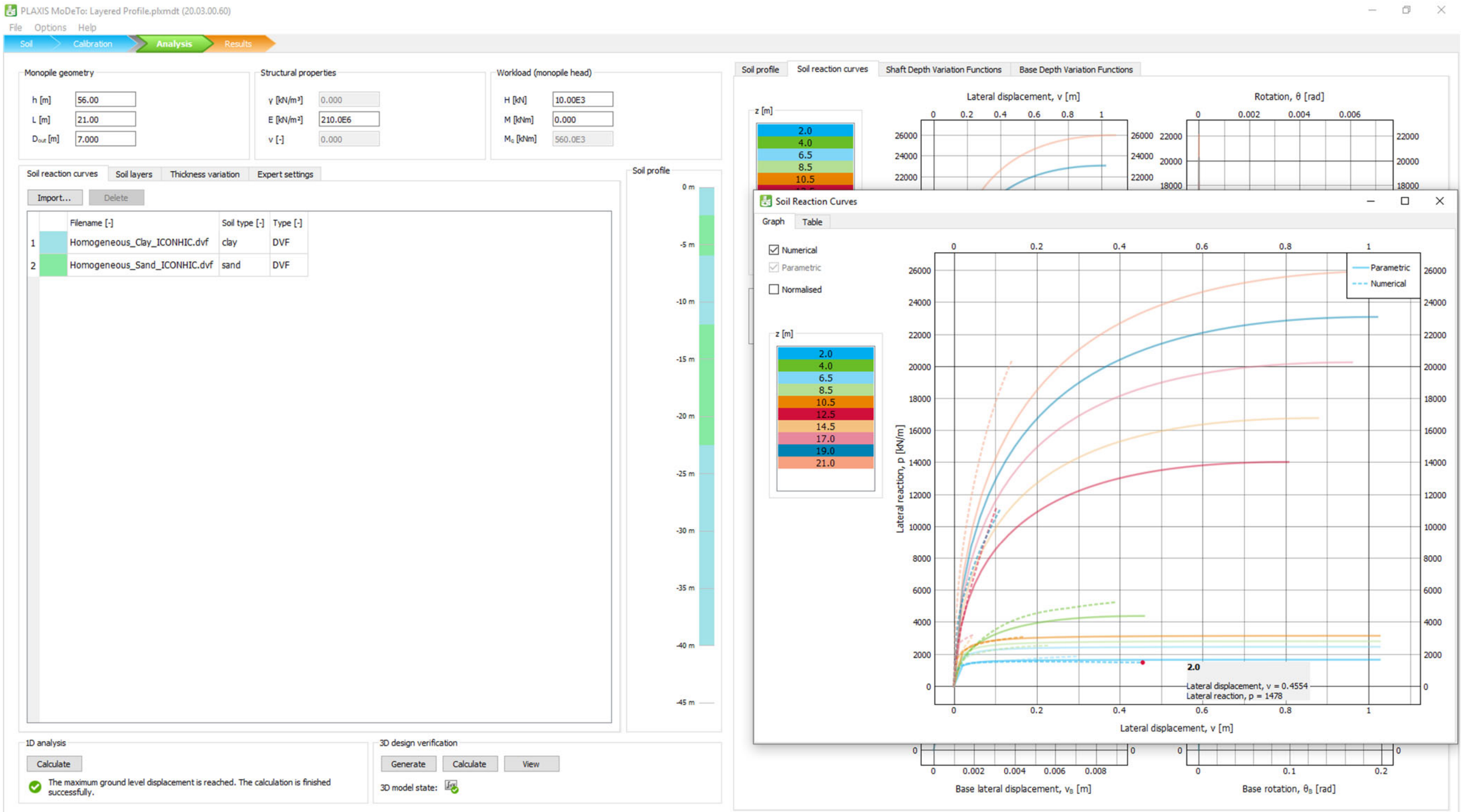
Rule-based design | Cowden till model

Byrne, B.W.; Houlsby, G.T.; Burd, H.J.; Gavin, K.G.; Igoe, D.J.P.; Jardine, R.J.; Martin, C.M.; McAdam, R.A.; Potts, D.M.; Taborda, D.M.G.; Zdravković, L.. (2020). **PISA design model for monopiles for offshore wind turbines: application to a stiff glacial clay till**. *Géotechnique,* Volume 70 Issue 11, November 2020, pp. 1030-1047 [doi:10.1680/jgeot.18.P.255]

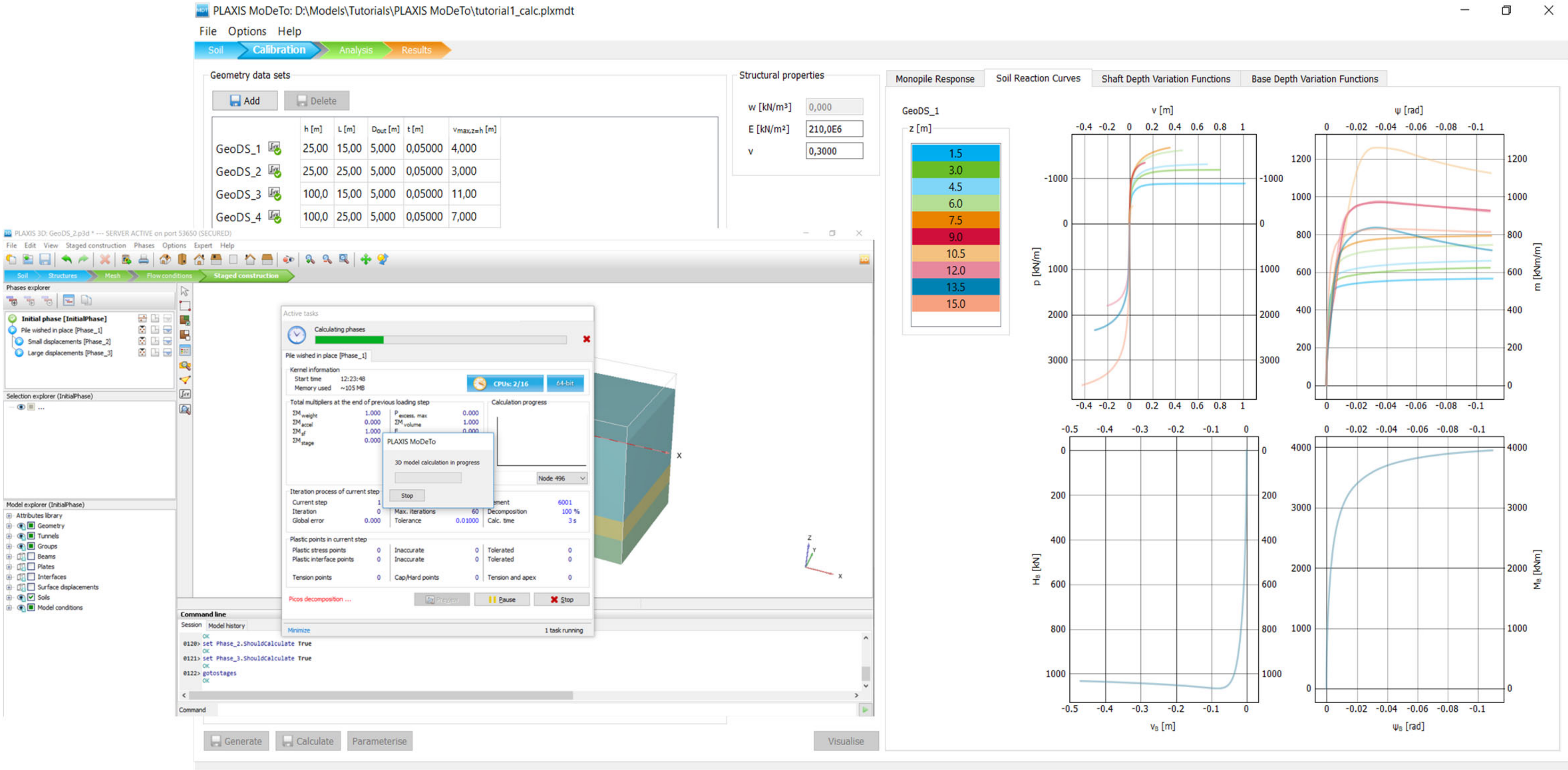
Table 4. Soil reaction curve parameters for Cowden till, calibrated within the parameter space set out in Table 1

Soil reaction component	Parameter	Depth variation functions First-stage calibration	Depth variation functions Second-stage calibration
Distributed lateral load, p	Ultimate displacement, $\bar{v}_{pu}$	200·0	241·4
	Initial stiffness, k_p	$8{\cdot}123 - 1{\cdot}103\frac{z}{D}$	$10{\cdot}60 - 1{\cdot}650\frac{z}{D}$
	Curvature, n_p	$0{\cdot}9225 - 0{\cdot}04834\frac{z}{D}$	$0{\cdot}9390 - 0{\cdot}03345\frac{z}{D}$
	Ultimate reaction, $\bar{p}_u$	$10{\cdot}21 - 7{\cdot}215e^{[-0{\cdot}3332(z/D)]}$	$10{\cdot}70 - 7{\cdot}101e^{[-0{\cdot}3085(z/D)]}$
Distributed moment, m	Ultimate rotation, $\bar{\psi}_{mu}$	Given by $\bar{m}_u/k_m$	Given by $\bar{m}_u/k_m$
	Initial stiffness, k_m	$0{\cdot}9710 - 0{\cdot}1144\frac{z}{D}$	$1{\cdot}420 - 0{\cdot}09643\frac{z}{D}$
	Curvature, n_m	0·0	0·0
	Ultimate moment, $\bar{m}_u$	$0{\cdot}3840 - 0{\cdot}04246\frac{z}{D}$	$0{\cdot}2899 - 0{\cdot}04775\frac{z}{D}$
Base horizontal force, H_B	Ultimate displacement, $\bar{v}_{Hu}$	300	235·7
	Initial stiffness, k_H	$2{\cdot}564 - 0{\cdot}3167\frac{L}{D}$	$2{\cdot}717 - 0{\cdot}3575\frac{L}{D}$
	Curvature, n_H	$0{\cdot}7396 - 0{\cdot}02658\frac{L}{D}$	$0{\cdot}8793 - 0{\cdot}03150\frac{L}{D}$
	Ultimate reaction, $\bar{H}_{Bu}$	$0{\cdot}6019 + 0{\cdot}06669\frac{L}{D}$	$0{\cdot}4038 + 0{\cdot}04812\frac{L}{D}$
Base moment, M_B	Ultimate rotation, $\bar{\psi}_{Mu}$	200	173·1
	Initial stiffness, k_M	$0{\cdot}1970 - 0{\cdot}002680\frac{L}{D}$	$0{\cdot}2146 - 0{\cdot}002132\frac{L}{D}$
	Curvature, n_M	$1{\cdot}006 - 0{\cdot}1616\frac{L}{D}$	$1{\cdot}079 - 0{\cdot}1087\frac{L}{D}$
	Ultimate reaction, $\bar{M}_{Bu}$	$0{\cdot}6504 - 0{\cdot}07843\frac{L}{D}$	$0{\cdot}8192 - 0{\cdot}08588\frac{L}{D}$

