# Comparing a Jacket Substructure with Suction Bucket Foundation to a Pile Foundation

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# Contents



Research project “WindBucket” (OVERDICK design)

# 1 Introduction

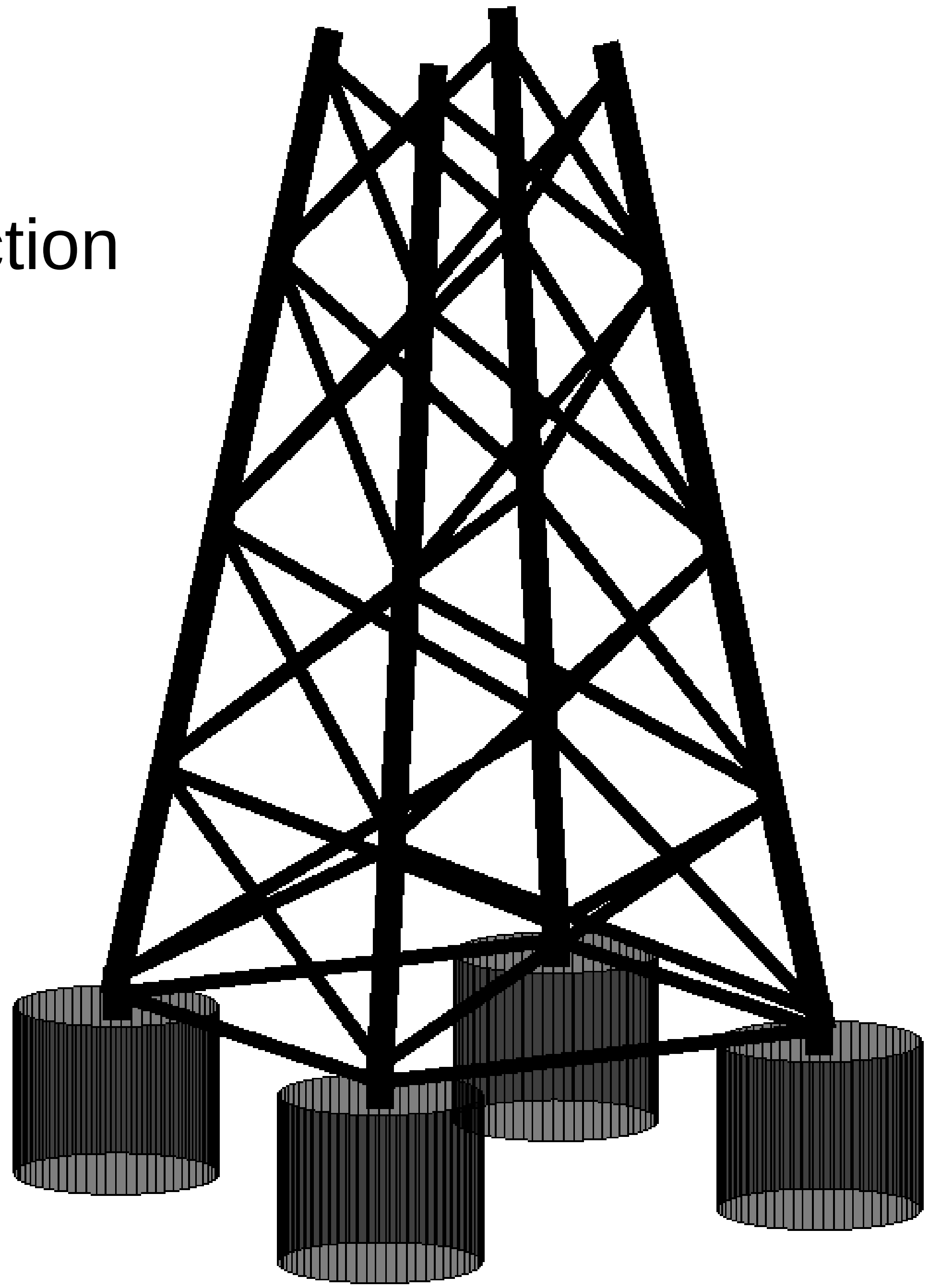


- Alternative to pile foundation
- Reducing pile driving noise
- Accelerated installation process
- Only one installation step (instead of piling, settling and grouting)
- No pile driving template necessary
- Prototype installed in 2014/2015 (OWF Borkum Riffgrund)

Suction Bucket Jacket in the OWF Borkum Riffgrund (DONG ENERGY)

# 2 Jacket Design
## 2.1 General Assumptions

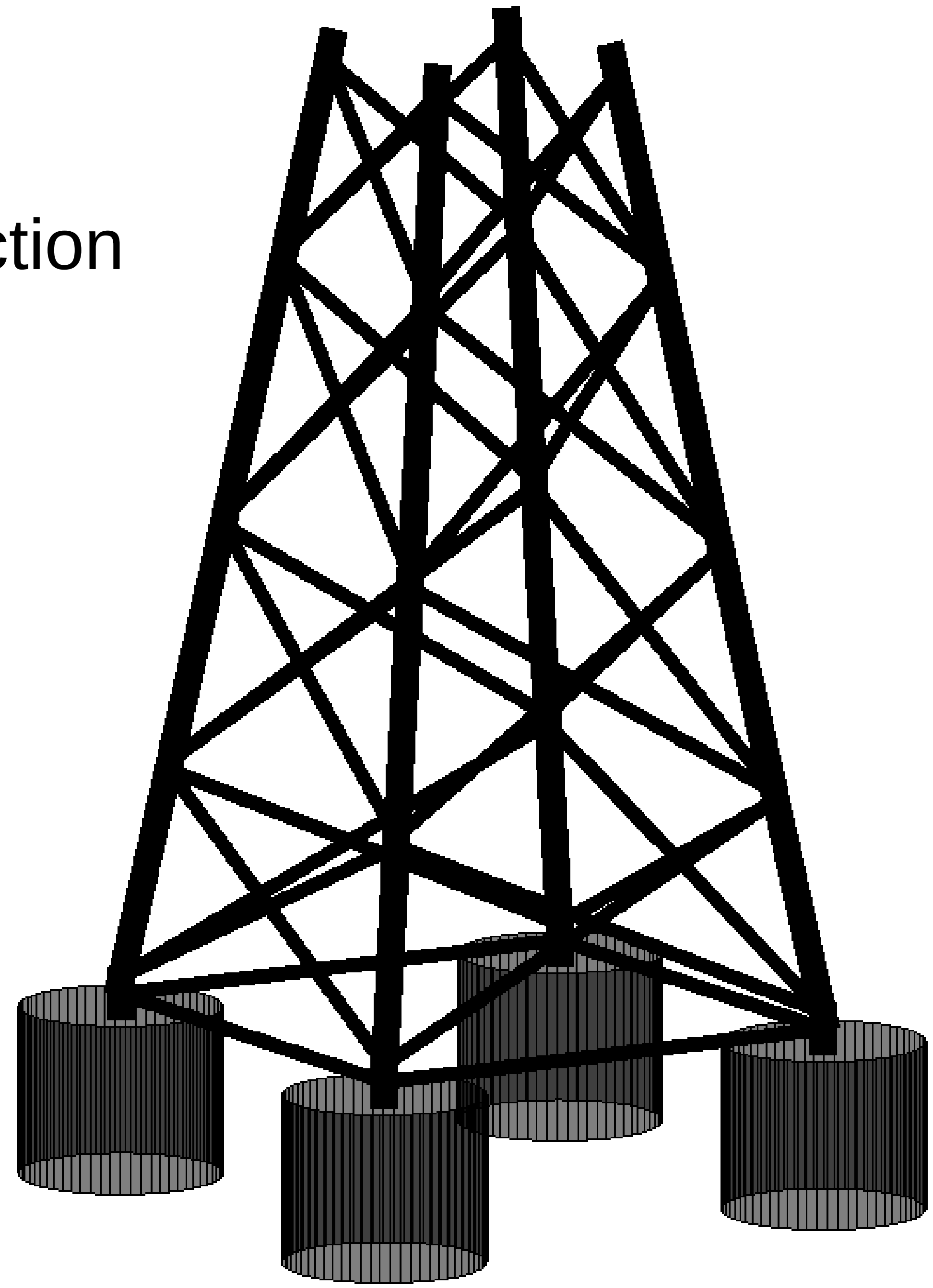
- 4-leg jacket with 4 bays
- Water depth 40 m (soil-structure-interaction considered at -38 mLAT)
- Footprint 25 m, headprint 10 m, transition piece bottom at +20 mLAT



