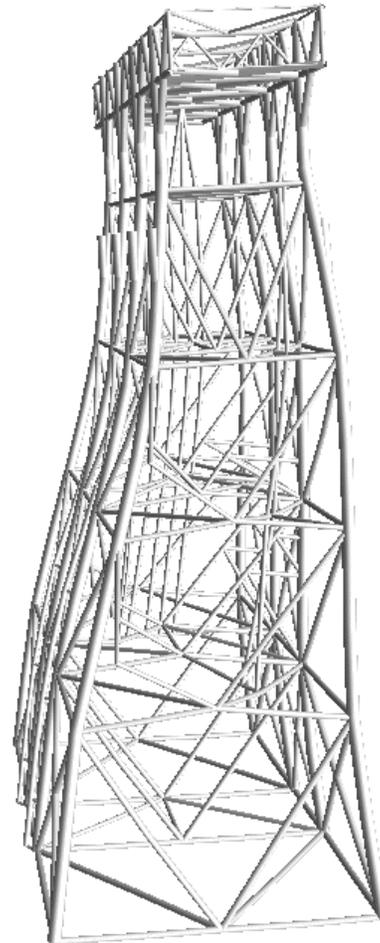


***MODELLING OF
LARGE DIAMETER PILES
IN
USFOS***



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1 Introduction

Offshore wind turbines located on moderate water depths are often using a mono pile foundation. The “pile” diameter could be in the order of 5-10m and having lengths in the order of 15-40m.

USFOS is a tool tailor made for jacket structures, where the foundation normally consists of a series of slender single piles connected to the legs. Each single pile gives axial resistance (T-Z and Q-Z) and horizontal resistance (P-Y) and the large distance between the piles gives the global bending resistance (overturning moment resistance).

When only one, relatively short (with huge diameter) “pile” is used to describe a “mono-pile foundation” a single pile in USFOS ***cannot*** describe the global bending moment resistance correctly.

The skin friction of a large diameter “pile” will provide additional bending resistance, which is not included in the conventional pile model in USFOS.

This document describes an extended pile model, which simulates the monopile by use of several standard single piles located along the circumferential of the large diameter pile.

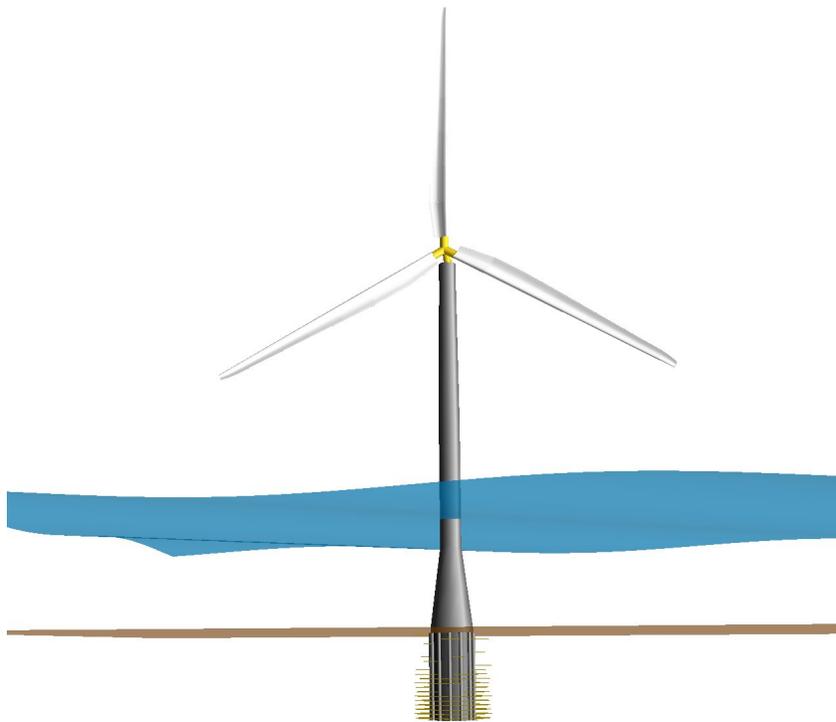


Figure 1-1 - MonoPile foundation of an offshore wind turbine

2 Theoretical Basis

2.1 General

The large diameter pile with diameter D and length L shown in Figure 2-1 is exposed to a global bending moment, M . This bending moment will introduce shear stresses τ on the pile surface (“skin friction”), which will balance the external bending moment. (Other effects also exist, here the effects from the skin friction is discussed)

The shear stress is defined as follows:

$$\tau = T-Z / D \pi , \text{ where } T-Z \text{ is the force per unit length in the } T-Z \text{ curves.}$$

