KARAKAS FRANÇAIS

ZSoil Day 2026

Digital twins of load tests for calibration of model parameters in ZSoil

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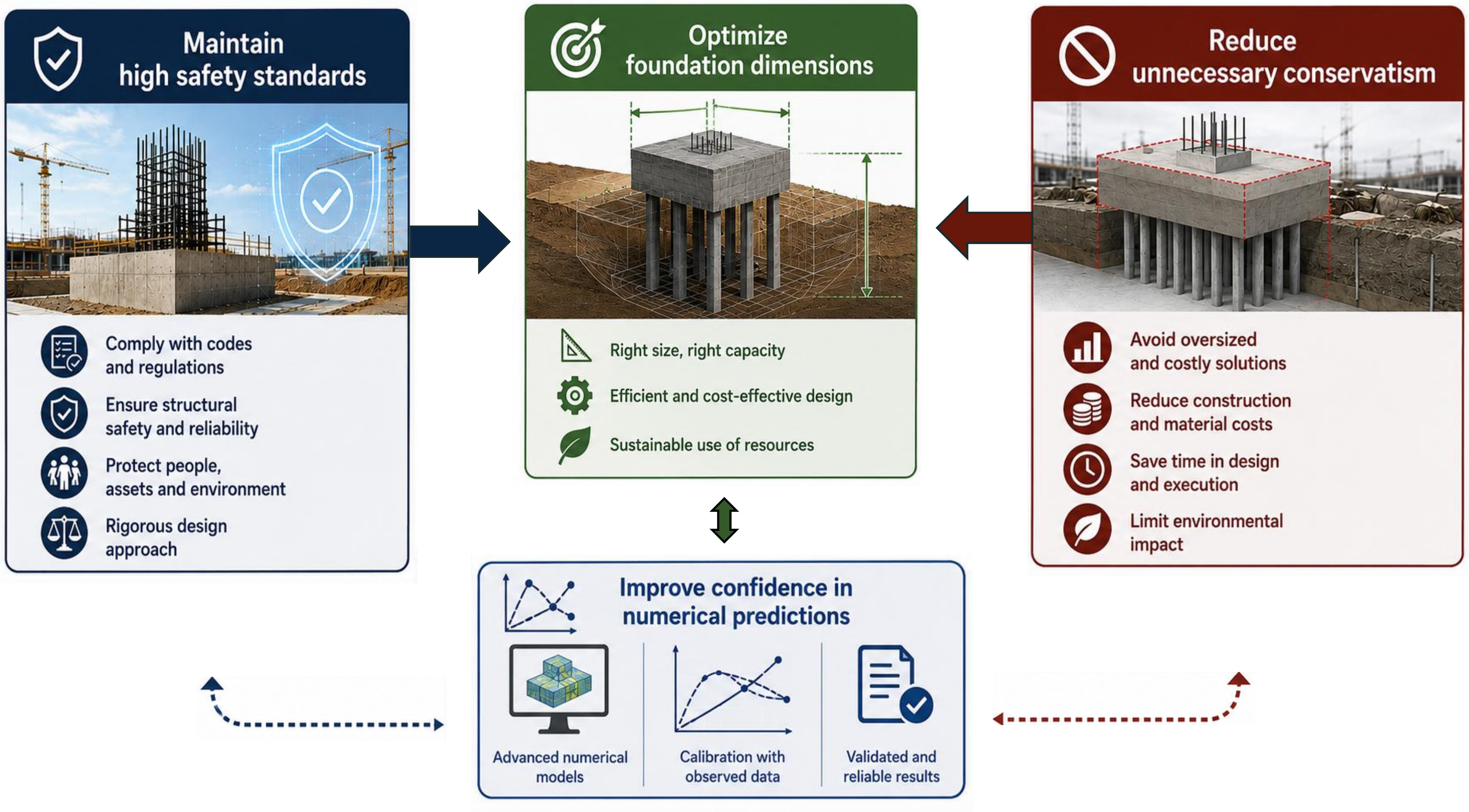
01 Context

Engineering in a cost-constrained world

Engineering challenges



Engineering challenges

- **Need to capture actual in-situ behaviour** → Field and Laboratory testing
- Need for precise knowledge of soil behaviour → Large scale in situ load tests
- Need for a better understanding of soil-structure interaction → Simulations

How can we make numerical models better reflect reality ? → ZSoil

02 Digital twins of load test concept

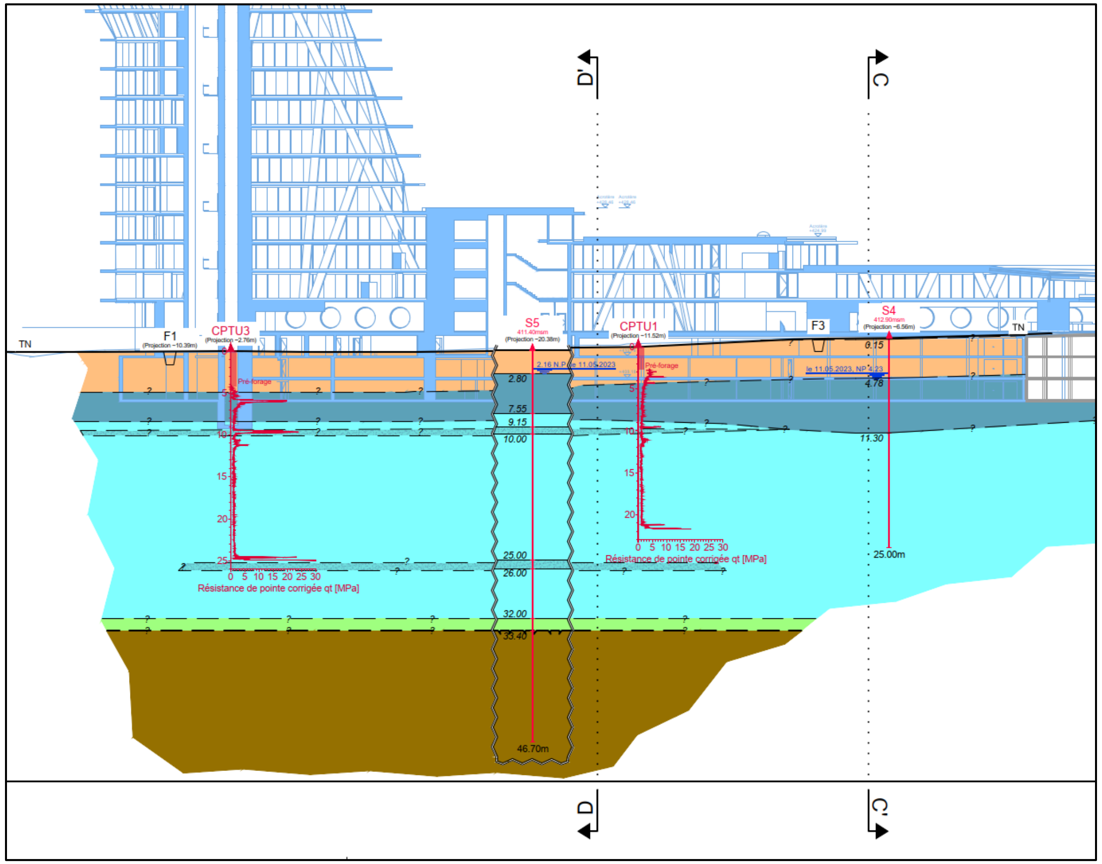
Site investigation

Main objectives of the site investigation

- Develop a representative geological model (*soil stratigraphy, layer boundaries and thicknesses*)

Close collaboration with geologists is essential

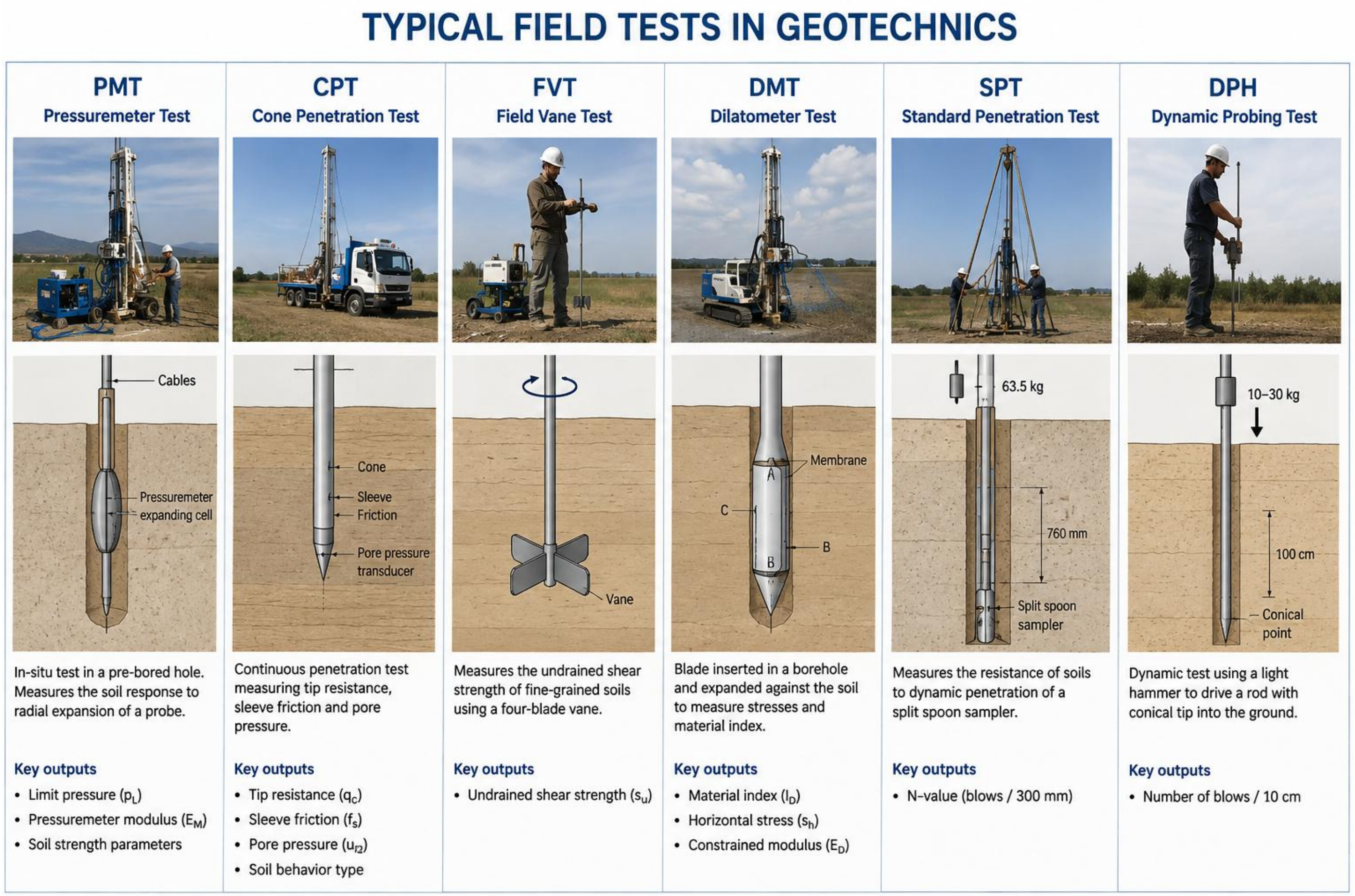
- Estimate initial constitutive model parameters for subsequent calibration



