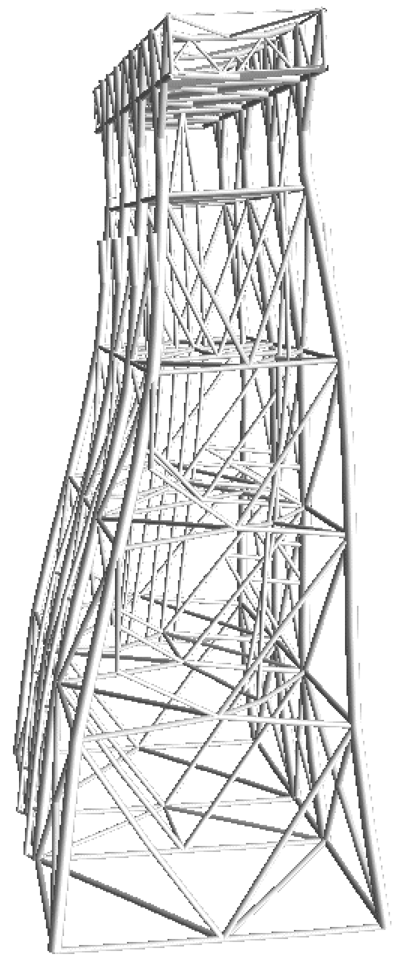
MODELLING OF

LARGE DIAMETER PILES

IN

USFOS



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Contents

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 a “workaround”, where use of several standard single piles located along the circumferential of the large diameter pile could represent the global response of typical wind turbine mono pile foundation.

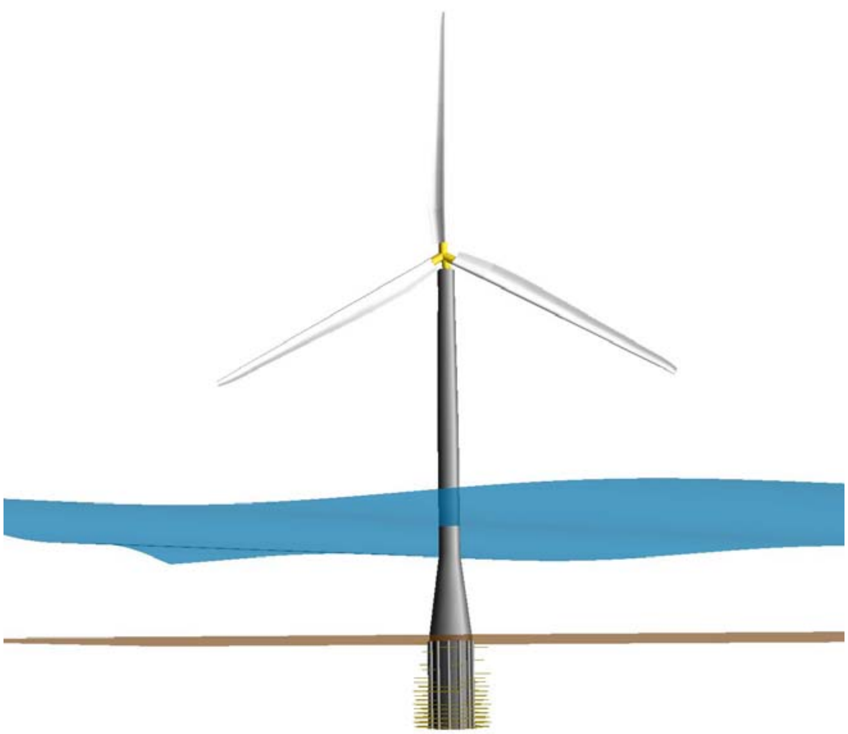

Figure 1-1 - MonoPile foundation of an offshore wind turbine

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:

τ = T-Z / D π , where T-Z is the force per unit length in the T-Z curves.