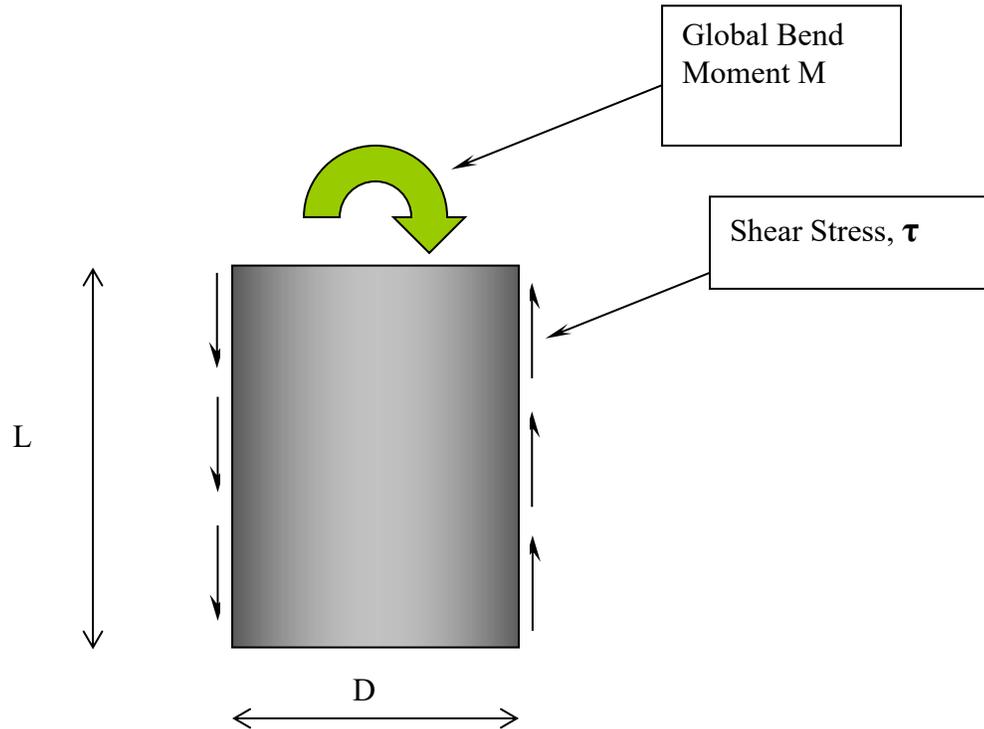


Figure 2-1 - Large Diameter Pile exposed to Global Bending, M .

2.2 Global Bending Resistance

2.2.1 Classical solution

The axial stresses σ multiplied with the wall thickness t are equal to the accumulated shear forces along the entire pile: $\tau \times L$:

$$t \times \sigma = \tau \times L$$

Where τ is the mobilized skin friction “T-Z”, (here for simplicity assumed to be constant over the entire pile length L . In a real case, the shear will vary, and the small length dL is used instead.)

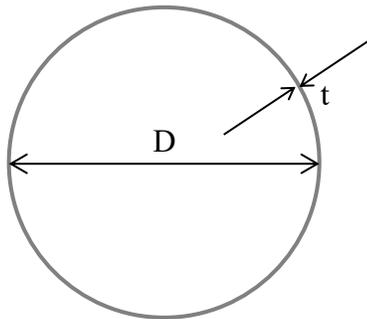


Figure 2-2 - Upper Section of the Large Pile

The bending capacities of a pipe section are:

- Elastic : $M_e = W_e \times \sigma$
- Plastic : $M_p = W_p \times \sigma$

Where

$$\begin{aligned} W_e &\approx \pi R^2 t \\ W_p &\approx 4 R^2 t \end{aligned}$$

The bending resistance provided by the skin friction then becomes:

$$\begin{aligned} M_e &\approx \pi R^2 t \sigma_y = \pi R^2 \tau_y \times L \\ M_p &\approx 4 R^2 t \sigma_y = 4 R^2 \tau_y \times L \end{aligned}$$

Where

- τ_y : is the maximum (yield) shear stress
- R : is the pipe radius.

2.2.2 Discrete (integration) points

Instead of using the classical expressions to find the bending resistance, it is possible to use a limited number of “integration points”. Each point represents a certain arc of the pipe, where the integration point area becomes:

$$dA = \alpha R t, \quad \alpha = 2\pi / n, \quad n \text{ is number of integration points.}$$

Each integration point’s contribution, dM to the total bending resistance is:

$$dM = dA \sigma \times r, \text{ where } r \text{ is the distance to the actual rotation axis.}$$

The product of dA and stress σ is the actual integration point force, dF , and the moment could then be written as:

$$dM = dF \times r$$

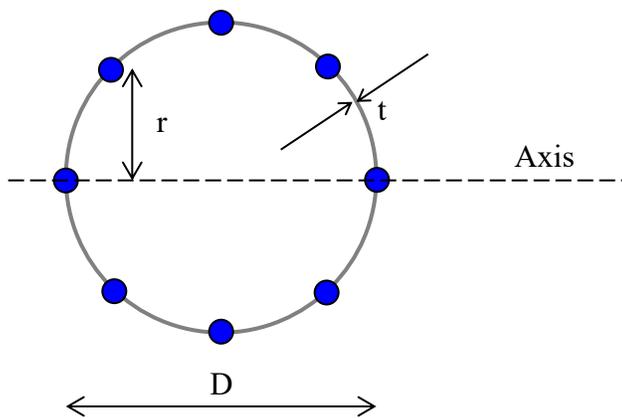


Figure 2-3 – Pipe with 8 integration points along the circumferential

This “integration point” technique will be used when a number of piles are placed along the circumferential of the real large diameter pile.

