Hydro-mechanically coupled explicit analyses with effective contact stresses using Abaqus

Patrick Staubach*

March 22, 2024

Version		
02.2021	:	Initial version
12.2021	:	Added description of `VUMAT` routine for Abaqus 2020 and newer. Added warning for usage of large bulk moduli. Added additional output
03.2022	:	Added information about defining the hydrostatic pore water pressure for the `VUMAT` routine for Abaqus 2020
11.2023	:	Calculation of correct friction with field variables
12.2023	:	Added warning if too many elements are considered in subroutine `VUSDFLD`
03.2024	:	Added pile driving example

Contents

*Chair of Geotechnics, Bauhaus-University Weimar, Germany / Ruhr-University Bochum, Germany. Email: patrick.staubach@uni-weimar.de

1 Background

The implementations are according to the following papers:

- Hydro-mechanically coupling according to Staubach et al. 2020; Staubach et al. 2021
- Consideration of effective contact stresses for calculation of friction according to Staubach 2024
- Incorporation of effects of cavitation according to Staubach et al. 2023
- Implementation of the hypoplastic model with intergranular strain extension according to Staubach 2022 (see Appendix)

Please cite if the routines have been useful to you.

2 Theory

This document explains how to conduct a hydro-mechanically coupled explicit simulation using Abaqus according to the approach documented in Staubach et al. 2020; Staubach et al. 2021 (note that the approach is based on the idea by Hamann 2015). The theory is explained first, the necessary settings in the input file are introduced subsequently.

The balance of mass of the pore water is given by:

$$\varphi^w \frac{1}{\bar{K}^w} \frac{dp^w}{dt} + \varphi^w \text{div}(\boldsymbol{v}^w) + (1-n)\ \text{div}(\boldsymbol{v}^s) = 0 \tag{1}$$

The generalized Darcy law is used to evaluate the relative velocity between solid skeleton and pore water which is derived from the linear momentum of the pore water:

$$\boldsymbol{w}^w = \frac{\boldsymbol{K}^{\text{Perm}}}{\eta^w} \cdot (-\text{grad}(p^w) + \bar{\rho}^w\,(\boldsymbol{b} - \ddot{\boldsymbol{u}})) \tag{2}$$

Combined these equations yield:

$$\varphi^w \frac{1}{\bar{K}^w} \frac{dp^w}{dt} - \frac{\boldsymbol{K}^{\text{Perm}}}{\eta^w} \cdot \text{div}\Big(- \text{grad}(p^w) + \bar{\rho}^w\,(\boldsymbol{b} - \ddot{\boldsymbol{u}}) \Big) - \text{div}(\boldsymbol{v}^s) = 0 \tag{3}$$

The energy balance is:

$$\rho c \dot{U} + k\ \text{div}\Big(\text{grad}(\theta)\Big) = -m_T \tag{4}$$

Combining Equation 3 and 4 one obtains:

$$c = \varphi^w \frac{1}{\bar{K}^w \rho} \tag{5}$$

$$k\ \text{div}\Big(\text{grad}(\theta)\Big) = \frac{\boldsymbol{K}^{\text{Perm}}}{\eta^w} \cdot \text{div}\Big(- \text{grad}(p^w) + \bar{\rho}^w\,(\boldsymbol{b}) \Big) \tag{6}$$

$$m_T = -\text{div}(\boldsymbol{v}^s) + \frac{\boldsymbol{K}^{\text{Perm}}}{\eta^w} \text{div}(\ddot{\boldsymbol{u}}) \tag{7}$$

3 Definition of the input file

A coupled-thermal analysis with Abaqus/Explicit is performed, where the specific heat and the thermal conductivity are modified in such a way that the mass balance of pore water is derived. The constant c is given in the input file by:

```
*SPECIFIC HEAT
1.03744454d-7
```

where $c = \dfrac{\varphi^w}{\bar{K}^w \rho} = \dfrac{0.48}{2200000 \cdot 1.884} = 1.03744454^{-7}$ was set exemplary. φ^w is the porosity, $\bar{K}^w$ the bulk modulus of water and ρ the total density.

It is not recommended to use the bulk modulus of "pure" water in general. This will lead to very small time increments. Better consider some trapped air bubbles in the soil, which will reduce the bulk modulus considerably.

k is given by using:

```
*CONDUCTIVITY, TYPE=ISO
1d-4
```

where $\dfrac{K^{\text{Perm}}}{\eta^w} = \dfrac{10^{-10}}{10^{-6}}$ was set exemplary.

