On consistent nonlinear analysis of soil structure interaction problems using ZSoil.
Diaphragm wall case study

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Introduction

- Nonlinear soil (**NSO**)-linear structure (**LST**) **computational strategy** is commonly used to solve certain soil-structure interaction problems
- Further **design procedure** of **structural elements** is using computed **elastic stress resultants**
- In the **ULS analysis** these **values are amplified by some safety factors**
- In the **SLS analysis** computed **results are used directly**
- Is this approach conservative ? (safe)
- To study this problem nonlinear soil (**NSO**)-nonlinear structure (**NST**) approach will be compared with the **NSO-LST** one
- Special **emphasis** will put on the **SLS state** analysis
- **Diaphragm wall case study** is used here for the analysis

General observations

- **Bending moments in diaphragms** are usually **larger** (locally) than the **cracking moment**
- **Consequences**:
  1. **Cracks** must occur
  2. **Overall bending stiffness** of the structure is **reduced**
  3. **Bending stiffness** is **not uniform** along the wall
  4. Certain **arching effects** may appear

Assumptions

- **Subsoil** consists of **uniform quaternary sandy clay** layer
- **Hardening Soil** model is used
- **Two-phase** coupling is considered
- **Linear elastic** and **modified plastic damage model (CDP) with the EC2 creep** is used for modeling concrete behavior
- **3D model** is analyzed (CDP model can be used only in continuum and shells)

Comments on HS model

Designing triax tests

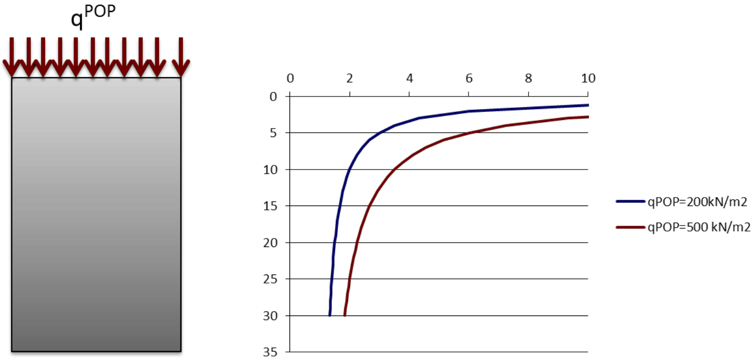
- **Triax CD tests** should be conducted on **overconsolidated samples**
- **Consequences**
  1. Stiffness modulus E_{50}^{ref} **is directly estimated**
  2. **Dilatancy** angle becomes **visible**
- **Do not rely** on laboratory test only (unless some other archival data is available)
- Request **digital data** from laboratory

In situ tests SCPTU, SDMT

- **SDMT** is **recommended**
- **Stress history (OCR)** is **well detected**

Comments on use of HS model

Modeling stress history in HS model



Damage plasticity model (CDP) for concrete

- This model is available in **ZSoil** since v2016
- **EC2 aging creep** is added to the model (2016)
- **Extension to elevated temperatures** is added in **ZSoil v2018**

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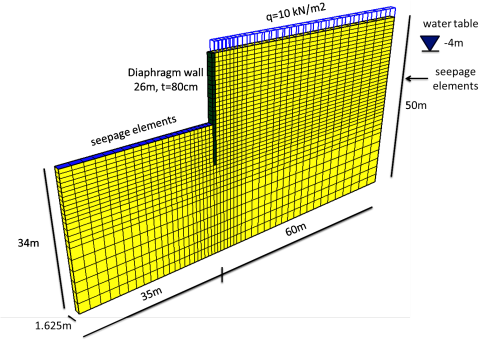
Computational model: 3D slice



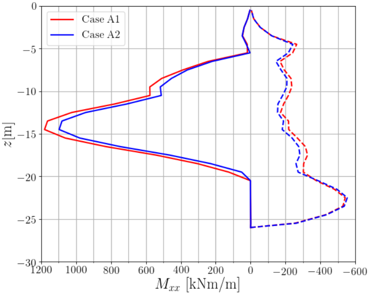
- Segment width 6.5m
- 4 anchors per segment at depths 5m, 11m
- Anchors length 17m
- Excavation depth 16m
- Excavation rate 0.17m/day
- Foundation raft installed 30 days after completing the excavation

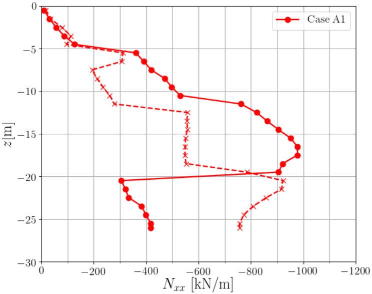
$E_0^{ref} = 328000\,\mathrm{kPa},\ \nu = 0.2,\ E_{50}^{ref} = 20000\,\mathrm{kPa},\ E_{ur}^{ref} = 70000\,\mathrm{kPa},\ \ m = 0.55,$
$\gamma_{0.7} = 5 \cdot 10^{-5},\ \phi' = 29^o,\ \psi' = 0^o,\ c' = 7\ \mathrm{kPa},\ k = 10^{-8}\ \mathrm{m/s},\ q^{POP} = 1300\ \mathrm{kPa}$