# 2 Jacket Design
## 2.1 General Assumptions



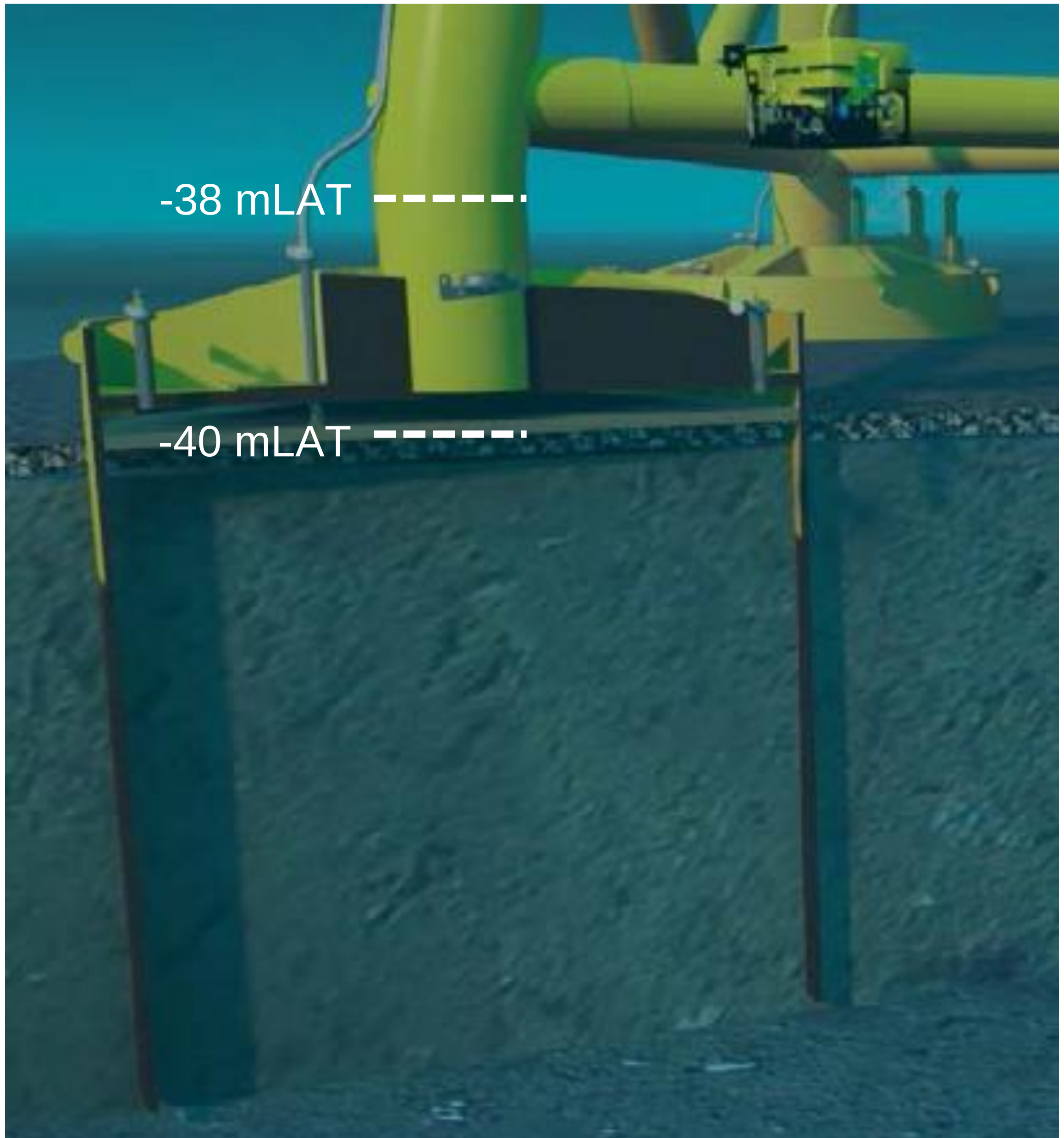
- 4-leg jacket with 4 bays
- Water depth 40 m (soil-structure-interaction considered at -38 mLAT)
- Footprint 25 m, headprint 10 m, transition piece bottom at +20 mLAT
- Loads from 5 MW turbine (NREL)
- 50-year extreme wave and 50-year extreme wind
- Tower geometry and rotor-nacelle-assembly (RNA) considered for modal analysis



# 2 Jacket Design
## 2.2 Foundation Assumptions

Model configurations:

- I: Jacket bottom fixed (clamped at -38 mLAT)
- II: Jacket with pile foundation (**$K_{SSI}$** at -38 mLAT)
- III: Jacket with suction buckets (**$K_{SSI}$** at -38 mLAT)
- Different stiffness matrices **$K_{SSI}$** regarding ULS & FLS loads and pressure & tension loads
- Inertia effects are not considered




Suction bucket example (source: DONG ENERGY)

# 2 Jacket Design
## 2.2 Steel Verifications



- Steel verifications according to DNV·GL and Eurocode 3
- Tower bottom loads combined with wave loads
  - Multi-directional (0 deg, 22.5 deg, 45 deg, …, 360 deg), equally aligned
- Ultimate limit state (50-year recurring events)
  - {Reduced wind + maximum wave} & {maximum wind + reduced wave}
  - Ultimate stress (normal, shear & equivalent stress) and column buckling

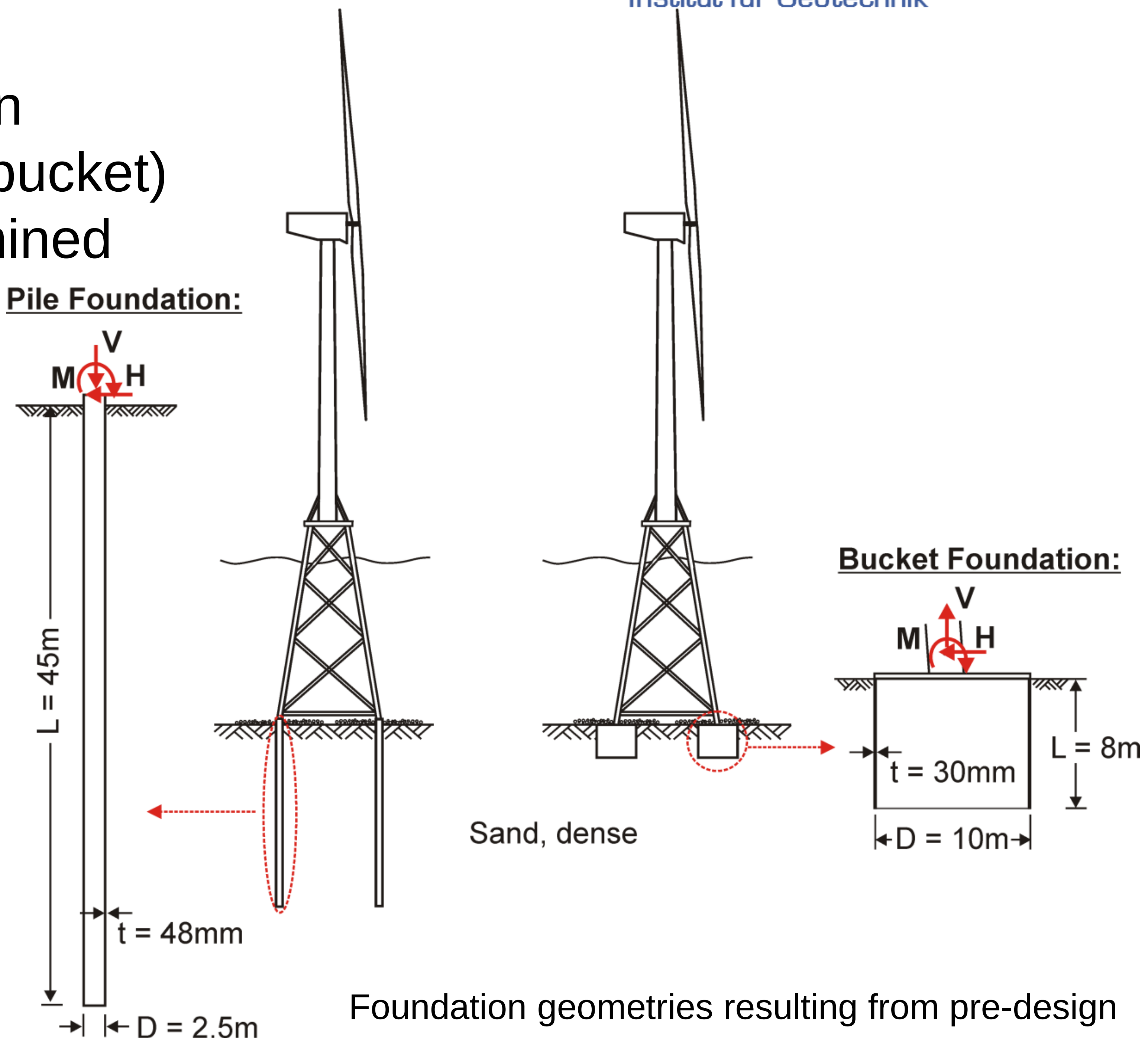
# 2 Jacket Design
## 2.2 Steel Verifications



