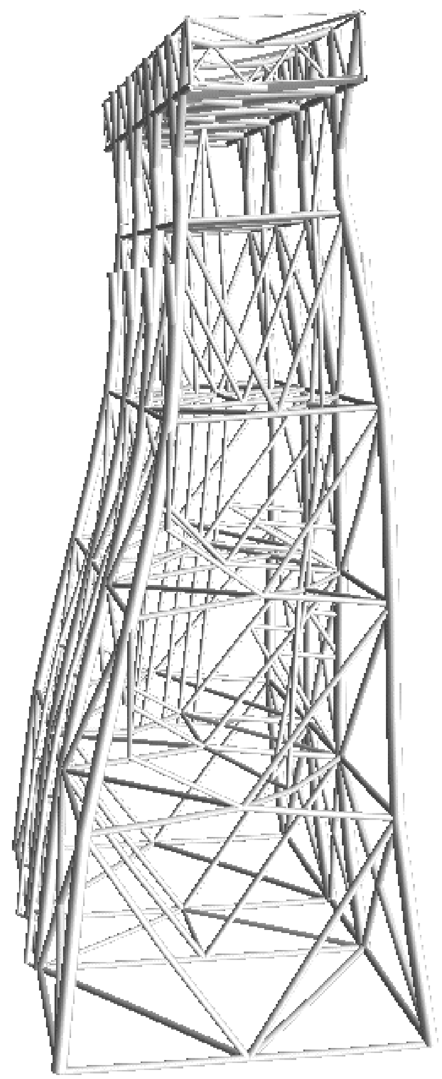

MODELLING OF

PILES

In USFOS

CONTENTS:

1 Introduction

The normal foundation of offshore jacket structures consists of single or groups of steel piles driven into the soil. This document describes how to define the non-linear pile-soil foundation in USFOS.

2 Typical Model

A typical USFOS model is shown in Figure 2-1. The part of the FE model below the seabed is generated by USFOS based on the definition of the soil and piles. The soil utilization as well as the soil strength is visualized, (see Figure 2-2).

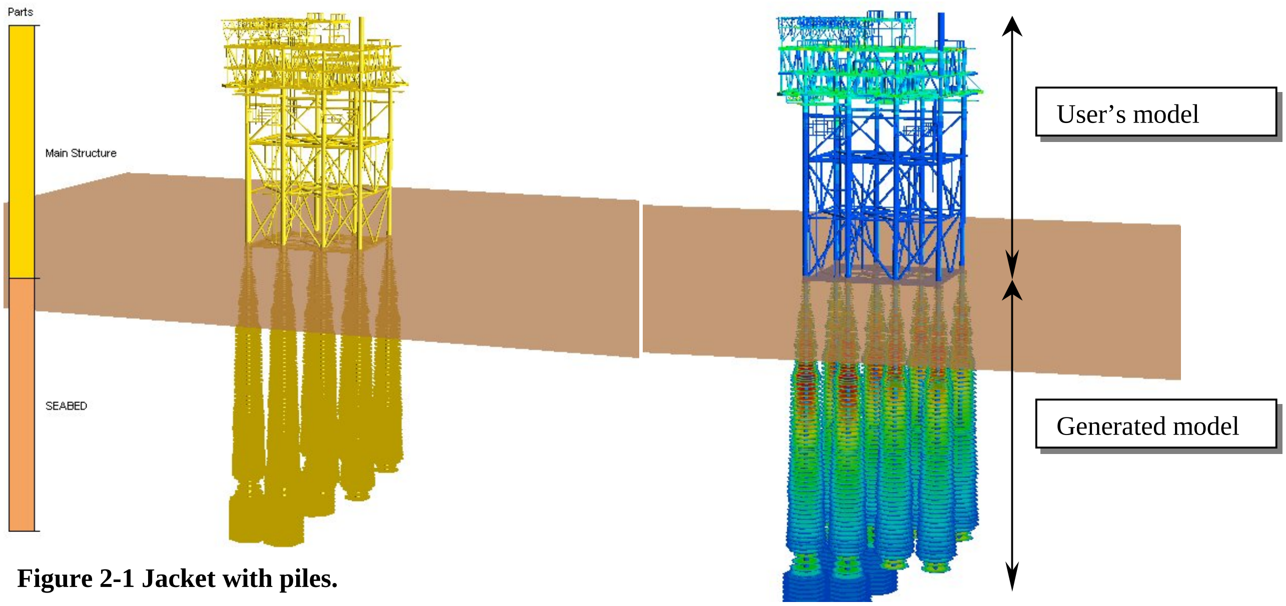

Figure 2-1 Jacket with piles.