Rule-based design | Layered soils



Numerical-based design | Calibration from PLAXIS 3D



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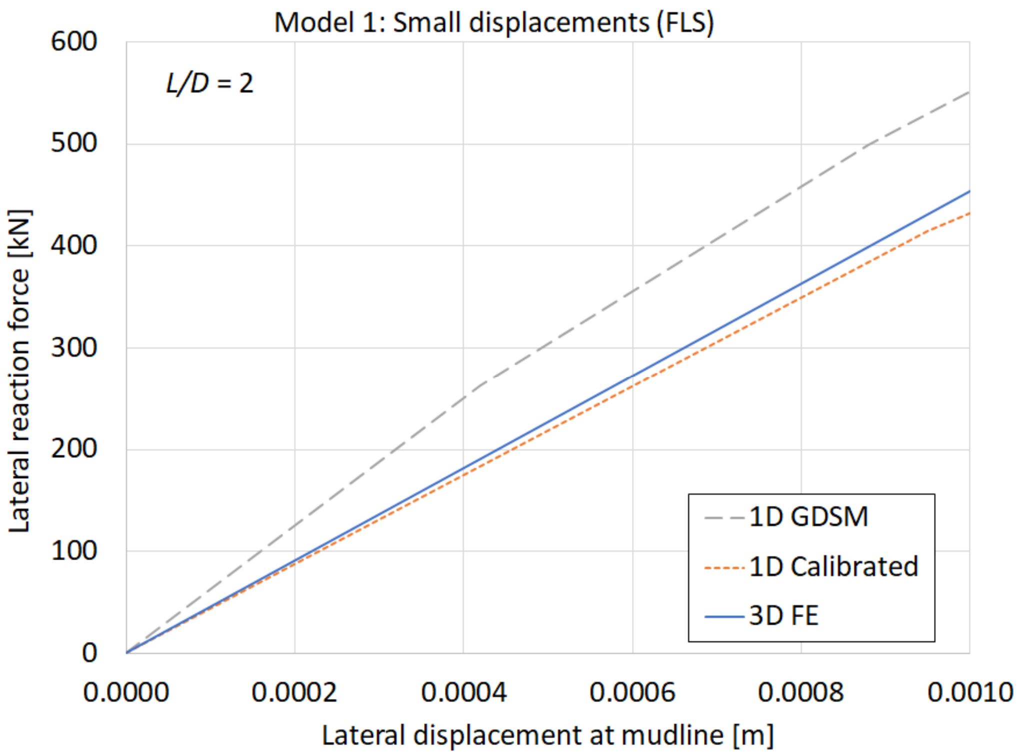
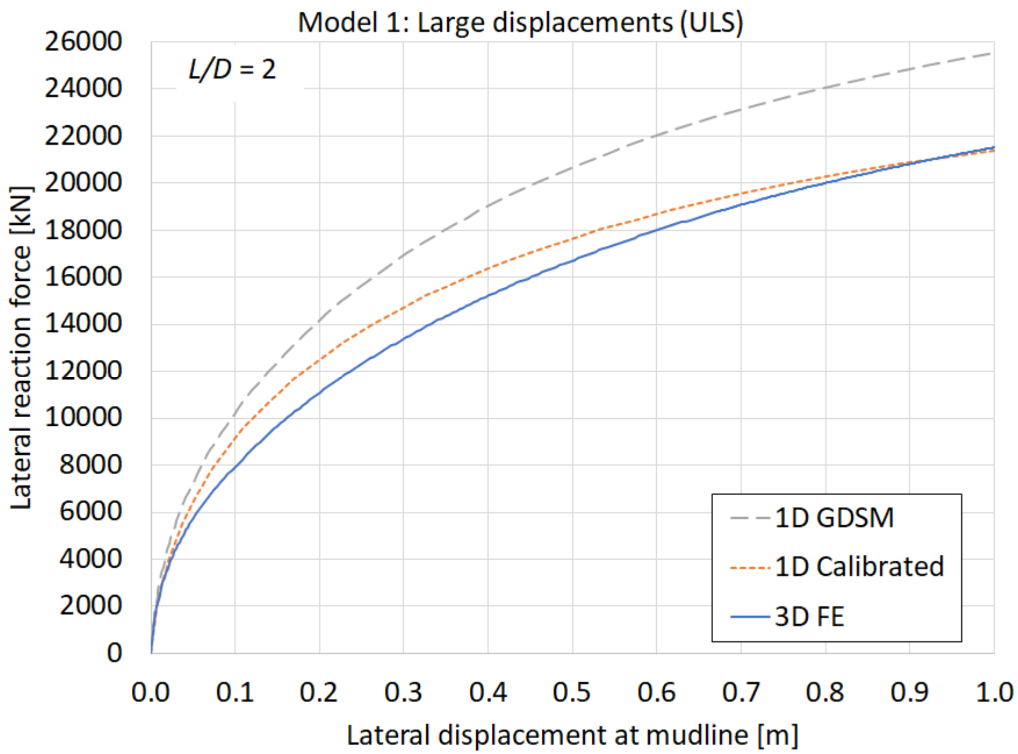
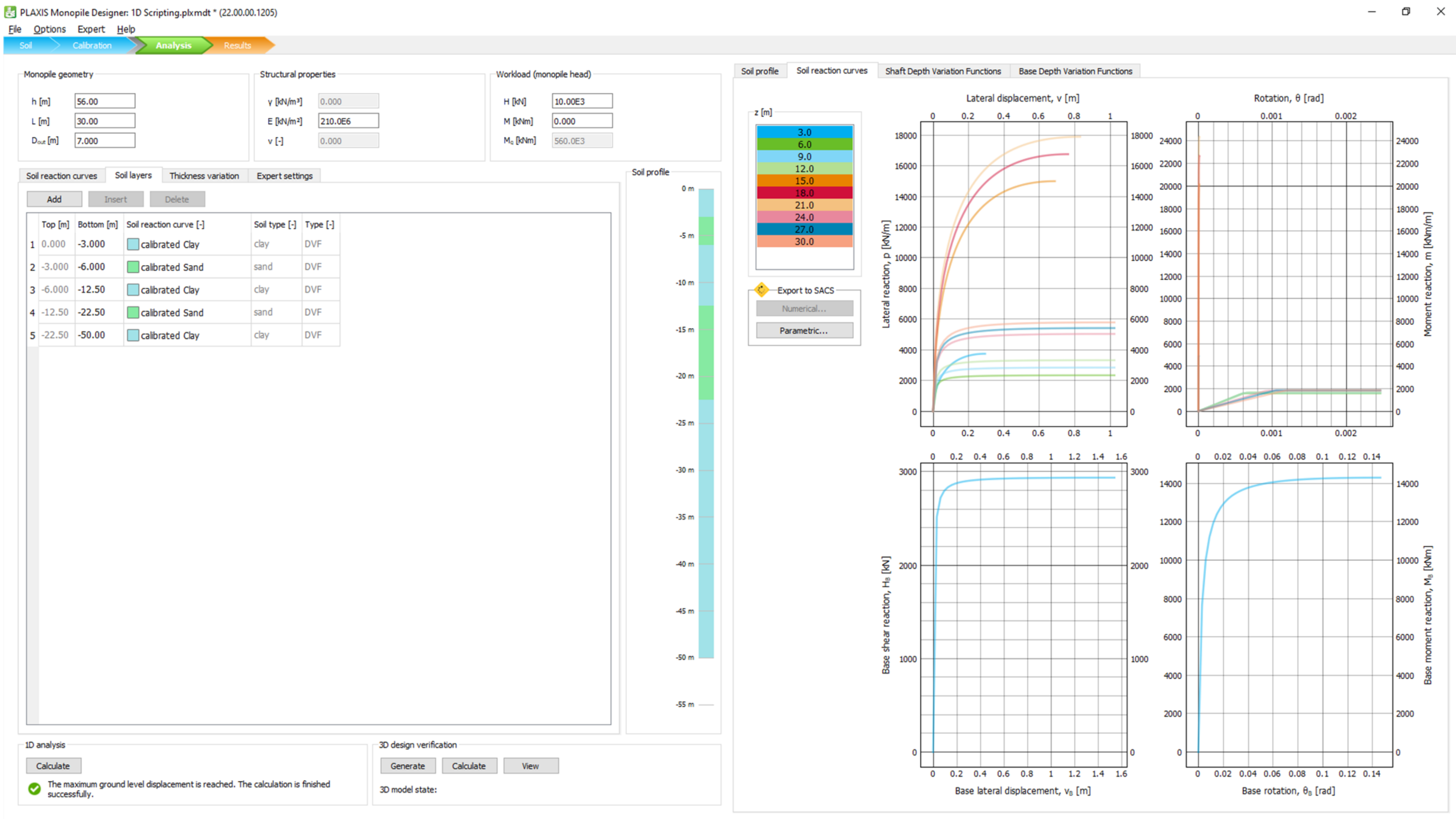
Rule-based or numerical-based?



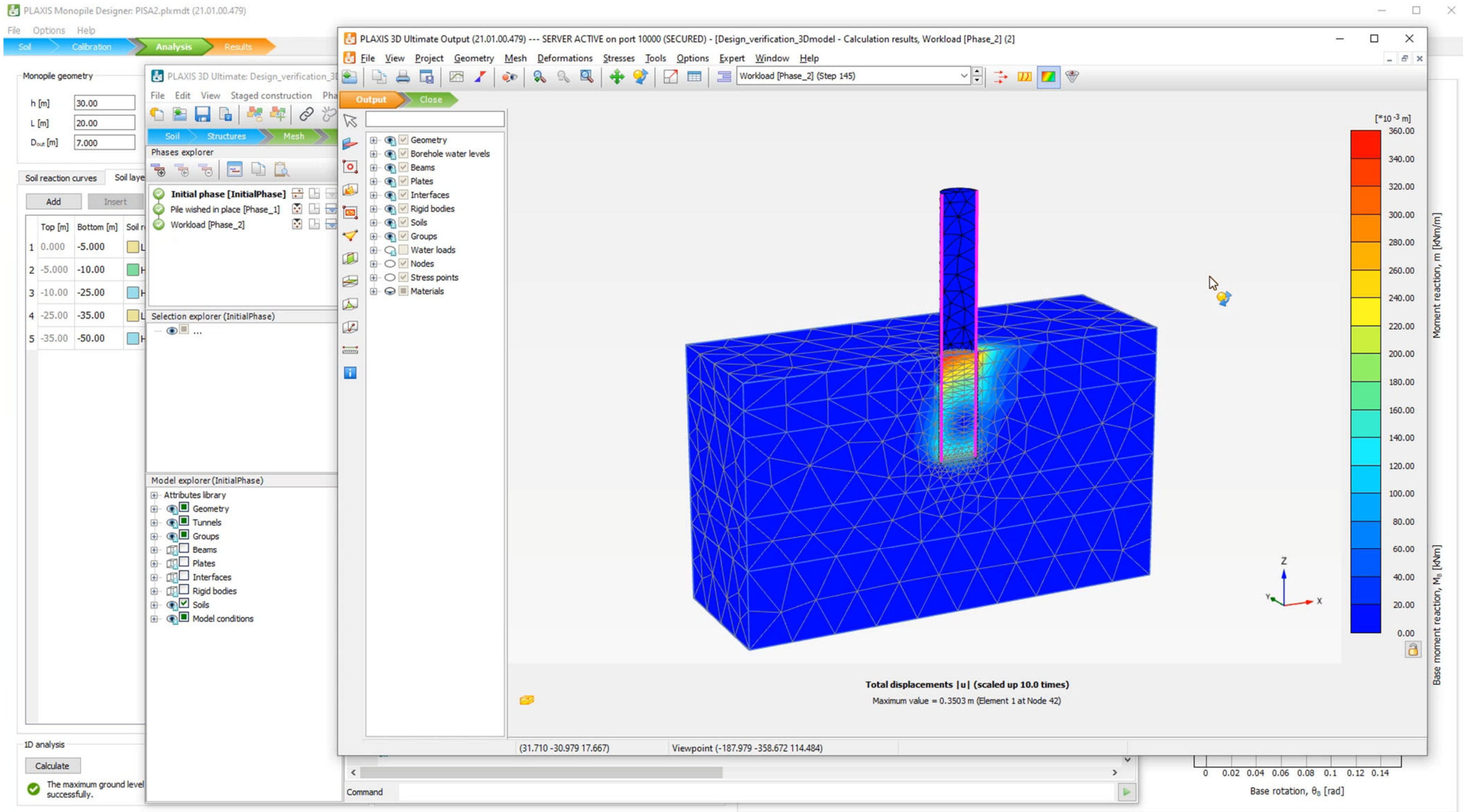


Brinkgreve, R.B.J.; Lisi, D.; Lahoz, M.; Panagoulias, S. (2020). **Validation and application of a new software tool implementing the PISA Design Methodology**. *J. Mar. Sci. Eng. 2020*, 8, 457.

Analysis of layered soils according to PISA Phase 2

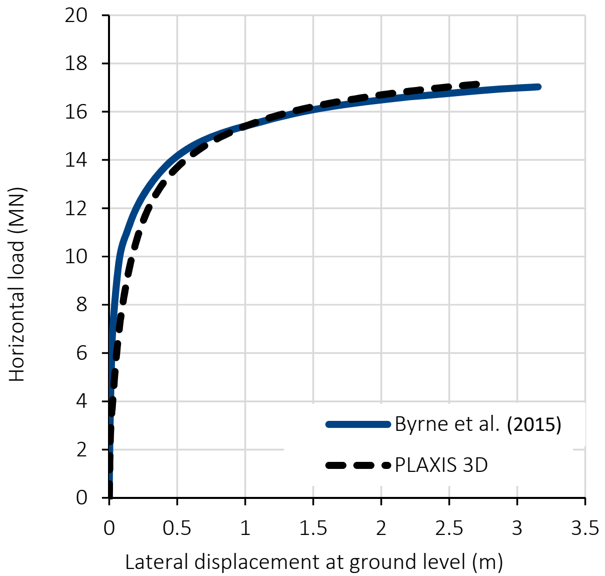


3D design verification



Validation

- Published validation cases (i.c.w. Oxford University, Fugro, Siemens)
  - Against PISA field test experimental data
  - Against 3D FEM models
- More information in [Bentley Communities]



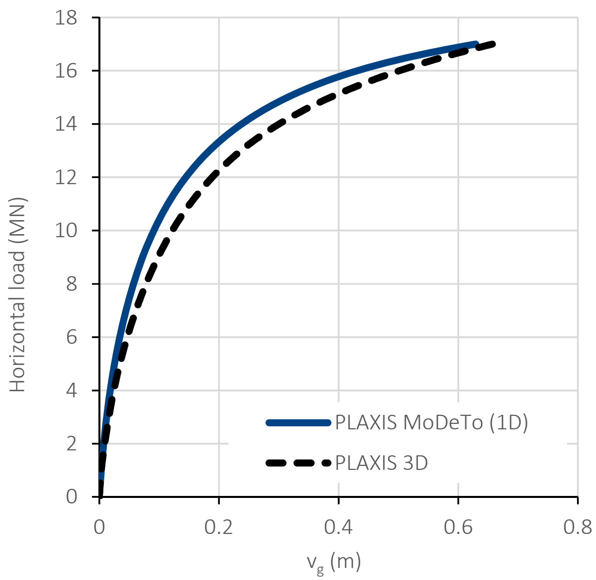


Image courtesy of Oxford University

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What's New, What's Coming

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Disclaimer Statement

Release plans and timelines are forward-looking estimates and projections only. All forward-looking statements are subject to various risks and uncertainties that could cause actual results to differ materially from expectations. Readers are cautioned not to place undue reliance on these forward-looking statements, which speak only as of their dates, and they should not be relied upon in making purchasing decisions.