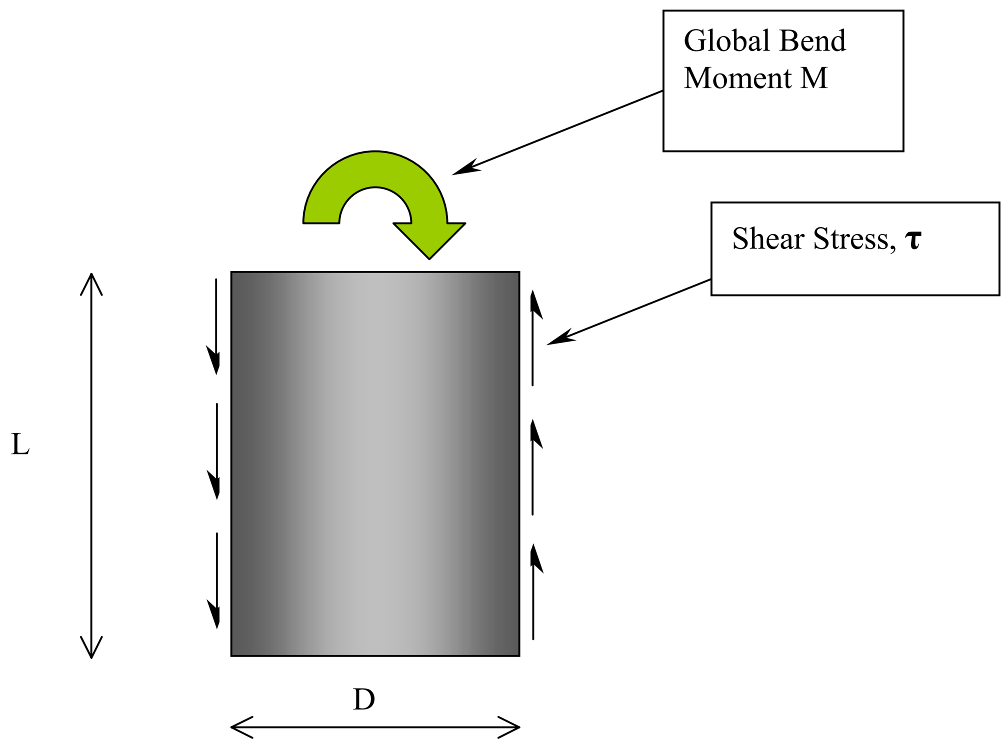

Figure 2-1 - Large Diameter Pile exposed to Global Bending, M.

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: τ x 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.)

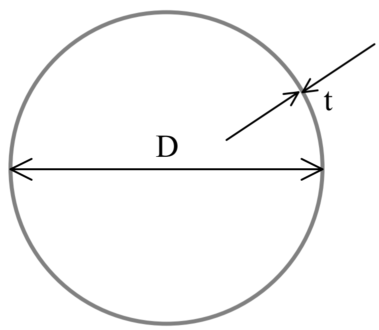

Figure 2-2 - Upper Section of the Large Pile

The bending capacities of a pipe section are:

- Elastic : Me = We x σ
- Plastic : Mp = Wp x σ

Where

$We \approx \pi R^2 t$

$Wp \approx 4 R^2 t$

The bending resistance provided by the skin friction then becomes:

$$Me \approx \pi R^2 t \sigma_y = \pi R^2 \tau_y \times L$$
$$Mp \approx 4 R^2 t \sigma_y = 4 R^2 \tau_y \times L$$

Where

τ_y : is the maximum (yield) shear stress

R : is the pipe radius.

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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:

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

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

$dM = dA \sigma x r$, where r 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:

$dM = dF x r$

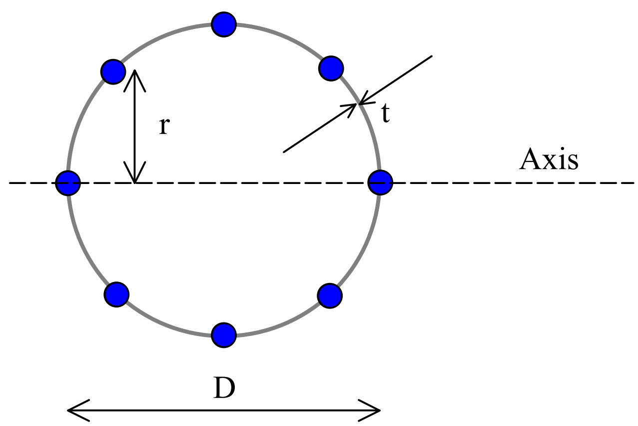

Figure 2-3 – Pipe with 8 integration points along the circumferential

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 diamter 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 ~$2 \pi r t$. 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 : $M = \sigma_N We = \sigma_N \pi R^3 / 4$ (massive pipe cross section)
- No Plug : $M = \sigma_N We = \sigma_N \pi R^2 t$ (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”.