Swissquote III tower, Gland Switzerland

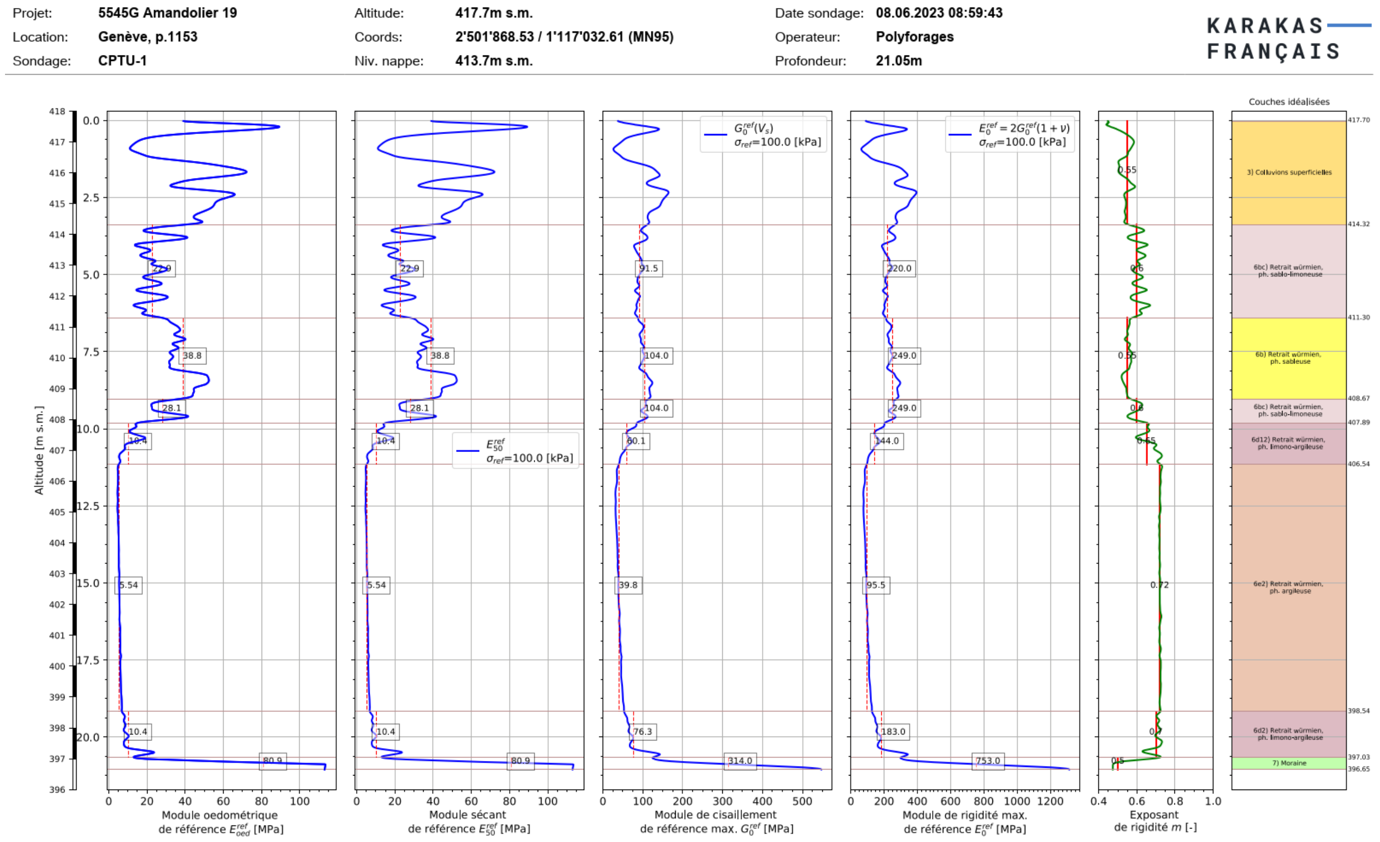
Site investigation

Typical field test in geotechnics



Site investigation

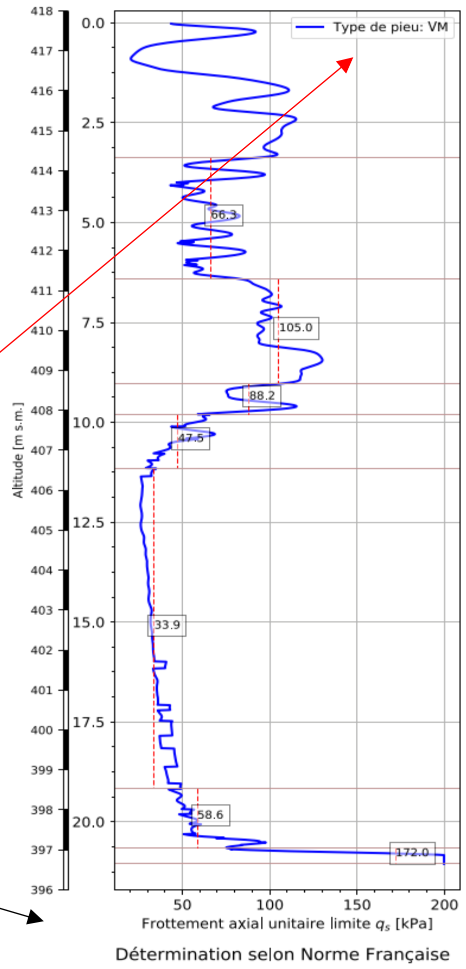
- **CPT/CPTu**
  - Direct measurements of cone tip resistance (q_c), sleeve friction (f_s) and pore pressure behind cone tip (u_2)
  - Dissipation test
  - SCPT
  - A variety of well-established empirical correlations for different soil characteristics (*Robertson, Lunne, etc.)*



Amandolier 19, Genève
Switzerland

Site investigation

- **CPT/CPTu**
  - Direct measurements of cone tip resistance (q_c), sleeve friction (f_s) and pore pressure behind cone tip (u_2)
  - Dissipation test
  - SCPT
  - A variety of well-established empirical correlations for different soil characteristics *(Robertson, Lunne, etc.)*
  - Estimation of unit shaft resistance -> installation method dependence



Screw (helical) pile (smartex)

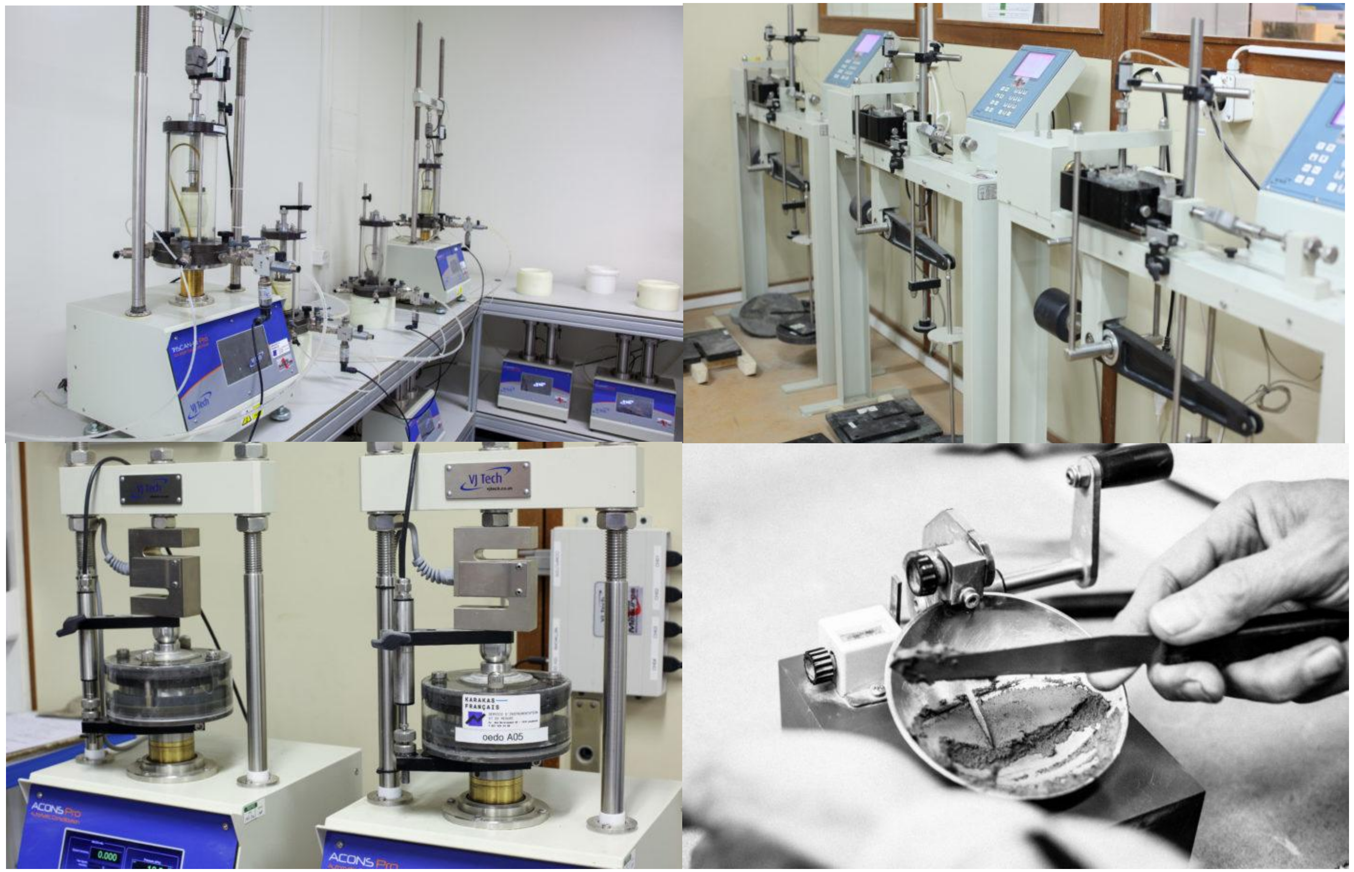
Site investigation

- **Collection of good quality undisturbed soil samples**
- **Laboratory tests**
  - Water content/unit weight
  - Grain size distribution
  - Atterberg limits
  - Oedometer
  - Direct shear test
  - Triaxial test

TransN, Couvet-Môtiers (NE), Switzerland

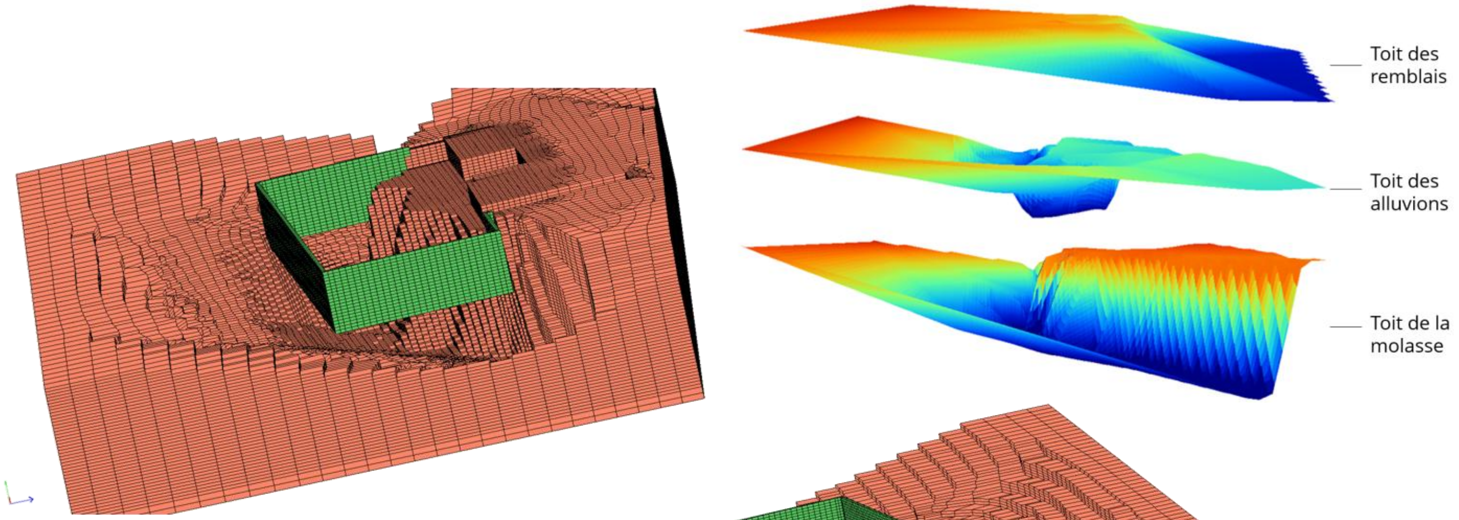
Site investigation

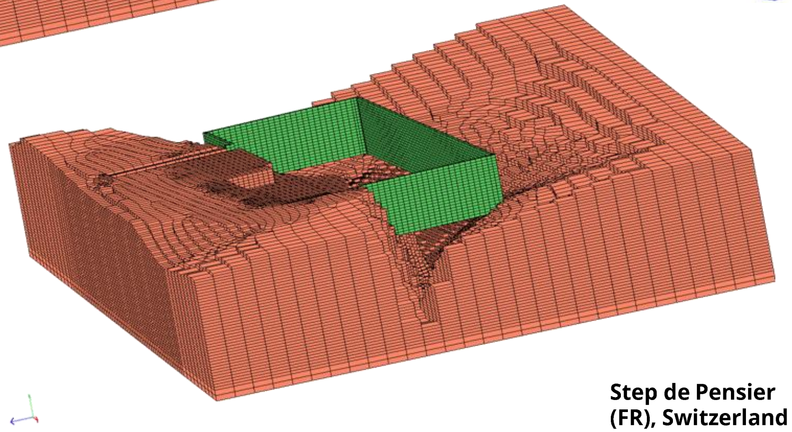
- **Laboratory tests**
  - Water content/unit weight
  - Grain size distribution
  - Atterberg limits
  - Oedometer
  - Direct shear test
  - Triaxial test



Site investigation

- **Geological model and initial constitutive parameter obtained**
  - Stratigraphy
  - Water table level





Step de Pensier (FR), Switzerland

Site investigation

- **Geological model and initial constitutive parameter obtained**
  - Stratigraphy
  - Water table level
  - Material parameter for the Hardening Soil Small-Strain model

Loi constitutive « Hardening Soil - small strain»

	Poids du sol	Poids du sol sec	Angle de frottement	Cohésion effective	Contrainte de référence	Module maximal (très petite déformation)	Module de décharge	Module sécant	Exposant pour la rigidité	Contrainte effective verticale de référence	Module œdométrique tangent	Surconsolidation
	γ	γ_D	ϕ	c'	σ_{ref}	E_0^{ref}	$E_{\mathrm{ur}}^{\mathrm{ref}}$	E_{50}^{ref}	m	$\sigma_{\mathrm{oed}}^{\mathrm{ref}}$	$E_{\mathrm{oed}}^{\mathrm{ref}}$	q_{pop} OCR
	[kN/m³]	[kN/m³]	[°]	[kPa]	[kPa]	[MPa]	[MPa]	[MPa]	[-]	[kPa]	[MPa]	[kPa] [-]
Remblais	20.5	19.5	28	1	100	100	30	10	0.5	188	10	80
GL-sableux	20.5	19.5	33	1	100	100	30	10	0.5	220	10	20
GL-argileux	20	15.6	25	5	100	50	25	5	0.8	173	5	20
Alluvions fluvio-glaciaires	21.5	19.3	35	0	100	140	60	20	0.5	234	20	20
Moraine aquatique	22	19.1	28	5	100	100	52	15	0.7	188	15	20
Moraine	22.5	20.3	30	15	100	200	120	30	0.7	200	30	2.5

Site investigation provides initial estimate of ground properties. How reliable are those initial estimates and how can we calibrate them ?