2.3 End Bearing (Q-Z).

A large diameter pile will, (in addition to the skin friction along the pile), mobilize the end-bearing.

For the normal small diameter pile (length is many times larger than the diameter) only the axial resistance is of interest. The pile tip resistance is either “plugged” or “not plugged”. The plugged tip gives assumes contact area = πr^2 , while the “not plugged” has a contact area of $\sim 2 \pi r t$. The “not-plugged” is the most relevant for mono piles.

Until the contact stress σ_N caused by the bending becomes zero (the vertical force gives compressions stresses under the pile), and/or σ_N exceeds the “yield” the linear elastic bending resistances are:

- Plugged : $M = \sigma_N W_e = \sigma_N \pi R^3 / 4$ (massive pipe cross section)
- No Plug : $M = \sigma_N W_e = \sigma_N \pi R^2 t$ (thin walled pipe section)

If a plugged case should be simplified, the equivalent thickness could be set as: $t' = R/4$. in connection with use of “integration points”.

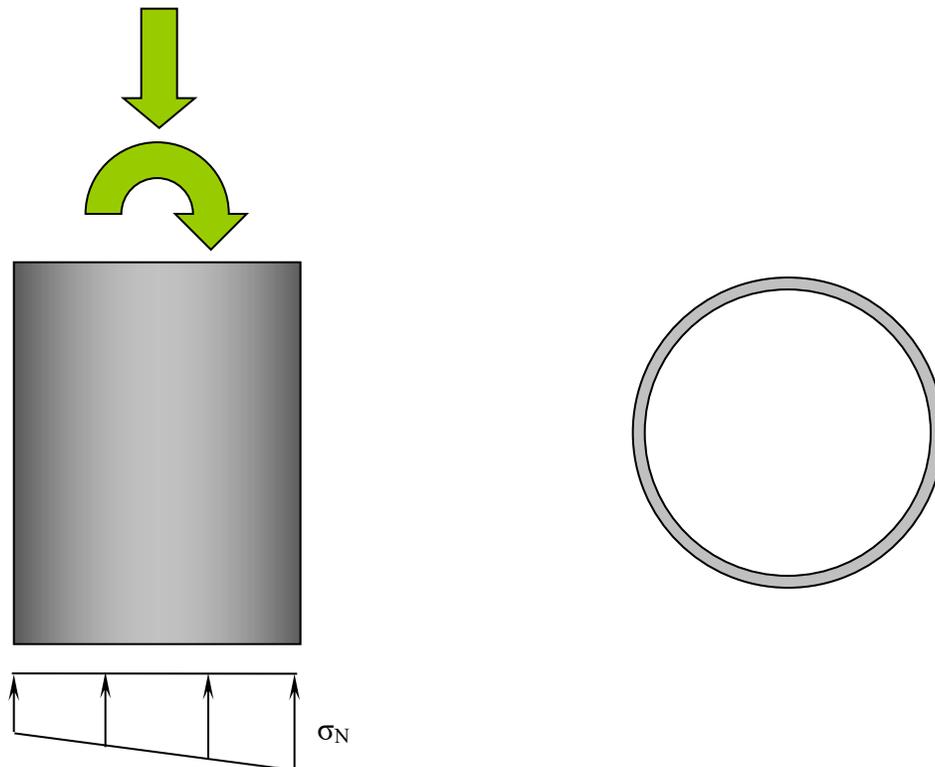


Figure 2-4 - Pressure on the end of the pile: "Q-Z"

The end bearing stress σ_N could be expressed as follows:

- Plugged : $\sigma_N = Q / \pi R^2$
- UnPlugged : $\sigma_N = Q / 2\pi R t$

where Q is the force in the Q-Z curve.

$M = \sigma_N W e = \sigma_N \pi R^2 t$, where t is either the pipe thickness (un-plugged) or the equivalent thickness (plugged, $t' = R/4$).