In addition, elements with thermal degree of freedom have to be used, e.g. CPE4RT (Lagrangian analysis) or EC3D8RT (Eulerian analysis) and

```
*INELASTIC HEAT FRACTION
1.0
```

has to be defined. Using the `VUMAT` together with the hypoplastic constitutive model, the following additional definitions are necessary

```
*Depvar
35
*User Material, constants=15, unsymm
0.578,    0.37,    4e+06,    0.27,    0.677,    1.054,    1.212,    0.14
2.5,      1.2,     2.4,   0.0001,     0.1,       6.,       0.
```

where the parameters for Karlsruhe fine sand have been used. The initial state variables have to initialized as well:

```
*Initial conditions,type=solution
Part-1-1.all,1.0d0,0,0,-0.0001d0,0,0,0
0,0,0,0,0,0,0,0
0,0,0,0,0,0,0,0
0,0,0,0,0,0,0,0
0,0,0,0,0
```

The element set *Part-1-1.all* has an uniform initial void ratio of 1 and a fully mobilized intergranular strain in z-direction of -0.0001.

In order to conduct a fully coupled dynamic analysis, the following type of analysis has to be defined in the step definition:

```
*Dynamic TEMPERATURE-DISPLACEMENT, explicit
```

Within the `VUMAT`, the internal energy m_T caused by inelastic heat generation is used to add the volumetric terms of the actual mass balance to the energy balance Abaqus enforces. As Abaqus requires the dissipated energy per unit mass, the terms are divided by the density of the mixture. As only the excess pore water pressure is described, the hydrostatic pore water pressure has to be taken into account separately. The definition of the ground water table is discussed in the following.

> Two `VUMAT` routines are supplied: one for Abaqus 2020 and one for Abaqus 2023. The arguments of the `VUMAT` have been changed for Abaqus 2023, for why it is important to use the correct version. You need only one of them.

Within the `VUMAT` for Abaqus 2020 and newer, the following additional parameters have to be set:

```
KPerm       = 1.00d-10 ! permeability
viscosity   = 1.00d-6  ! dynamic viscosity
density2    = 1.884d0  ! density
gamma_w     = 10.0d0   ! dead weight water
gravity     = 10.0d0   ! gravity
KO          = 0.5d0    ! lateral stress coefficient
water_table = 10.0d0   ! water table height
dir_grav    = 2        ! direction of gravity
cavitation  = -100.0d0 ! Total pore water pressure at which cavitation occurs
```

In addition, one has to make sure that the direction of gravity used for the calculation of the hydrostatic pore water pressure in line 155 or line 161

```
statev(24) = (-coords(int(dir_grav)) + water_table)*gamma_w
```

is correct for the numerical model used.

The excess pore water pressure can be viewed in the odb using:

```
*Node Output
NT
```

In addition, the hydrostatic pore water pressure is obtained using:

```
*Element Output
SDV24
```

The effective stresses are obtained by:

```
*Element Output
SDV27,SDV28,SDV29,SDV30,SDV31,SDV32
```

The simulation has to be started using `user=call` or `user=call2020`, depending on the `VUMAT` version used.

4 Calculation of friction with effective contact stresses

Two additional user files are required if effective contact stresses are used to calculate friction: `VUFIELD` and `VUSDFLD`.

4.1 Statements in the input file

The following additional considerations in the material definition are required:

```
*Depvar
36
*USER DEFINED FIELD
```

When defining the interaction behavior, the following definition of the friction coefficient is required:

```
*Friction,DEPENDENCIES = 1
0.0, , , ,0
0.25, , , ,0.5
```

Here, the 'real' friction coefficient is 0.25, i.e. in the simulation this friction coefficient is active.

For all steps, the following commands have to be added:

```
*field,user
*field,user, NUMBER =2
Set-euler_all
```

Here, *Set-euler_all* is a node set containing all nodes of the eulerian region.