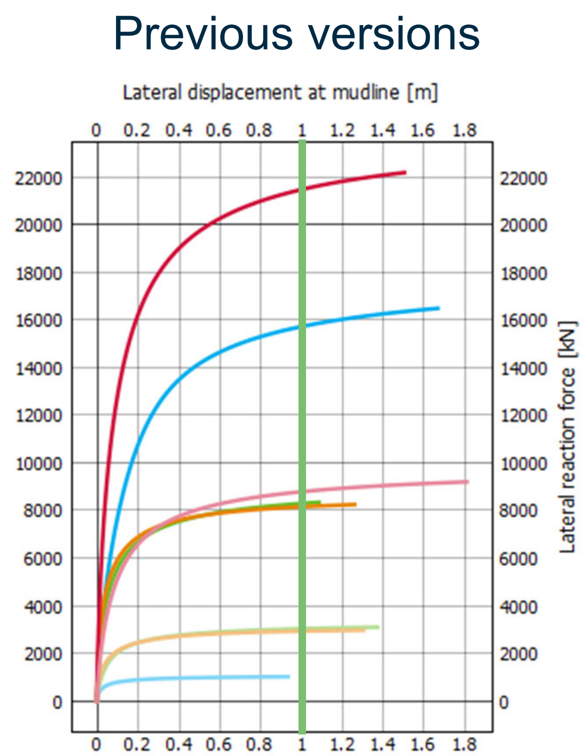
Version 21

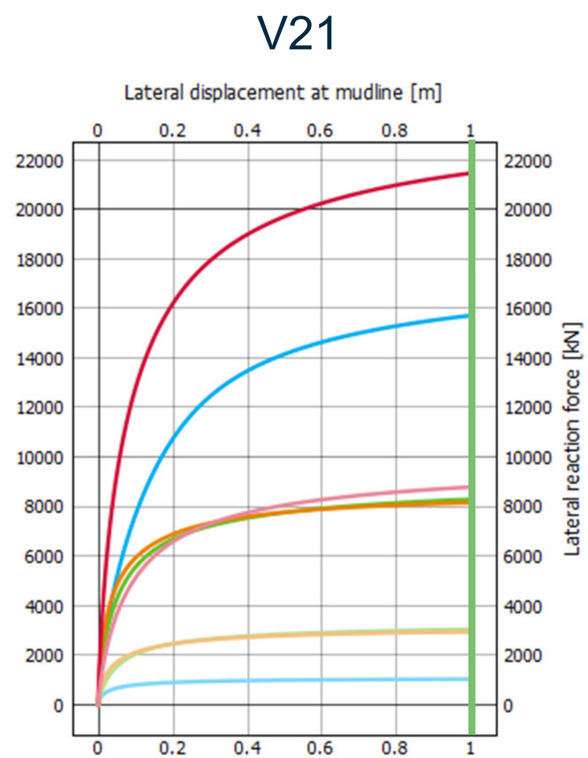
PLAXIS® Monopile Designer
CONNECT Edition

- Renamed: **PLAXIS Monopile Designer**
- Functionality stays the same
  - Stand-alone use for rule-based design (1D)
  - Full interoperability with PLAXIS 3D for numerical-based design (1D+3D)
    - All 3 tiers
    - Requires active Geotechnical SELECT Entitlements

Version 21 | Calibration with target displacement at mudline

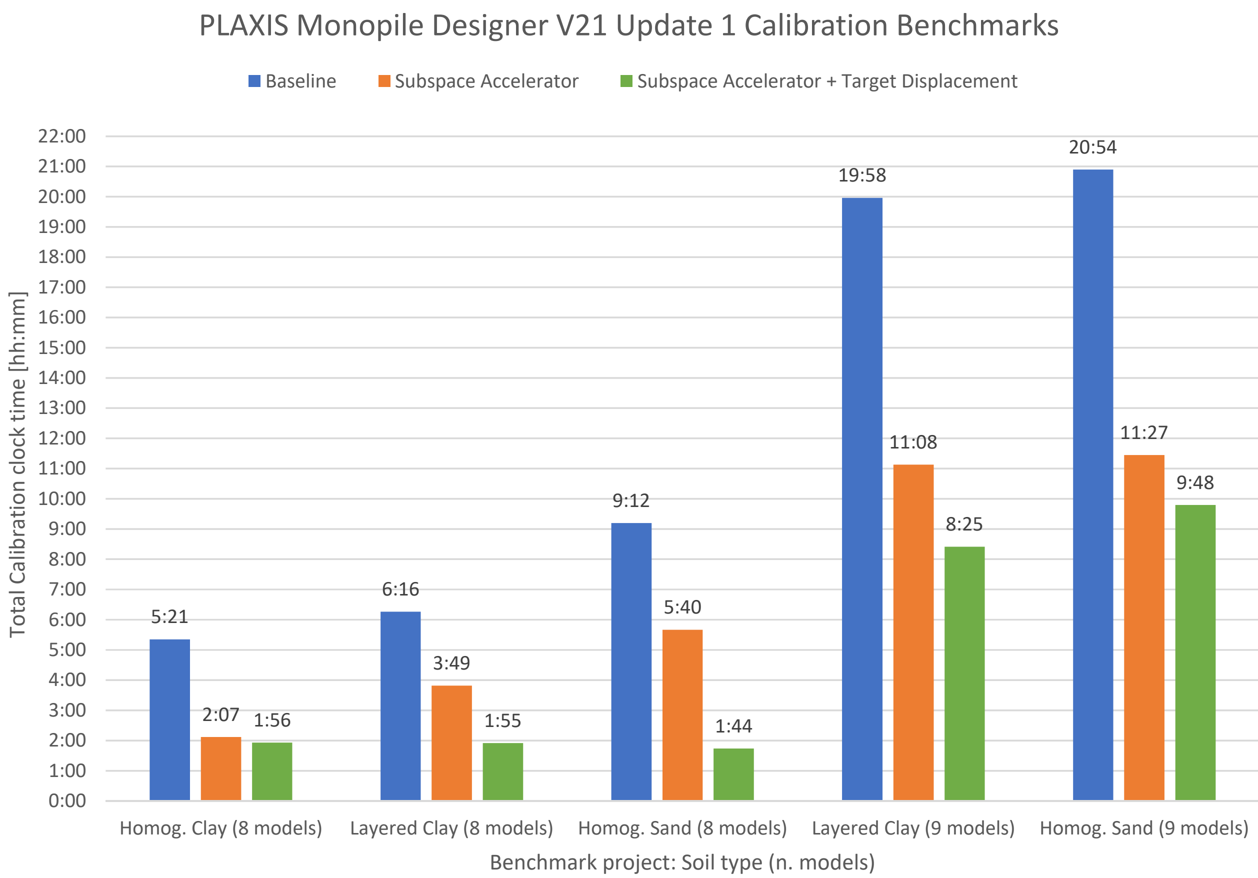
- Calculation automatically stops when target displacement (v_g/D) is achieved
- No need to guess before calculating; no trial-and-error
- Saves unnecessary steps, reducing total calculation time





V21 Update 1 | Subspace accelerator

- New numerical setting in PLAXIS 3D
- Enabled by default in Monopile Designer models
- Significant speed improvement
- Additional gain when combined with Calibration with target displacement



Q4 2021 | Product Roadmap

PLAXIS Monopile Designer

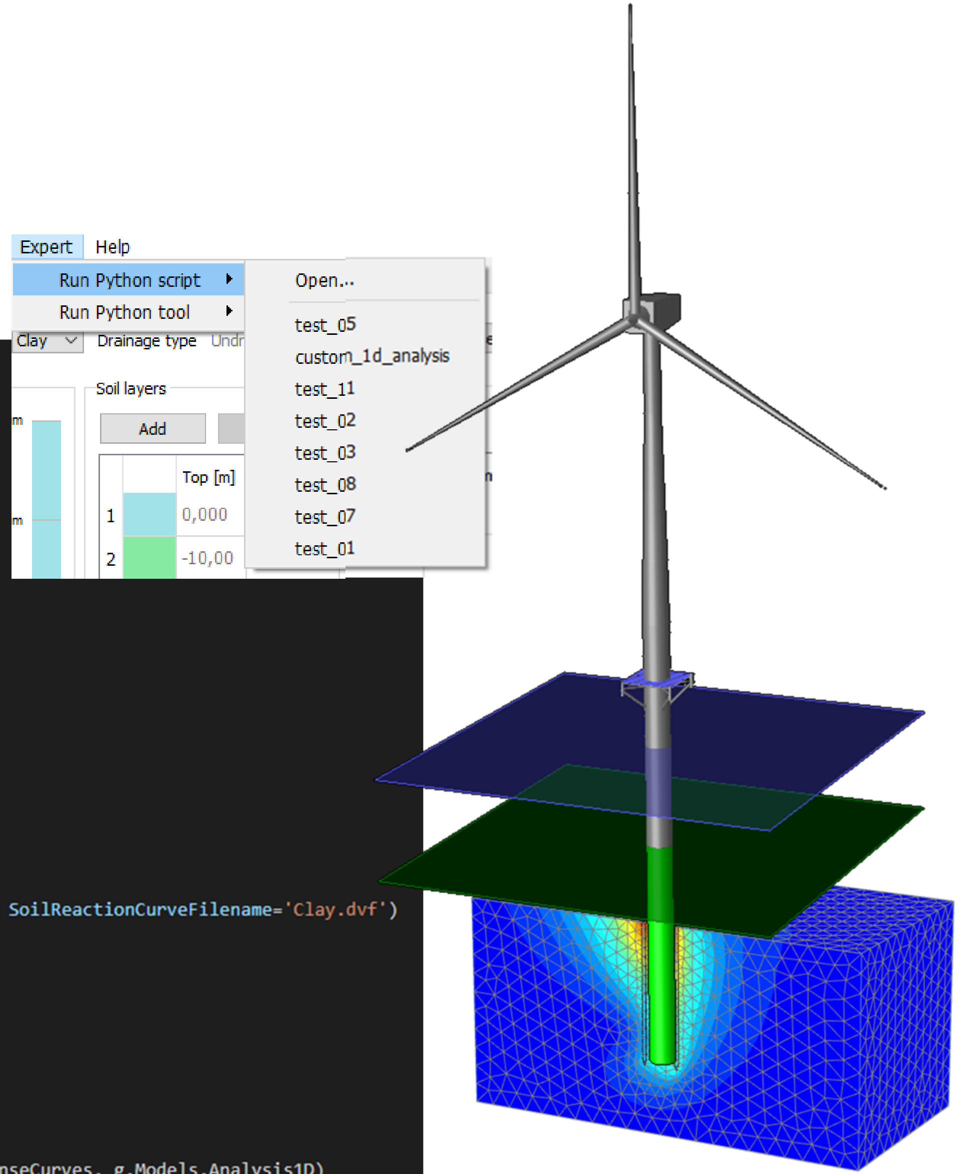
Short Term (Recent & next releases)	Season Plan (6 months)	6-18 months

▪ Calibration with target displacement
▪ Subspace accelerator
▪ Python scripting API
▪ Updated Manuals
	▪ 1D eigenvalue analysis
	  ▪ Cone trunk sections
	  ▪ Mass distribution
	▪ Extensions to Python scripting API
	  ▪ Project and file operations
	  ▪ 3D design verification
	▪ Export to SACS: Technology Preview to General Availability
		▪ Cyclic loading
		▪ Calibration of multiple soil profiles
		▪ Increased control over material models and material parameters
		▪ Streamlined rule-based design workflow

Version 22 | Python scripting API

- *Problem/Pain* | Design of foundations for offshore wind requires thousands of calculations with different load cases, geometries, and soil profiles
- *Value*
    - Run more analyses in less time
    - Automate your workflows across PLAXIS Monopile Designer, PLAXIS 3D, and/or OpenWindPower, all using the same scripting language
- *When* | 2021 Q4

```python
from plxmdt.easy import new_server

# Creating the server and global objects
s, g = new_server()

# Retrieving current data
print("Analysis feedback:")
print(g.Analysis)
print("First soil layer:")
print(g.Analysis.SoilLayers[0])
print("First segment:")
print(g.Analysis.Segments[0])

# Changing data
g.Analysis.H = 10000
g.Analysis.M = 500
g.Analysis.h = 59
g.Analysis.SoilLayers[0].Bottom = -8.5
g.Analysis.Segments[0].t = 0.07

# Adding new objects to a collection
g.Analysis.SoilLayers.append(Bottom=-40, SoilReactionCurveFilename='Clay.dvf')
g.Analysis.Segments.append(t=0.08)

# Deleting objects from a collection
del g.Analysis.SoilLayers[0]

# Running analyses
g.Analysis.calculate()

# Getting results
g.getresults(g.ResultTypes.MonopileResponseCurves, g.Models.Analysis1D)
```