- Steel verifications according to DNV·GL and Eurocode 3
- Tower bottom loads combined with wave loads
  - Multi-directional (0 deg, 22.5 deg, 45 deg, …, 360 deg), equally aligned
- Ultimate limit state (50-year recurring events)
  - {Reduced wind + maximum wave} & {maximum wind + reduced wave}
  - Ultimate stress (normal, shear & equivalent stress) and column buckling
- Fatigue limit state (related to 20 year lifetime)
  - Damage equivalent loads (DEL) at tower bottom
  - Fatigue waves according to scatter diagram distribution
  - Nominal stress concept (fatigue classes 71 MPa + 90 MPa)
- Modal analysis (eigenfrequencies)

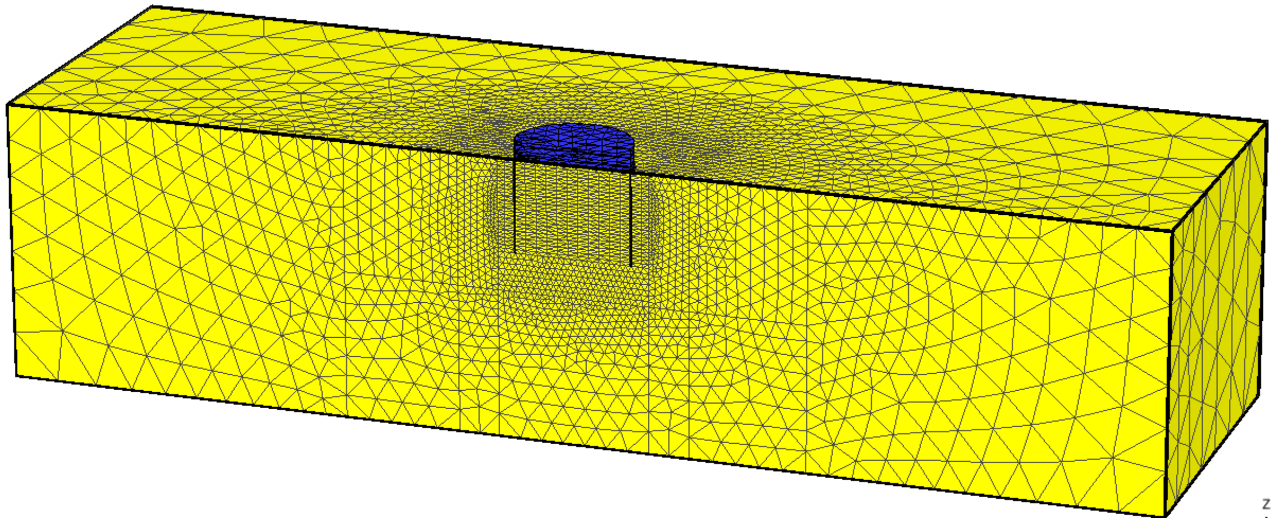
# 3 Soil-Structure-Interaction
## 3.1 Foundation Geometry

- Pre-design of foundation elements (pile, suction bucket) based on before determined internal forces
- Homogenous soil (non-cohesive)
- Scour protection
- Restoring moments




Foundation geometries resulting from pre-design

# 3 Soil-Structure-Interaction
## 3.2 Numerical Simulation



Bucket foundation (PLAXIS3D)

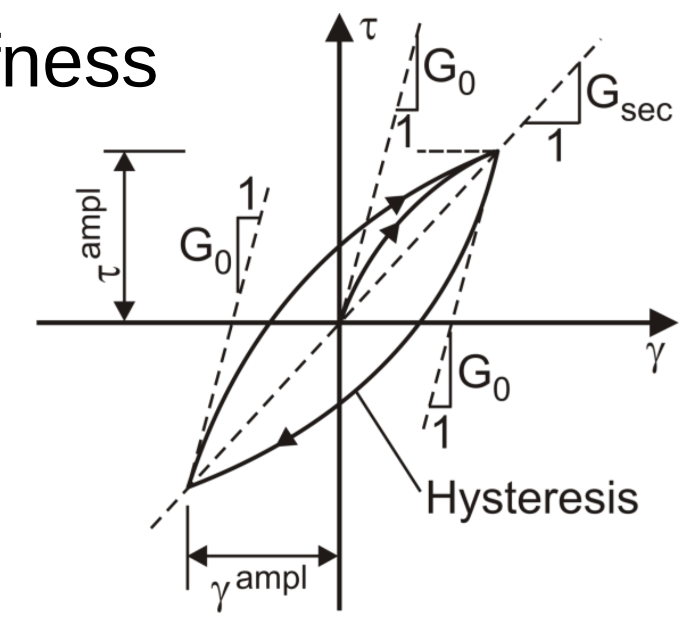
- Drained conditions
- Hardening Soil-small model (HS-small)
- Stress-dependent soil stiffness

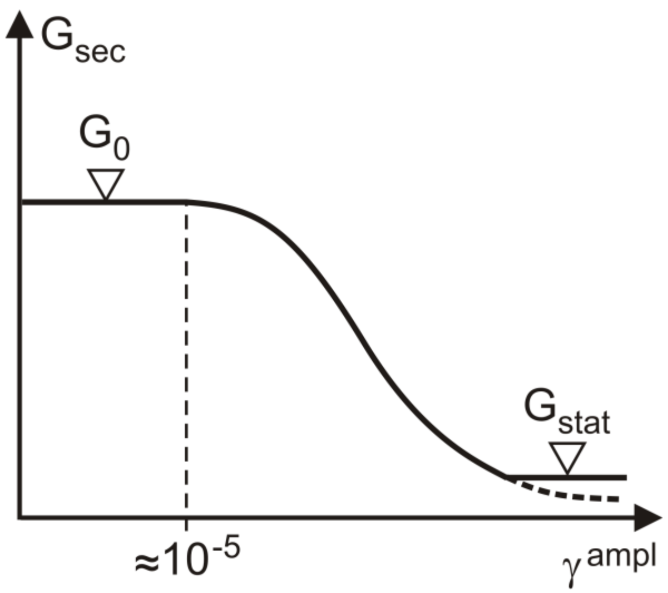
$$E_{oed} = 50000\,\frac{\text{kN}}{\text{m}^2}\cdot\left(\sigma'_m / 100\,\frac{\text{kN}}{\text{m}^2}\right)^{0.55}$$