To check if the field variable used to calculate the ratio of effective to total contact stresses is calculated correctly, the field variable is added to the output:

```
*Element Output
FV
```

4.2 Statements in the user files

Additional considerations are required for the files `VUFIELD` and `VUSDFLD`. At the start of `VUSDFLD`, the following variables have to be set:

```
pile_radius      = 0.0165d0
min_coords3      = 0.5d0
pile_center(1:2) = [0.0d0,0.0d0]
```

By default, a pile driving analyses is considered. To save time, only in a zone 1.4 times the pile radius, the field variable is assigned. In addition, for z-coordinates lower than *min_coords3* the field variable is not assigned. Both is done to save time and can be modified for other problem positions. The variable *pile_center* denotes the central axis of the pile, to which all normal vectors of the pile shaft are assumed to point.

> At the moment, the files `VUFIELD` and `VUSDFLD` shipped together with this document only support analyses with a maximum of 8 threads.

At the start of `VUFIELD`, the following variables have to be set:

```
pile_radius      = 0.0165d0
min_coords3      = 0.5d0
pile_center(1:2) = [0.0d0,0.0d0]
frequency_update = 10
bytes_per_line   = 62
```

In addition to the aforementioned variables, *frequency_update* and *bytes_per_line* have to be set. *frequency_update* denotes the frequency with which the field variable is updated. To save time, the field variable is only updated every 10th increment. Because there seems to be a general problem with reading files with Fortran within subroutines of Abaqus, *bytes_per_line*, setting the number of bytes of one line of the files that the `VUSDFLD` routine generates is required. As this number stays constant for all analyses, it is not required to be modified. However, one should check that the correct number of lines is read.

Independent of the number of threads used, Abaqus crashes if the files written by the user routines contain to many elements. A critical number was found to be around 5000. If your simulation crashes and reports a dumped core in the main executable, reduce the number of elements included in the region of the model considered by the subroutines, e.g. reduce the multiplier of the pile radius.

4.3 Benchmark

In order to show how field variables can be used to modify the friction coefficient, a large scale interface shear test is simulated using the CEL method. The wall is meshed with Lagrangian elements and the soil with Eulerian elements. Only elastic materials and no influence from pore fluid pressure is considered. After establishing the normal contact stresses within the first 4 s of the simulation, the wall is moved downwards with a constant velocity. During this, the field variable is changed such that the friction coefficient changes with time. Two different functions for the field variable are considered, which are depicted in Fig. 1. As can be seen from Fig. 1 the field variable gives the correct ratio of friction forces to normal forces by means of the friction coefficient.

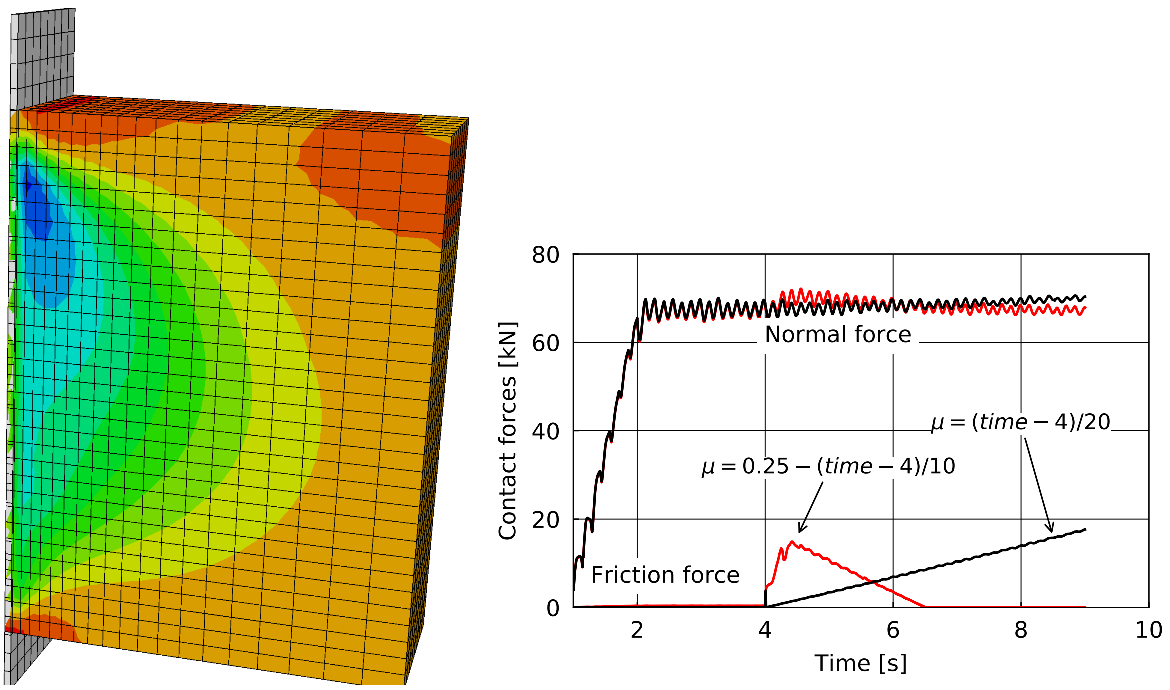
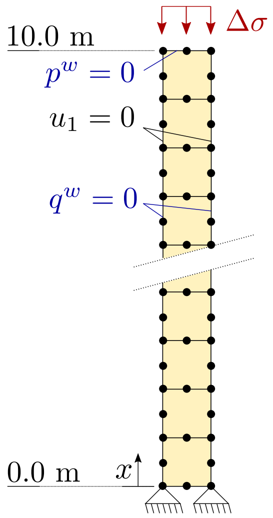
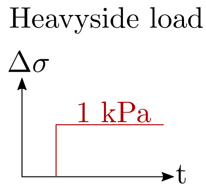