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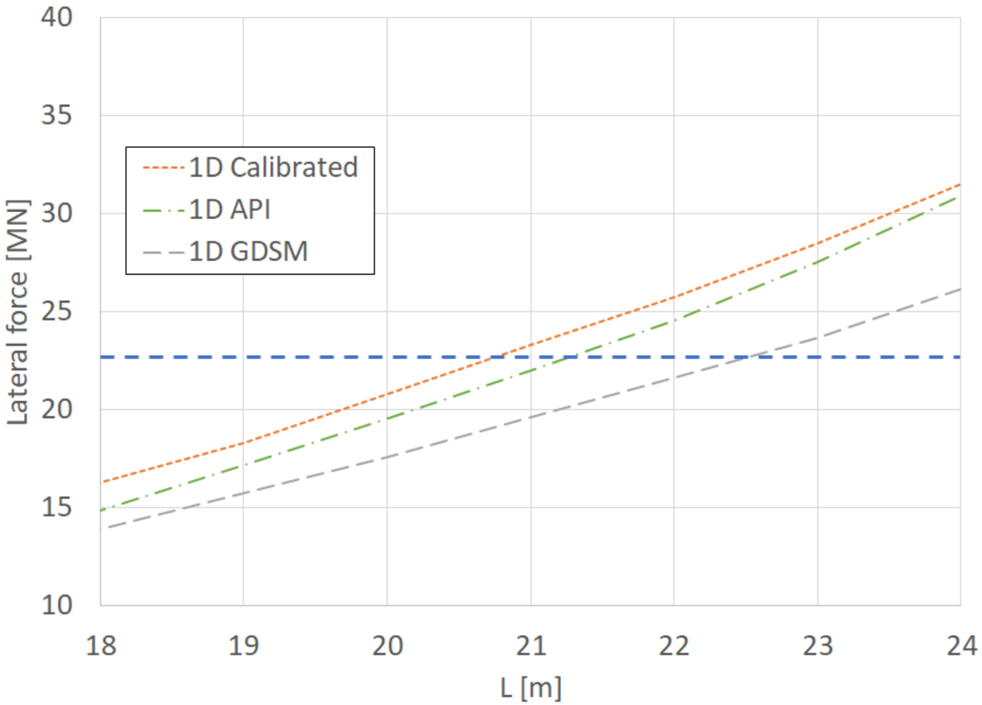
Scripting example | Parametric studies

- Combining a fast solver and scripted automation, generating parameter-response graphs becomes inexpensive



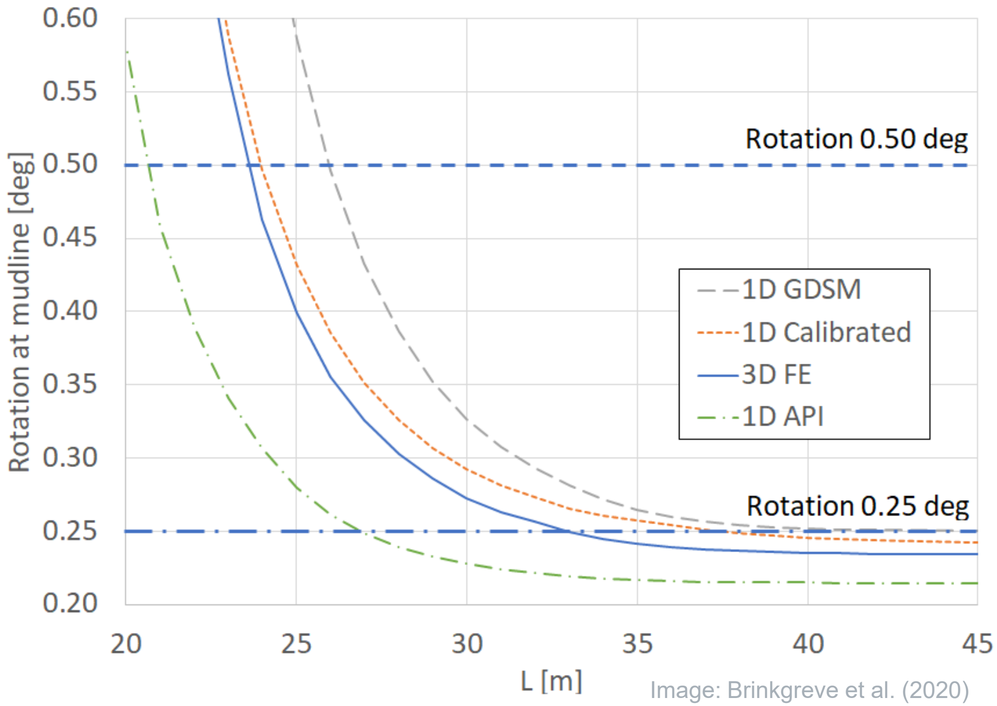
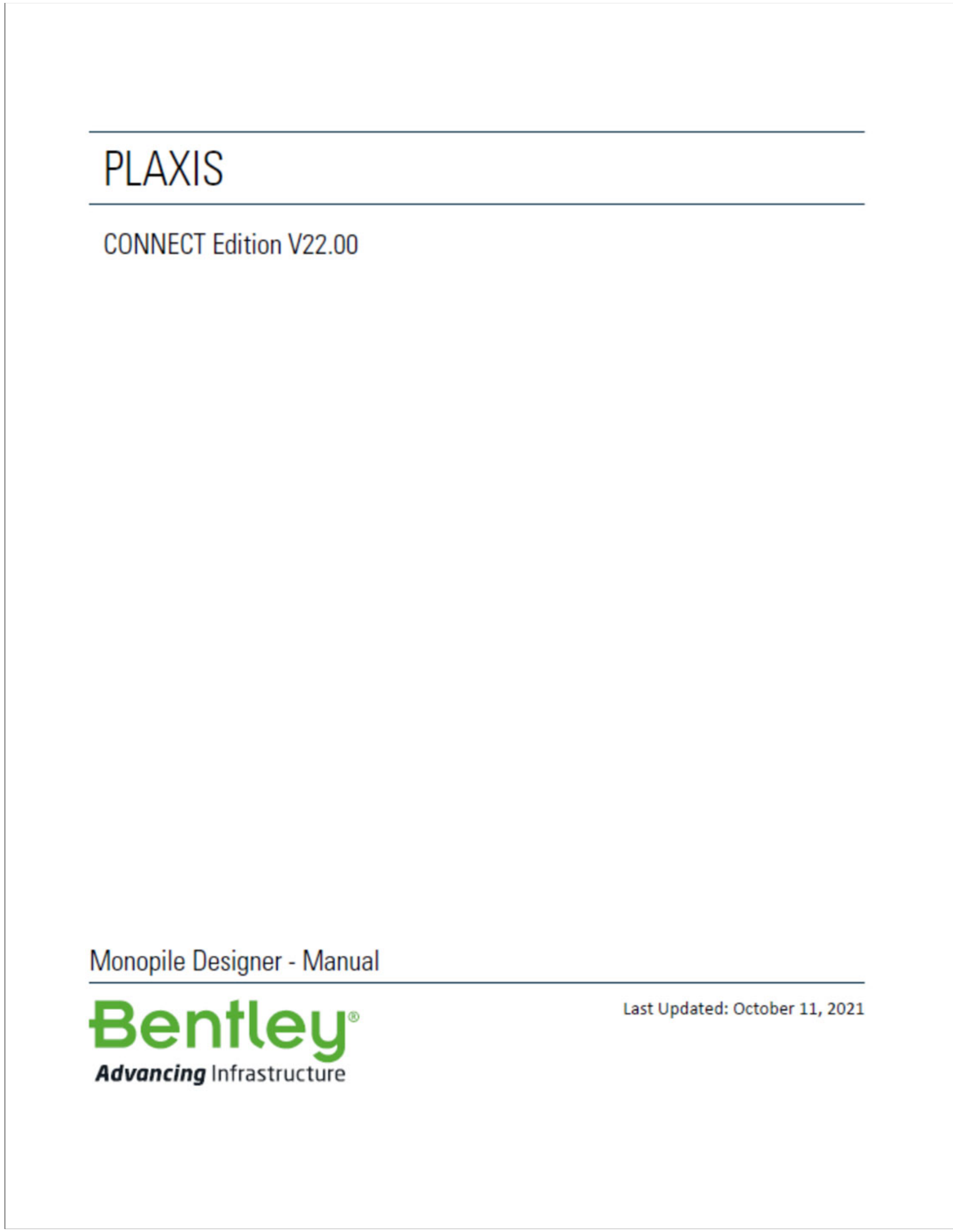


Image: Brinkgreve et al. (2020)

Version 22 | Updated Manuals

- Full review of documentation, including
  - All PISA publications (Phases 1 and 2)
  - Published PISA rule-based models
    - Cowden clay model for **stiff clays**
    - Bothkennar clay model for **soft clays**
    - General Dunkirk sand model (GDSM) for **sands**
  - Use of conventional (API) p-y curves
  - 3D design verification models
  - Changes to user interface
  - Python scripting reference
- New Tutorial: Layered soils
  - Rule-based design
  - Numerical-based design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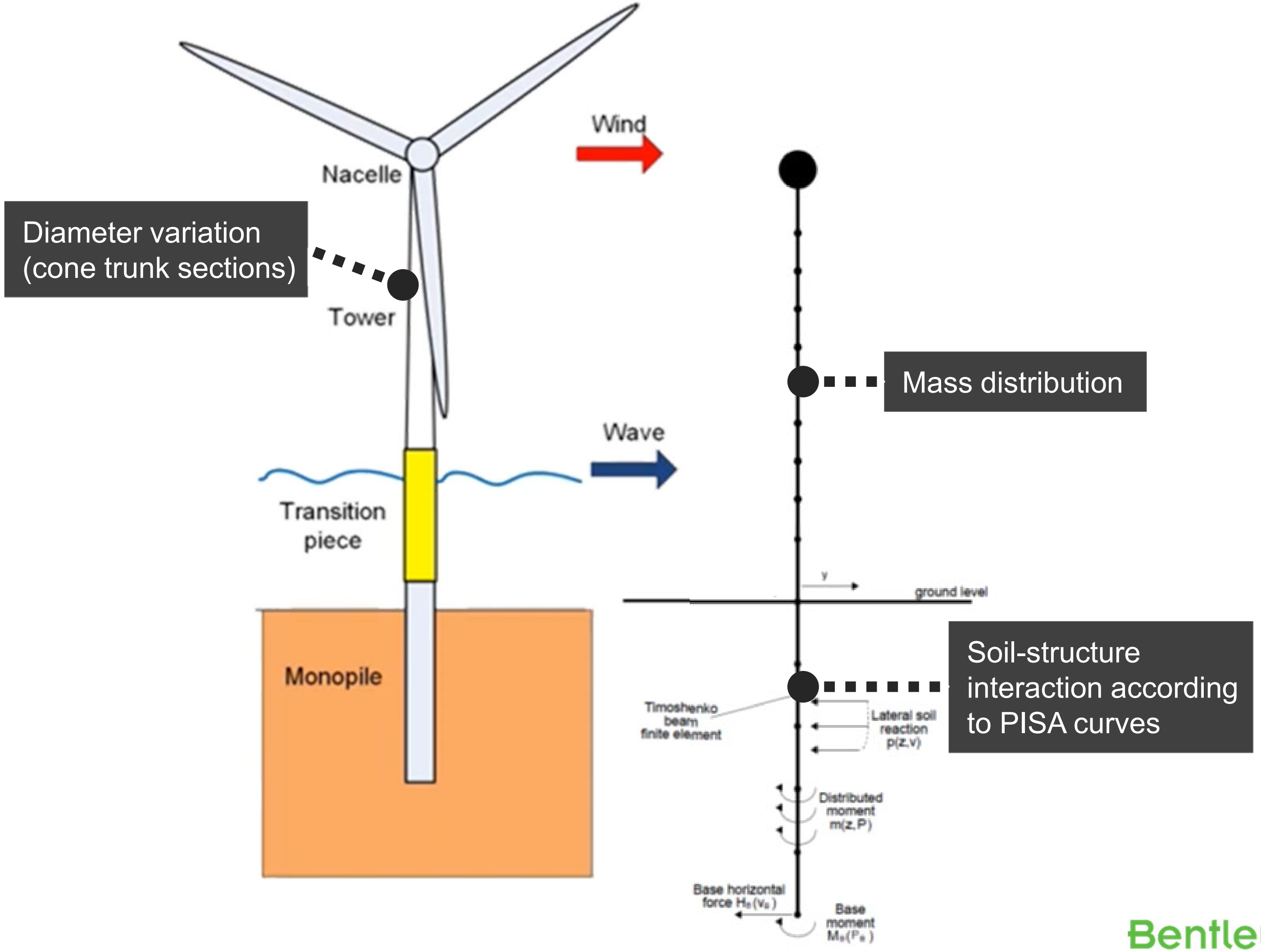
CONNECT Edition V22.00

Monopile Designer - Manual

Last Updated: October 11, 2021

Season Plan | 1D eigenvalue analysis (modal analysis)

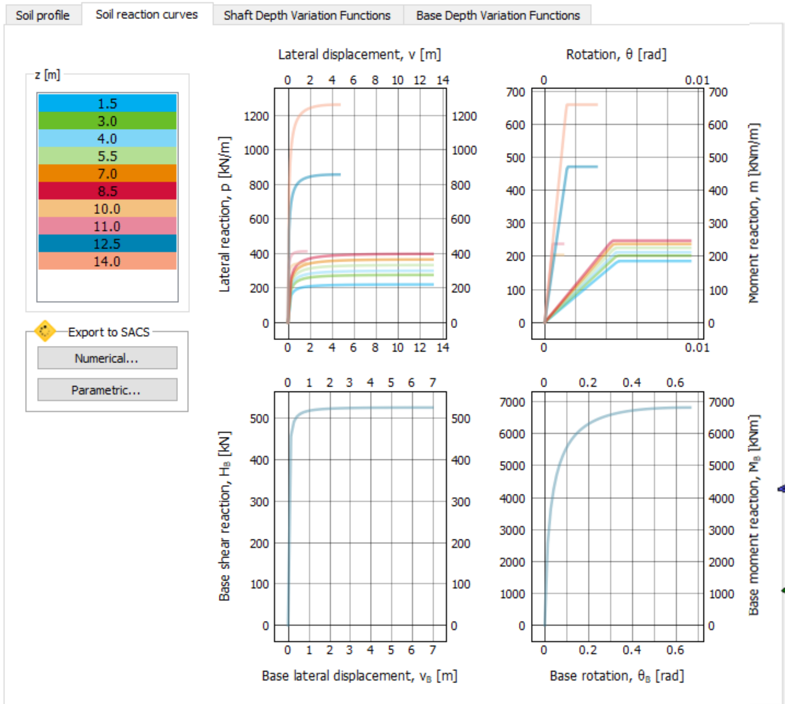
- *Problem/Pain* | Determine the natural frequency and natural modes of monopile-tower-turbine systems
- *Value* | Eigenvalue analysis considering soil-structure interaction from initial stiffness of PISA soil reaction curves
- *When* | 2022