- Strain-dependent soil stiffness

$$G_0 = 9660\,\text{kN/m}^2 \cdot (\sigma'_m / 3)^{0.5}$$

$$G / G_0 = \left(1 + \frac{0.385\cdot\gamma}{1\cdot 10^{-4}}\right)^{-1}$$

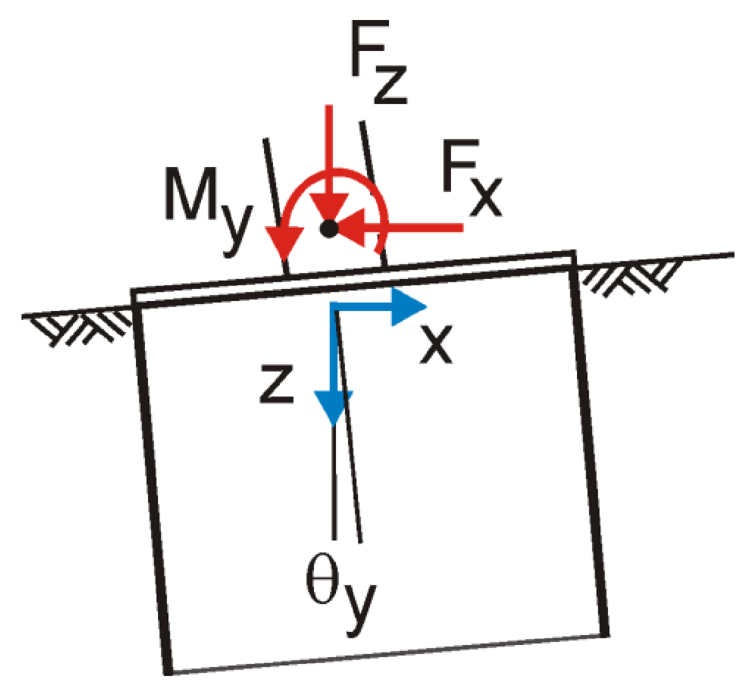


# 3 Soil-Structure-Interaction
## 3.3 Determination of stiffness matrix (i)

- Support node representing foundation elements (at -38 mLAT)
- 6 x 6 stiffness matrix (GUYAN reduction)
- Determination of relevant entries (co-directional consideration)

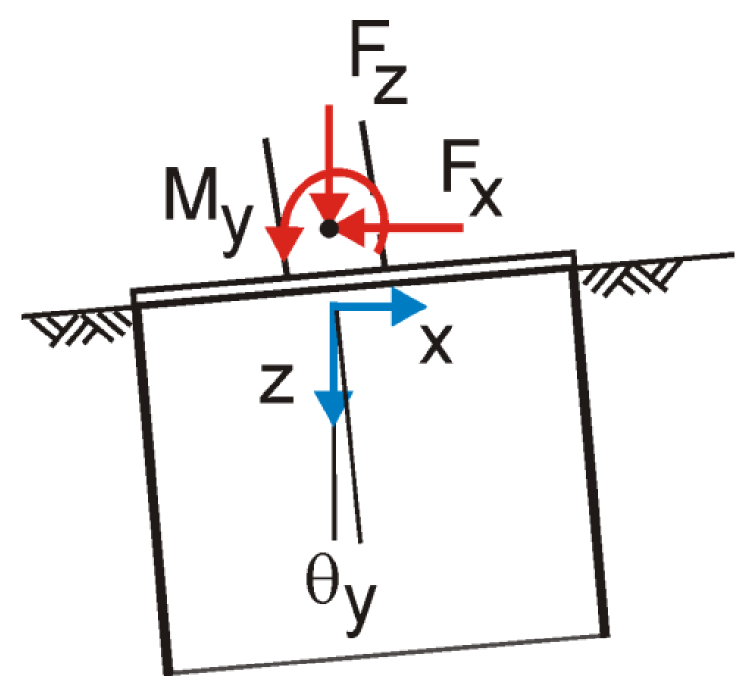
$$\begin{bmatrix} \Delta F_x \\ \Delta F_y \\ \Delta F_z \\ \Delta M_x \\ \Delta M_y \\ \Delta M_z \end{bmatrix} = \begin{bmatrix} K_{xx} & & & & K_{x\varphi} & \\ & K_{xx} & & -K_{x\varphi} & & \\ & & K_{zz} & & & \\ & -K_{\varphi x} & & K_{\varphi\varphi} & & \\ K_{\varphi x} & & & & K_{\varphi\varphi} & \\ & & & & & K_{\alpha\alpha} \end{bmatrix} \cdot \begin{bmatrix} \Delta x \\ \Delta y \\ \Delta z \\ \Delta\Theta_x \\ \Delta\Theta_y \\ \Delta\Theta_z \end{bmatrix}$$



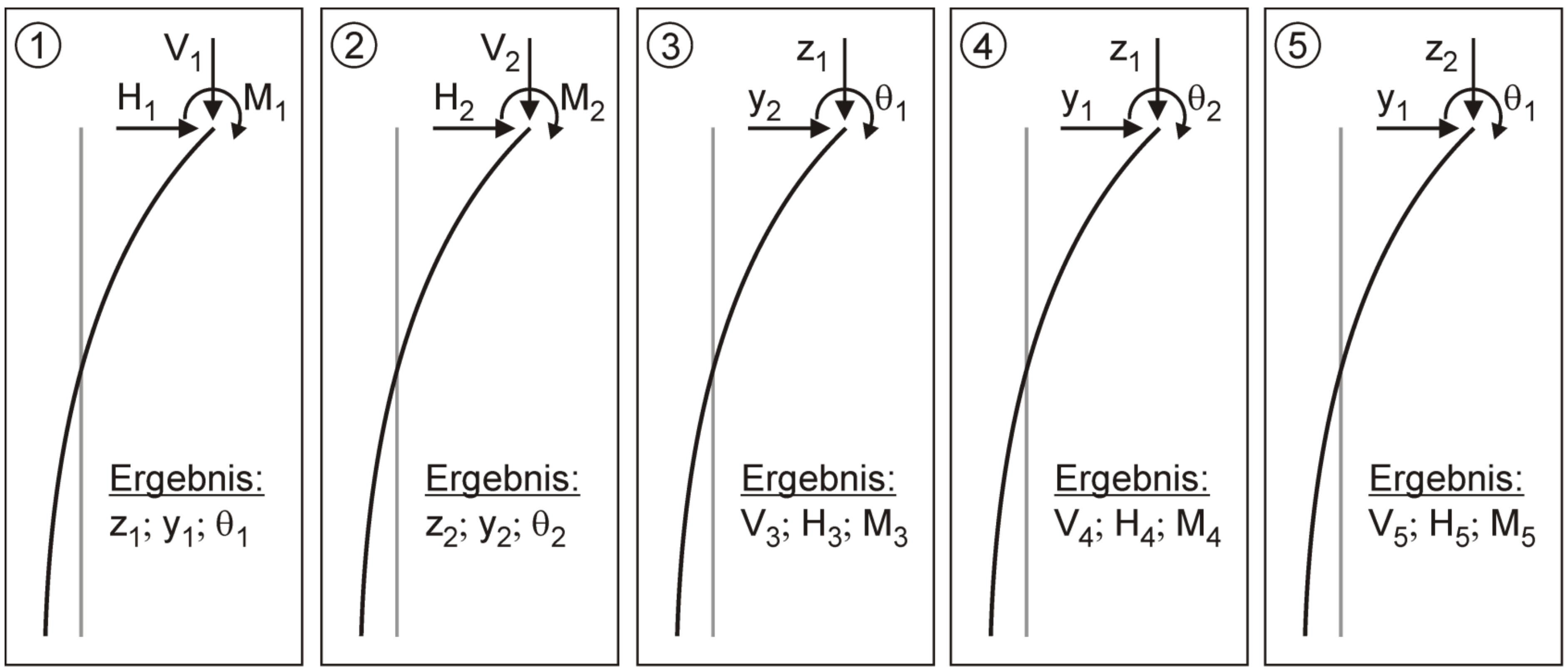
# 3 Soil-Structure-Interaction
## 3.3 Determination of stiffness matrix (i)

- Support node representing foundation elements (at -38 mLAT)
- 6 x 6 stiffness matrix (GUYAN reduction)
- Determination of relevant entries (co-directional consideration)
- Relevant coupling with vertical component

$$
\begin{bmatrix} \Delta F_x \\ \Delta F_y \\ \Delta F_z \\ \Delta M_x \\ \Delta M_y \\ \Delta M_z \end{bmatrix}
=
\begin{bmatrix}
K_{xx} & & K_{xz} & & K_{x\varphi} & \\
 & K_{xx} & K_{xz} & -K_{x\varphi} & & \\
K_{zx} & K_{zx} & K_{zz} & K_{z\varphi} & K_{z\varphi} & \\
 & -K_{\varphi x} & K_{\varphi z} & K_{\varphi\varphi} & & \\
K_{\varphi x} & & K_{\varphi z} & & K_{\varphi\varphi} & \\
 & & & & & K_{\alpha\alpha}
\end{bmatrix}
\cdot
\begin{bmatrix} \Delta x \\ \Delta y \\ \Delta z \\ \Delta\Theta_x \\ \Delta\Theta_y \\ \Delta\Theta_z \end{bmatrix}
$$