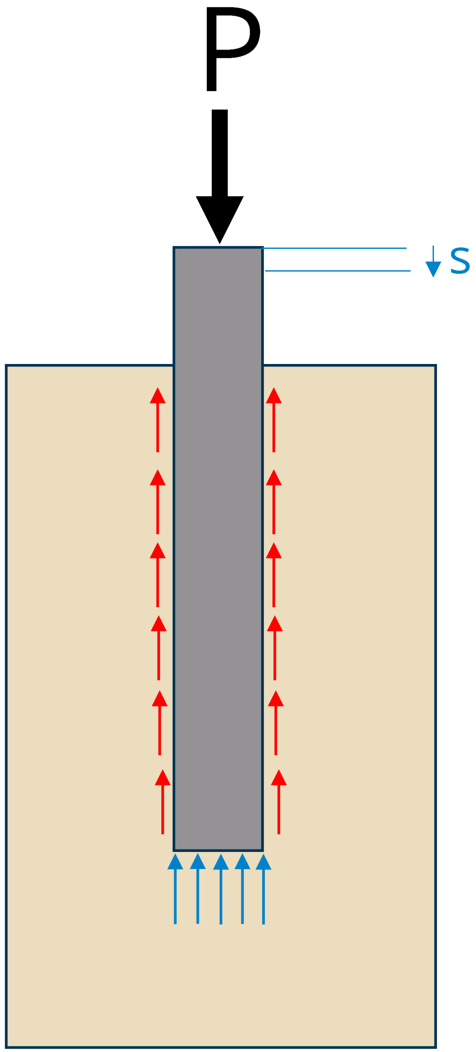
03 Digital twins of load test concept

Full-scale pile load test

Static load test

Principle

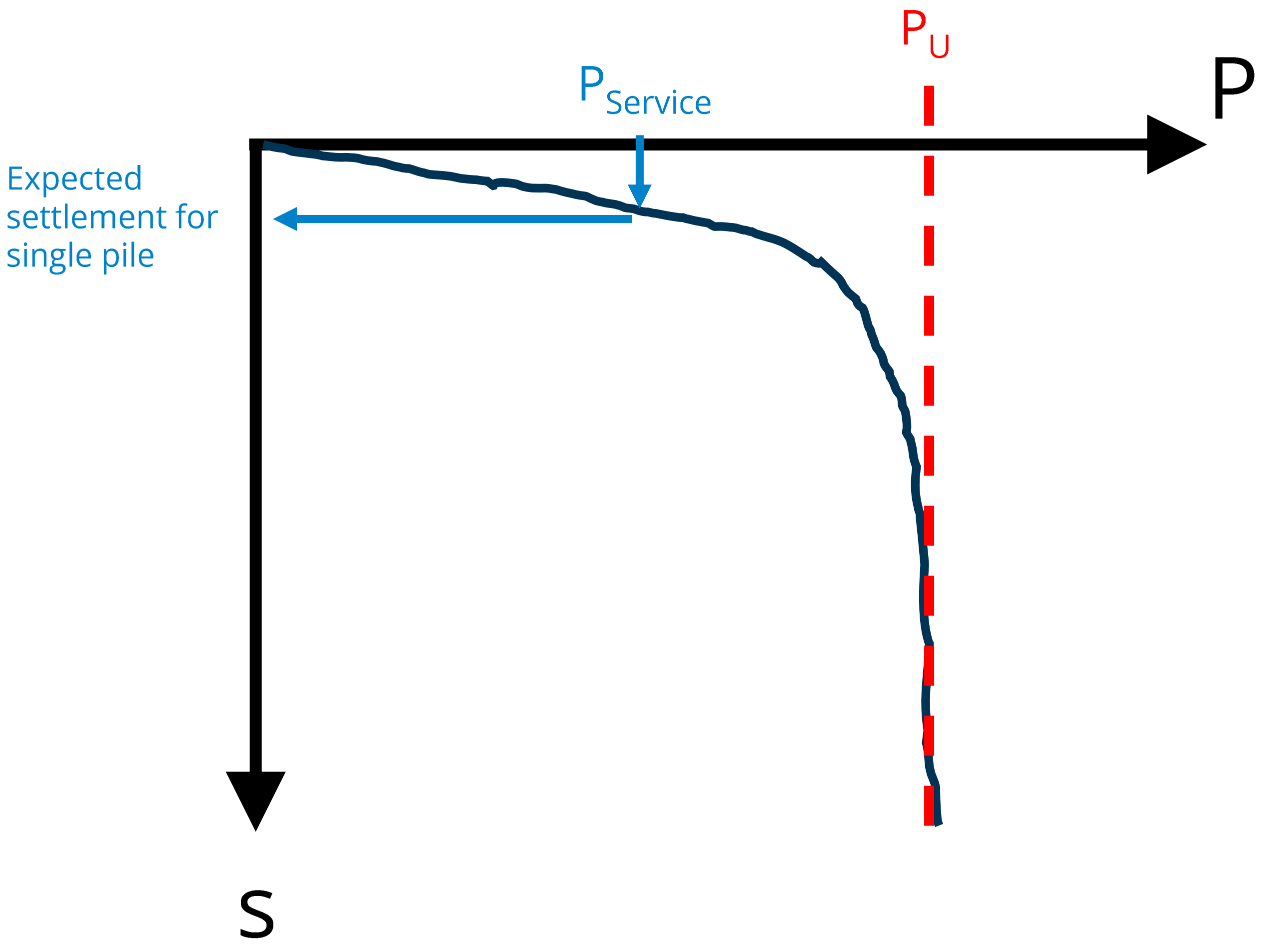
- Apply incremental axial load
- Measure corresponding pile head displacement
- Continue loading until target load or failure
- Unload pile and evaluate irreversible displacement



Static load test

Main results

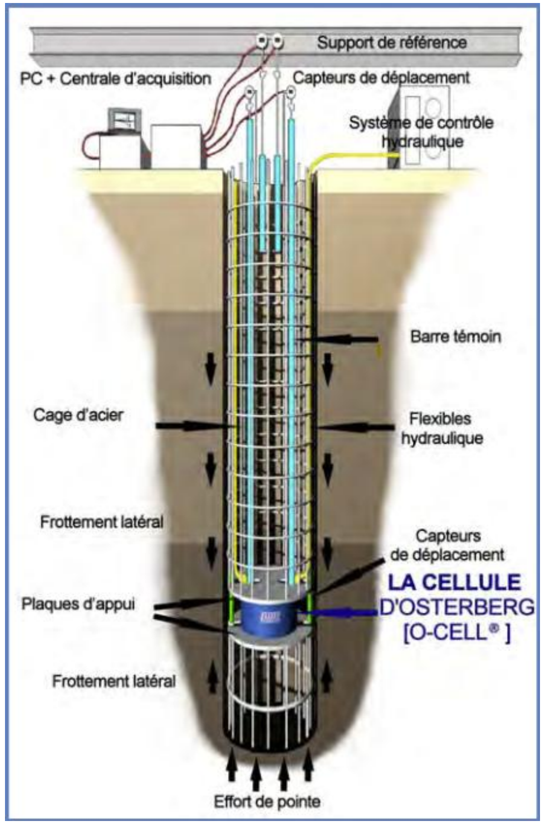
- Load settlement curve
- Serviceability behaviour
- Ultimate pile capacity



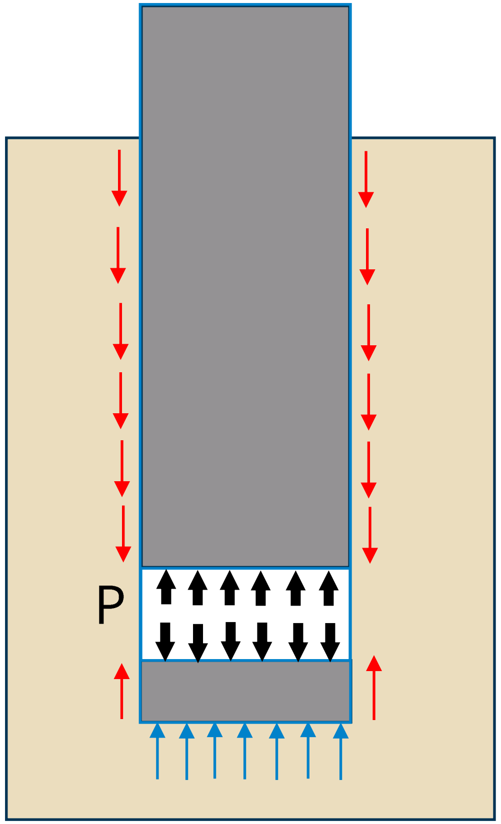
Bidirectional load Test (O-cell)

Principle

- Hydraulic Jack (O-Cell) inside the pile
- Application of equal and opposite forces
- Measure corresponding upward and downward displacement
- No external reaction needed



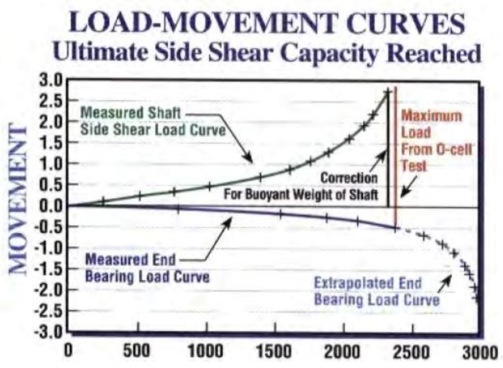
Fugro documentation

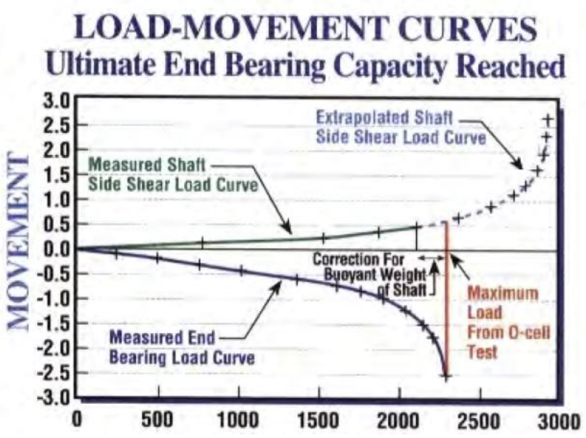


Bidirectional load Test (O-cell)

Main results

- Load displacement curve
- Shaft resistance distribution
- Base resistance
- Separation of shaft and base contribution





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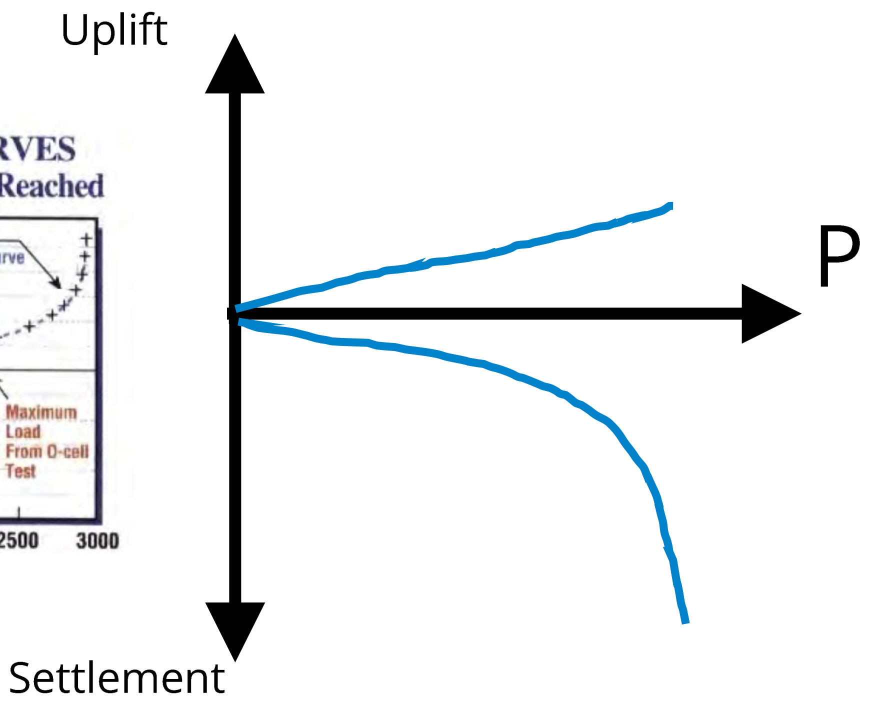


Dynamic load test

Principle of Pile Driver Analyser (PDA) - high-strain dynamic load testing of piles

- Stress wave generation by a hammer impact
- Strain gauges and accelerometers record the response
- CAPWAP back-analysis
- Estimation of static load-displacement behaviour

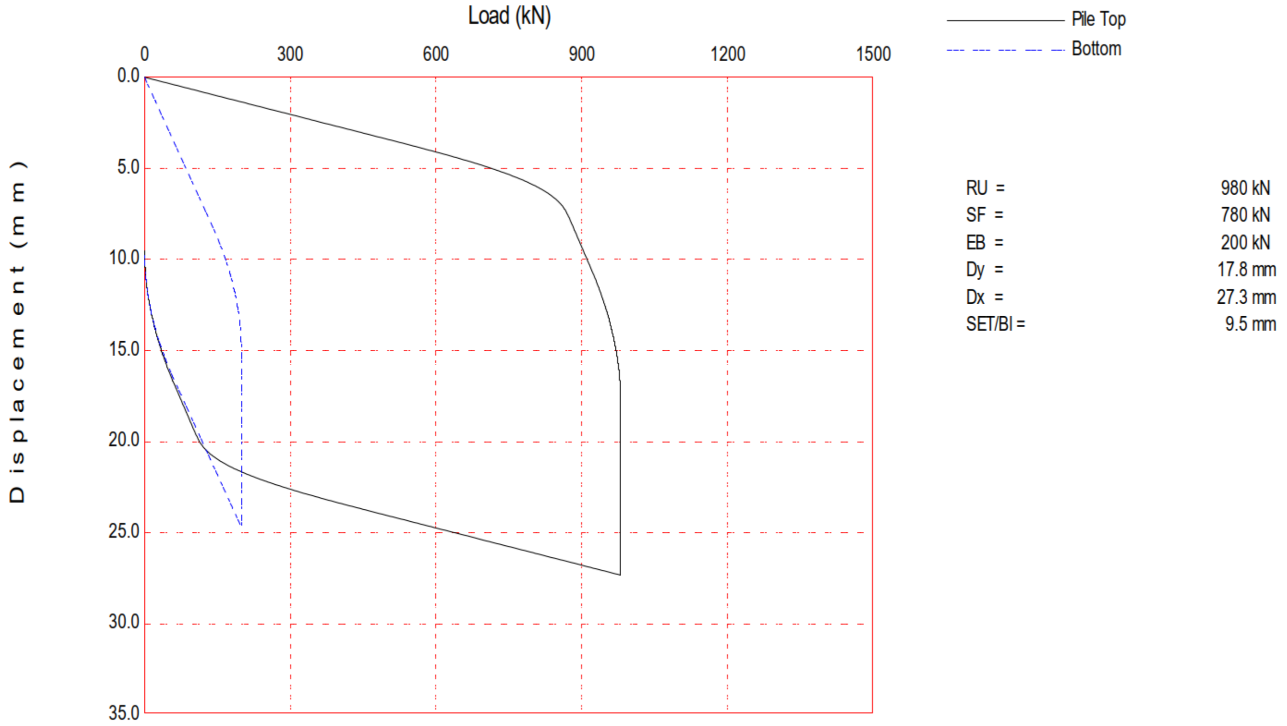
PDA on micropile (StreetBox Vallorbe, VD)

PDA installation (Amandolier, GE)