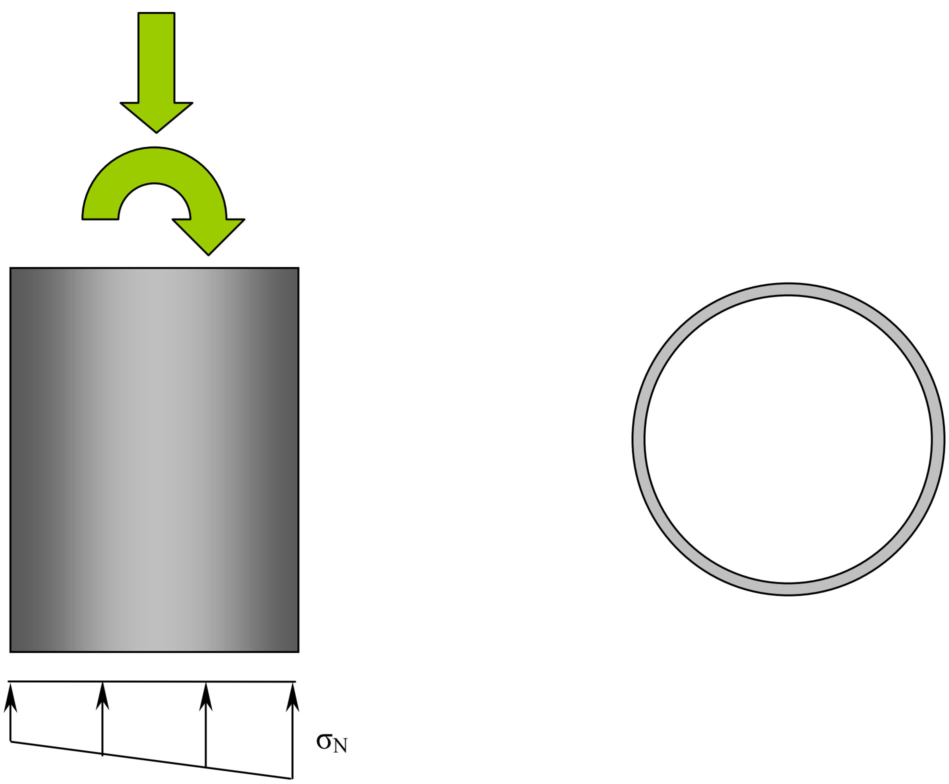

Figure 2-4 - Pressure on the end of the pile: "Q-Z"

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.

$M = \sigma_N We = \sigma_N \pi R^2 t$, 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:

$dA = \alpha R t$, $\alpha = 2\pi / n$, n 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 Work-Around for USFOS version 8-8.

3.1 Overview

Two possible work-arounds exists :

1. Using single piles attached to a manually modelled interface structure ("Bicycle wheel" connection: rigid "spokes" from the main pile "hub" to the outer surface).
2. Using the PILEGEO "group" option (*earthquake* ***not*** available with this alternative)

For both alternatives, the input parameters have to be modified slightly. Description of necessary changes is described.

Both alternatives give the same global (overturn) bending resistance.

The PILEGEO group alternative is the simplest, (requires less extra input compared with the "bicycle wheel" alternative). However, the group alternative cannot handle earthquake.

3.2 Alternative-1: Single piles attached to a"bicycle wheel"

3.2.1 Modeling.

In order to create a model with a given number of small piles, rigid elements with length equal to the large pile radius are modelled as shown in Figure 3-1. These elements are given high yield strength and stiffness to ensure a "rigid" transition and no local failure.

The small piles are then going from these beams' end to the node defining the small pipe's tip.

Figure 3-2 shows the soil definition in USFOS. The large pile has diameter, D=10 and the chosen number of single piles is set to 8 in the example.

Note that the small pile diameter has to be set to 10/8m (PILEGEO input). The D_Ref in the SOILCHAR input is unchanged.