If the discrete point approximation is used (as shown above for the skin friction), each point's area becomes:

$$dA = \alpha R t, \quad \alpha = 2\pi / n, \quad n \text{ is number of integration points.}$$

- Plugged : $dA = \alpha R t' = \alpha R R/4 = \alpha R^2/4$
- UnPlugged : $dA = \alpha R t$

The peak resistance per integration point would then become:

$$dF = \sigma_N dA$$

- Plugged : $dF = \sigma_N dA = \sigma_N \alpha R^2/4$
- UnPlugged : $dF = \sigma_N dA = \sigma_N \alpha R t$

Total end bearing (vertical force) becomes for the plugged alternative:

$$F = n dF = n \sigma_N \alpha R^2/4 = n \sigma_N (2\pi / n) R^2/4 = \pi R^2/2 \sigma_N$$

$$F = \pi R^2/2 (Q / \pi R^2) = Q/2$$

I.e.: 50% of the actual

The un-plugged alternative:

$$F = n dF = n \sigma_N \alpha R t = n \sigma_N (2\pi / n) R t = 2\pi R t \sigma_N$$

$$F = 2\pi R t Q / 2\pi R t = Q$$

I.e.: 100% of the actual

This means that the “plugged” alternative will under estimate the total end bearing if the bending is computed accurately. However, in a normal case for large diameter piles, the foundation is not governed by failure due to vertical loads. The bending resistance is the most important. Mono piles are not “plugged”.

3 MonoPile Input

3.1 Description

The input for a mono-pile is identical to the input for a single pile, except for the keyword “MonoPile” given under PILEGEO. The user may specify the number of “integration points” using the parameter next to the pile thickness. If the number is not given the default number of 8 is used.

The actual pile has a diameter of 10m and a length of 40m. 16 auxiliary piles (“integration points”) located at the circumferential of the large (real) pile represent the mono-pile resistance. The forces going into each integration point is transferred to the (real) monopile.

```

'
      Node ID          X          Y          Z  Boundary code
NODE          2          0.000      0.000      0.000
NODE         2000          0.000      0.000     -40.000
'
'
      Mat ID      E-mod      Poiss      Yield      Density
MISOIEP        2      210000E6      0.3      340E6      7850
'
      Pile_id  Node1  Node2  Soil_id  Pile_mat  Pile_geo
PILE         1001     2     2000     1000     2      1000
'
      Pile_geo  type      Do      T      N
PILEGEO     1000  MonoPile  10      .050  16
'
      ID  Type  Z_mud  D_ref  F_Fac  L_Fac  Z_top  Z_bott  PY  TZ  QZ
SOILCHAR 1000 Curve  0.0   10     1.0   1.0   0.0   -1.0  101 201 0
          -1.0  -2.0  101 201 0
          -2.0  -3.0  101 201 0
  
```

Figure 3-1 – Pile/Soil definition in USFOS

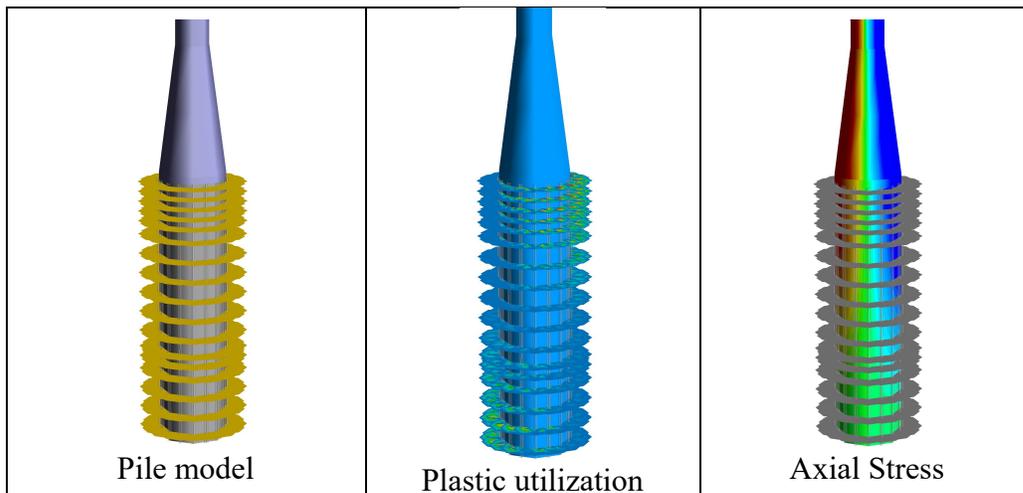


Figure 3-2 - Generated Monopile model.