Dynamic load test

Main results

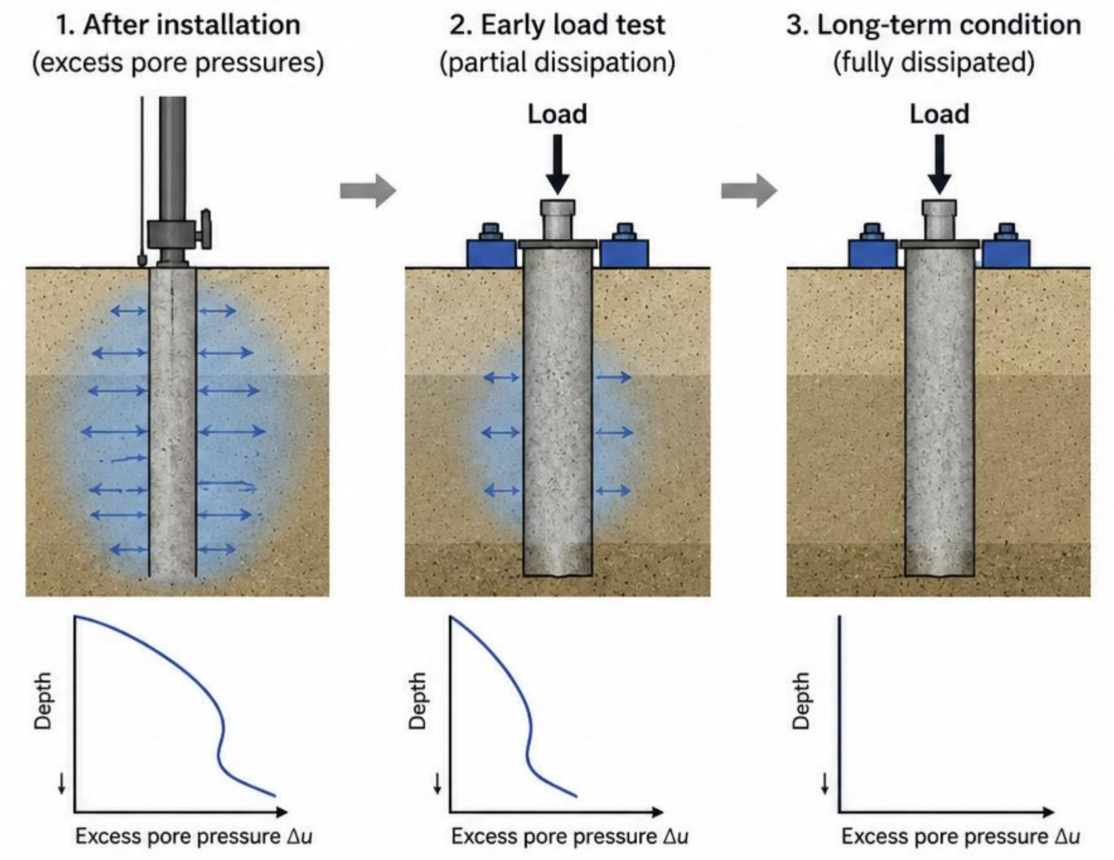
- Static behaviour response estimated using CAPWAP analysis
- Estimated ultimate pile capacity
- Shaft and base resistance



Load settlement curve obtained from CAPWAP analysis (Amandolier, GE)

Real life testing - Drawback

- Loads tests are often performed shortly after installation
- Excess pore pressures may not be fully dissipated in real time conditions
- Soil response may therefore be partially drained or undrained
- Measured behaviour may differ from the long-term drained response
- Test results must be interpreted considering **the installation-to-testing time**



04 Digital twins of load test concept

Digital twins development

From measurements to predictions

Field investigations → Soil conditions

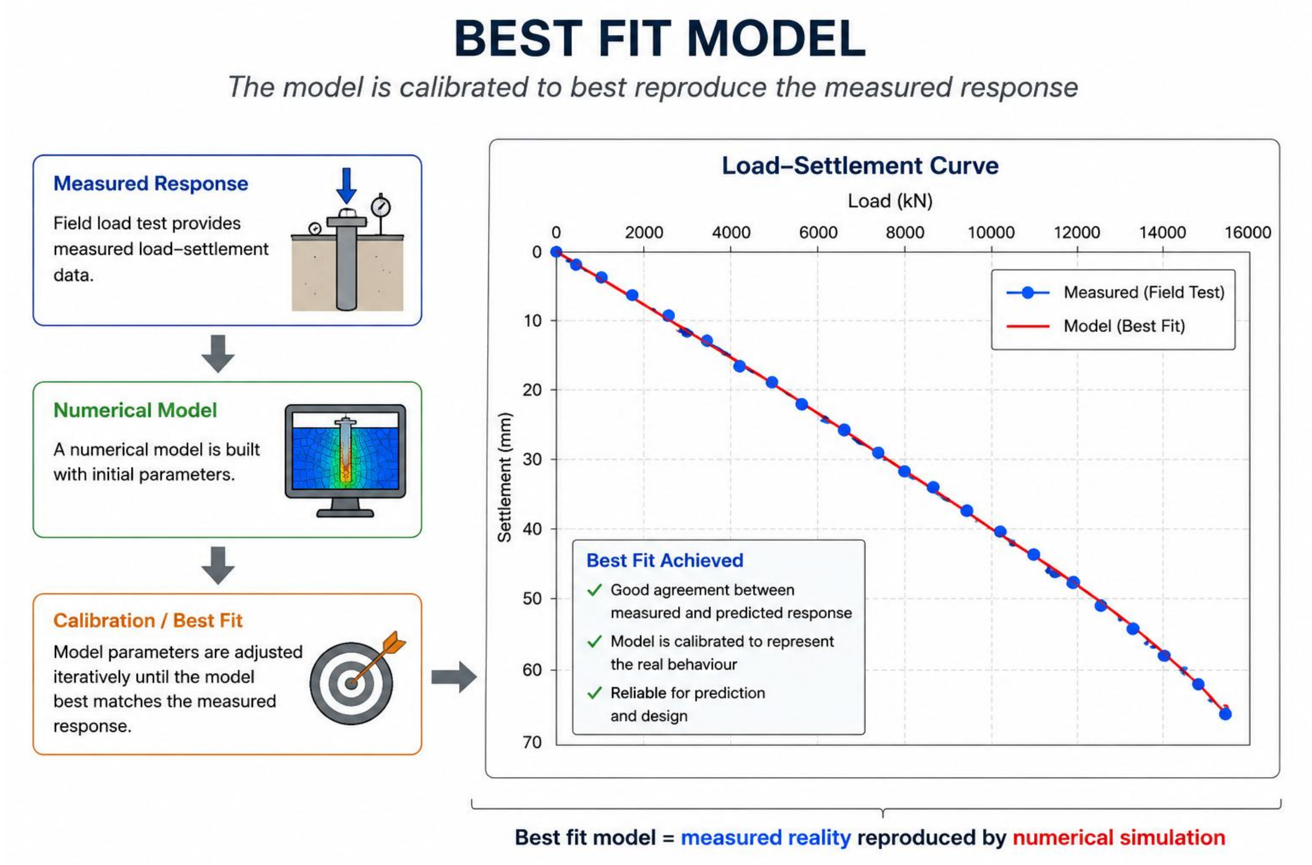
Full-Scale Load test → Real pile behaviour

How can we use measurements to improve the design of future foundations ? → ZSoil

Numerical model development

Main objectives

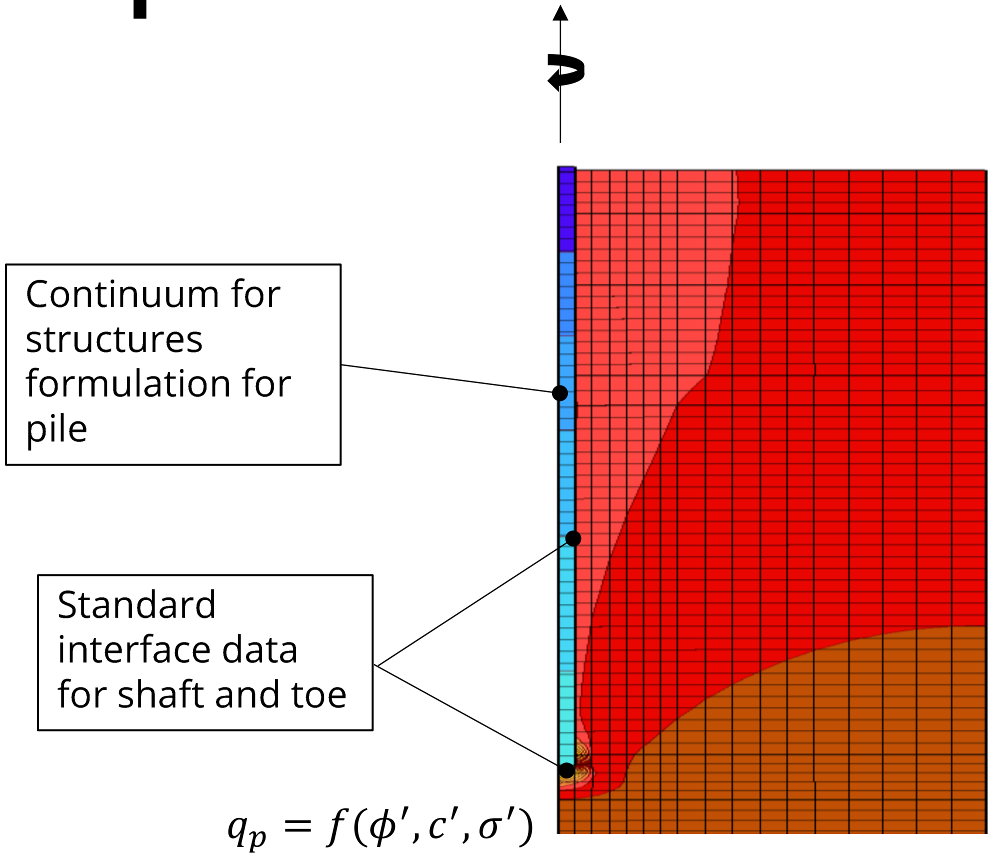
- Create a numerical model that reproduces the real test
- Construct a numerical Load-settlement curve and compare with the real curve obtained from the load test.
- Calibrate numerical model to get real behaviour **at test conditions**



Numerical model development

2D Axisymmetric model

- Explicit pile representation (continuum 2D)
- Very low computation time
- Can use fine mesh around the pile
- Well suited for static load test for for an isolated axially loaded pile
- Can be adapted easily to represent pile group behaviour if needed

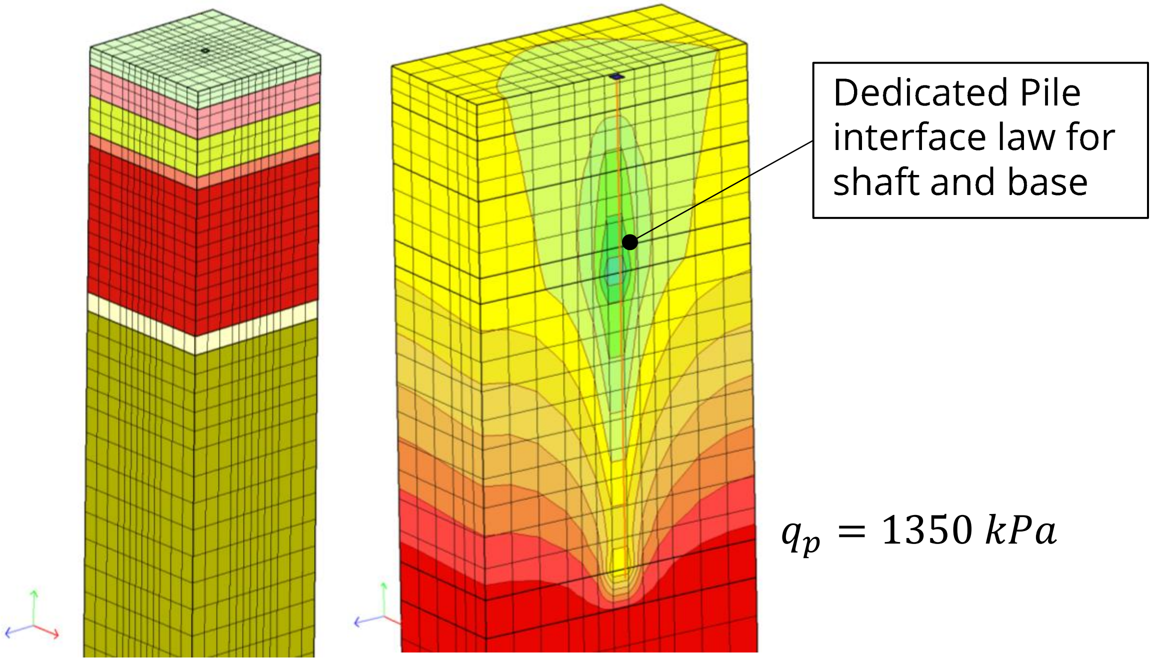


Numerical model development

3D Cell model with macro-pile

- Pile representation with macro-pile elements (1D embedded beam element within a 3D continuum soil model)
- 3D cell model used to calibrate the macro-pile response against the calibrated axisymmetric model with mesh size and discretization of full 3D model

Calibrate the macro-pile under numerical conditions **representative of its final use.**



Numerical model development

Unit shaft resistance consideration

Standard interface data -> 2D or 3D explicit pile formula

Pile interface data -> Macropile

Tables of scaling factors to cohesion, friction and dilatancy angles of adjacent continuum

Selected table: Pieu | Add table | Copy table | Delete table

Index	Material	Model	Active	Original continuum strength parameters			Standard Interface data			Piles interface data					Nails/Fixed anchor zone interface data
				Phi [deg]	c [kN/m^2]	Psi [deg]	tg(Phi) mult.	c mult.	tg(Psi) mult.	tg(Phi) mult.	c mult.	tg(Psi) mult.	Tensile bearing capacity qt [kN/m^2]	Compressive bearing capacity qc [kN/m^2]	Ultimate shear stress tau [kN/m^2]
1	6b Retrait sabl...	HS-small strai...	✓	32	1	2	0.8	0	0	0.6	0	0	0	1e+38	1e+38
2	6c2 Retrait lim...	HS-small strai...	✓	27.5	0	0	0.8	0	0	0.6	0	0	0	1e+38	1e+38
3	6d2 Retrait lim...	HS-small strai...	✓	27	2	0	0.8	0	0	0.6	0	0	0	1e+38	1e+38
4	6e2 Retrait ar...	HS-small strai...	✓	25	4	0	0.8	0	0	0.6	0	0	0	1e+38	1e+38
5	6e2 Retrait ar...	HS-small strai...	✓	27	5	0	0.8	0	0	0.6	0	0	0	1e+38	1e+38
6	6e12 Retrait ar...	HS-small strai...	✓	28	7	0	0.8	0	0	0.6	0	0	0	1e+38	1e+38
7	7c1 Moraine li...	HS-small strai...	✓	33	15	3	0.8	0	0	0.6	0	0	0	1e+38	1e+38
8	No name	Elastic	✓	40	0	0	0.8	0	0	0.6	0	0	0	1e+38	1e+38
11	Pieu	Elastic Structure	✓	40	0	0	0.8	0	0	0.6	0	0	0	1e+38	1e+38
13	verin	Elastic	✓	40	0	0	0.8	0	0	0.6	0	0	0	1e+38	1e+38

Numerical model development

Unit shaft resistance q_s consideration

Tables of scaling factors to cohesion, friction and dilatancy angles of adjacent continuum