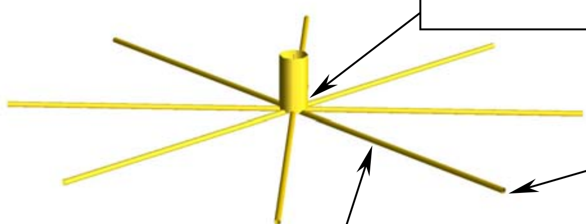

Figure 3-1 – "Bicycle Wheel" model.

```
'        Pile_geo    type       Do      T
 PILEGEO  1000       Single     10/8   0.050  ! Diameter is scaled with "N"
'

'            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
                                                    -3.0    -4.0   101  201  0
                                                    -4.0    -5.0   101  201  0
                                                    -5.0    -6.0   101  201  0
                                                    -6.0    -7.0   101  201  0
                                                    -7.0    -8.0   101  201  0
                                                    -8.0    -9.0   101  201  0
                                                    -9.0   -10.0   101  201  0
'
```

Figure 3-2 – Pile/Soil definition in USFOS

3.2.2 Necessary modifications of the pile/soil data

The input data need to be modified:

- Pile Geometry : Adjust diameter.
- Pile definition : One PILE and Pile Tip node per single pile is needed.

With the the parameters:

- D : Diameter of the (real) pile
- N : Number of single piles used to represent the large pile (e.g.: 8, 12)

Define the input as follows:

1. Define the single pile diameter to be d = D/N, (do *not* change the reference diameter given under SOILCHAR!). The pile thickness should be set to the thickness of the (real) large diameter pile.

2. Define the location of each single pile around the real pile's circumferential, (the "integraton point" coordinates in the horizontal plane). Precision could be increased by using more piles or by enlarging the circle radius*) slightly.
E.g. defining circle radius=1.05*D/2 if N=8, to get exact solution with only 8 integration points, r=1.015*D/2 if N=12. See section 3.2.3 on page 13.

3. Define one single pile per "integration point". (ref Figure 3-3). The pile tip node has to be defined for each single pile.

**) The circle radius is the distance from the centre of the large pile to the location of the small piles.*

```
'        Pile_id    Node 1   Node 2  Soil_id Pile_mat  Pile_geo Lcoor
 PILE      01001     1001     2001     1000      2      1000       0
 PILE      01002     1002     2002     1000      2      1000       0
 PILE      01003     1003     2003     1000      2      1000       0
 PILE      01004     1004     2004     1000      2      1000       0
 PILE      01005     1005     2005     1000      2      1000       0
 PILE      01006     1006     2006     1000      2      1000       0
 PILE      01007     1007     2007     1000      2      1000       0
 PILE      01008     1008     2008     1000      2      1000       0
'
'        Pile_geo    type        Do      T
 PILEGEO  1000       Single     10/8    0.050
```

Figure 3-3 – Defining 8 single piles to represent one large diameter pile.

The complete pile "cluster" used to represent on large diameter pile is shown in Figure 3-4 on the next page.