# 3 Soil-Structure-Interaction
## 3.3 Determination of stiffness matrix (ii)




Rechenoperationen:

$$K_{xx} = \frac{H_3 - H_1}{y_2 - y_1} \text{ [kN/m]}$$

$$K_{\varphi\varphi} = \frac{M_4 - M_1}{\theta_2 - \theta_1} \text{ [kNm/rad]}$$

$$K_{zz} = \frac{V_5 - V_1}{z_2 - z_1} \text{ [kN/m]}$$

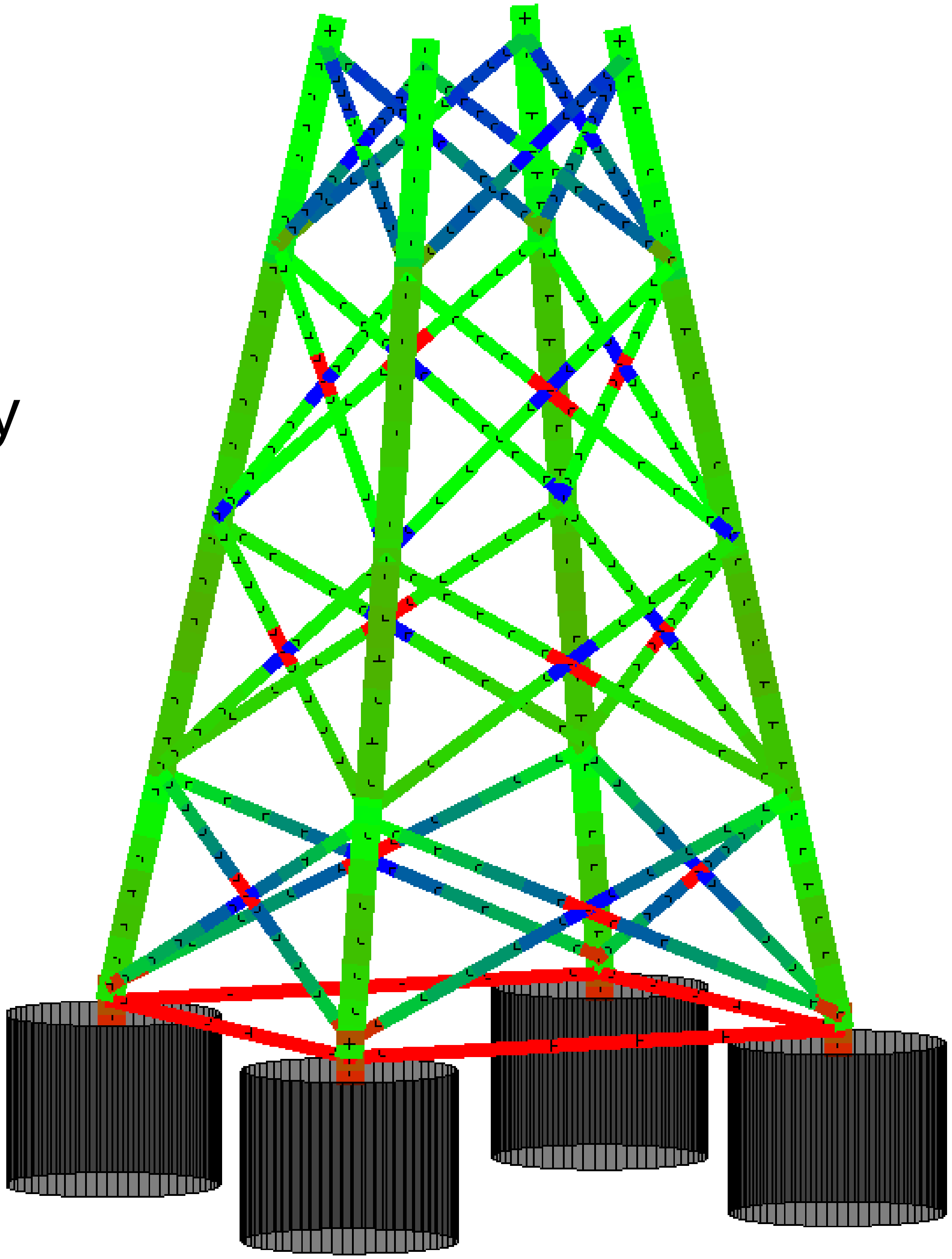
$$K_{x\varphi} = \frac{H_4 - H_1}{\theta_2 - \theta_1} \text{ [kN/rad]} \qquad K_{xz} = \frac{H_5 - H_1}{z_2 - z_1} \text{ [kN/m]} \qquad K_{z\varphi} = \frac{V_4 - V_1}{\theta_2 - \theta_1} \text{ [kN/rad]}$$

$$K_{\varphi x} = \frac{M_3 - M_1}{y_2 - y_1} \text{ [kNm/m]} \qquad K_{zx} = \frac{V_3 - V_1}{y_2 - y_1} \text{ [kN/m]} \qquad K_{\varphi z} = \frac{M_5 - M_1}{z_2 - z_1} \text{ [kNm/m]}$$

# 4 Comparison Study
## 4.1 Ultimate Stress and Buckling (i)

**Bucket foundation vs. bottom fixed**

- Higher utilized mudbrace
- Lower utilized diagonal braces of top bay



$\rho_{bucket} / \rho_{fixed} \leq 0.80$
$\rho_{bucket} / \rho_{fixed} = 1.00$
$\rho_{bucket} / \rho_{fixed} \geq 1.25$

# 4 Comparison Study
# 4.1 Ultimate Stress and Buckling (i)

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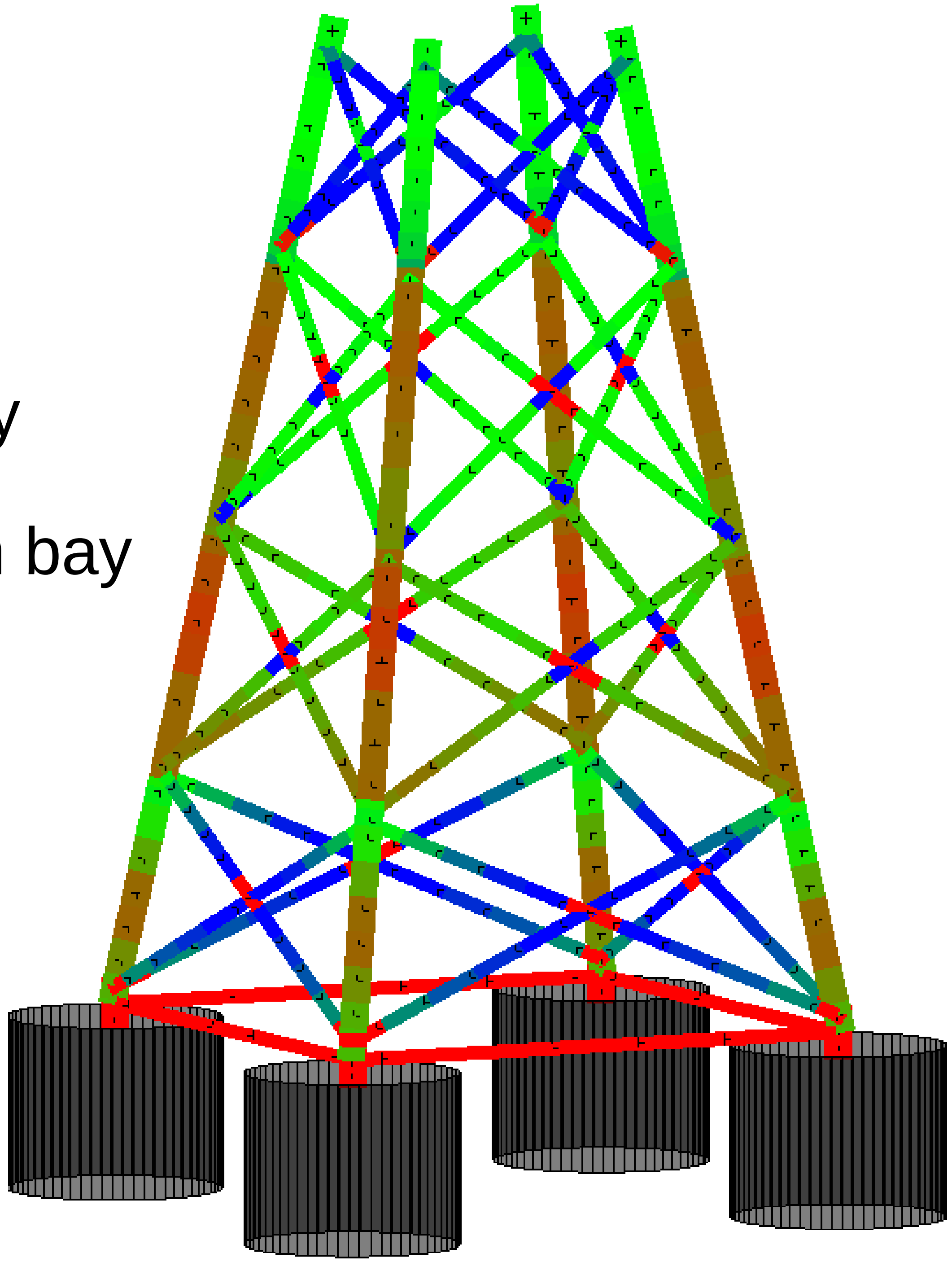
## Bucket foundation vs. bottom fixed