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Index	Material	Model	Active	Original continuum strength parameters Phi [deg]	c [kN/m^2]	Psi [deg]	Standard Interface data tg(Phi) mult.	c mult.	tg(Psi) mult.
1	6b Retrait sabl...	HS-small strai...	✓	32	1	2	0.8	0	0
2	6c2 Retrait lim...	HS-small strai...	✓	27.5	0	0	0.8	0	0
3	6d2 Retrait lim...	HS-small strai...	✓	27	2	0	0.8	0	0
4	6e2 Retrait ar...	HS-small strai...	✓	25	4	0	0.8	0	0
5	6e2 Retrait ar...	HS-small strai...	✓	27	5	0	0.8	0	0
6	6e12 Retrait ar...	HS-small strai...	✓	28	7	0	0.8	0	0
7	7c1 Moraine li...	HS-small strai...	✓	33	15	3	0.8	0	0
8	No name	Elastic	✓	40	0	0	0.8	0	0
11	Pieu	Elastic Structure	✓	40	0	0	0.8	0	0
13	verin	Elastic	✓	40	0	0	0.8	0	0

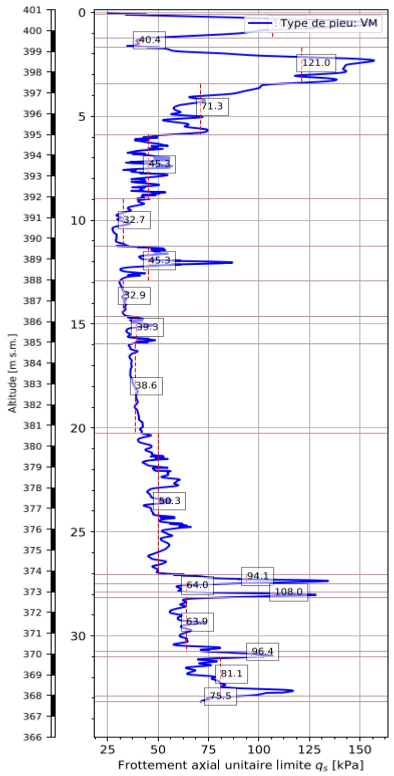
Use of an interface friction coefficient

Direct q_s values from CPTu use

Direct consideration of the pile execution technology

Détermination selon Norme Française

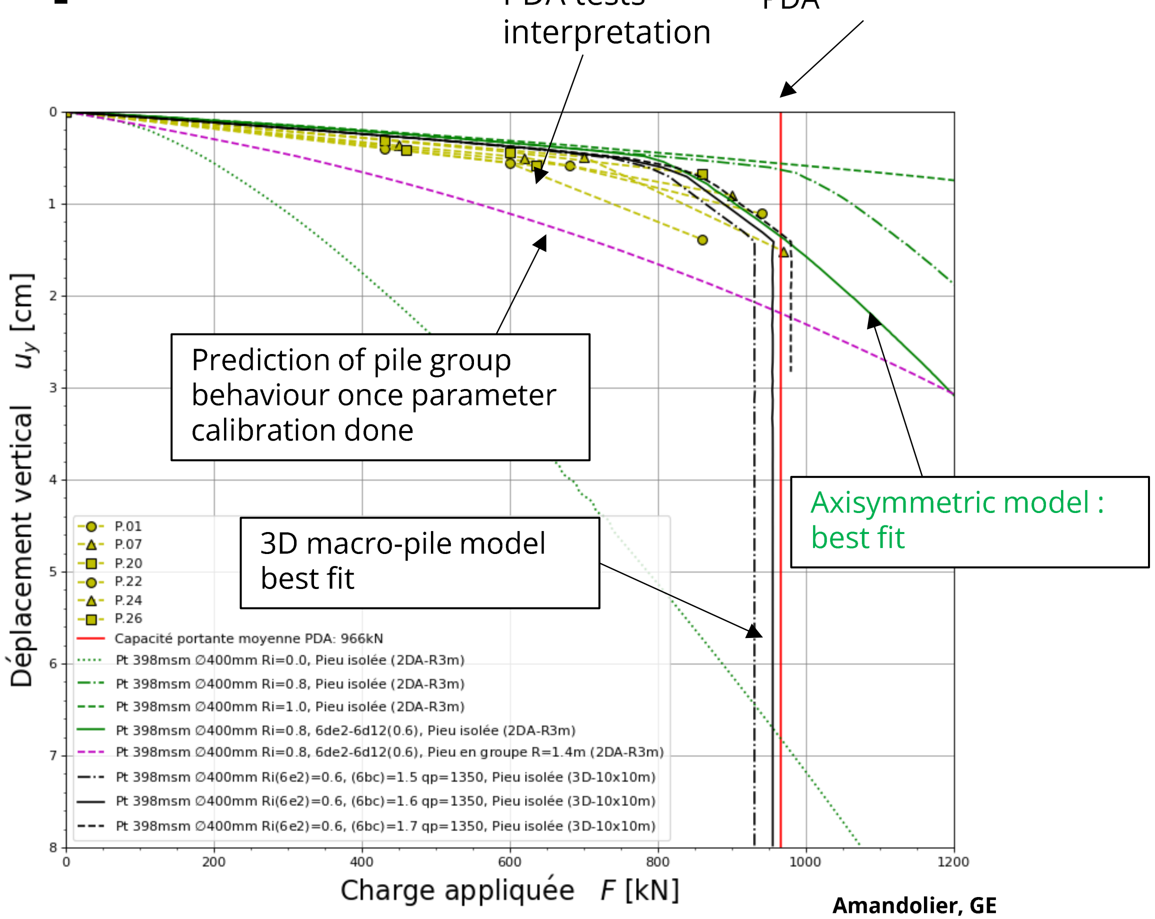
1-FS: Foré simple
1-FB: Foré boue
1-FTP: Foré tubé (virole perdue)
1-FTR: Foré tubé (virole récupérée)
1-FSR, FBR, PU: FS,FB rainurage ou puits
2-FTC, FTCD: Foré tarrière creuse
3-VM: Vissé moulé
3-VT: Vissé tubé
4-BPF, BPR: Battu bét. préfa. ou précontr.
4-BE: Battu enrobé
4-BM: Battu moulé
4-BAF: Battu acier fermé
5-BAO: Battu acier ouvert
6-HB: Profilé H battu
6-HBi: Profilé H battu injecté



Numerical model development

➡ Digital Twins model obtention

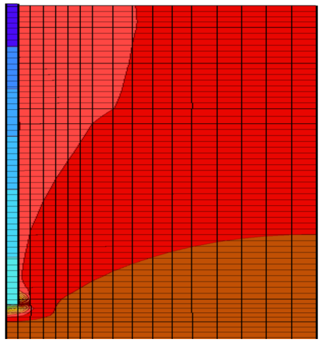
➡ Real behaviour caught by model – Project optimization



Amandolier, GE

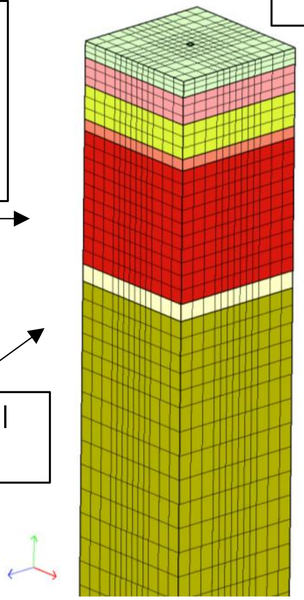
From load test to full 3D prediction

2D Model



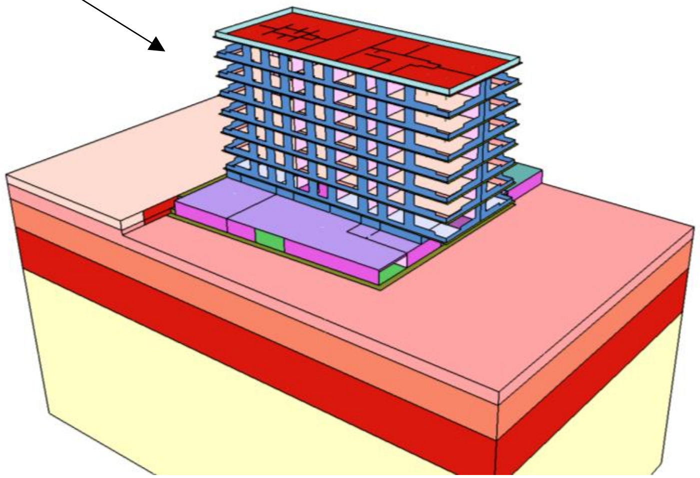
Calibrate macro-pile response to the 2D axisymmetric model
Interface law calibration
$\tau_f = \sigma_n \cdot \mathrm{R}_{i,2} \tan(\phi_{soil})$

Macro Pile in 3D cell model



Prediction of real behaviour

Macro piles in full 3D model



Soil parameter calibration
Calibrate soil and interface parameters to match real load test
Interface law calibration
$\tau_f = \sigma_n \cdot \mathrm{R}_{i,1} \tan(\phi_{soil})$

Verification with real load test

Full scale pile load test

05 Digital twins of load test concept

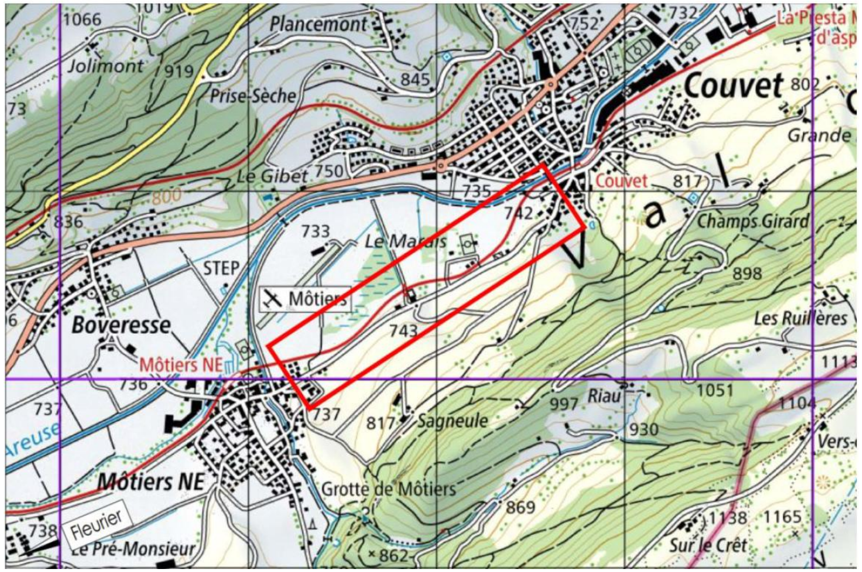
Cases studies

Couvet–Motier Railway Line – Railway Infrastructure Renewal

Project context

- Existing obsolete railway line between Couvet and Môtiers (NE)
- Railway founded on very soft marsh deposits and peat
- Significant track deformations and **high maintenance requirements**
- Major instability observed after the heavy rainfall of summer 2021
- Railway operation and speed subsequently restricted due to track instability

Neuchâtel



Buttes

Couvet–Motier Railway Line – Railway Infrastructure Renewal

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- Railway founded on very soft marsh deposits and peat
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- Major instability observed after the heavy rainfall of summer 2021
- Railway operation and speed subsequently restricted due to track instability

Need for a **global rehabilitation and ground improvement solution**

Couvet–Motier Railway Line – Railway Infrastructure Renewal

Project context

- Sensitive environmental context : nationally protected peatland
- Main challenge: improve track stability while preserving groundwater flow and the natural hydrological regime
- Floating Stone columns ($\emptyset\ 800\ mm$) selected by the project designer as the ground improvement solution
- Karakas & Français appointed as independent geotechnical expert to assess and validate the proposed solutions

Couvet–Motier Railway Line – Railway Infrastructure Renewal

Why a full-scale load test ?

- **Unusual ground conditions**: very soft peat and marsh deposits
- **Limited experience** with stone columns in such soft soils
- **Significant uncertainties** regarding soil–column interaction and deformation behaviour
- Need to verify the feasibility and performance of the proposed ground improvement solution
- **Validate** the stone-column layout and design assumptions under representative field conditions
- **Provide reliable field measurements** for finite element model calibration
- **Increase confidence** before implementation along the entire railway section (1.7 km)

Couvet–Motier Railway Line – Railway Infrastructure Renewal

Site investigation – CPTu tests

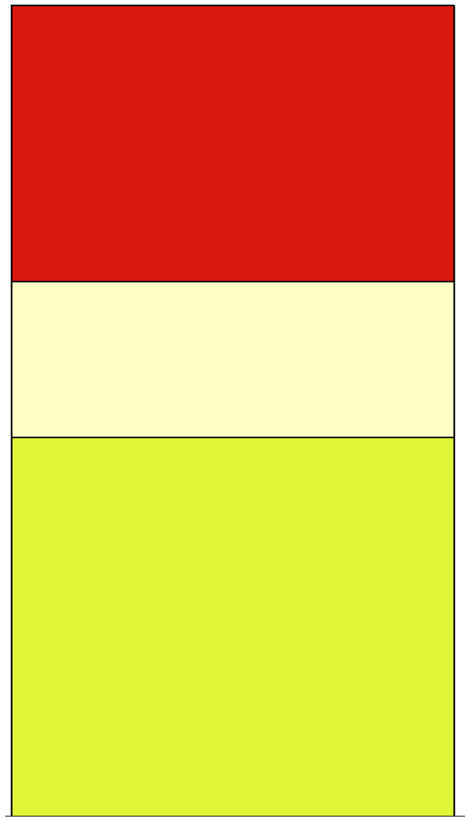
Real in situ stratigraphy

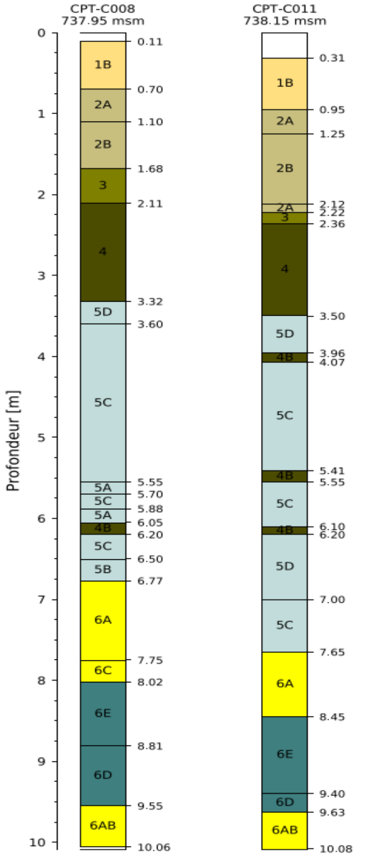
Before CPTu
Initial stratigraphy based on previous investigations