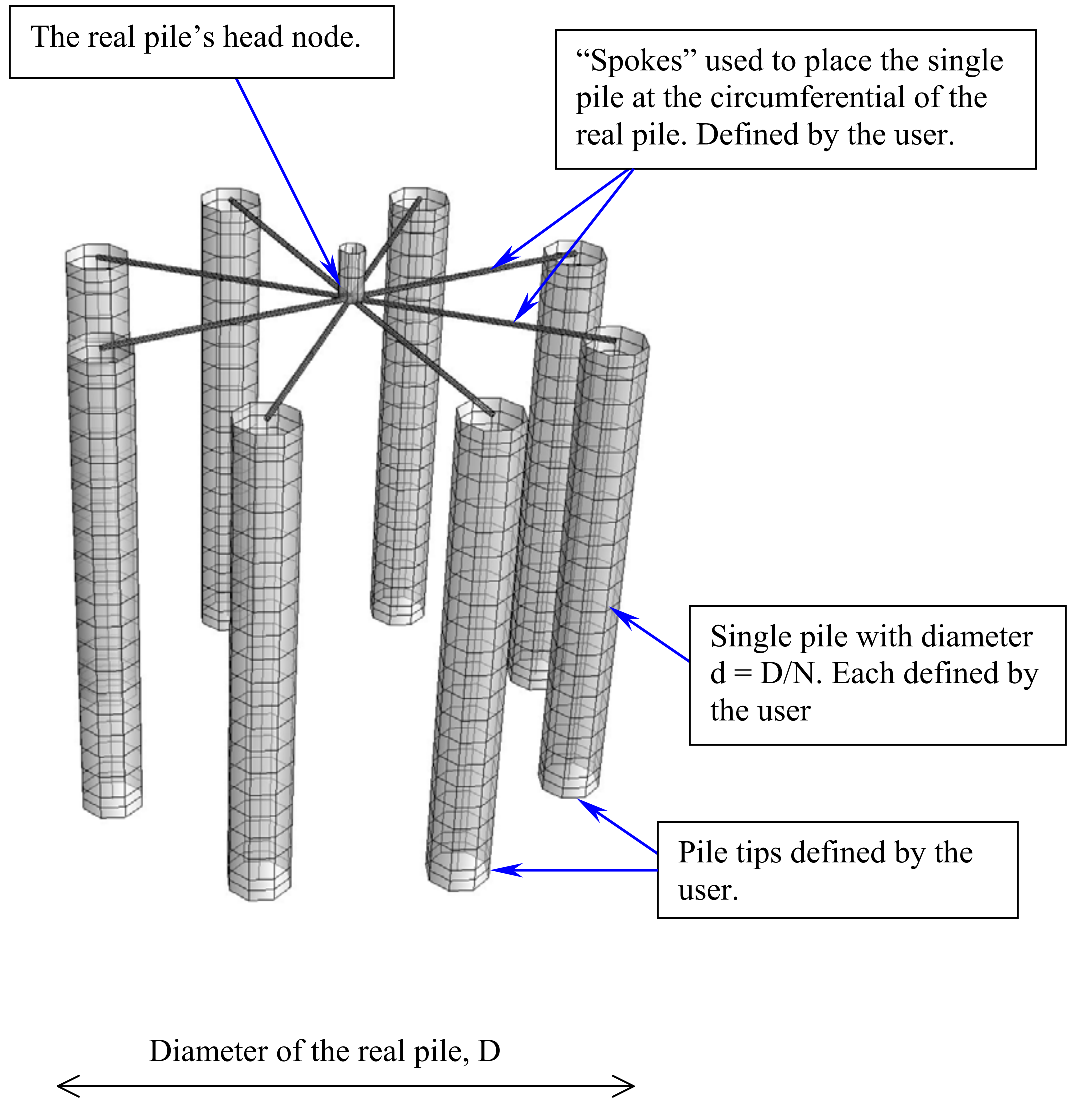

Figure 3-4 - Pile "cluster" model used to represent one large diameter pile.

3.2.3 Number of small single-piles vs. precision

I could be shown that use of a number of small pipes placed around the circumferential of the large pipe will give correct bending resistance as well as the other resistances (Vertical, T-Z and horizontal, P-Y).

Using e.g. 8 small piles ("integration points"), however, will give a resistance of 95% compared with "exact" solution. The precision could be increased by either using more points or simply by using an artificial larger circle radius *) to the 8 piles:

- 12 piles : 98.5% of exact
- 8 piles, increased R** : 100% of exact.

**) The circle radius is the distance from the centre of the large pile to the location of the small piles.*

***) R is multiplied with 1.05, i.e. is 5m x 1.05 = 5.25m*

The comparison of the response is shown in Figure 3-5.