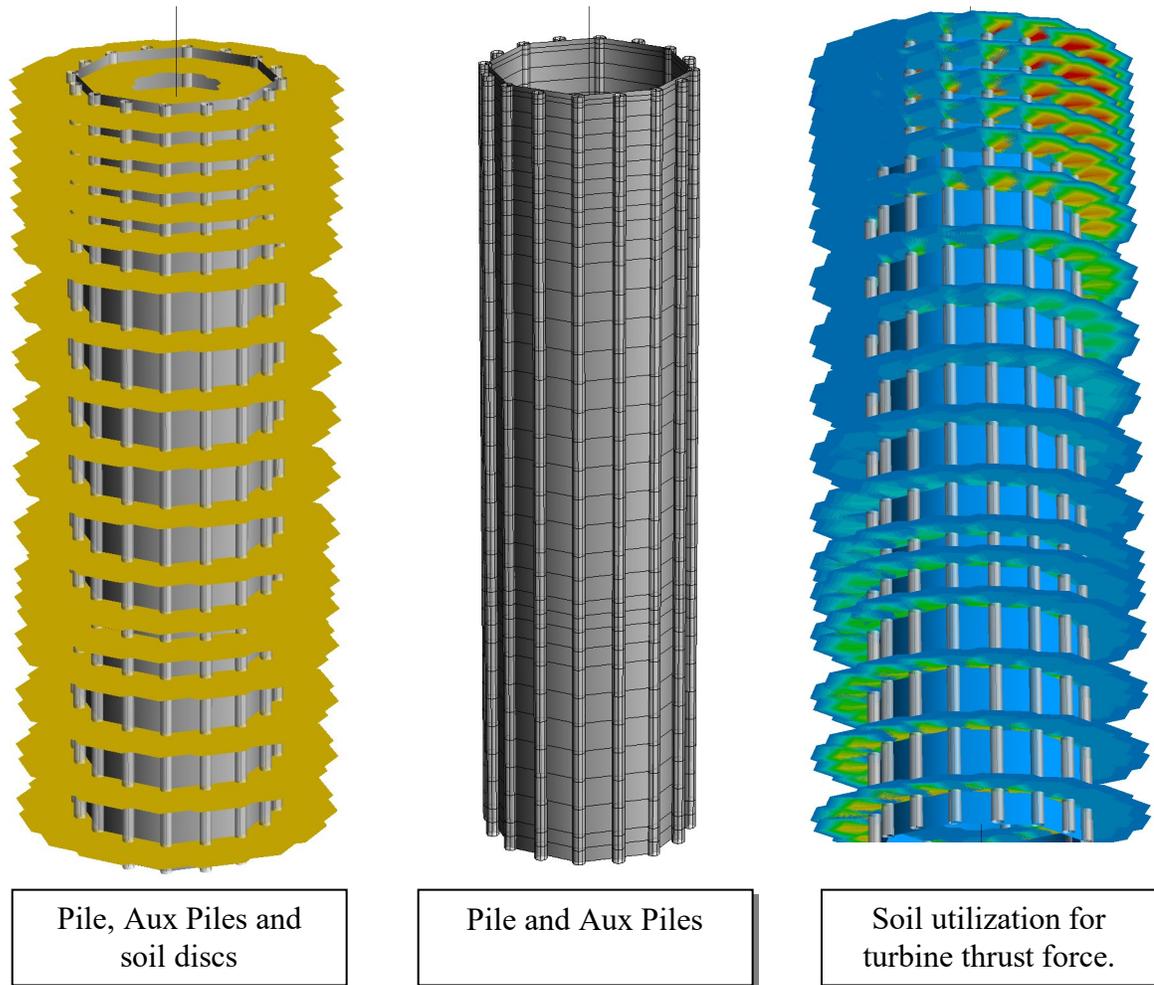


Figure 3-3 - Foundation model. Length = 40m

Figure 3-4 shows a 30 m long monopile supporting a “real” wind turbine.