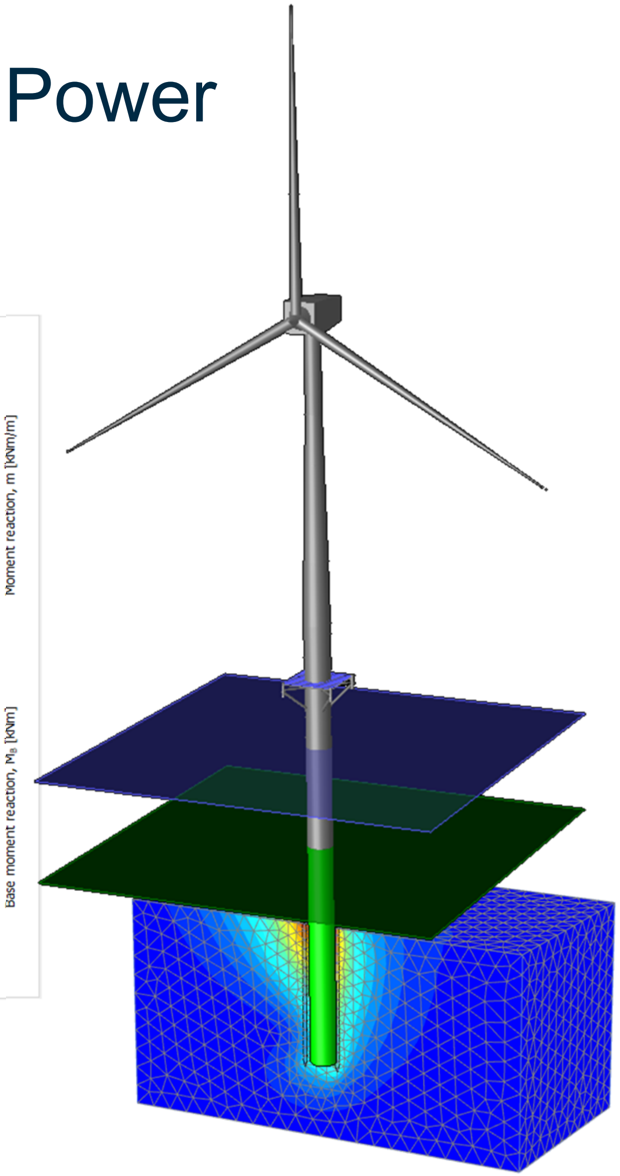


 |

Season Plan | Export to SACS / OpenWindPower

- *Problem/Pain* | Geotechnical design and structural design workflows are often disconnected
- *Value* | Export geometry and soil response to a SACS Pile3D Input file, which can be directly used for soil-structure interaction analysis in OpenWindPower
- *When*
  - *Technology Preview* | 2020
  - *General Availability* | 2022





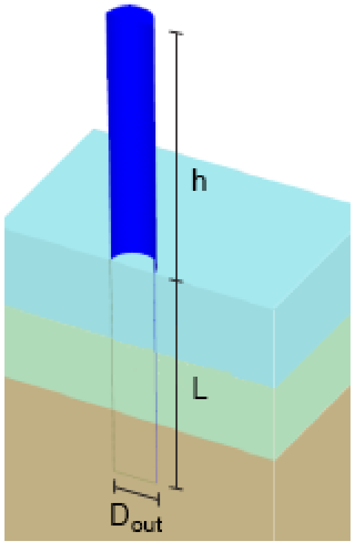
Bentley

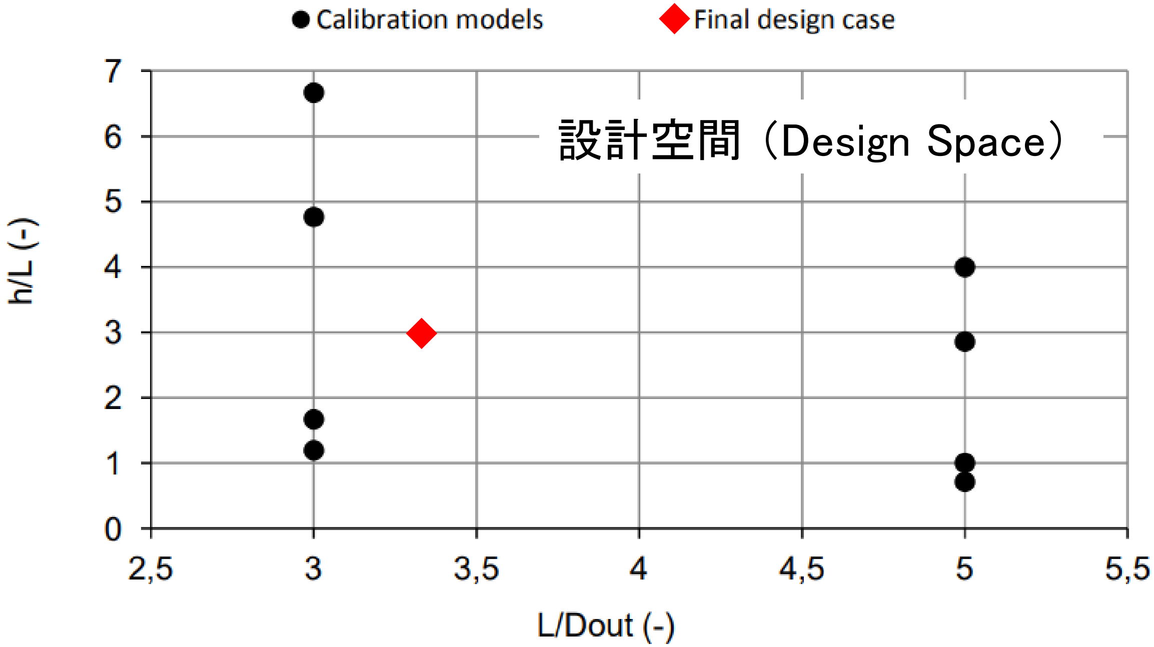
当社製品による洋上風力分野の解析事例

JIPテクノサイエンス株式会社
解析ソリューション事業部
伊藤　肇

不確かさを考慮したモノパイル基礎の解析事例

- Monopile Designerの機能の概要

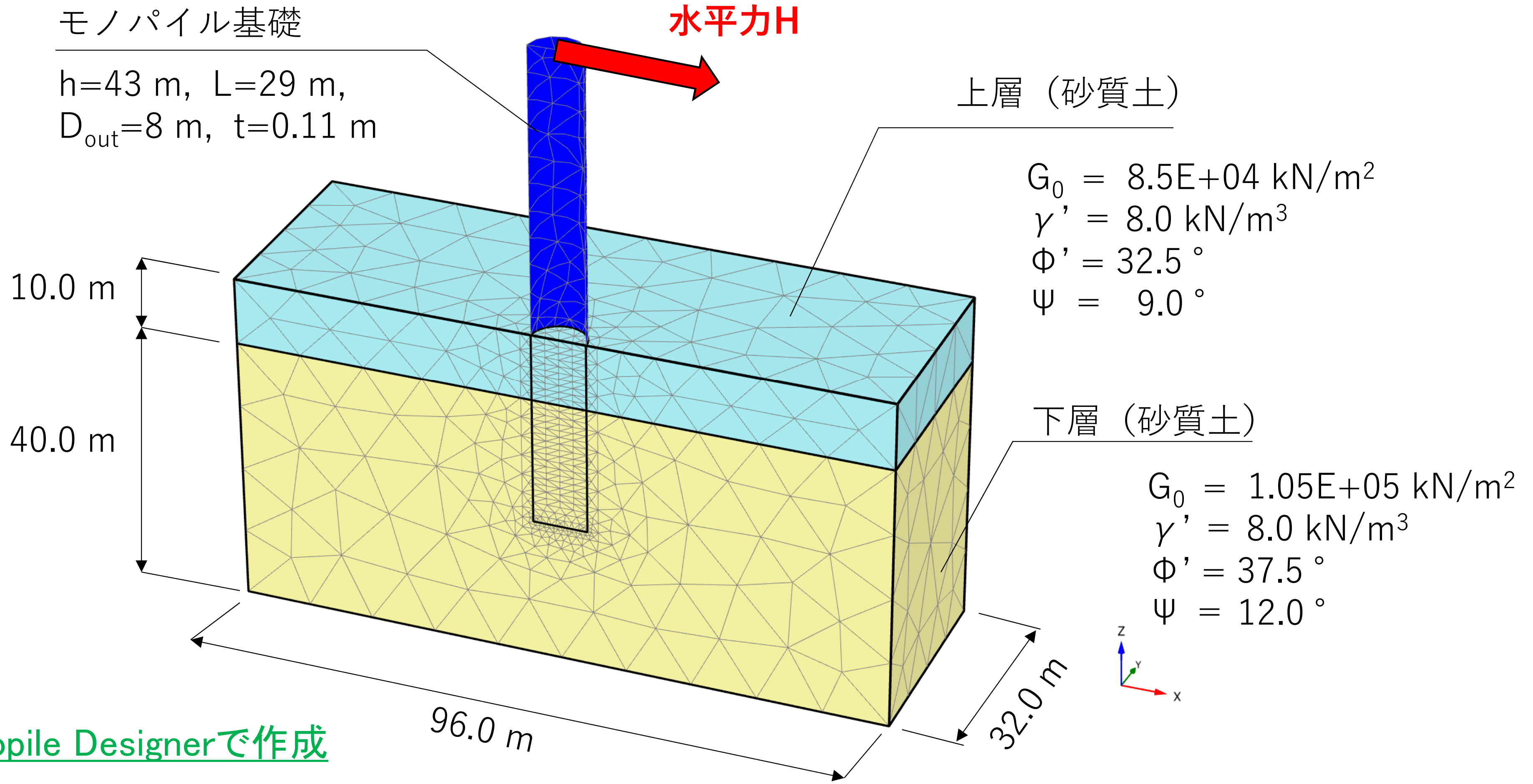




仮定した地盤条件において、モノパイルの幾何寸法（h, L, D_{out}）の決定を行う

地盤条件の不確かさを考慮した検討

不確かさを考慮したモノパイル基礎の解析事例

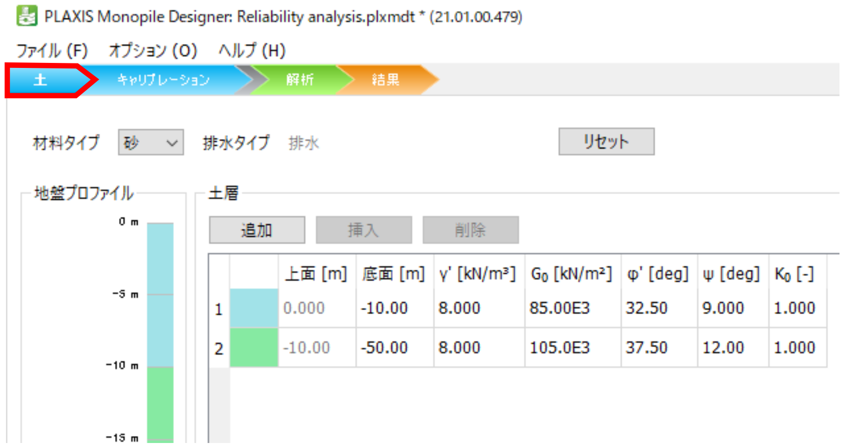


Monopile Designerで作成

不確かさを考慮したモノパイル基礎の解析事例

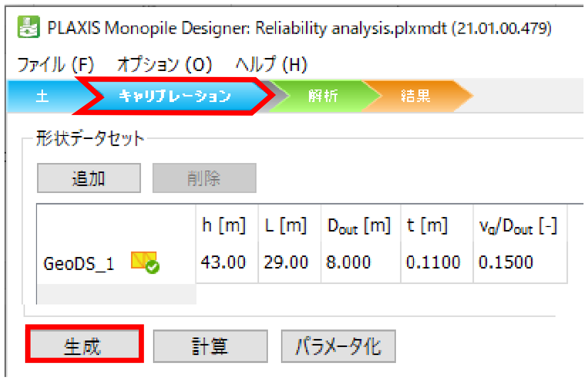
・ モノパイル基礎のモデル作成（Monopile Designer）

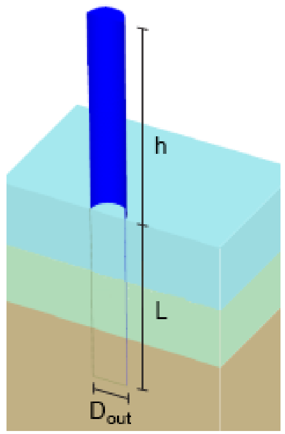
土モード



・ 材料タイプ（砂／粘土）
・ 土層（上面高／底面高）
・ 地盤材料（砂／粘土）

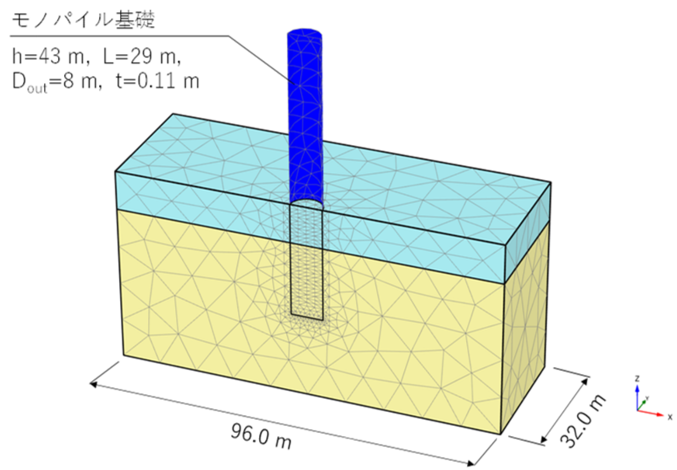
キャリブレーションモード





・ h　（海底より上）
・ L　（海底より下）
・ D_{out}（杭の外径）
・ t　（板厚）

不確かさを考慮したモノパイル基礎の解析事例



- Monopile Designerのモデル作成の仕様

【地盤のモデル】

- 1/2対称モデル
- X方向のモデルの幅：杭径の12倍
- Y方向のモデルの幅：杭径の 4倍
- モノパイル基礎の周辺（杭径の0.2倍の範囲）と底面（杭径の0.15倍の範囲）は細かく要素分割
- 砂の場合はHardening Soil model with small strain stiffness、粘土の場合はNGI-ADP