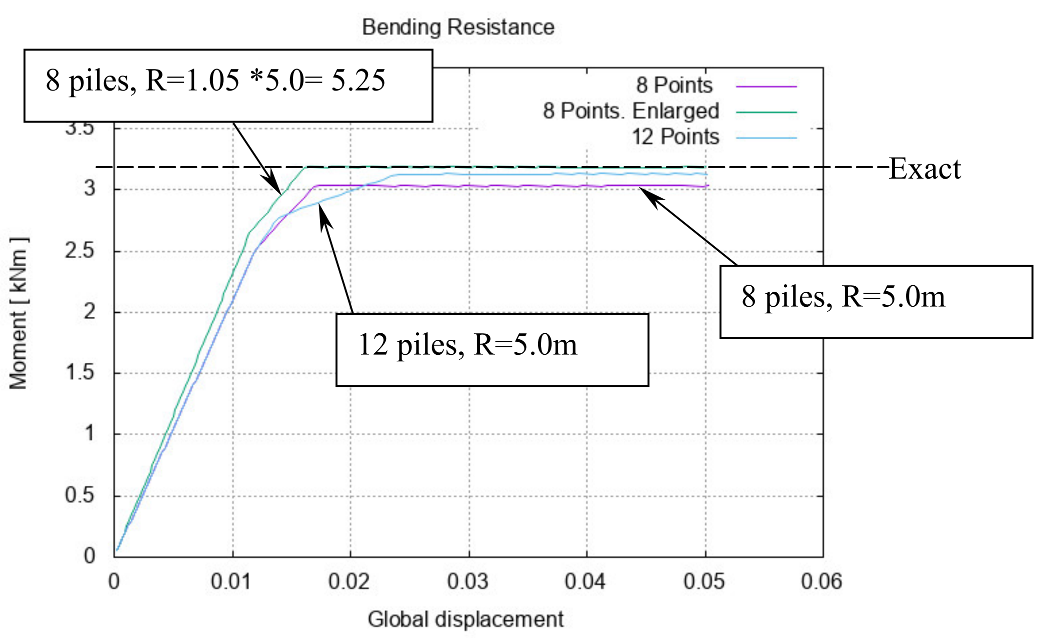

Figure 3-5 - Comparison of 8 / 12 piles and enlarged circle radius

3.2.4 Failure modes

The main purpose of the “work around” is to achieve best possible global response of the structure supported by the mono pile (e.g.: the wind turbine).

The modelling technique described in this document assumes that no failure takes place in the steel part of the pile. All possible yield/failures take place in the soil.

To obtain correct total weight of the equivalent large pile foundation, the weight of the individual piles should be tuned using a combination of pile thickness and steel density.

Check of possible failures in the large diameter steel pipe need to be done manually using separate models and forces from the small piles.

3.2.5 Ground Motion ("SoilDisp")

The turbine foundation is exposed to a ground motion, which is applied as "SOILDISP" in USFOS. The motion history shown in the figure is scaled with a factor 0.1 giving peak motions in the order of 0.3m. The soil moves according to this motion history and the soil elements get forces and transfers movements into the foundation and the tower.

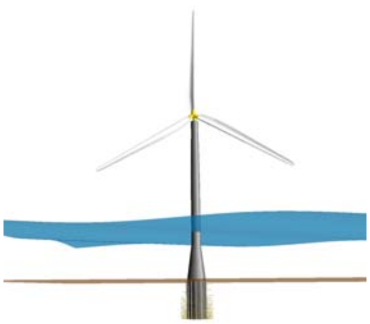	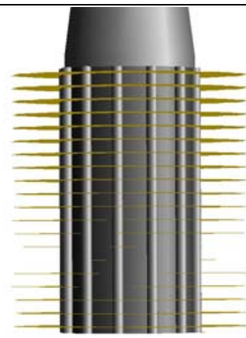	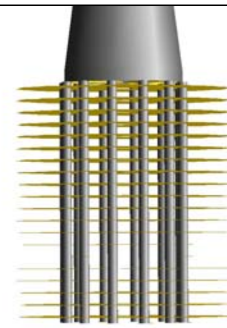
Wind turbine with mono pile foundation	Monopile using single piles (visualization of large pile included for information only)	Monopile using single piles (actual piles only)