Figure 1: Interface shear test

5 Comparison of numerical and semi-analytical results for 1D wave propagation

The following example aims to assess the performance of the proposed fully coupled explicit approach by comparison with an analytical solution for the wave propagation in a poro-elastic medium. This validation example has been published in Staubach et al. 2020. Consider a one-dimensional column with a length of $l = 10$ m, as depicted in Fig. 2. The lateral and bottom boundaries are assumed to be rigid, frictionless and impermeable. At the top, the stress $\Delta\sigma = 1$ kPa and the pore-water pressure $p^w = 0$ kPa are prescribed (thus, drainage along the top surface is allowed).





Parameter	Quantity	Unit
$\bar{\rho}^s$	2.7	t/m^3
$\bar{\rho}^w$	1.0	t/m^3
$\bar{K}^w$	2.2	GPa
K^w_{ii}	10^{-4}	m/s
e_0	0.5	-
E	15	MPa
ν	0.3	-

Figure 2: Schematic illustration of the numerical model of the one-dimensional soil column and important parameters for the simulations

It is assumed that the time history of the loading is a Heaviside step function. The simulation results are compared to a semi-analytical approach, which accounts for the relative acceleration of the pore-water phase. A detailed derivation of the semi-analytical solution as well as a comparison to different finite element formulations are given in Staubach and Machaček 2019. The parameters used for the numerical as well as for the semi-analytical approach are listed in Fig. 2. For the analytical solution and the explicit approach, the time increments are set to $\Delta t = 10^{-5}$ s and $\Delta t = 10^{-6}$ s, respectively. The soil column was once discretised using 100 elements and once using 1000 elements. For the explicit calculations a time scaling factor, which can be used to change the maximum stable time increment of an explicit calculation, of 0.1 is used.

The development of excess pore water pressure at the bottom of the column and the settlement-time history recorded at the top of the column are illustrated in Figure 3. For both the predicted excess pore-water pressure Δp^w as well as the vertical displacements u_2 the semi-analytical solution matches the explicit numerical solution well. The displacement of the top of the column follows a triangular cyclic pattern. With ongoing consolidation process (drainage along the top surface is allowed), the absolute value of the mean displacement increases, while the amplitude is reduced. The time needed by the wave to pass through the column increases gradually, as visible in the Δp^w-time history in Fig. 3.
Although the accordance with the semi-analytical solution is generally good, strong oscillations of the excess pore water pressure Δp^w are observed in the numerical solution in case of a discretisation with 100 elements. However, these oscillations are absent in case of the displacements u_2. The oscillations can be noticeably reduced by refining the spatial discretisation, as evident from the results obtained with 1000 elements. Note in addition that implicit elements based on the u-p approximation exhibit similar oscillations (see Staubach and Machaček 2019).