【モノパイル基礎のモデル】

- 地中に埋まる杭は高さ方向は約1mの間隔、円周方向は9分割（20°）で要素分割
- モノパイル基礎は板要素でモデル化（線形弾性体）
- 上端部は閉じられ、下端部は開口
- モノパイル基礎の側面（外側）と底面にインターフェース要素を設置

不確かさを考慮したモノパイル基礎の解析事例

- 地盤材料の不確かさを考慮するための確率変数

X		Parameter	Unit	μ	σ
Top layer	Soil Stiffness	G_{0ref}	kN/m^2	8.50E+04	5000
	Friction angle	ϕ'	°	32.5	2.5
Bottom layer	Soil Stiffness	G_{0ref}	kN/m^2	1.05E+05	5000
	Friction angle	ϕ'	°	37.5	2.5

- パラメータの相関 （ Hardening Soil model with small strain stiffness ）
  - $\mathrm{RD} = 100 \cdot (G_0^{ref} - 60000)/68000$ (%)
  - $E_{50}^{ref} = 60000 \cdot RD/100$ (kN/m^2)
  - $E_{oed}^{ref} = E_{50}^{ref}$ (kN/m^2)
  - $E_{ur}^{ref} = 3 \cdot E_{50}^{ref}$ (kN/m^2)
  - $\gamma_{0.7} = (2 - RD/100) \cdot 1\mathrm{E}\text{-}4$ (-)
  - $K_0^{NC} = 1 - \sin\varphi'$ (-)

不確かさを考慮したモノパイル基礎の解析事例

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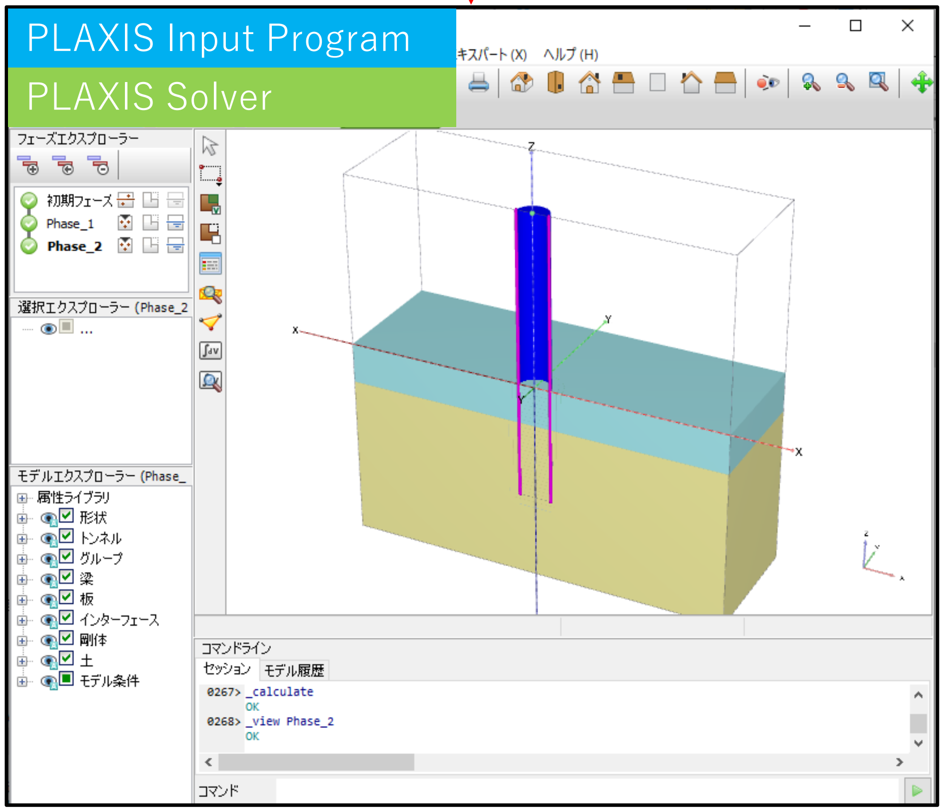
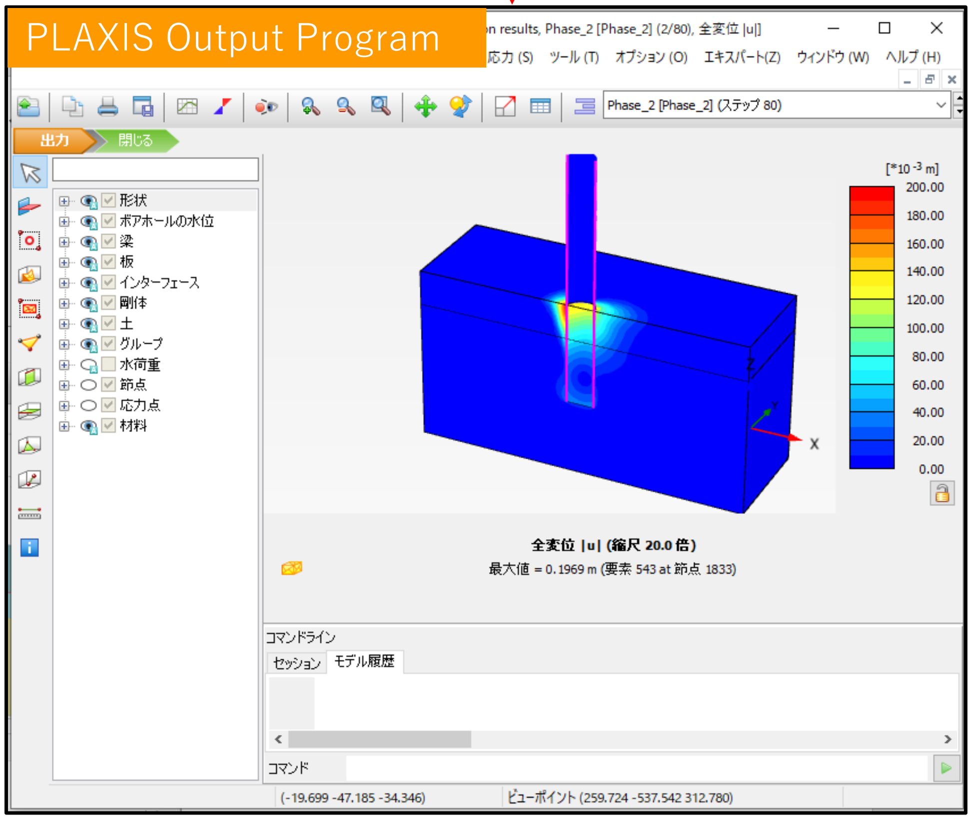
JIPテクノサイエンス株式会社

python™

- 起動命令
- 条件変更
- 解析実行命令
- 終了命令

- 起動命令
- 出力命令
- 終了命令





不確かさを考慮したモノパイル基礎の解析事例

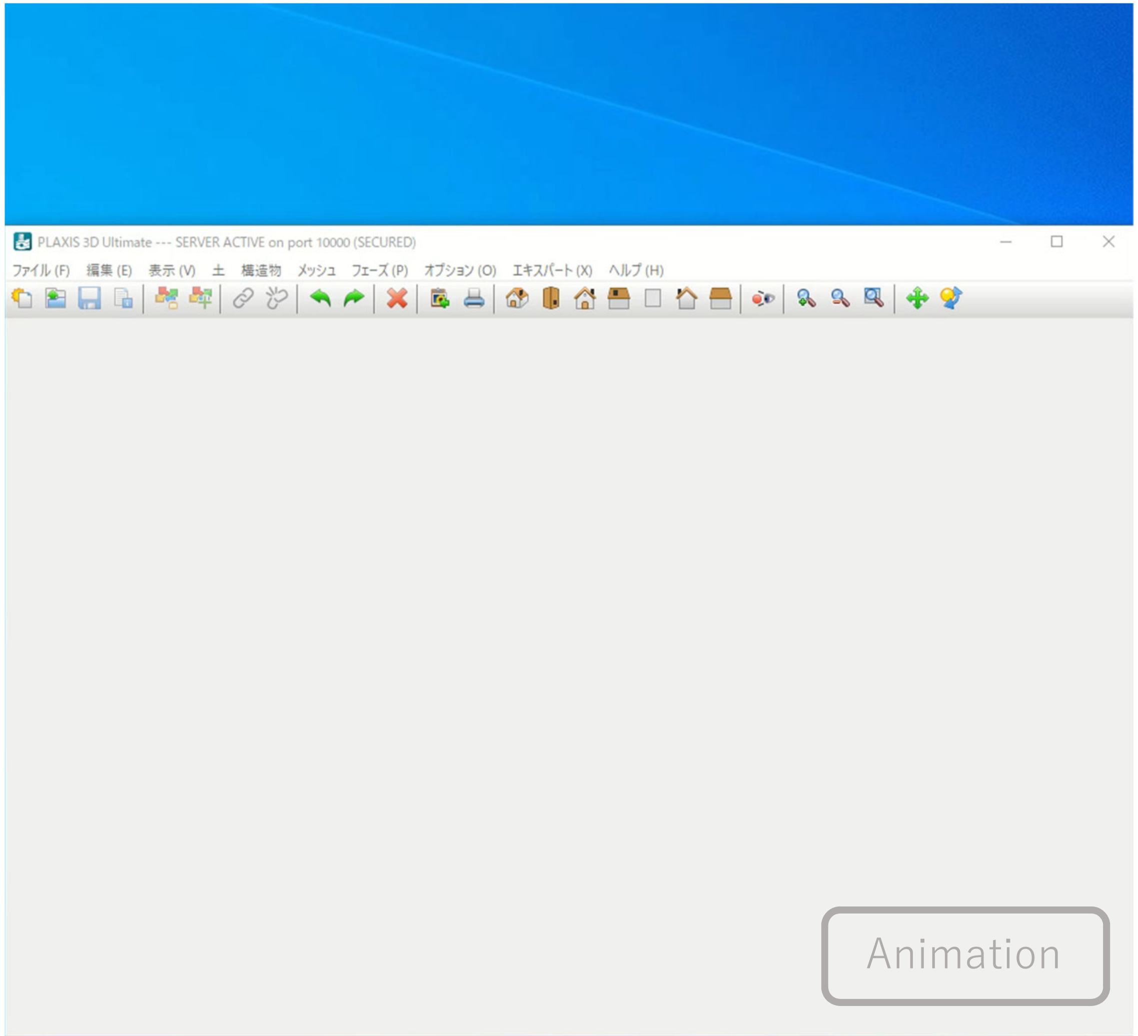
- Python スクリプトの実行状況

完全自動

- ファイルオープン
- パラメータ変更（CASE-1）
- 解析実行
- 出力プログラム起動
- 結果数値出力
- 出力プログラム終了
- パラメータ変更（CASE-2）