Results for NSO-LST approach

- **Case A1**: $E_{cm} = 31000$ MPa
- **Case A2**: $E_{cm} = 25000$ MPa

M_{xx} and N_{xx} envelopes at time of raft installation





Results for NSO-LST approach

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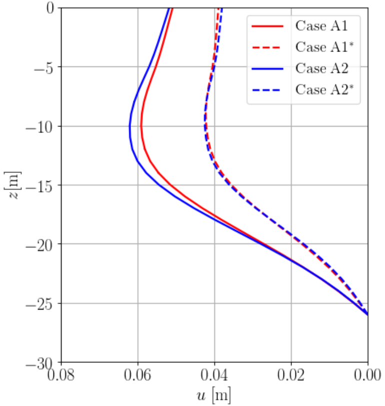
Wall deflections



Results for NSO-LST approach

Preliminary dimensioning

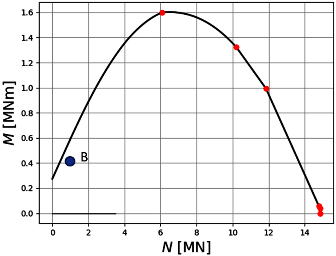
- Bending moments: $M_{Ed} = M_{xx} \times 1.35$
- Membrane forces: $N_{Ed} = N_{xx}$

Depths range [m]	A_{s1} [cm^2/m]	A_{s2} [cm^2/m]
0 - 7	12.5	12.5
7 - 10	25	12.5
10 - 18	50.0	12.5
18 - 20	12.5	12.5
20 - 26	12.5	18.75

NSO-NST approach

- **Soil**: "characteristic" values of parameters are used
- **Concrete**: characteristic values of concrete strength (f_{ck}, $f_{ctk0,05}$) and stiffness E_{cm} are used
- **Steel**: characteristic strength value f_{yk} and stiffness E_s are used

NSO-NST approach: checking the ULS state



Projecting stress resultant pairs $\{N_{xx}, M_{xx} \cdot \tilde{\gamma}\}$ on domain bound by $N - M$ interaction diagram

- $\tilde{\gamma}$ combines two partial safety factors ie. the one corresponding to the dead load (1.35) and the material one (1.4 for the concrete (according to Polish EC2) and 1.15 for the steel)
- The upper bound is $\tilde{\gamma} = 1.35 \ \cdot 1.4 \approx 1.9$ while the lower bound is $\tilde{\gamma} = 1.35 \ \cdot 1.15 \approx 1.55$
- Here we will use upper bound value $\tilde{\gamma} = 1.9$

NSO-NST approach: concrete properties

Basic model parameters:

- $E_{cm} = E_{28} = 31000$ MPa, $\nu = 0.2$, $\gamma = 25$ kN/m^3
- $f_c = 25$ MPa, $f_{co}/f_c = 0.4$, $f_{cbo}/f_c = 1.16$
- $\tilde{D}_c = 0.435$ at $\tilde{\sigma}_c/f_c = 1.0$, $G_c = 13.5 * 10^{-3}$ MN/m
- $f_t = 1.8$ MPa, $\tilde{D}_t = 0.5$ at $\tilde{\sigma}_t/f_t = 0.5$, $G_t = 0.135 * 10^{-3}$ MN/m
- $s_o = 0.2$
- $\alpha_p = 0.2$, α_d=1.0

Creep parameters (for $RH = 0.8$ and $h_o = 0.8$ m)

- $\phi_o \, \beta(f_{cm})/E_{28} = 1.14 * 10^{-4}$ MPa^{-1}
- $\beta_H = 2000$ days and $s = 0.38$

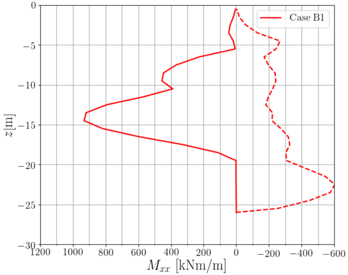
Characteristic length for RC structures

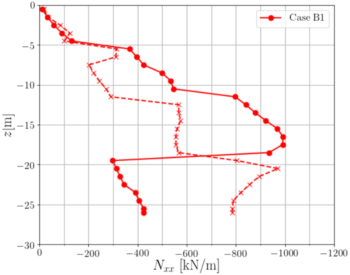
- $l_{RC} \approx \dfrac{2 \; G_f \; E_s}{f_{ctk0,05} \; f_{yk}} = 0.06m$