Peat

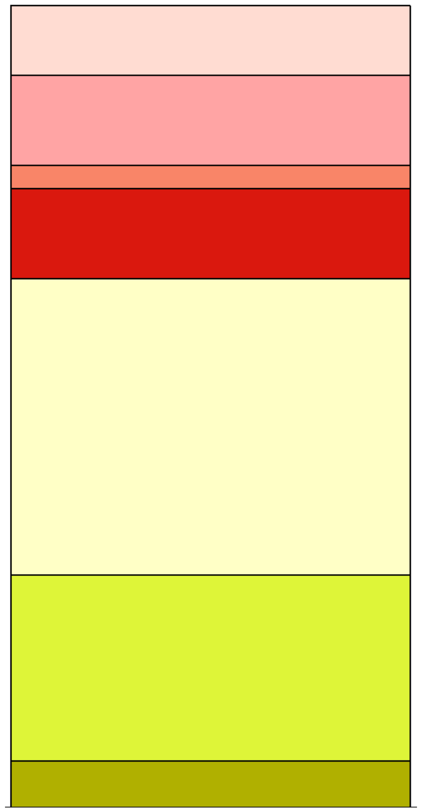
Lacustrine Deposits

Glaciolacustrine deposits





After CPTu
Refined stratigraphy based on CPTu results



Gravel

Clayed silt

Soft organic clay

Peat

Sandy clay

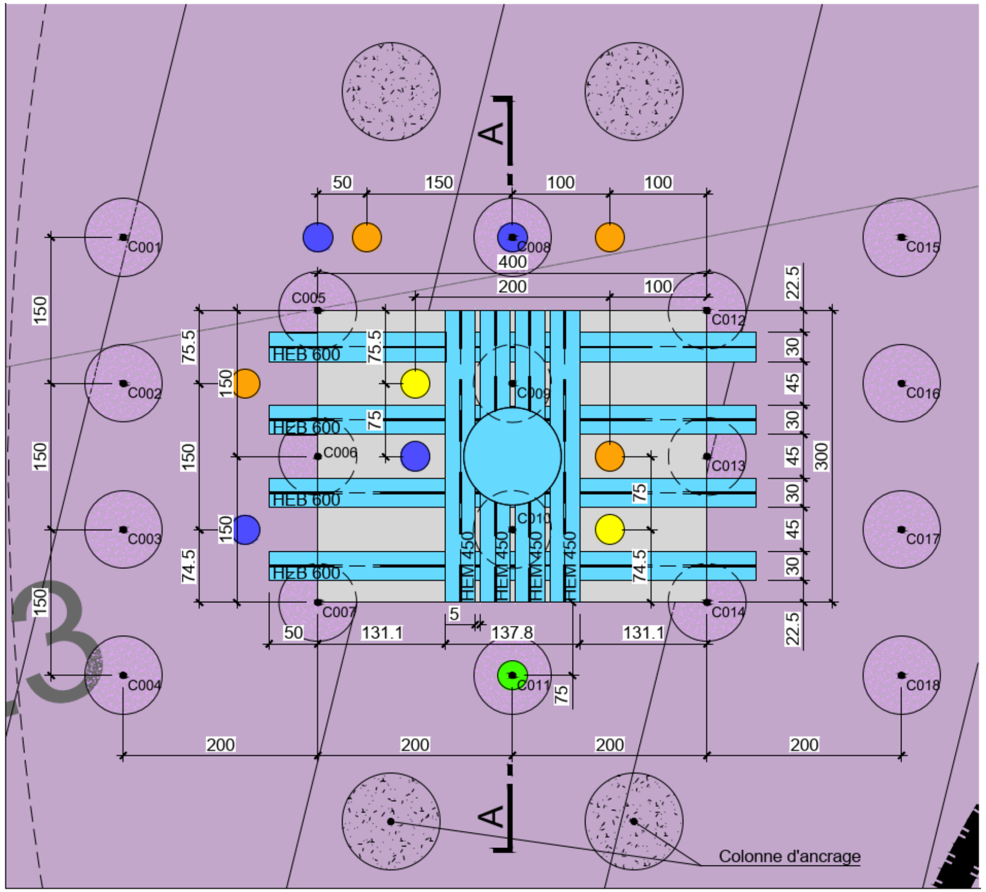
Gravelly sand

Firm clay

Couvet–Motier Railway Line – Railway Infrastructure Renewal

Static load test installation setup

- Representative grid of **Ø800 mm stone columns**
- Stone-column spacing representative of the **proposed railway reinforcement**
- Steel **reaction frame** for application of the vertical load
- Peripheral **reaction anchors** providing the required reaction force
- Extensive instrumentation around the loaded area



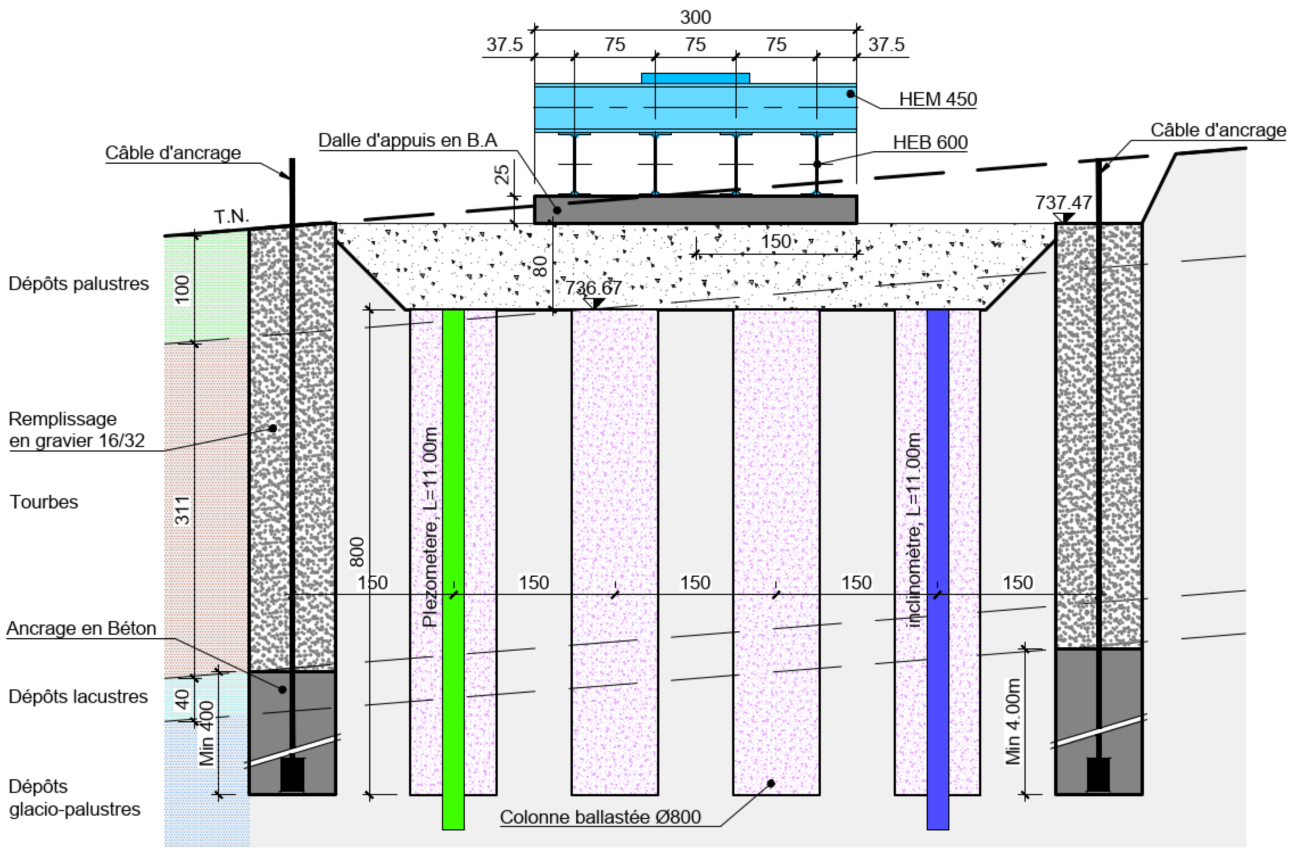
Couvet–Motier Railway Line – Railway Infrastructure Renewal

Instrumentation

- Vertical and horizontal displacement measurements
- Pore water pressure monitoring within the peat layer
- Groundwater level monitoring

Expected outcome

- Comparison between measured and predicted behaviour
- Calibration of the FE model (Digital Twin)
- Increased confidence for the final design



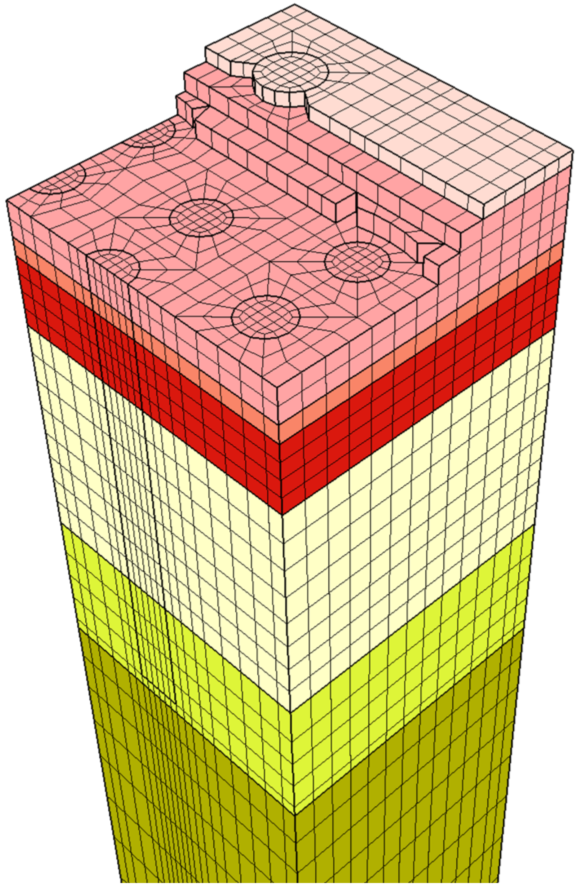
Couvet–Motier Railway Line – Railway Infrastructure Renewal

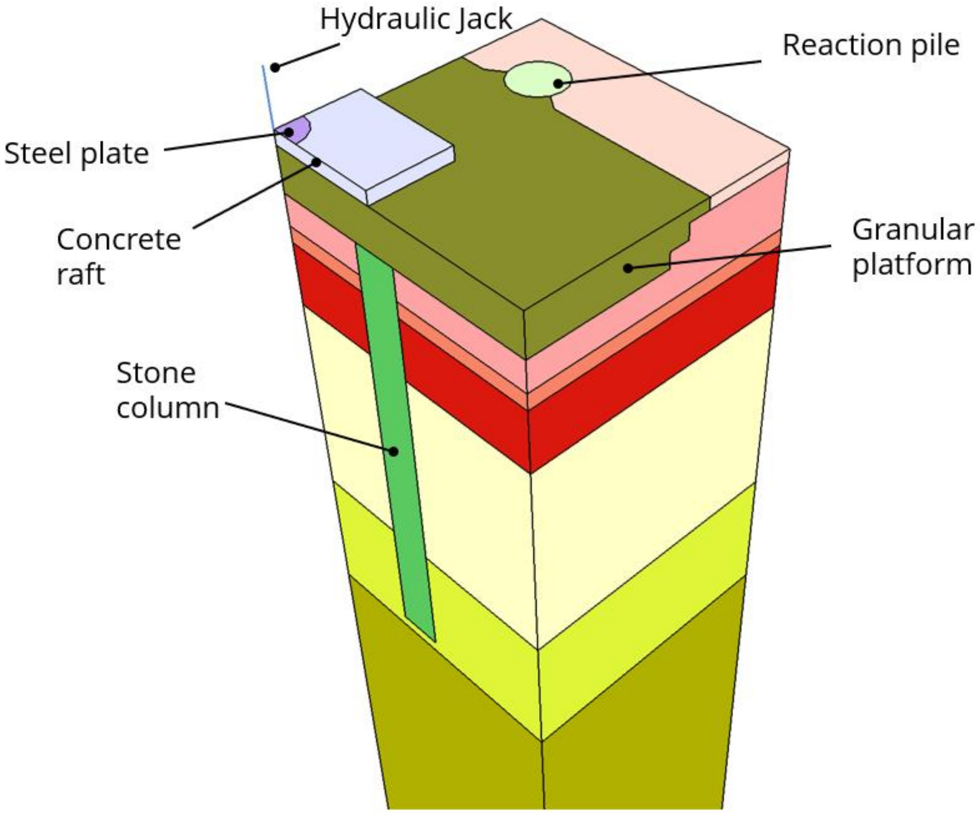
Static load test installation setup

Couvet–Motier Railway Line – Railway Infrastructure Renewal

Initial model creation

- Quarter symmetry model representations
- Adaptation with new CPTu Profiles
- Correct representation of the surrounding piles (reaction pile discretization)
- Real loading conditions through the hydraulic jack





Couvet–Motier Railway Line – Railway Infrastructure Renewal

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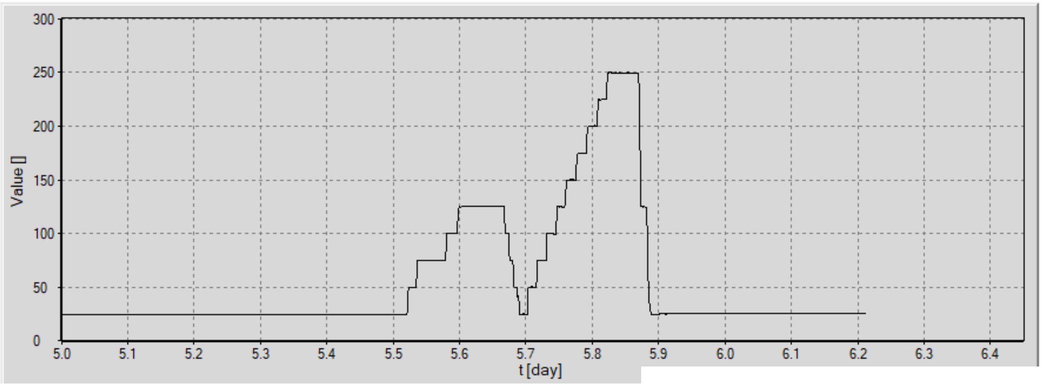
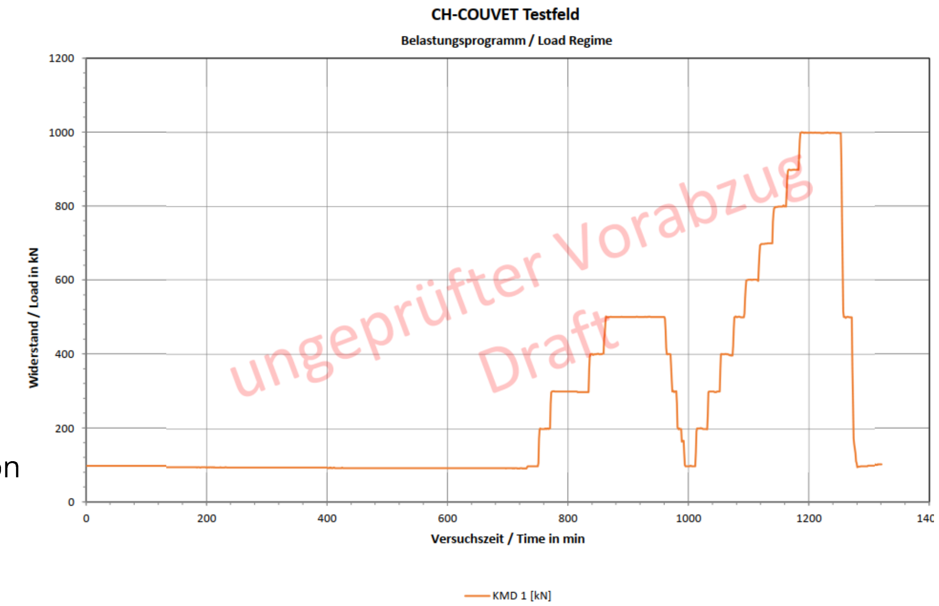