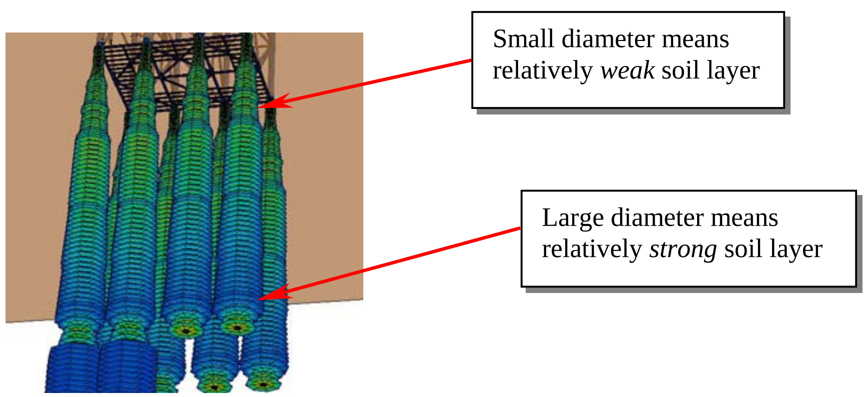

Figure 2-2 Soil disc diameter reflects the relative soil strength.

3 Pile-Soil modelling.

3.1 Basic concept

Figure 3-1 describes one pile, which penetrates 5 different (real) soil layers. The structural model (gold) ends at the mud line and is attached to the pile at the interface node (green). The pile tip node has to be defined by the user as an ordinary “NODE” (with xyz coordinates) and is used by USFOS to define the pile. The pile is defined from the pile head towards the tip, (ie: the local pile X-axis goes downwards).

Based on the definition of the pile and soil, USFOS will generate the necessary nodes and elements to describe the foundation. The nodes are inserted in the centre of each soil layer, and one soil element representing the entire soil layer is attached to this node. Between these centre nodes, ordinary USFOS beam elements are generated (automatically) with actual diameter, thickness and steel material properties.