- Higher utilized mudbrace
- Lower utilized diagonal braces of top bay
- Lower utilized diagonal braces of bottom bay
- Higher utilized jacket legs

$\rho_{bucket} / \rho_{fixed} \leq 0.90$

$\rho_{bucket} / \rho_{fixed} = 1.00$

$\rho_{bucket} / \rho_{fixed} \geq 1.10$







Forschungsverbund Windenergie

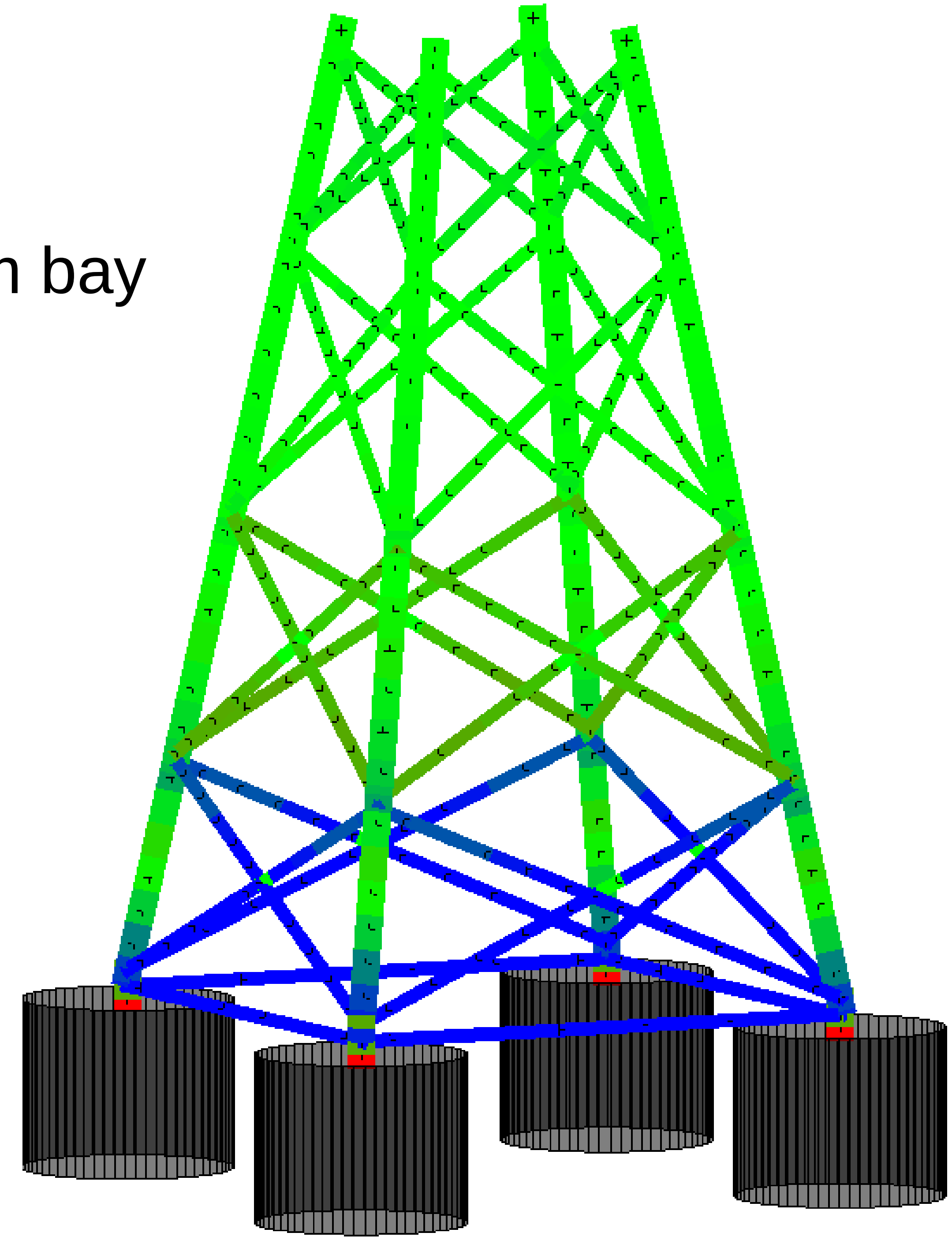
ForWind Zentrum für Windenergieforschung Bremen Hannover Oldenburg

# 4 Comparison Study
# 4.1 Ultimate Stress and Buckling (ii)

## Bucket foundation vs. pile foundation

- Lower utilized diagonal braces of bottom bay
- Lower utilized mudbrace

$\rho_{bucket} / \rho_{pile} \leq 0.80$
$\rho_{bucket} / \rho_{pile} = 1.00$
$\rho_{bucket} / \rho_{pile} \geq 1.25$