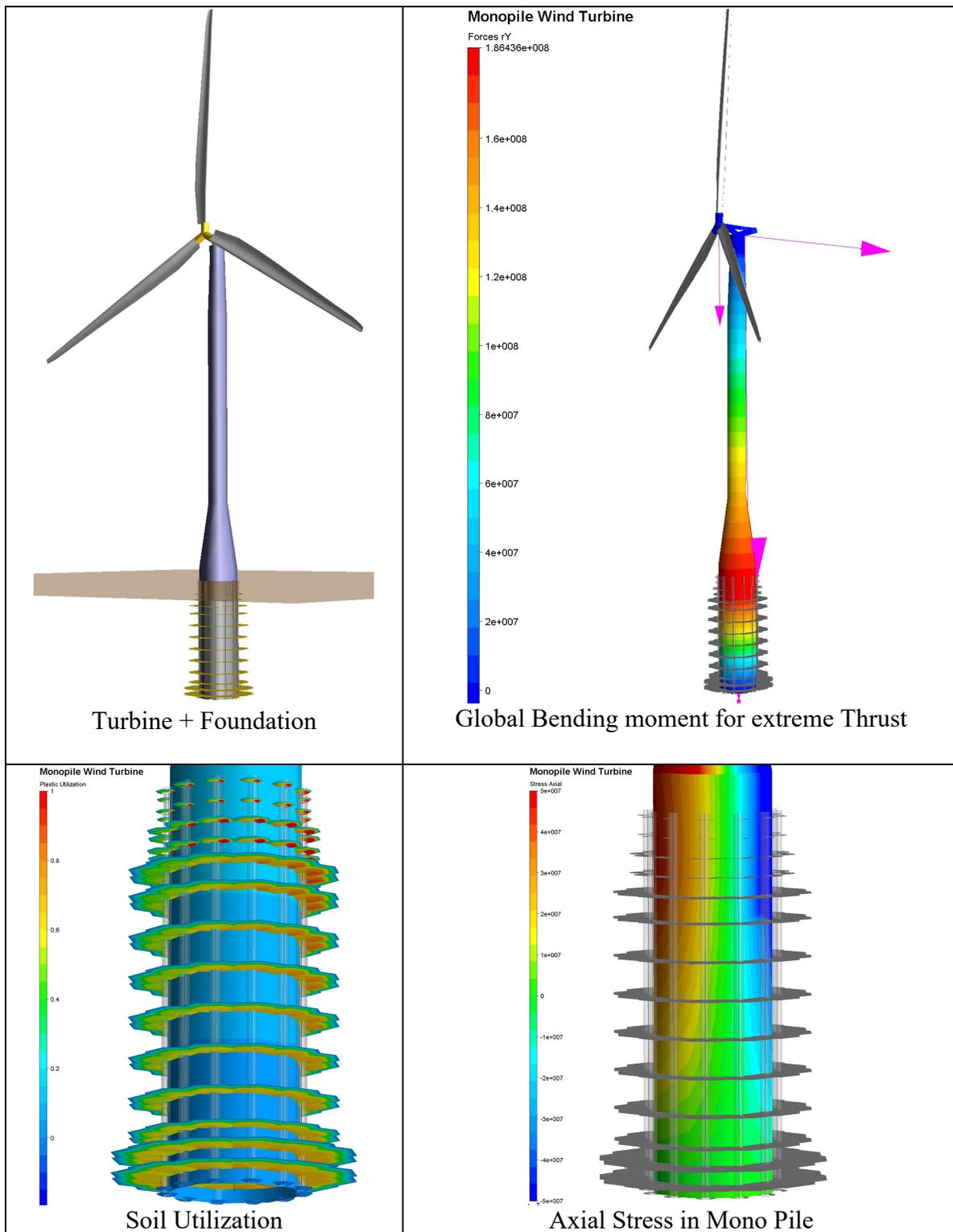


Figure 3-4 - Illustration of possible analysis results. Pile Length = 30m

3.2 Comparison with ordinary (single) pile

3.2.1 P-Y and T-Z only (no end-bearing)

The conventional pile (“single”) and the modified (“monopile”) are compared for varying L/D ratios (from 1 to 4). No end bearing is accounted for. For L/D ~4, the bending resistance is dominated by P-Y, and the conventional “single” pile gives approx same resistance as the monopile, which accounts for skin friction.