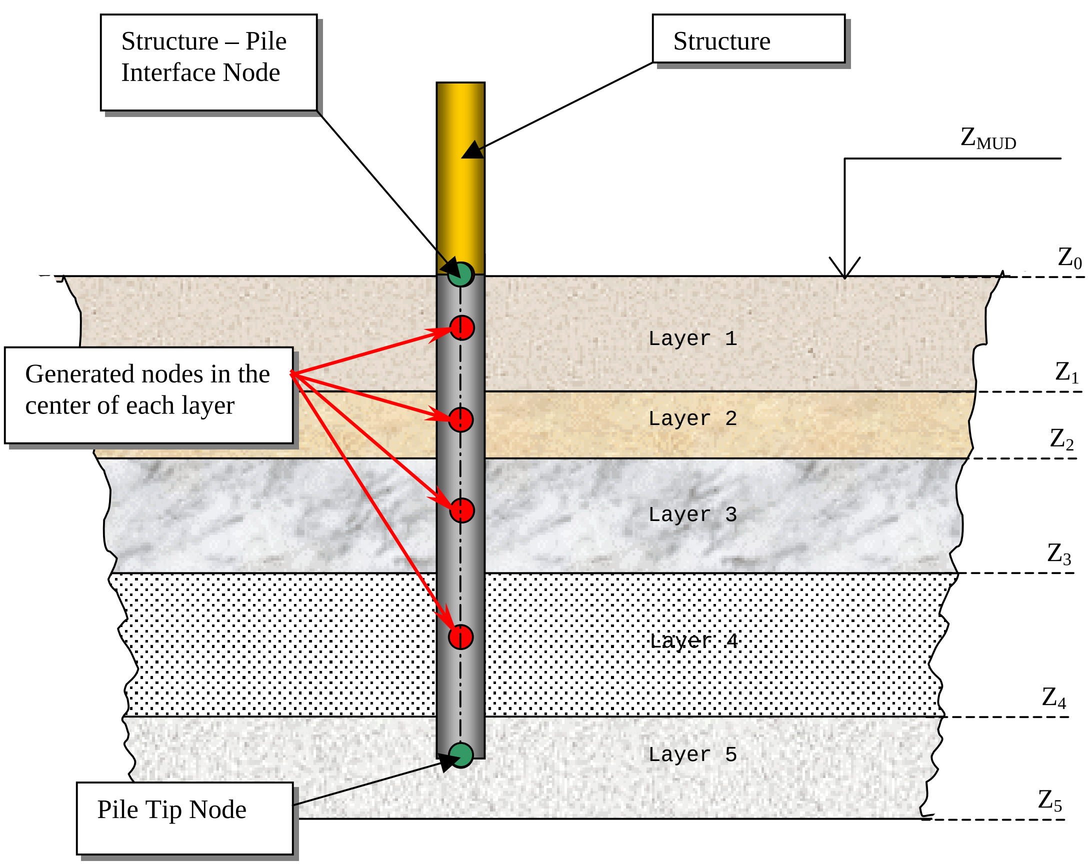

Figure 3-1 Description of one pile penetrating 5 different soil layers.

3.2 Coordinate system

The localization of the different soil layers is specified with the top/bottom coordinates of each layer. Following convention is used with respect to coordinate systems:

- Node Coordinates follows the normal Global system. (Pile Tip Nodes)
- The Z-coordinate of the mud line is specified in the Global Coordinate system (the same system as used for the structural model).
- All Soil Layer Z-coordinates are given ***relative*** to Z_{MUD}. This means that the upper layer always starts with Z=0.0 (in Soil Coordinates).
- NOTE that the soil Z coordinate points upwards.

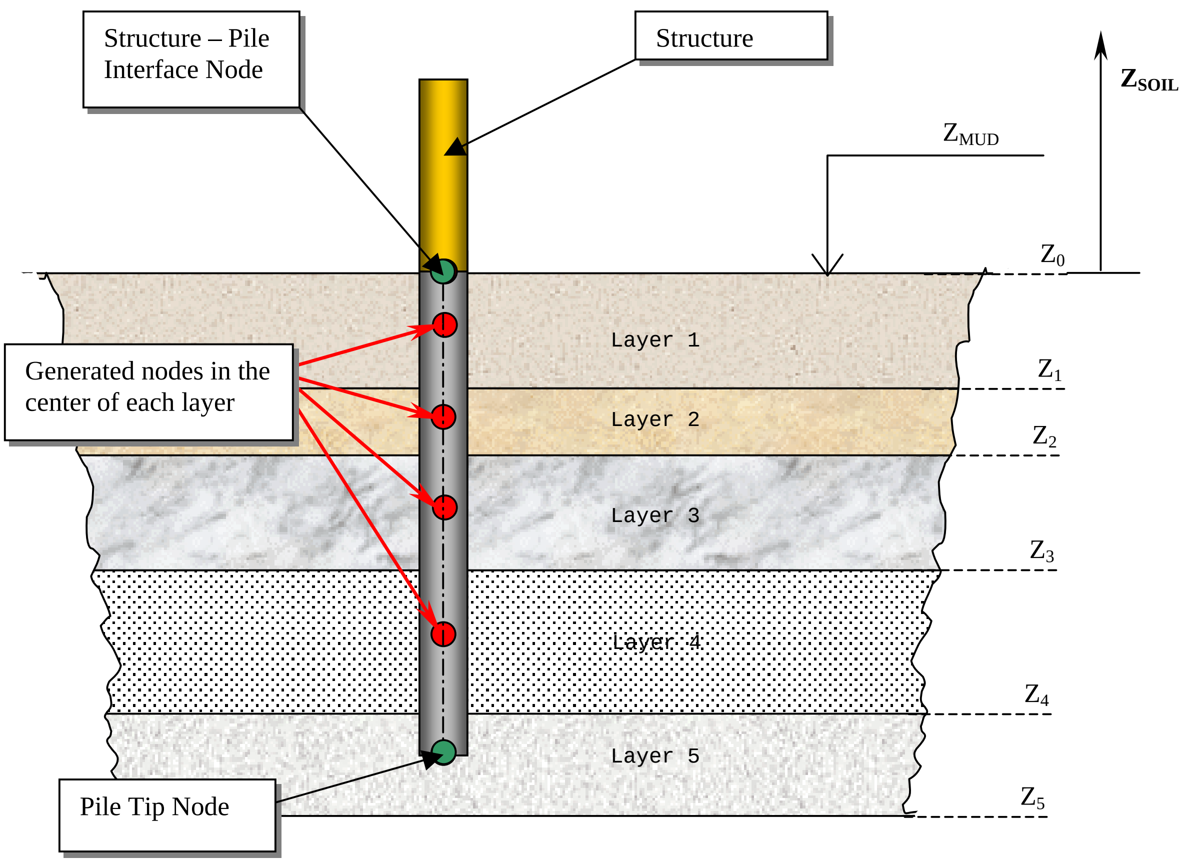

Figure 3-2 The soil layers are defined by the Z-coordinates relative to the Mud Line..