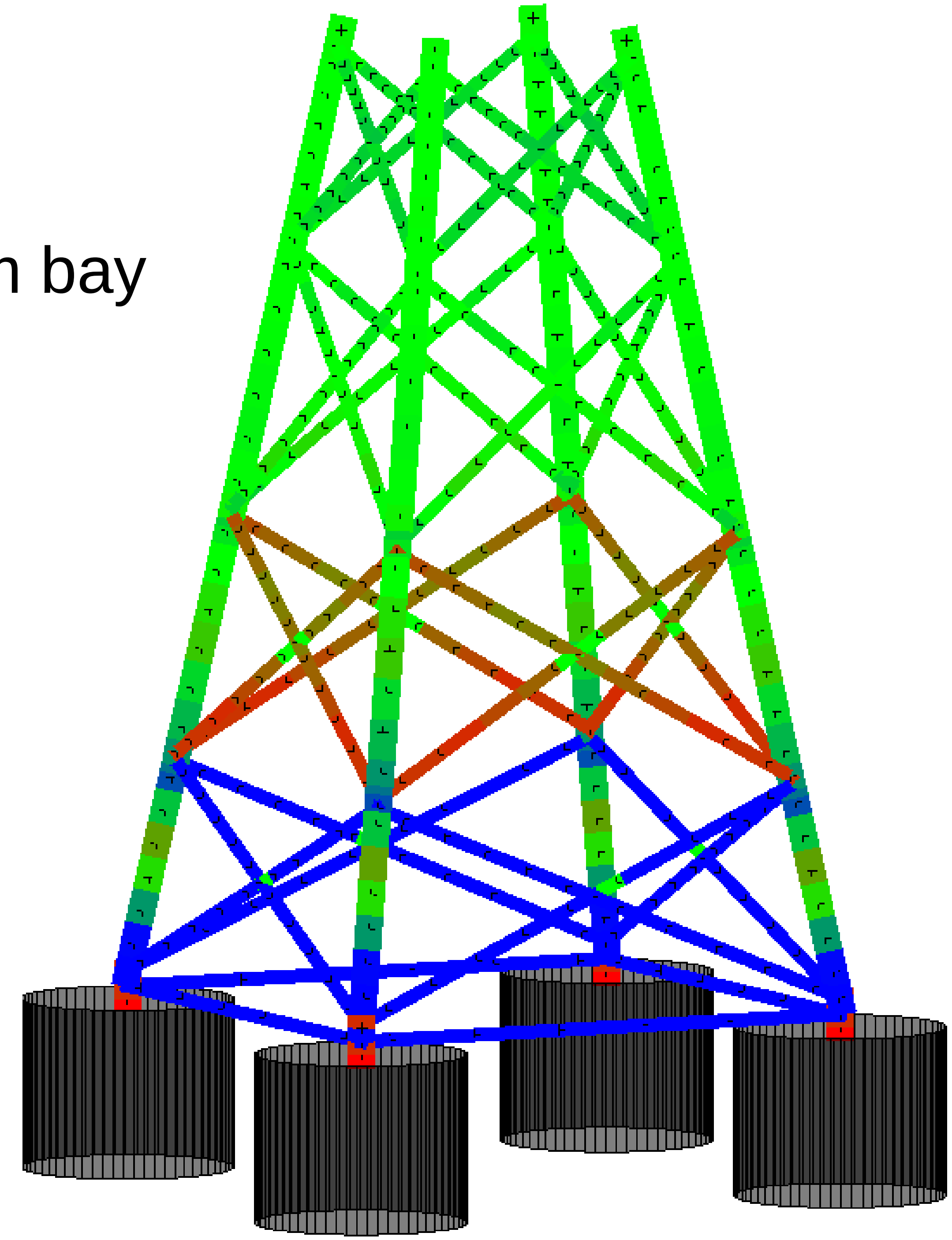


# 4 Comparison Study
## 4.1 Ultimate Stress and Buckling (ii)

### Bucket foundation vs. pile foundation

- Lower utilized diagonal braces of bottom bay
- Lower utilized mudbrace
- Lower utilized jacket legs in height of bottom bay
- Higher utilized diagonal braces of the second bottom bay
- Higher utilization at connection legs with buckets

$\rho_{bucket} / \rho_{pile} \leq 0.90$
$\rho_{bucket} / \rho_{pile} = 1.00$
$\rho_{bucket} / \rho_{pile} \geq 1.10$



# 4 Comparison Study
## 4.2 Fatigue Stress (i)



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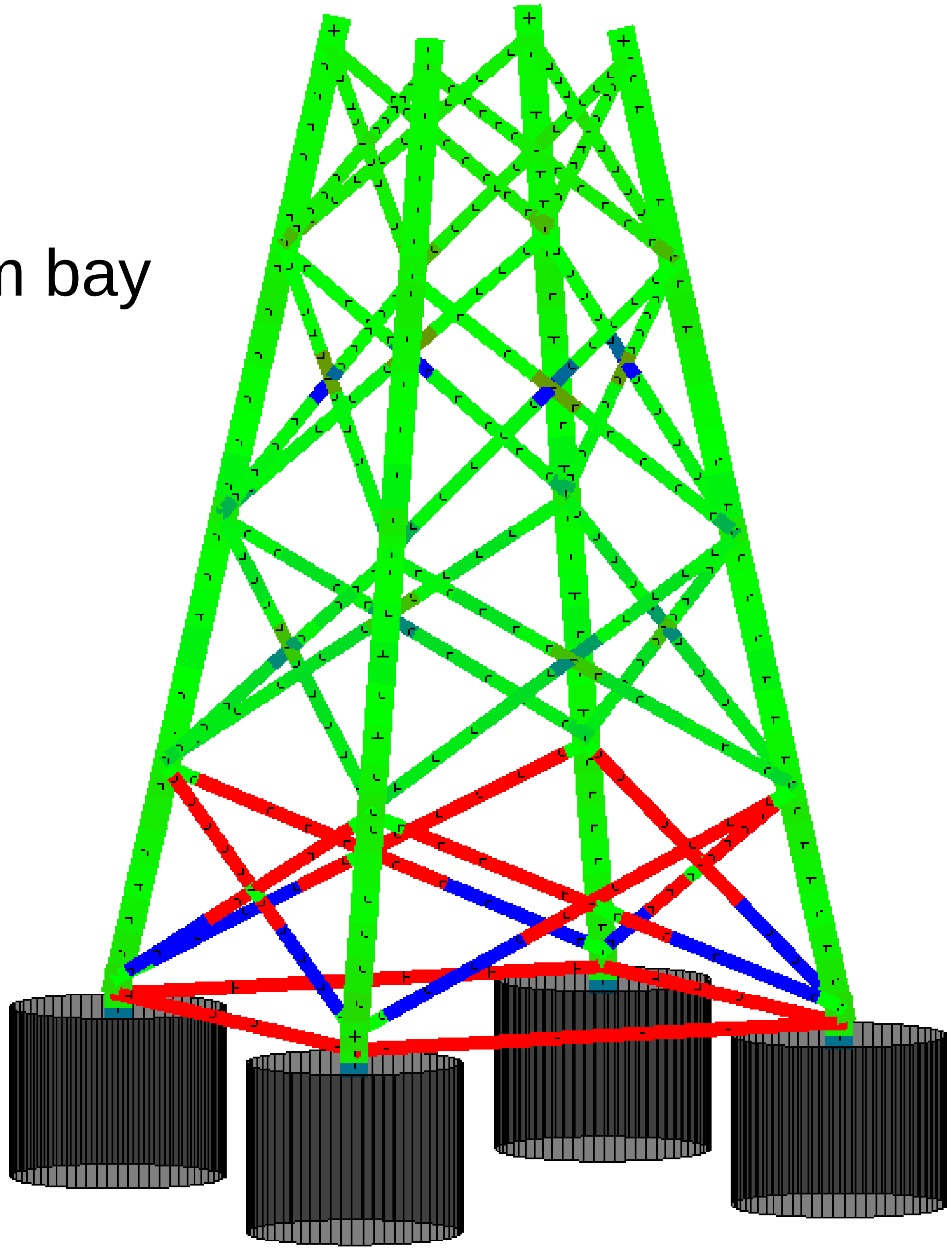
### Bucket foundation vs. bottom fixed