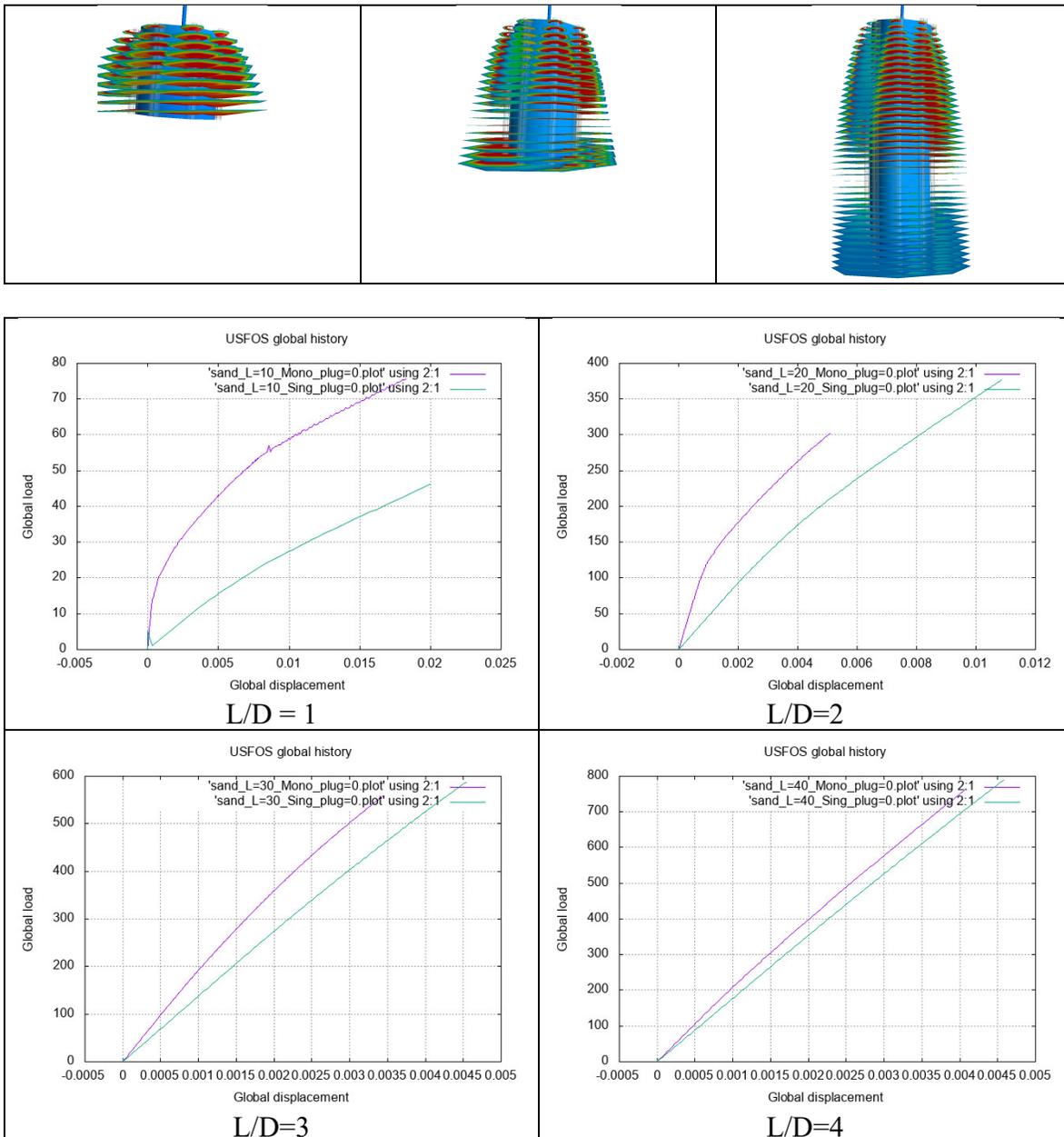


Figure 3-5 - Moment vs. Rotation for L/D 1 to 4. Ordinary (“single”) vs. MonoPile. “No Plug”

3.2.2 P-Y, T-Z and Q-Z

If end bearing were accounted for (not relevant for most monopile designs), the bending resistance increases substantially for the short piles ($L/D=1$). For $L/D > 3$, the end bearing has no practical impact on the bending resistance of the monopile.

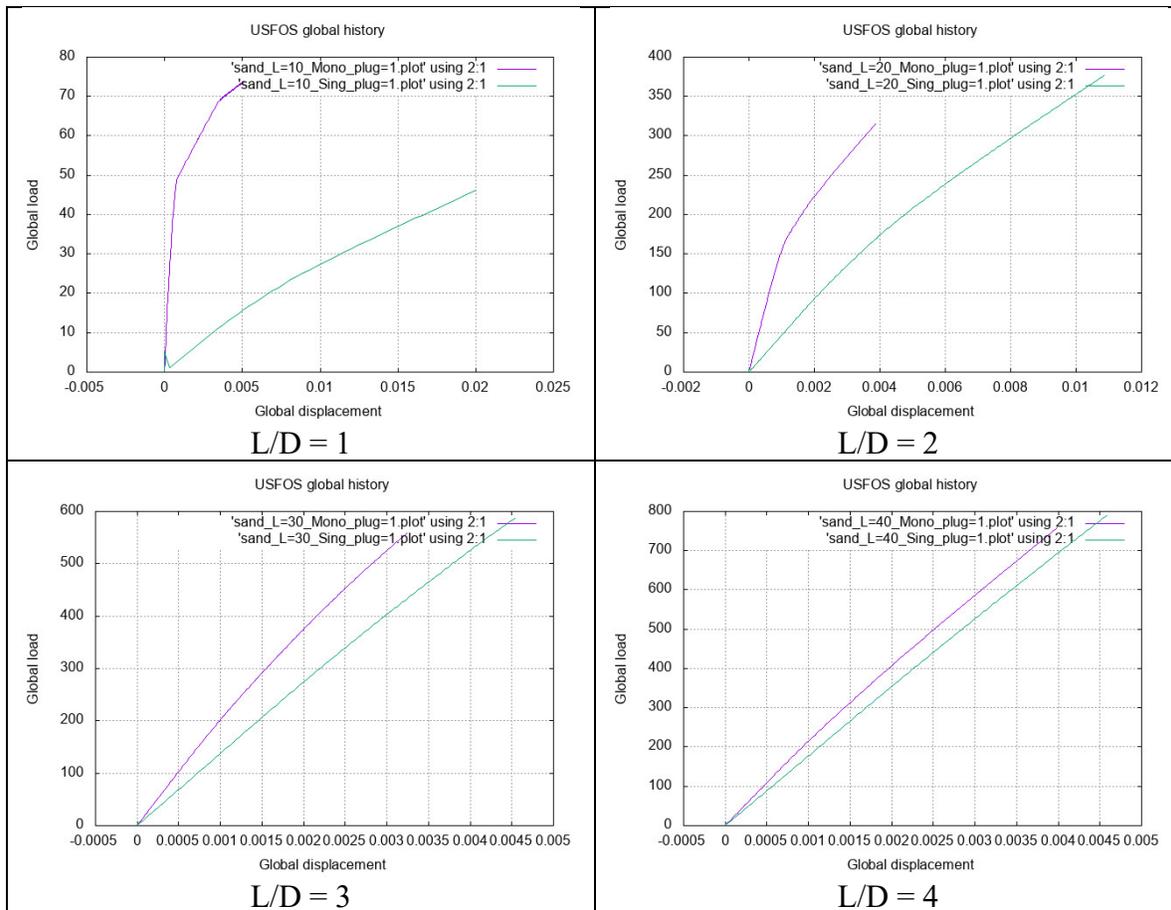


Figure 3-6 - Comparison Modified Pile. Impact from Q-Z

3.3 Ground Motion (“SoilDisp”)

The soil is moving according to a certain TimeHist, and these soil movements will be transferred to the monopile through the soil elements. The stronger/stiffer soil, the more efficient will the motions be transferred to the monopile. The usual results, such as time histories of forces are extracted from XACT.