Figure 3-6 - Model of wind turbine with mono pile using equivalent single piles

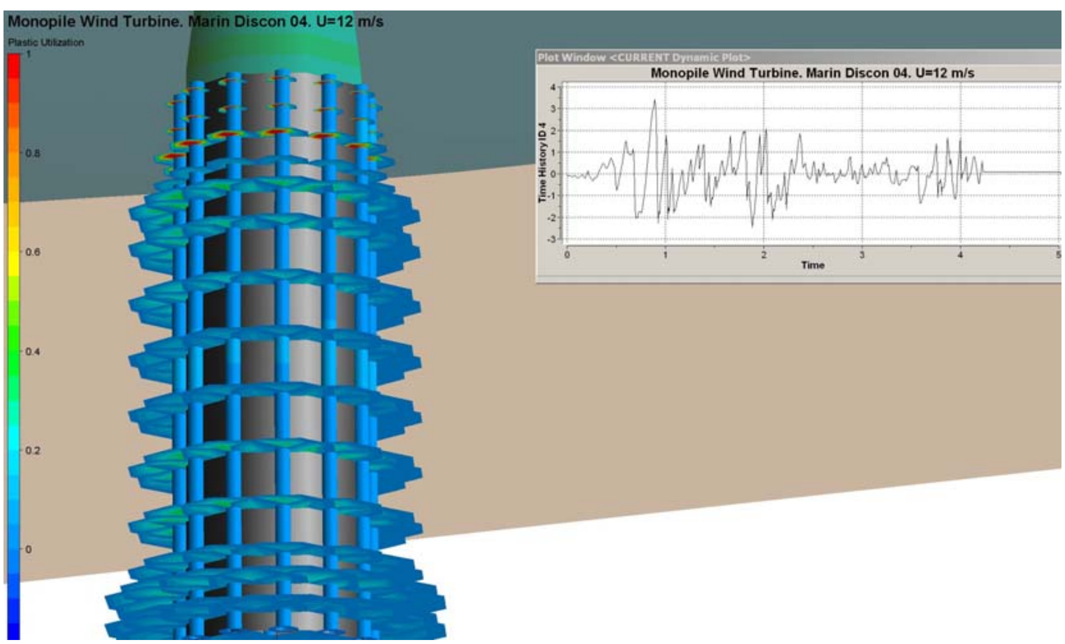

Figure 3-7 – Earthquake response. (ground motion is indicated). Upper soil-layers yield.

3.3 Alternative-2: Pile group option

The PILEGEO **"group"** could be used as an alternative to create "N" single piles. The user needs to define only one PILE, but the PILEGEO input has to contain the definition of the location of the local piles relative to the main pile's centre.

Here, USFOS will use eccentricity to connect the local pile heads to the main pile top node.

Figure 3-8 describes the input for the example with D=10m and N=8. (Same as above).

The N single piles are placed on the circle with radius 5m, and the SIN and COS functions are used in the input to ease the definition. (The arithmetic operations are interpreted and executed by USFOS during read-in of the data).

The complete foundation is shown in Figure 3-9.

```
'        Pile_id    Nodex1   Nodex2  Soil_id Pile_mat  Pile_geo Lcoor Imper
 PILE      01001       2      2000     1000      2      1000       0
'
' ----------------------------------------------------------------------
'     Pile - Soil Model
' ----------------------------------------------------------------------
'
'            Mat  ID     E-mod        Poiss     Yield      Density
 MISOIEP         2     210000E6*100    0.3     340E6*1000     0
'
'
'
'          ID     Type    Do     T      Npile
 PILEGEO  1000  Group  10/8  0.050     8
'
'                          Y_loc                Z_loc
                        5*COS(000*PI/180)  5*SIN(000*PI/180)
                        5*COS(045*PI/180)  5*SIN(045*PI/180)
                        5*COS(090*PI/180)  5*SIN(090*PI/180)
                        5*COS(135*PI/180)  5*SIN(135*PI/180)
                        5*COS(180*PI/180)  5*SIN(180*PI/180)
                        5*COS(225*PI/180)  5*SIN(225*PI/180)
                        5*COS(270*PI/180)  5*SIN(270*PI/180)
                        5*COS(315*PI/180)  5*SIN(315*PI/180)
'
'
'            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
```

Figure 3-8 - Pile model using the PILEGEO group option.

NOTE ! The use of "Group" could give some problems, see notes on next page.

Table 3-1 - Notes

Note	Description	Solution
1	The large offset (ecc) made by USFOS for the upper pile element could result in the "illegal ecc" message	Specify the needed "Illegal Ecc" commands to bypass the check
2	SOILDISP and SOILACC fail	Cannot be used together with the PILEGEO group option. Use "bicycle wheel" interface.