6 Example: Pile driving in water-saturated sand with effective contact stress

The model used for the simulation of pile driving in water-saturated sand with effective contact stress including the finite element mesh is shown in Figure 4. Considering the symmetry only one quarter of the problem is modelled. The red area represents the region initially filled with material while the blue area is initially empty but could be filled if the material moves into the elements during the sim-

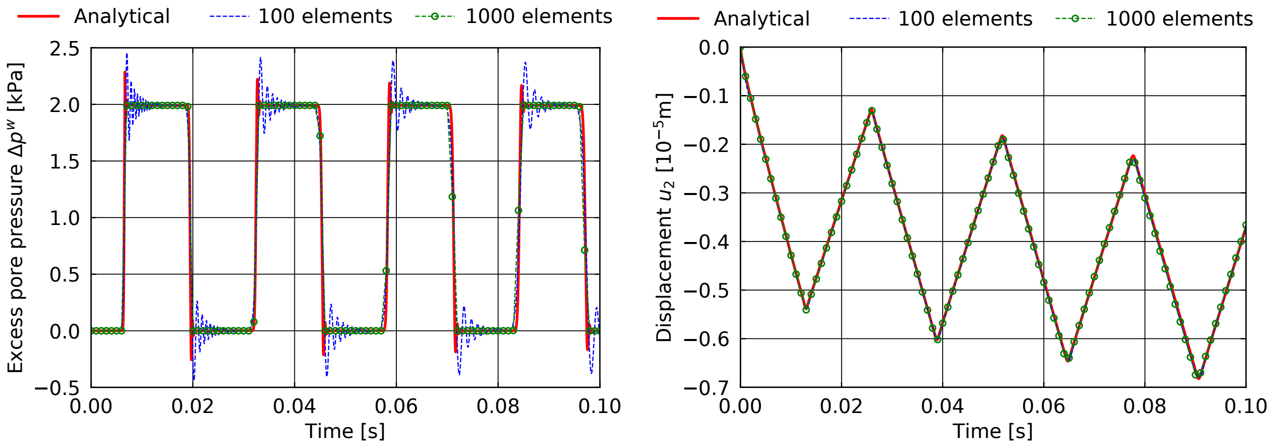


Figure 3: Comparison of numerical and semi-analytical results for the one-dimensional wave propagation problem. Top: Development of excess pore water pressure (Δp^w) recorded at the bottom of the column. Bottom: Settlement-time history $u_2(t)$ recorded at the top of the column.

ulation. The pile has an outer diameter of 2 m, a wall thickness of 9 cm and is driven into the soil up to a depth of 10 m. Since the exemplary simulation is supposed to run fast, a too coarse mesh is used.

The pile is assumed to be rigid. The considered soil area has a diameter and a height of 100 m. The model size is chosen such that all mechanical waves resulting from the installation process are damped out before they approach the boundaries. The size of the elements increases towards the boundaries of the model in order to achieve a "damping" effect by damping the waves when travelling towards the borders as no transparent boundary conditions were used. The applicability of this approach was verified by examining the acceleration magnitudes during the driving process which were found negligible for distances to the pile greater than approximately 30 m.

The phreatic level is assumed to be located 1 m below the ground level. The bulk modulus of the pore water is assumed to be $\bar{K}^w = 10,589$ kPa. The hydraulic conductivity is 10^{-3} m/s.

A Coulomb friction model with a friction coefficient of $\mu = 0.5$ is used, which is calculated using effective normal contact stresses using the approach described in Section 4.

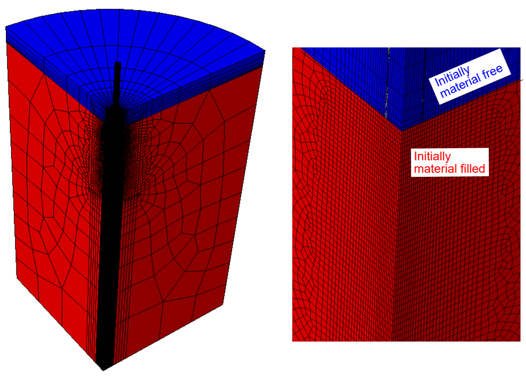


Figure 4: Finite element model for the installation process

In the first step of the calculation the gravity ($g = 10$ m/s^2) is applied to the soil, without generating any deformations. In the second step, the self weight of the pile and the ram is applied in the second step, leading to an initial penetration of the pile into the soil. After 2 s, the impact load is brought up on the pile in the third step. Again, this third step lasts until the pile is driven 10 m into the soil. Note that the inertia of the ram is not considered.