'		Ildcs	Tim Hist			
LOADHIST	4	4	!	Earthquake		
'						
'	lCase	Type	z_Top	z_Bot	iCode	Value
SoilDisp	4	1	0.0	-30	1	0.1

Figure 3-7 - Definition of soil motion.

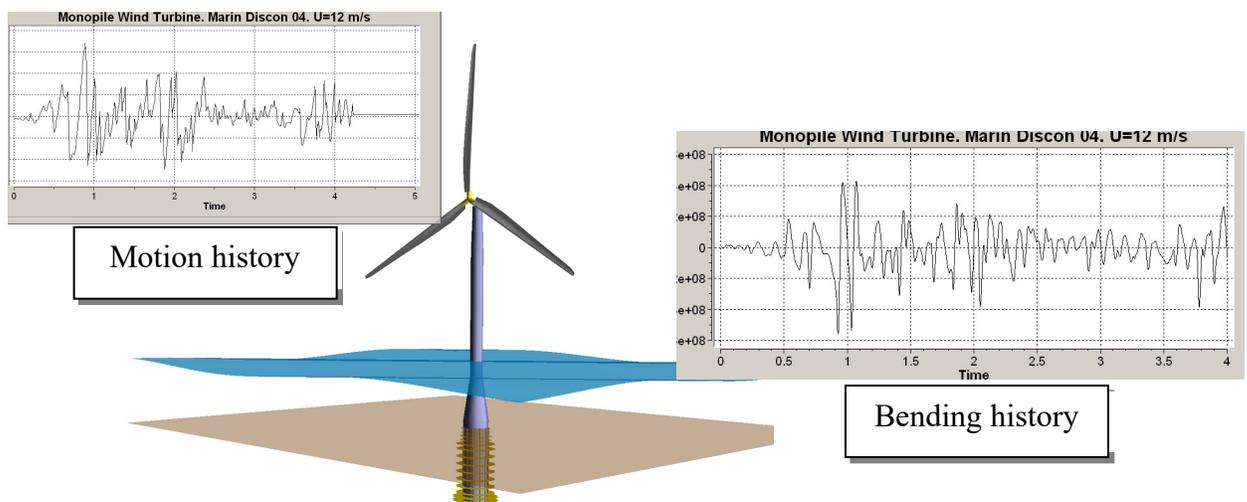
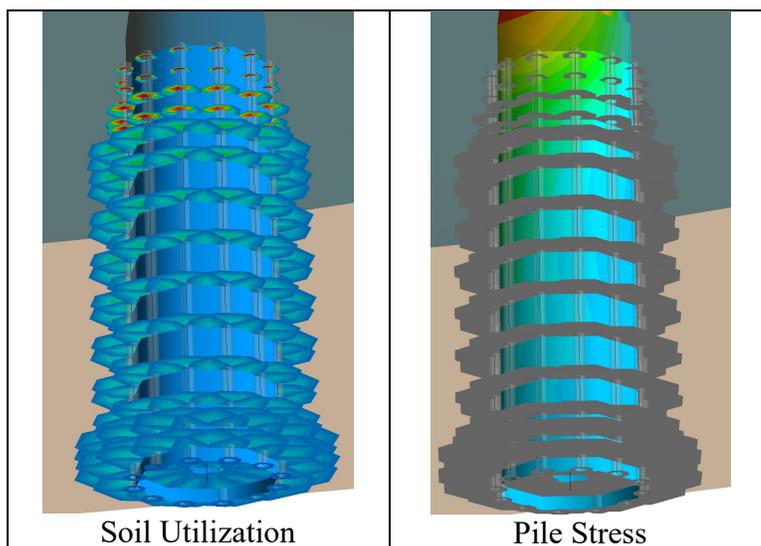


Figure 3-8 - Motion history applied on the soil.



4 Discussions

Using a single (jacket) pile to represent a large diameter mono-pile will always *underestimate* the global bending resistance (overturn moment).

The smaller Pile-Length to Pile-Diameter ratio (L/D), the more will a single standard pile *underestimate* the bending.

For a L/D ratio in the order of 3-4, the *under* prediction could be in the order of 20%. (Depends on the soil data).

For L/D around 1, the single pile could *under-predict* in the order of 50%.