- Higher utilized diagonal braces of bottom bay
- Higher utilized mudbrace



$\rho_{bucket} / \rho_{fixed} \leq 0.50$

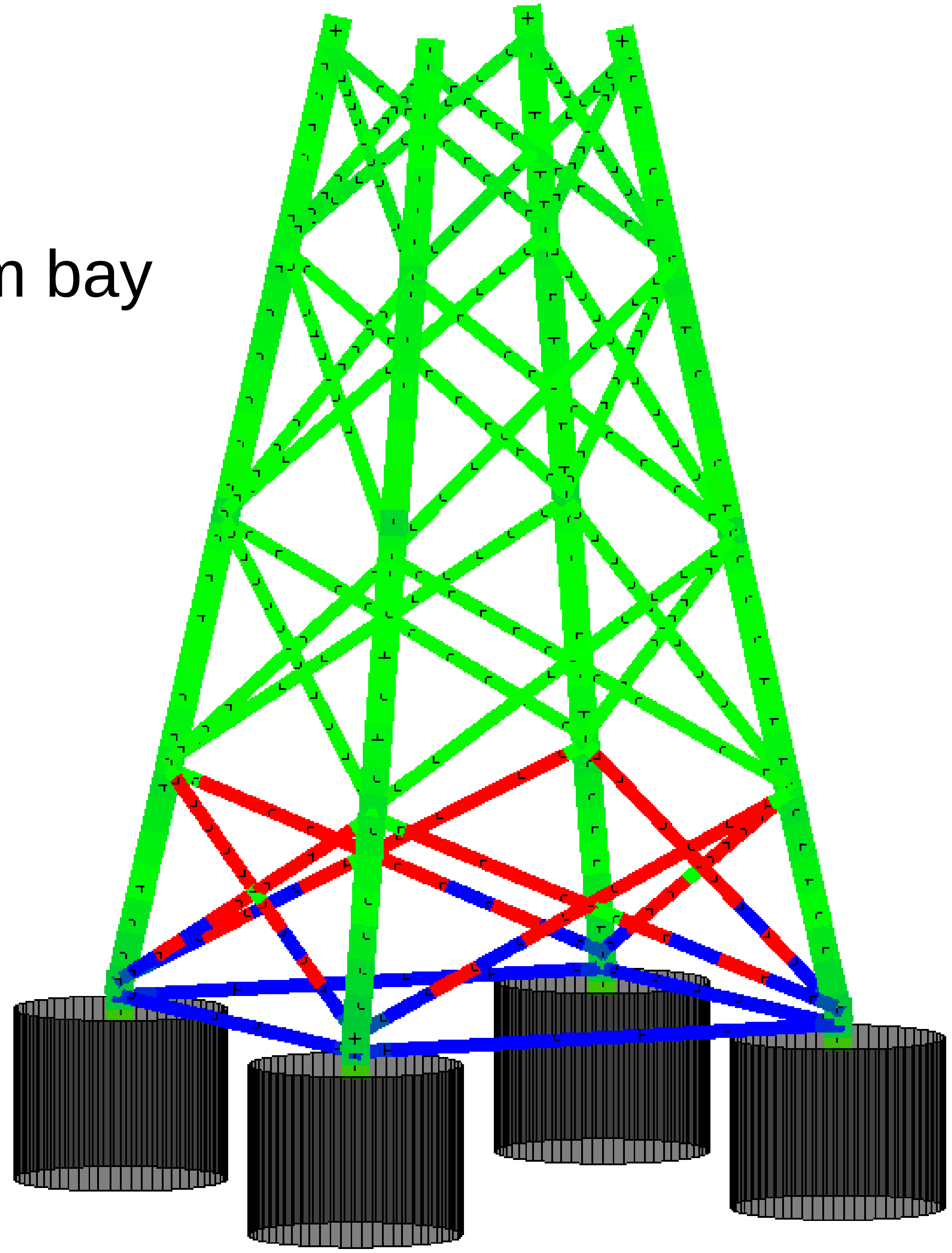
$\rho_{bucket} / \rho_{fixed} = 1.00$

$\rho_{bucket} / \rho_{fixed} \geq 2.00$

# 4 Comparison Study
# 4.2 Fatigue Stress (ii)

**Bucket foundation vs. pile foundation**

- Higher utilized diagonal braces of bottom bay
- Lower utilized mudbrace

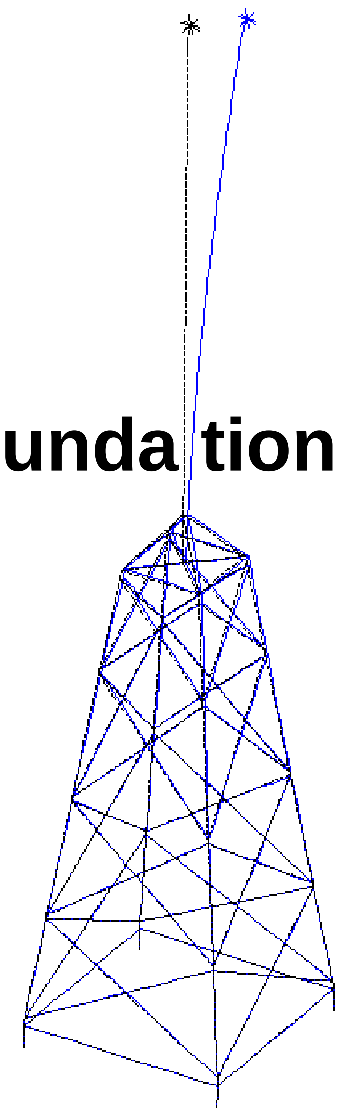


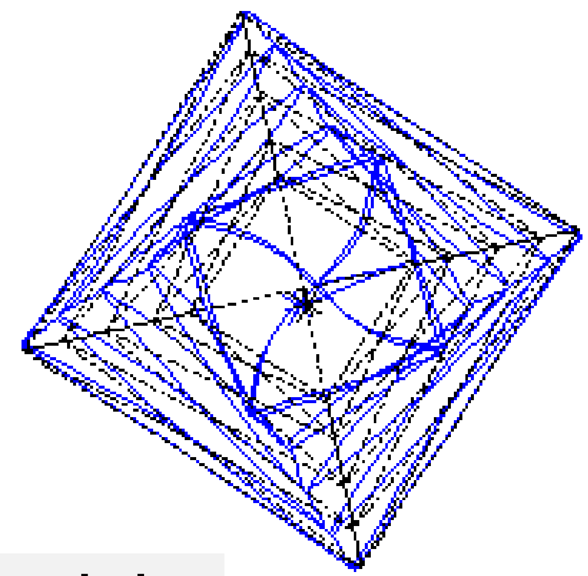
$\rho_{bucket} / \rho_{pile} \leq 0.50$
$\rho_{bucket} / \rho_{pile} = 1.00$
$\rho_{bucket} / \rho_{pile} \geq 2.00$

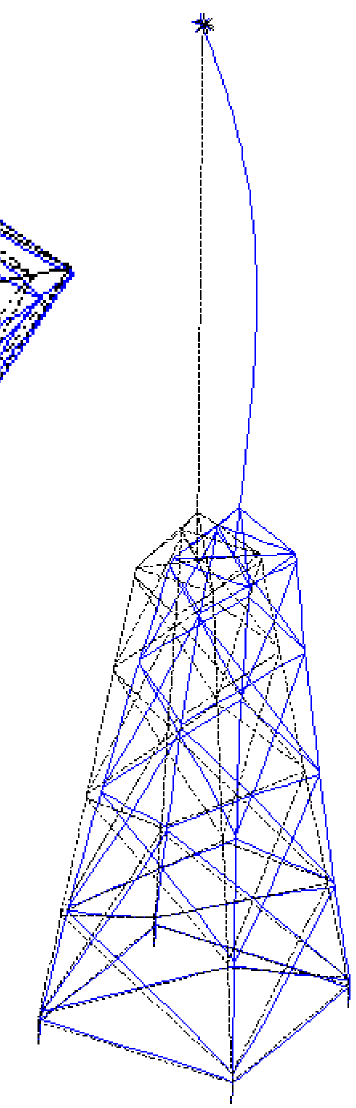
# 4 Comparison Study
# 4.3 Eigenfrequencies

## Bucket foundation vs. pile foundation (vs. bottom fixed)

- First three eigenfrequencies are nearly identical
- Bucket foundation is slightly softer than pile foundation







| Eigenfrequency/ eigenmode | | Bucket | Pile Foundation | | Fixed Foundation | |
|---|---|---|---|---|---|---|
| | | EF (Hz) | EF (Hz) | ΔEF (%) | EF (Hz) | ΔEF (%) |
| 1. | 1.gl.bending EM (s-s) | 0.3377 | 0.3379 | 0.1 | 0.3439 | 1.8 |
| 2. | 1.gl.bending EM (f-a) | 0.3386 | 0.3388 | 0.1 | 0.3450 | 1.9 |
| 3. | 1.torsional EM | 1.4101 | 1.4194 | 0.7 | 1.4222 | 0.9 |
| 4. | 2.gl.bending EM (s-s) | 1.9779 | 2.0666 | 4.5 | 2.2714 | 14.8 |
| 5. | 2.gl.bending EM (f-a) | 2.0151 | 2.1147 | 4.9 | 2.3439 | 16.3 |

# 5 Summary and Conclusions



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- Potential weight saving in the lower jacket part for the ULS verification (mudbrace, diagonal braces and legs of the lower bay)
- Potential weight saving of the mudbrace for the FLS verification, however weight increase for diagonal braces of the lower bay, otherwise no significant variations
- Bucket foundation reacts slightly softer to first couple of eigenfrequencies than pile foundation

# 5 Summary and Conclusions

- Potential weight saving in the lower jacket part for the ULS verification (mudbrace, diagonal braces and legs of the first bay)
- Potential weight saving of the mudbrace for the FLS verification, however weight increase for diagonal braces of the lower bay, otherwise no significant variations
- Bucket foundation reacts slightly softer to first couple of eigenfrequencies than pile foundation

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- *Results **only** apply to the **considered geometries** of jacket, bucket and pile as well as to the **environmental and turbine conditions**!*
- *The study has to be continued (with an integrated dynamic simulation) to obtain **general statements** concerning suction bucket foundations!*

# Thank you for your attention!

# Vielen Dank für Ihre Aufmerksamkeit!