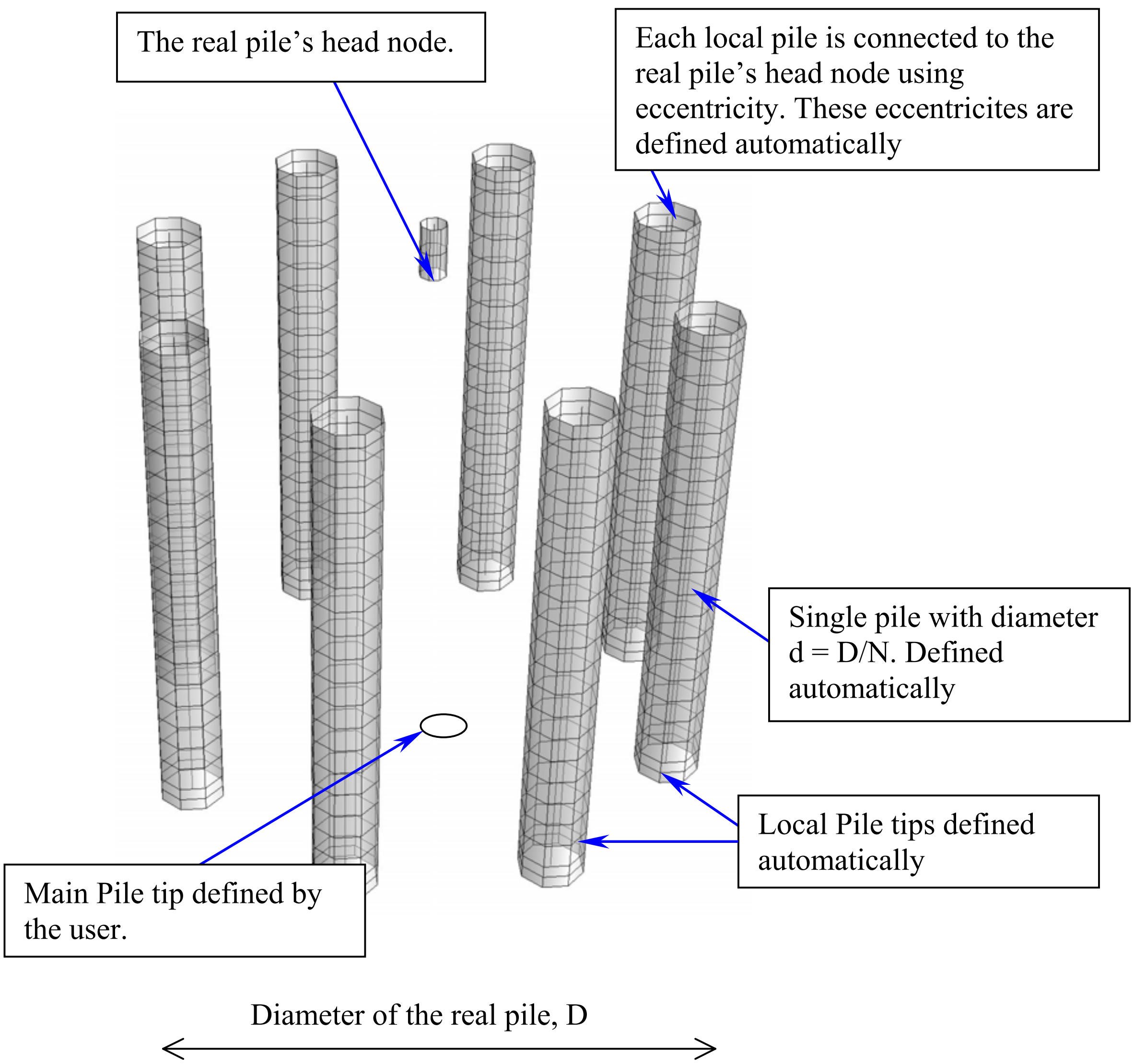

Figure 3-9 - Pile "group" model used to represent one large diameter pile.

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%.

In order to use the pile model available in USFOS, some “workarounds” are given. These workarounds make it possible to get a reasonable global response of the actual main structure and also of the soil, but cannot describe the local response of the (real) mono-pile (the steel section).

USFOS does not modify any soil performance data (P-Y, T-Z and Q-Z curves), and the soil curves used for large diameter piles have to be representative for such large diameters.

Except for specifying an artificial pile diameter d=D/n for the “n” single piles used to “integrate” the large pile resistance, no other changes in the input is needed. This artificial diameter is specified under PILEGEO.

The two alternatives:

1. Manual modelling of “Bicycle wheel” + “n” conventional single piles
2. Using the “PILEGEO group” option

… will give same (improved) global bending resistance, but the “group” option, (which requires less extra input from the user) cannot describe earthquake.

The number of single piles used in the “cluster” or in the “group” has impact on the precision. Using 8 single piles gives reasonable accuracy. In particular if the radius of the circle the piles are placed along is enlarged slightly (r = 1.05* D/2).