Load application in ZSoil

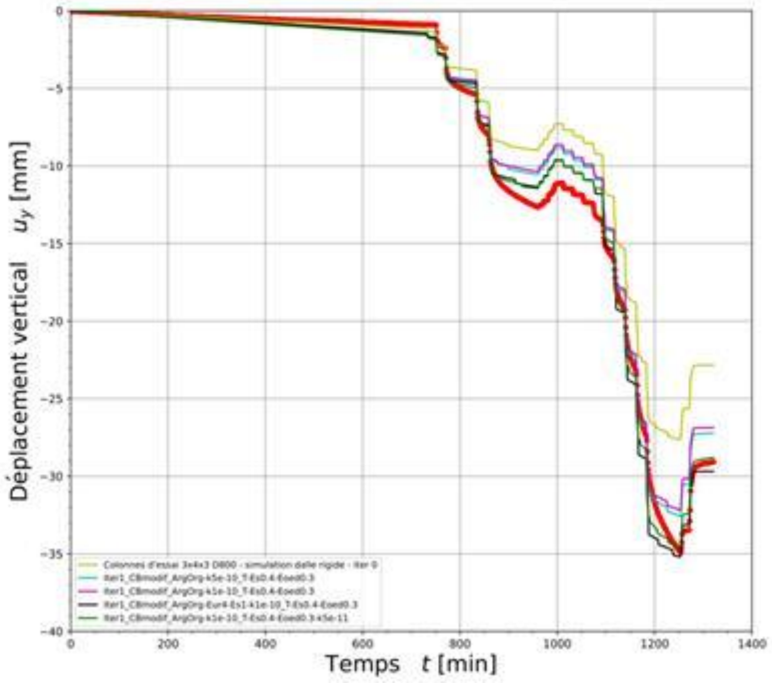


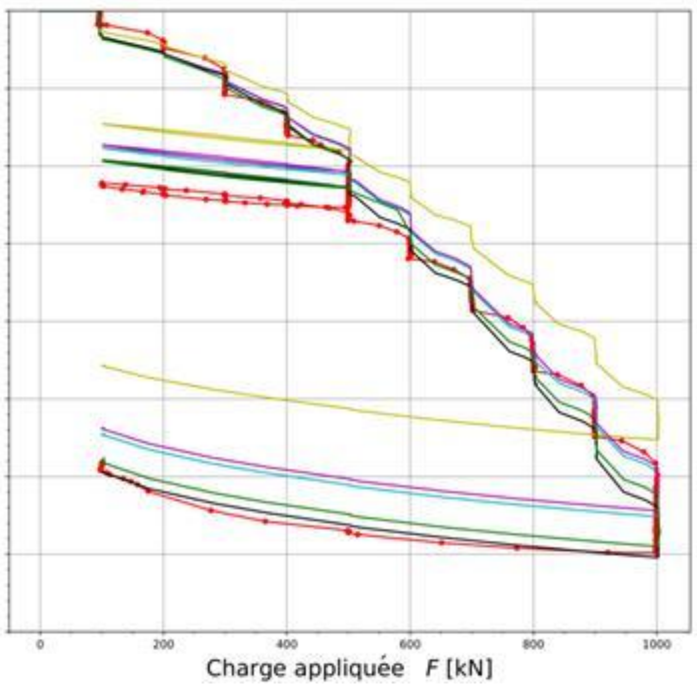
Effective load application

Couvet–Motier Railway Line – Railway Infrastructure Renewal

Parameter calibration

- Calibration of permeability coefficient and oedometric modulus of peat
- Few iterations to get **Digital twins**
- **Can rely now on the numerical model**





Case Study – Osterberg Load Test on Test-Pile (Geneva)

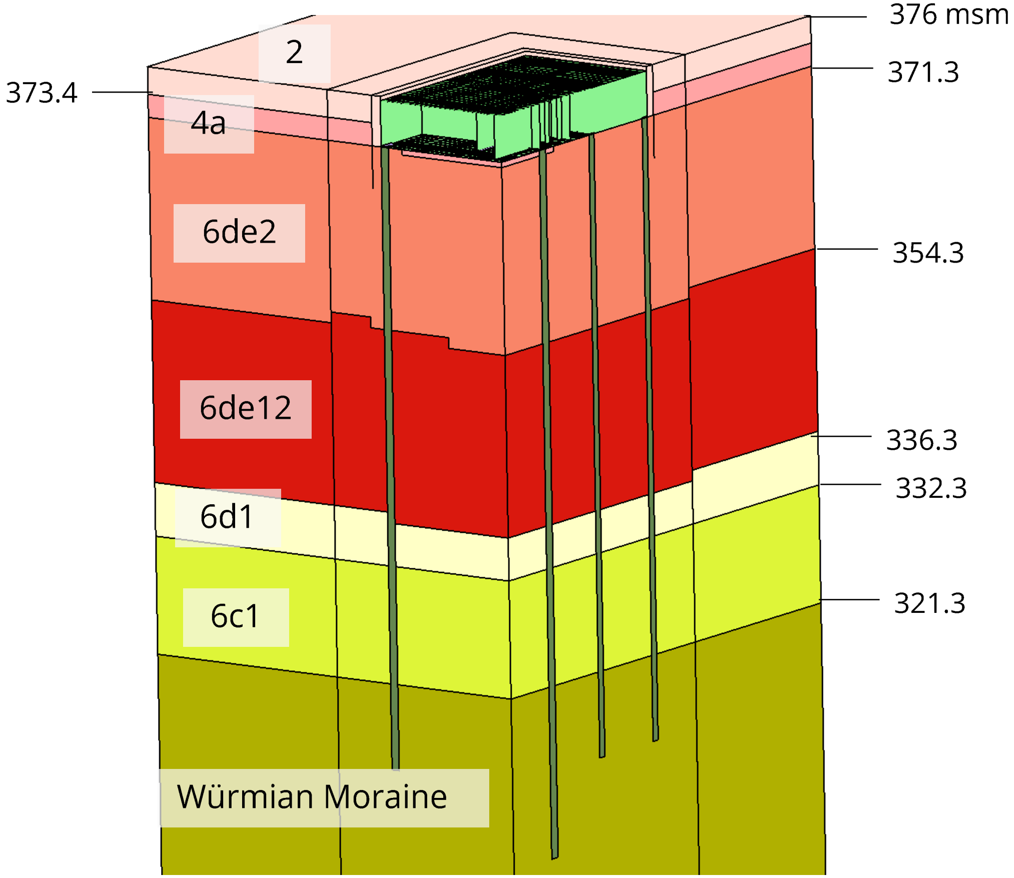
Project Overview

- Major urban development on the former military barracks site in Geneva close to the Arve River
- Construction of three buildings (A, B, C) and one high-rise tower (D) – 26 storeys
- Focus on construction of the **Building D tower** at **Quai des Vernets (Geneva)**
- High-rise structure founded on **barrettes**

Case Study – Osterberg Load Test on Test-Pile (Geneva)

Initial geological model

- Existing investigations indicated **compressible soils down to about 50 m**
- **Würmian moraine expected at approximately 50 m depth**
- Initial barrette lengths: **58-66 m**
- Design assumption: **barrettes founded within the competent Würmian moraine**



Case Study – Osterberg Load Test on Test-Pile (Geneva)

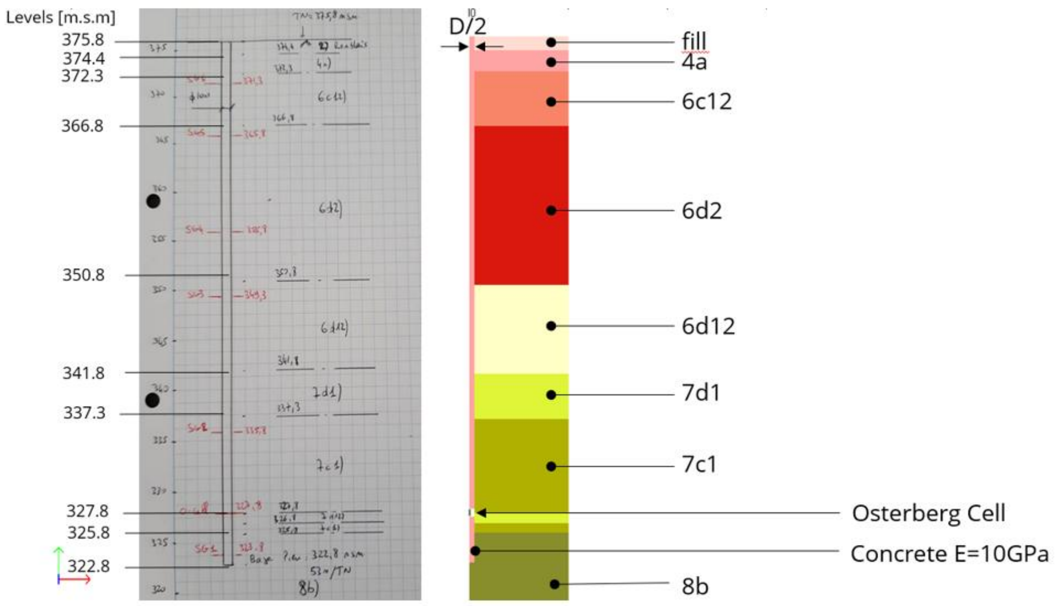
Full-Scale Osterberg Cell – Unexpected ground conditions

- **Osterberg load test planned** to investigate the **deep soil response** and validate the foundation design assumptions
- Test barrette initially designed to be **embedded in the competent Würmian moraine**

Case Study – Osterberg Load Test on Test-Pile (Geneva)

Full-Scale Osterberg Cell – Unexpected ground conditions

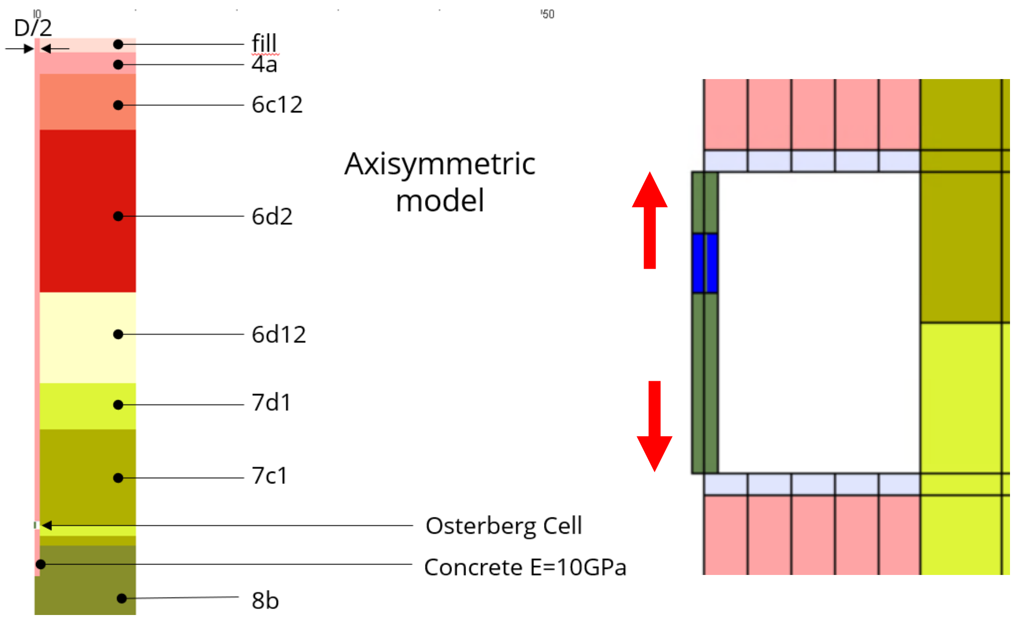
- **Osterberg load test planned** to investigate the **deep soil response** and validate the foundation design assumptions
- Test barrette initially designed to be **embedded in the competent Würmian moraine**
- During drilling, the expected moraine was **not encountered at the anticipated depth. Barrette toe located in poor-quality intramoraine deposits**



Case Study – Osterberg Load Test on Test-Pile (Geneva)