⋮

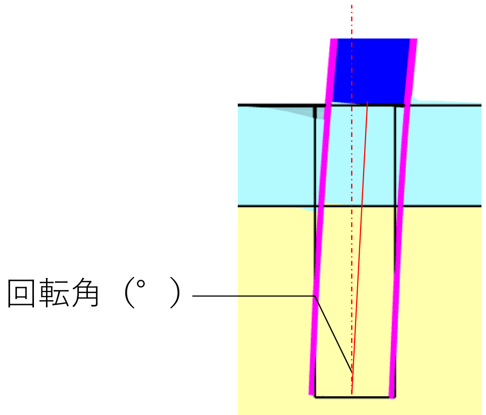
49ケースの実行



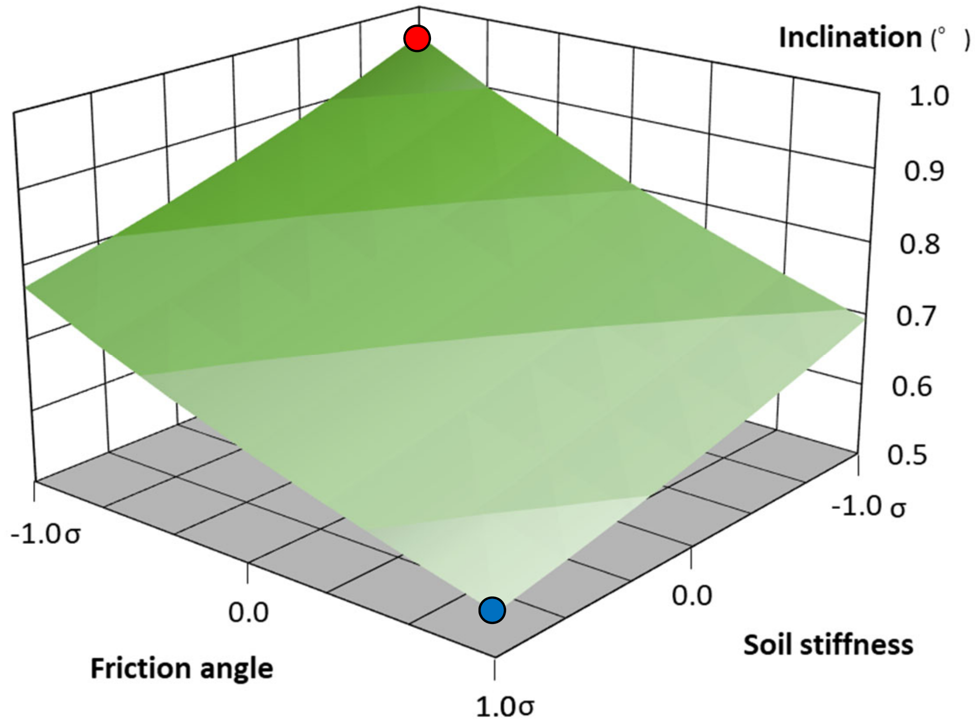
不確かさを考慮したモノパイル基礎の解析事例

・ モノパイルの回転角（解析結果一覧）

	G0ref	Soil stiffness						
φ'	σ	-1	-2/3	-1/3	0	+1/3	+2/3	+1
Friction angle	-1	0.958	0.919	0.884	0.852	0.822	0.795	0.770
	-2/3	0.902	0.865	0.832	0.802	0.774	0.748	0.725
	-1/3	0.851	0.817	0.786	0.757	0.731	0.707	0.684
	0	0.806	0.774	0.744	0.717	0.692	0.669	0.648
	+1/3	0.765	0.734	0.706	0.680	0.657	0.635	0.615
	+2/3	0.727	0.698	0.671	0.647	0.624	0.603	0.584
	+1	0.692	0.664	0.639	0.615	0.594	0.574	0.556

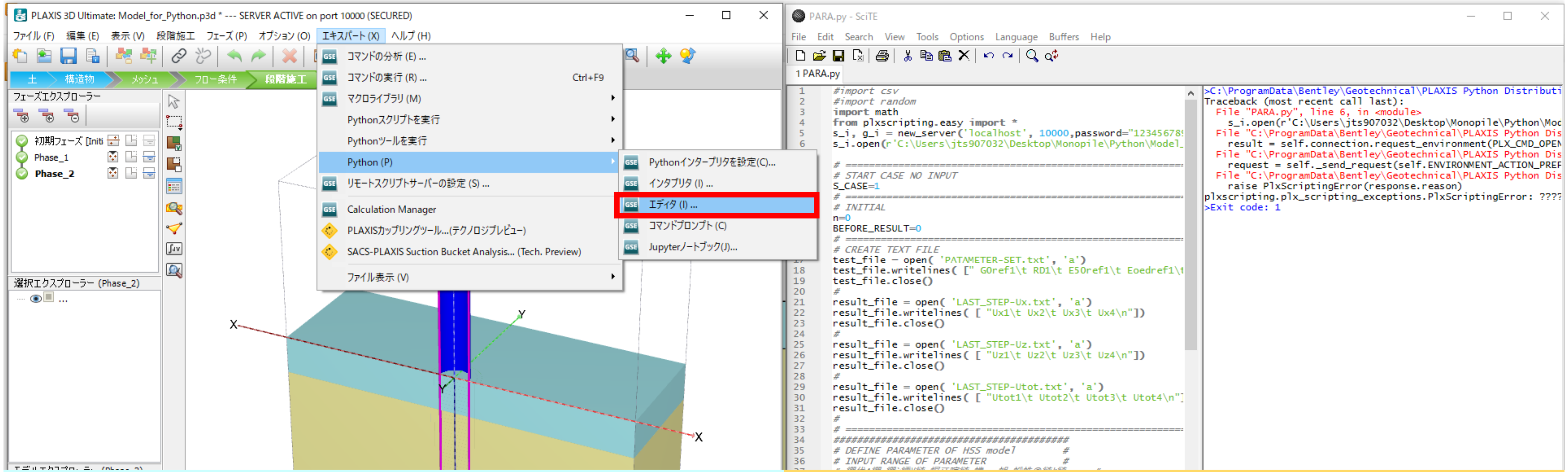


・ Response surface（応答値面）



不確かさを考慮したモノパイル基礎の解析事例

- Python スクリプトのコーディングと実行



PLAXIS 3D V21

SciTE（Scintilla based Text Editor）

ジャケット式＋サクションパイル基礎の解析事例

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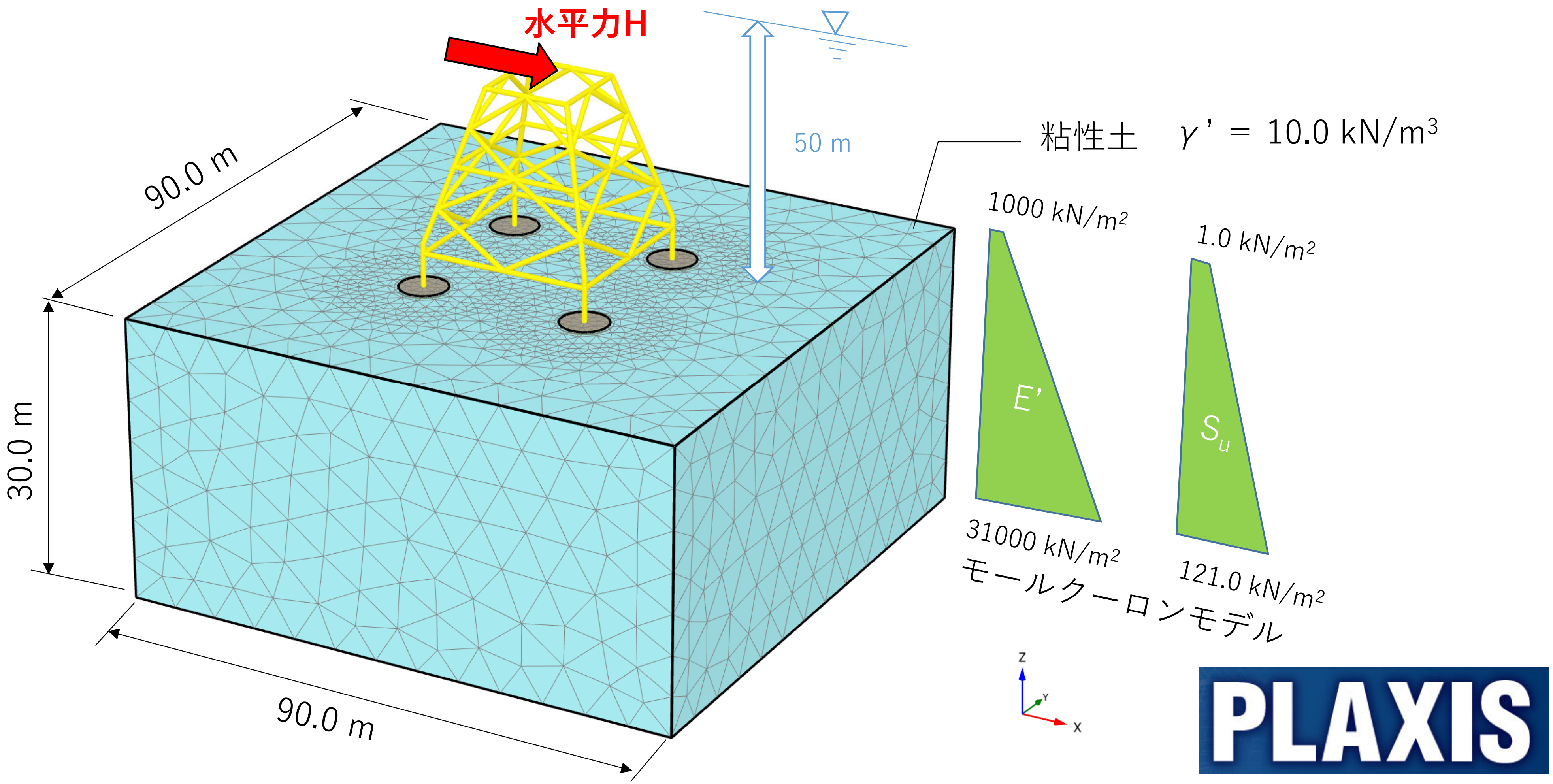
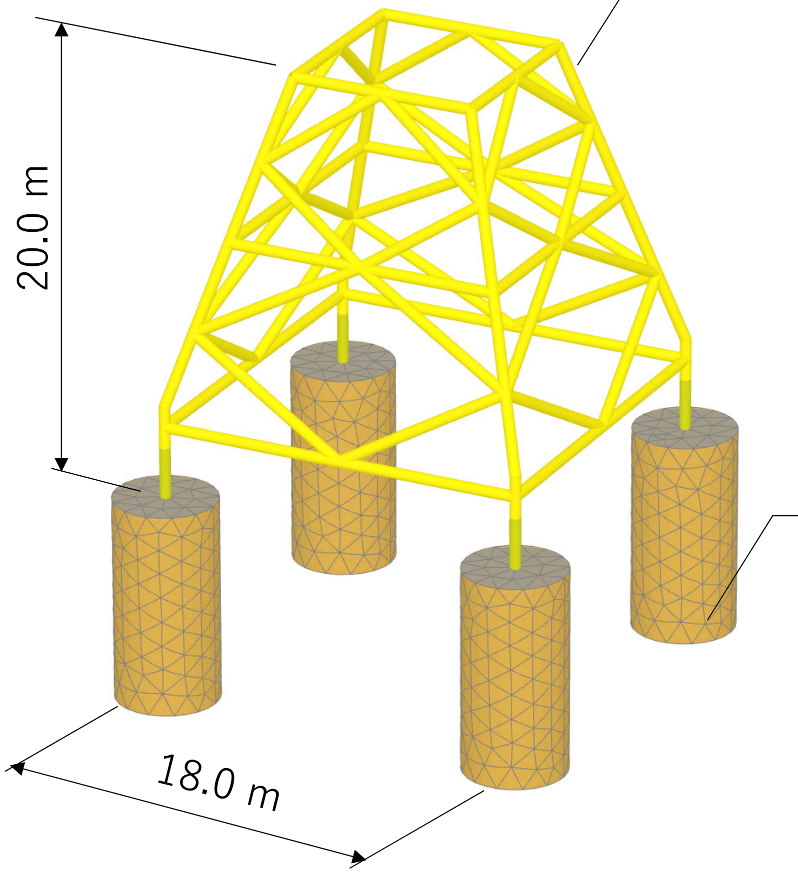