Results for NSO-NST approach

- **Case B1**: creep OFF (**ULS state**)

M_{xx} and N_{xx} envelopes at time of raft installation (**B1**)



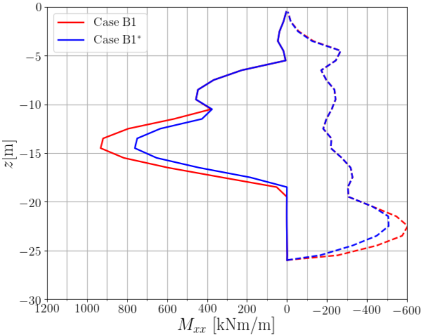


M_{xx}^{max} in case **B1** was nearly **930** kNm/m. If we scale it by $\tilde{\gamma} = 1.9$ then we get **1770** kNm/m. In case **A1** the M_{xx}^{max} was **1180** kNm/m (value used for dimensioning was $1.35 * 1180 \approx$ **1590** kNm/m). So we see that nonlinear computational strategy for $\tilde{\gamma} =$**1.9** leads to more conservative design.

Results for NSO-NST approach: ULS state

- **Case B1**: creep OFF (**ULS state**)

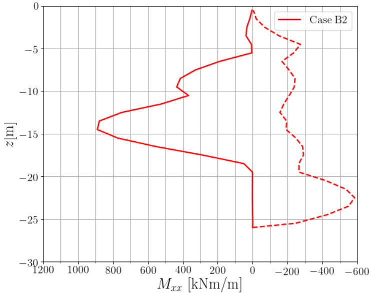
M_{xx} envelopes at time of completing the excavation (**B1***) and time instance of raft installation (**B1**)

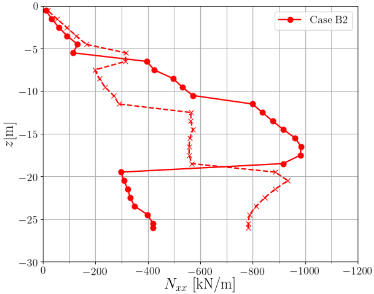


Results for NSO-NST approach: SLS state

- **Case B2**: creep ON (**SLS state**)

M_{xx} envelopes at time instance of raft installation

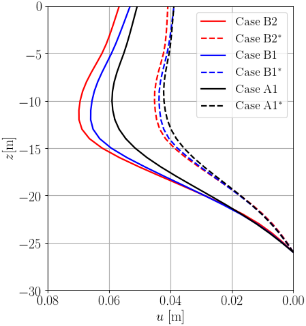




NB. max. moment reduction due to creep is approx. 3%

Results for NSO-NST approach: SLS state

Wall deflections for all cases



Comparizon of wall deflections at the time instance corresponding to the last excavation step (dashed lines)(cases A1*, B1*, B2*) and at the time instance when foundation raft is installed (solid lines)(cases A1, B1, B2)

NB. influence of creep is more visible in deformations

Results for NSO-NST approach: SLS state

What about cracks opening ?

- **Strain compatibility** between **steel** and **concrete** is preserved
- Additional kinematic hypotheses in shells or beams smear the deformation
- To remedy the problem we assume that $\varepsilon_{sm} - \varepsilon_{cm} \approx \varepsilon_s$
- The ε_s can easily be read from **reinforcement layer in shell cross section**
- Hence $w_k = s_{r,max} \left(\varepsilon_{sm} - \varepsilon_{cm}\right) \approx s_{r,max}\, \varepsilon_s$
- Then the **EC2 procedure** is used to get crack opening (it is +/- generic)

Results for NSO-NST approach: SLS state

Max. crack opening

- In the (**B2**) case $\varepsilon_s^{max} = 6.2e - 4$
- For steel cover $c = 10$ cm and equivalent steel bars diameter $\phi_{eq} = 0.0225$ (mixture of 20/25 mm bars) the $h_{c,ef} = 0.275$m, $\rho_{p,eff} = 0.0182$ and $s_{r,max} = 0.55$m
- Hence: $w_k = 0.55 \cdot 6.2e - 4 \cdot 1000 = 0.34\text{mm} > 0.3\text{mm}$ **!!**
- Designed **reinforcement in zone of the maximum moment** was **increased** to $A_{s1} = 57$ cm^2 (**by 15%**)
- For this **modified design** $\varepsilon_s^{max} = 5.35e - 4$ which yields **maximum crack opening** $w_k = 0.028$ mm < 0.3mm

Conclusions

- The **NSO-NST** approach including creep allows to properly assess both **ULS** and **SLS** states
- In case of modeling **RC structures** using **shell elements** (recommended) it is very important to declare the l_{RC} value otherwise **tension stiffening effect will not be present** in the resulting force-displacement diagram curves and **cracks/deflections may be overestimated**