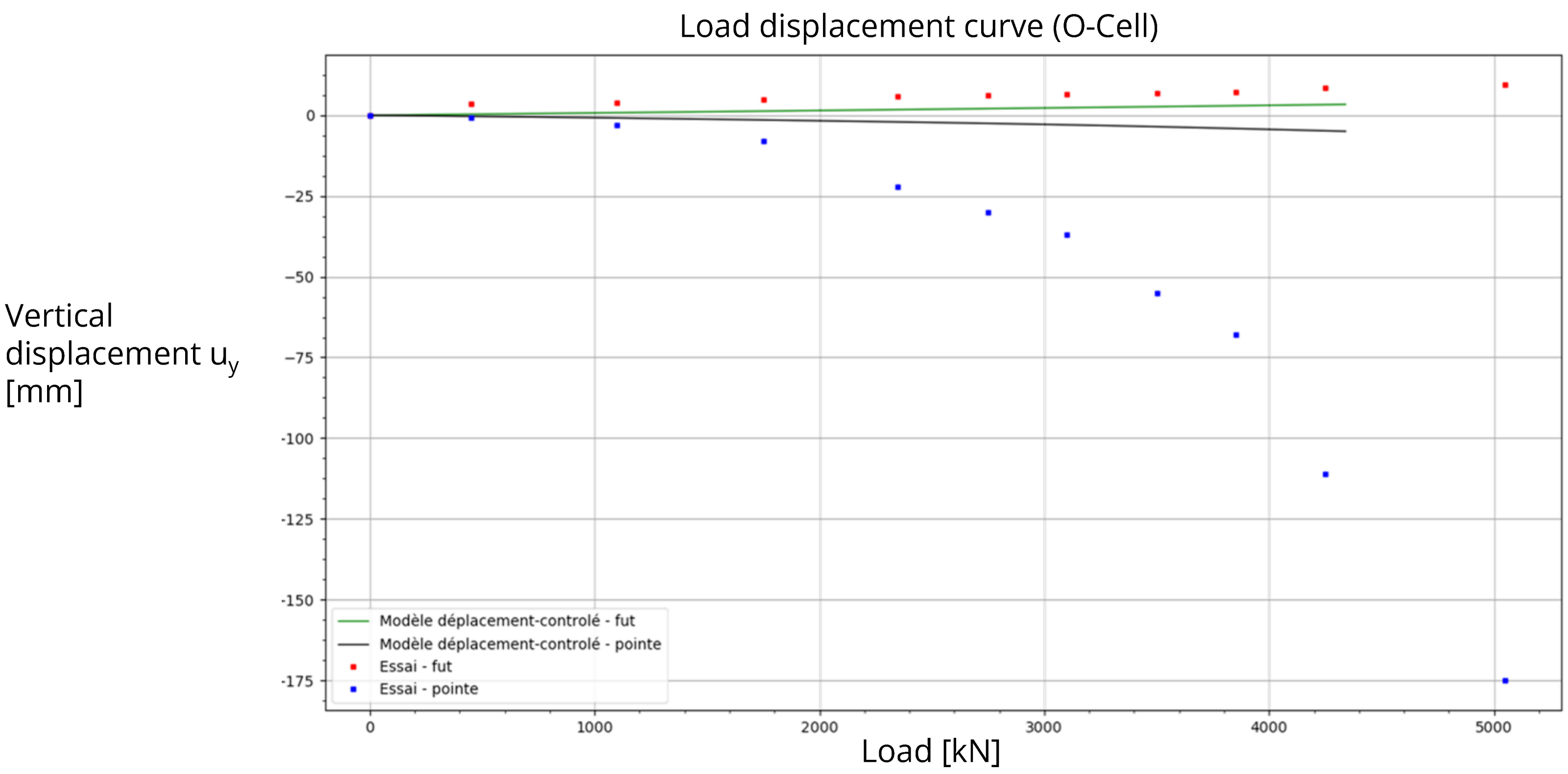
Model setup

- Urgent numerical assessment required before additional investigations were available.
- FE model developed using the **stratigraphy observed during drilling**
- 2D axisymmetric FE model of the Osterberg test
- Representative geometry and boundary conditions
- Incremental loading through the numerical O-cell (imposed displacement using truss element)
- Measured and predicted upward and downward displacements compared at each load stage



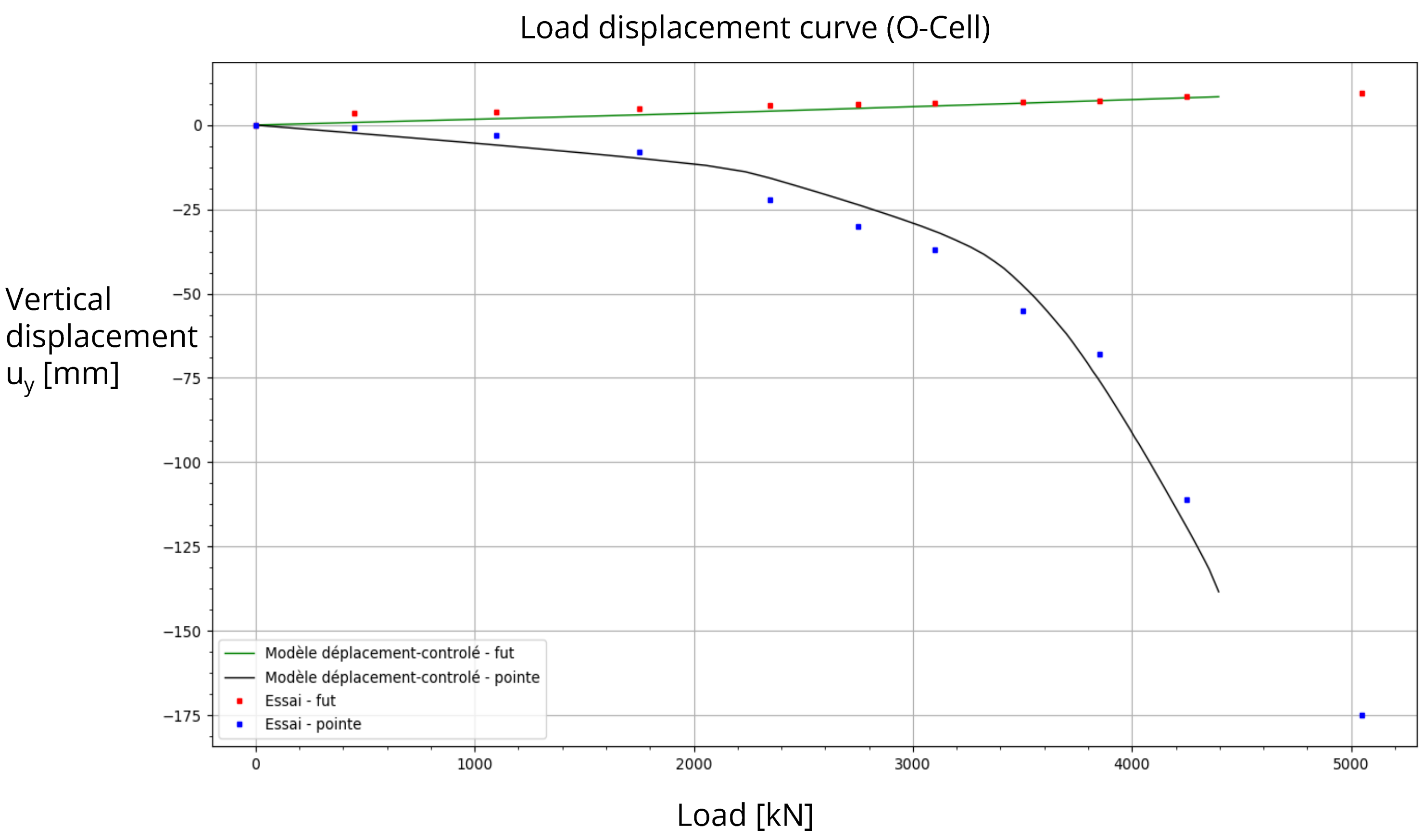
Case Study – Osterberg Load Test on Test-Pile (Geneva)

Base results with original parameters



Case Study – Osterberg Load Test on Test-Pile (Geneva)

Results after parameters calibration

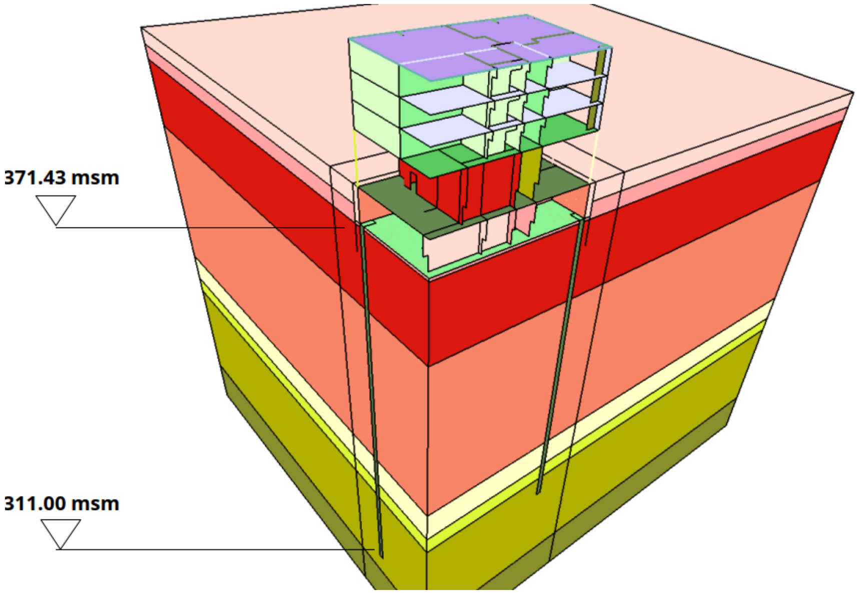


- Calibration focused on the most influential and uncertain parameters:
  - **Deformation moduli E_{50} and E_{oed}** of the moraine, intramoraine deposits and 6d2 / 6d12 deposits
  - **OCR** of the moraine and intramoraine deposits
  - Pile–soil interface **reduction factors R_i**
- The load-test back-analysis successfully captured the behaviour and relative stiffness of the newly encountered stratigraphy before laboratory data became available.
- An additional investigation campaign was carried out after the Osterberg test, including deep boreholes, soil sampling and laboratory testing.
- The results provided an independent assessment of the soil properties and were compared with the parameters previously derived from the load-test back-analysis.

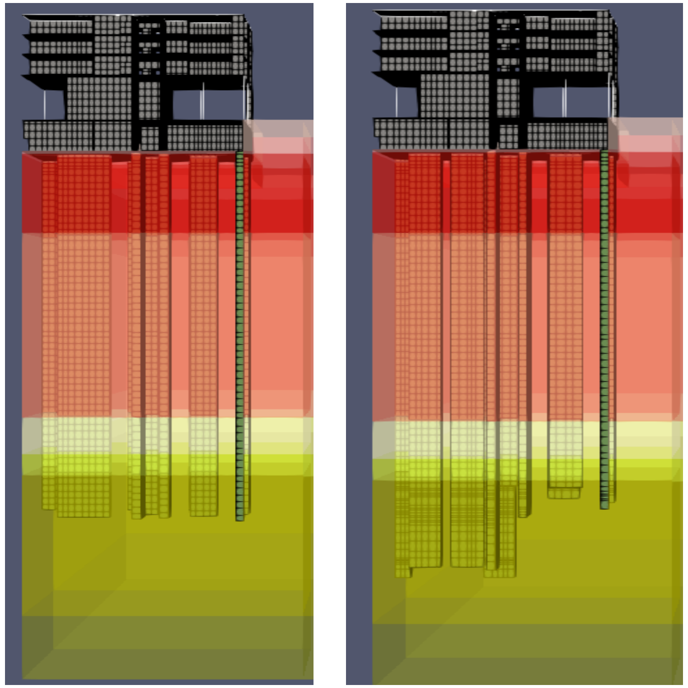
Case Study – Osterberg Load Test on Test-Pile (Geneva)

- Adaptation of the stratigraphy and parameters in full-scale 3D model
- Optimization of barrette lengths

	Model 1	Model 2				
$L_{barette}$ [m]	54	48.9	51.4	52.9	60.4	63.4



Quai des Vernets Bat D, GE



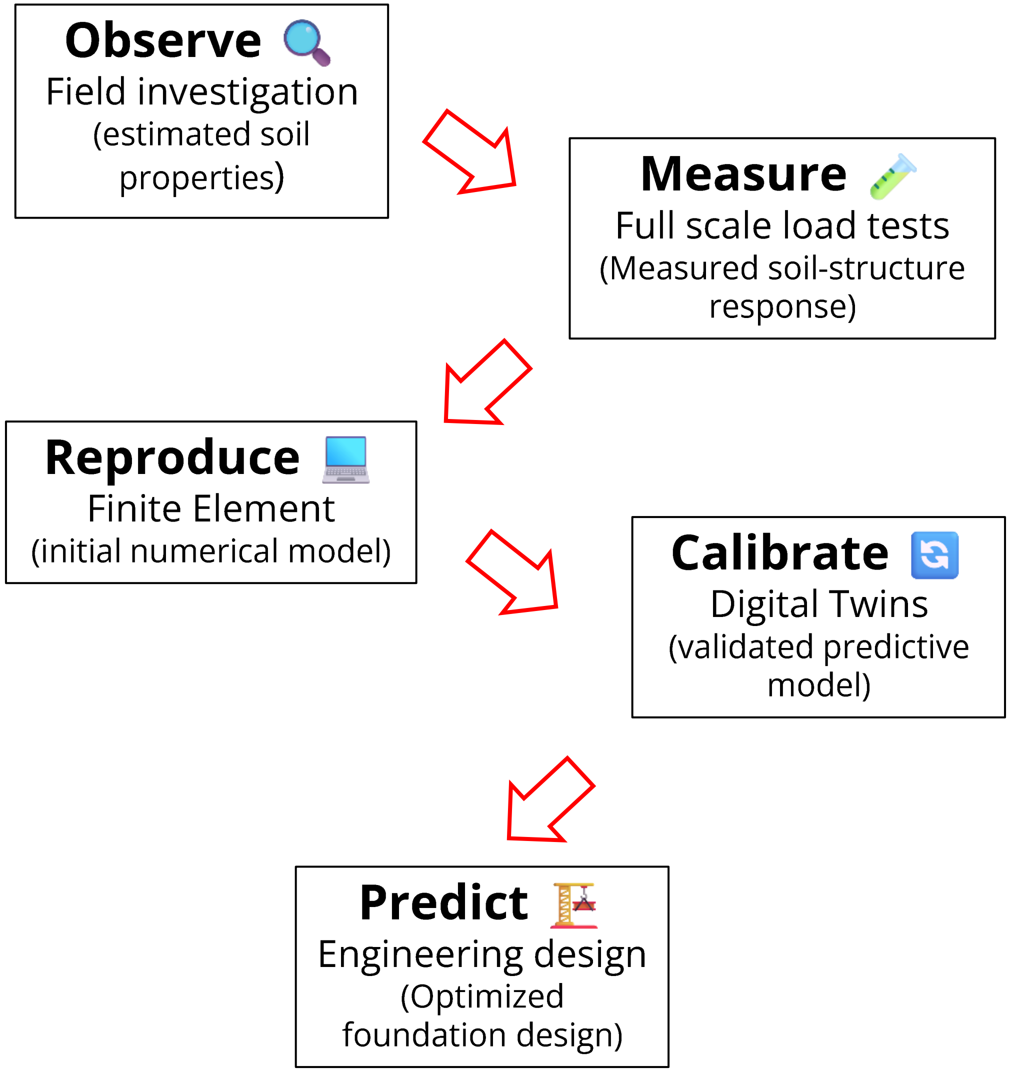
Barrette length optimization

06 Conclusion

Conclusion

- Site investigations provide an initial estimate of ground properties
- Full-scale load tests capture the actual soil–structure interaction
- Calibration transforms a numerical model into a reliable Digital Twin
- A calibrated Digital Twin increases confidence in design predictions
- More reliable predictions enable safer and more economical foundation designs

- **A Digital Twin is not just a numerical model : it is a calibrated predictive engineering tool.**



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