ジャケット式＋サクションパイル基礎の解析事例



鋼管（中空円形）

Beam要素でモデル化

	管径	板厚
CASE-1	750	100
CASE-2	1000	100
CASE-3	1500	100
CASE-4	2000	100

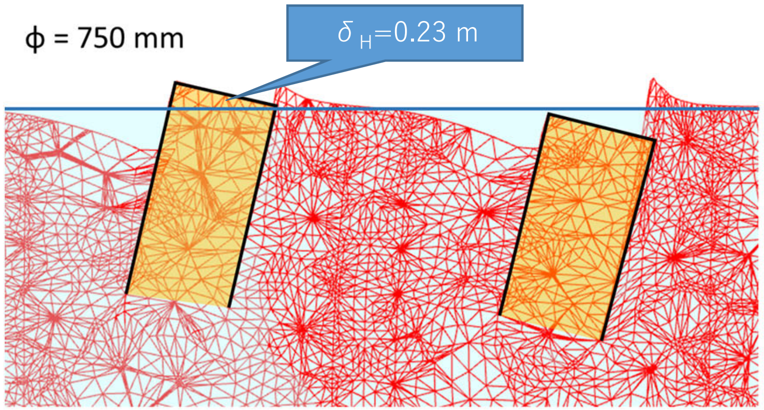
サクションパイル基礎部

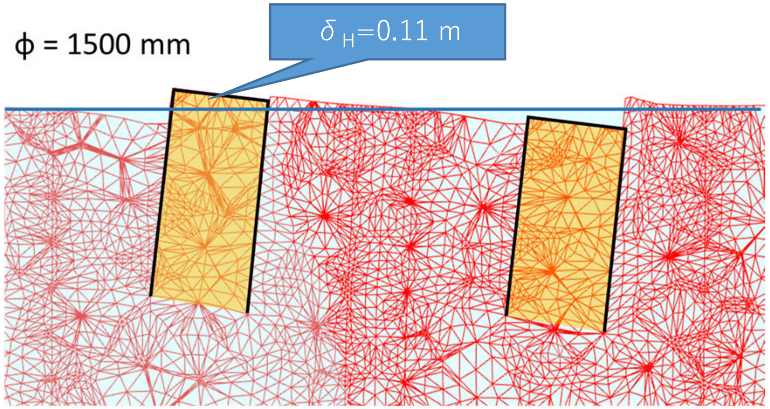
L=10 m，D=5 m，t=0.1 m

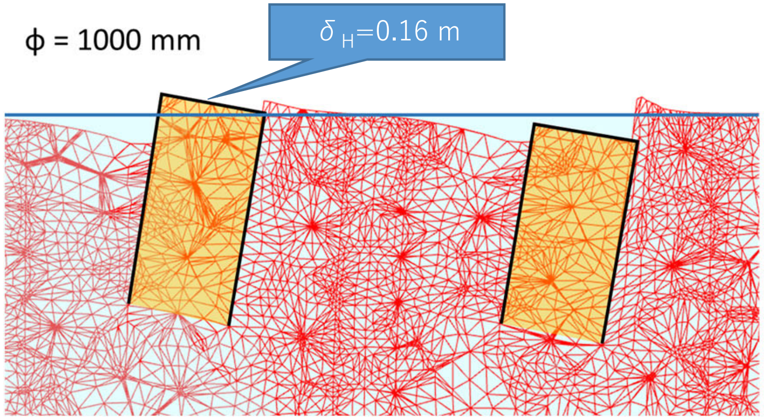
板要素でモデル化

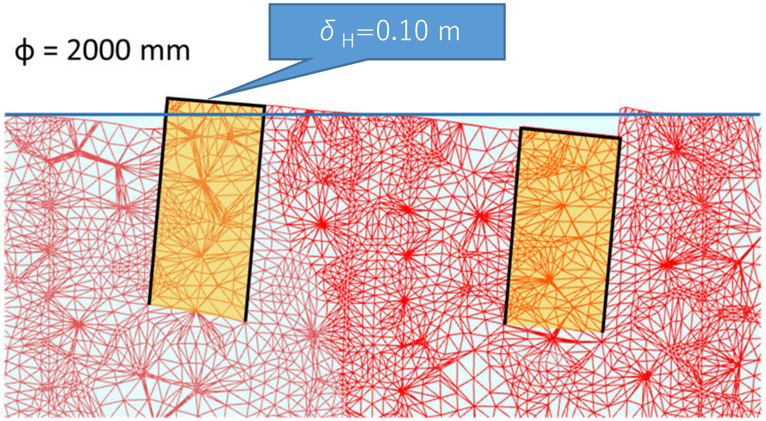
ジャケット式＋サクションパイル基礎の解析事例

・ 基礎の傾き



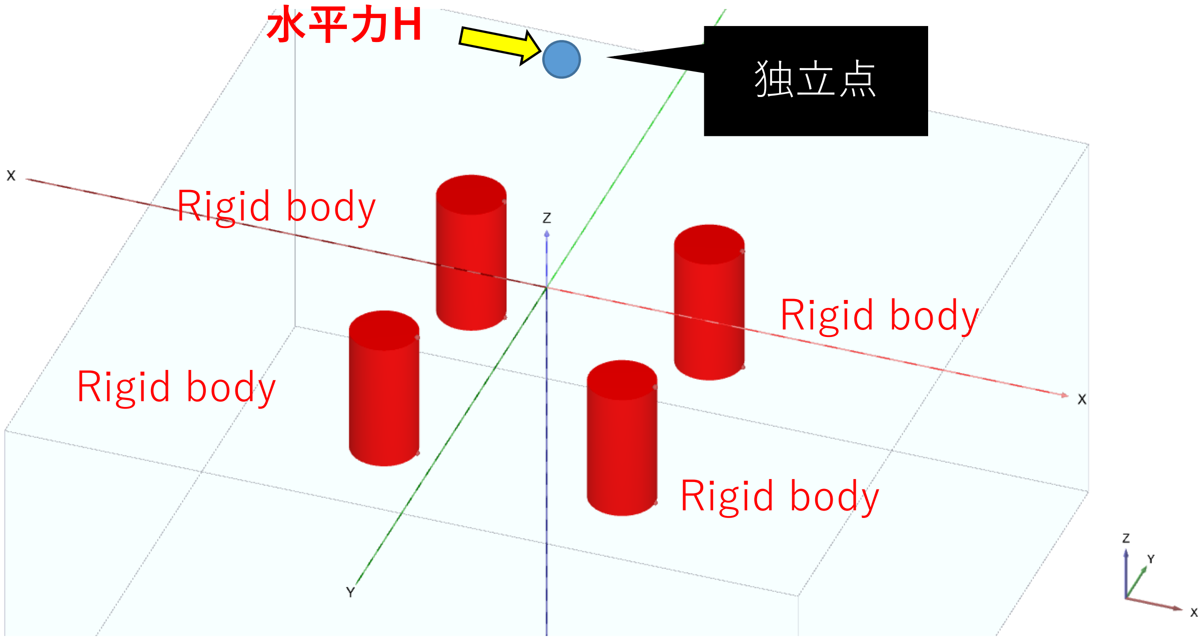




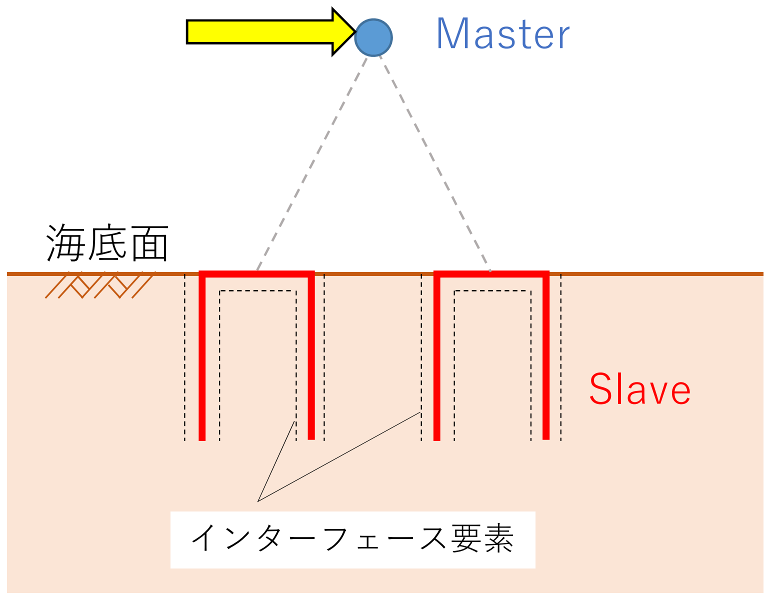


ジャケット式＋サクションパイル基礎の解析事例

- Rigid body（剛体要素）



荷重・強制変位



多点拘束条件 (Multi-point-constraint)

ジャケット式＋サクションパイル基礎の解析事例

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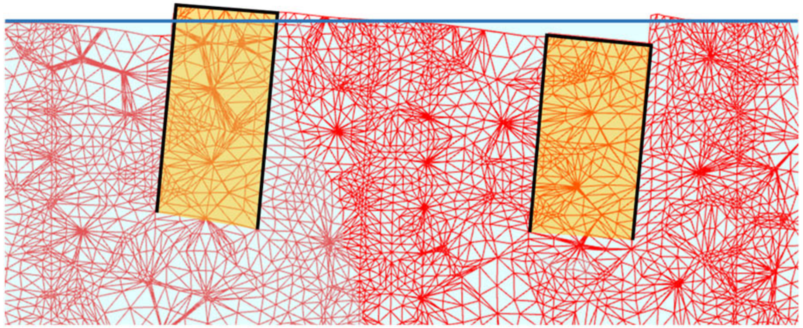
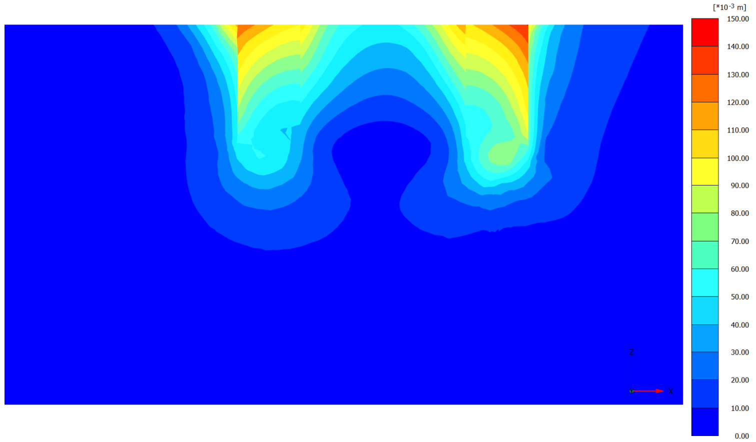
- Rigid bodyとの比較

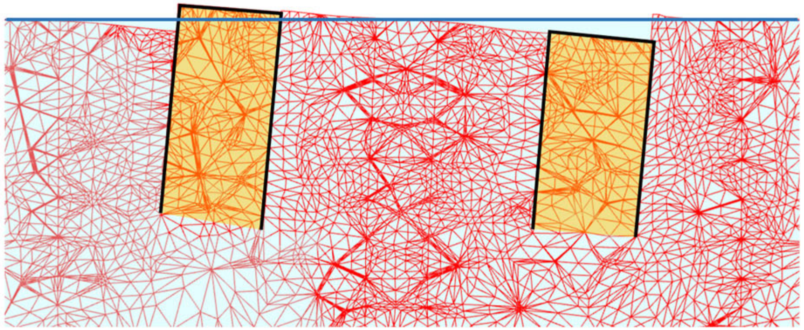
ϕ = 2000 mm

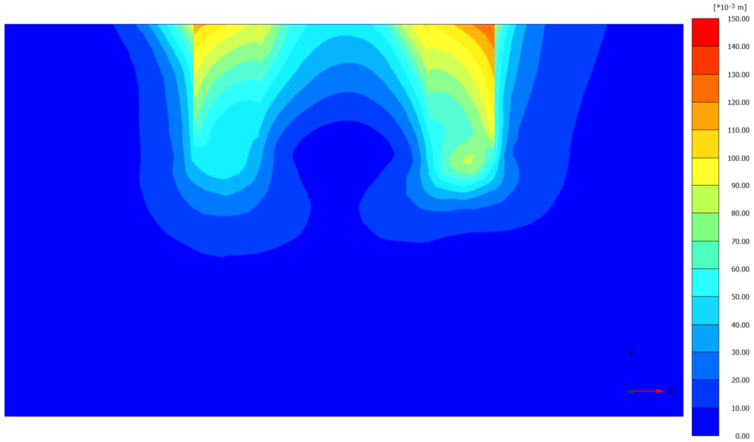




全変位 |u| (縮尺 20.0 倍)
最大値 = 0.1409 m

Rigid body



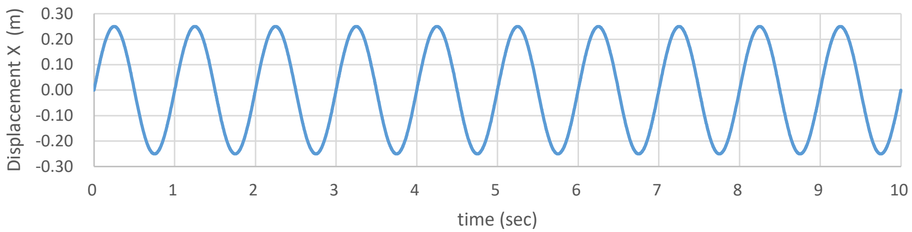


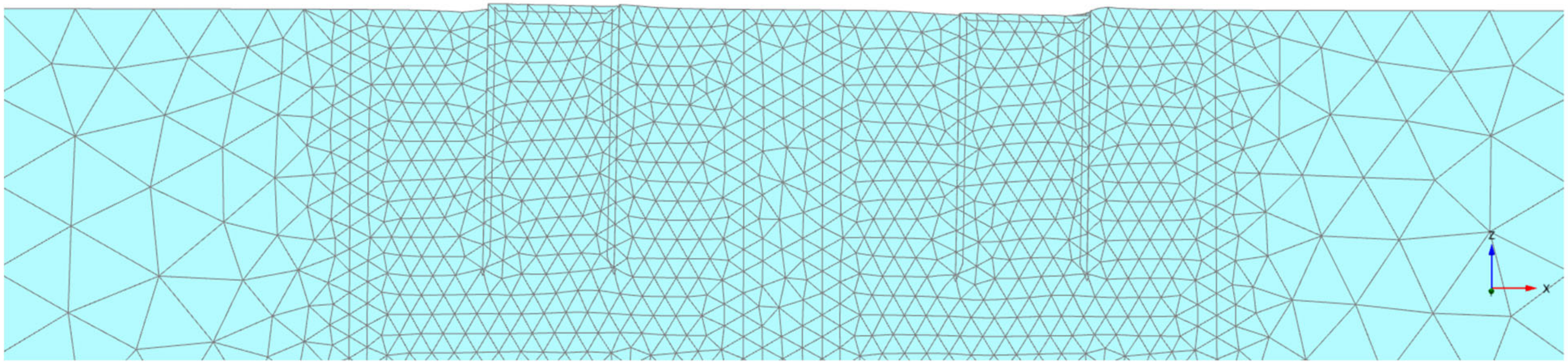
全変位 |u| (縮尺 10.0 倍)
最大値 = 0.1308 m

ジャケット式＋サクションパイル基礎の解析事例

- Rigid bodyを使用した動的解析

Master（調和関数：±0.25m）





杭頭変位