Figure 5 depicts the field variable (FV) 1 (defined as $\frac{t_N - p^w}{t_N}$) at the start of the driving and excess pore water pressure at approximately 1.5 s of driving. FV 1 indicates the ratio of effective to total normal contact stresses and is only evaluated around the pile in order to save computational time. The area of evaluation is defined in the files `VUFIELD` and `VUSDFLD`. It has to be changed if the geometry of the pile or the soil changes. FV 1 is used to modify the friction coefficient such that effective normal contact stresses are used for the calculation of friction.

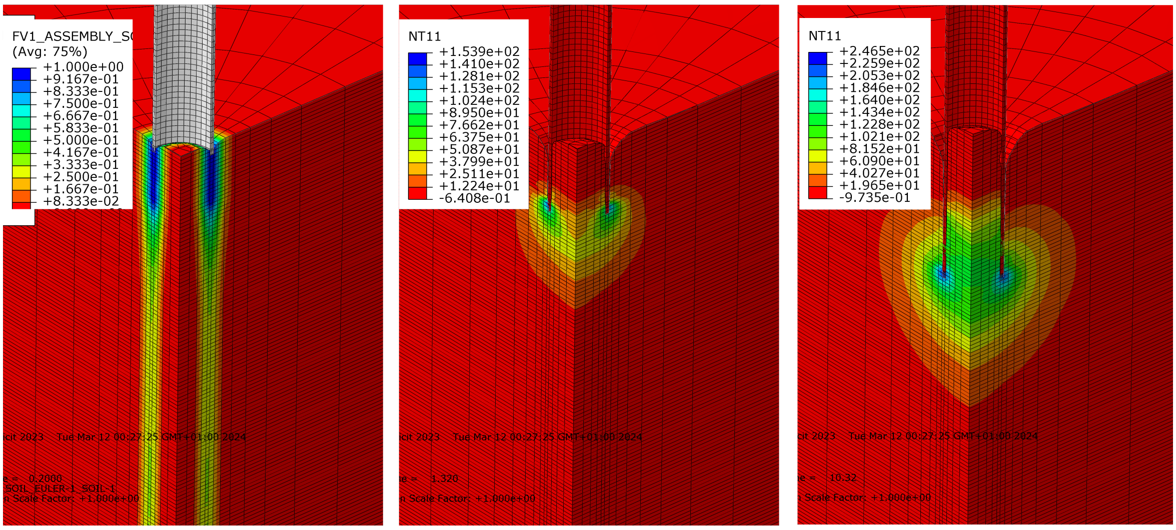


Figure 5: Field of the field variable 1 (defined as $\frac{t_N - p^w}{t_N}$) at the start of the driving and excess pore water pressure (NT11) at approximately 1.5 s / 10 s of driving

References

Hamann, T. (2015). "Zur Modellierung wassergesättigter Böden unter dynamischer Belastung und großen Bodenverformungen am Beispiel der Pfahleinbringung". In.

Staubach, P. and J. Machaček (2019). "Influence of relative acceleration in saturated sand: Analytical approach and simulation of vibratory pile driving tests". In: *Computers and Geotechnics* 112, pp. 173–184. DOI: `10.1016/j.compgeo.2019.03.027`.

Staubach, P. (2022). "Contributions to the numerical modelling of pile installation processes and high-cyclic loading of soils". In: DOI: `10.13154/294-9088`.

Staubach, P. et al. (2020). "Impact of the installation on the long-term cyclic behaviour of piles in sand: A numerical study". In: *Soil Dynamics and Earthquake Engineering* 138, p. 106223. DOI: `10.1016/j.soildyn.2020.106223`.

Staubach, P. et al. (2021). "Vibratory pile driving in water-saturated sand: Back-analysis of model tests using a hydro-mechanically coupled CEL method". In: *Soils and Foundations* 61 (1), pp. 144–159. DOI: `10.1016/j.sandf.2020.11.005`.

Staubach, P. (2024). "Hydro-mechanically coupled CEL analyses with effective contact stresses". In: *International Journal for Numerical and Analytical Methods in Geomechanics*. DOI: `10.1002/nag.3725`.

Staubach, P. et al. (2023). "Monopile installation in clay and subsequent response to millions of lateral load cycles". In: *Computers and Geotechnics* 155, p. 105221. DOI: `https://doi.org/10.1016/j.compgeo.2022.105221`.