For each soil layer, following information has to be defined:

- Z_{TOP} and Z_{BOTTOM}, (relative to mud line)
- Soil properties (P-Y, T-Z and Q-Z)

The soil properties could be defined as user-defined curves defining strength per unit length of the pile, (one curve per property), or by soil data, (sand and clay parameters).

3.3 Defining Mesh density

The definition of the soil layers defines implicitly the finite element mesh density of the piles. The nodes are inserted in the centre of each layer, and the soil element is attached to this node, (one node "soil-to-ground" element). Between these centre nodes, ordinary beam elements are inserted. The pile diameter/thickness is either constant from pile head to tip (default) or varying (additional information is required).

If soil layers are relatively thick, the length of the pile element could become too long, (and, for example, may buckle in compression). In order to get appropriate length of the pile elements, it's just to defined "soil layers" with wanted thickness, but referring to the same soil properties several times.

Figure 3-3 describes a case with 3 different real soil layers, and where the model consists of 7 layers in order to reduce the pile element length. Layer 1-3 refers to the same Soil-1 data, layers 4-6 refers to Soil-2 data, while layer 7 refers to Soil-3 data.

If the *user defined soil curves* are used, identical strength per unit length of the pile will be used for the "layers" within each "Soil".

If the soil is defined by it's geotechnical properties (sand/clay etc), USFOS will account for the increasing overburden pressure within each soil. The layers within the same soil type will then get increasing strength for increasing depths, (overburden pressure at centre node is used).

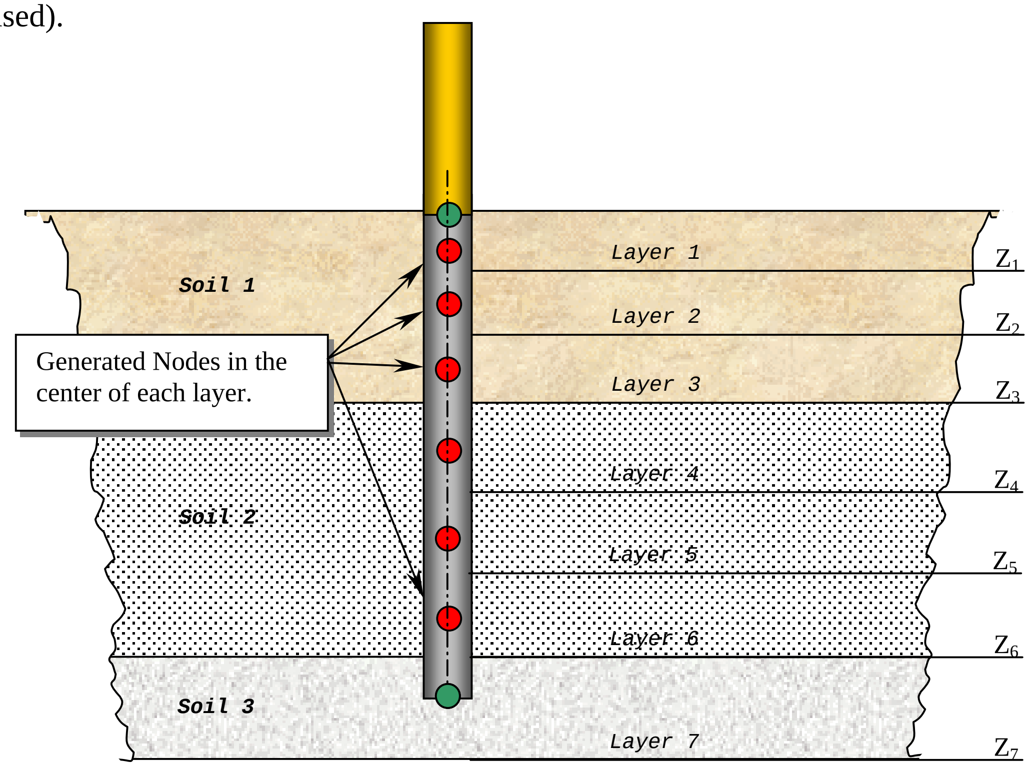

Figure 3-3 Sub dividing the mesh within thick soil layers.

4 Examples.

4.1 User Defined Soil Curves

This example describes the use of “User Defined” curves. User defined curves means that the soil data are describes in terms of Pile Strength per unit length of the pile for each soil layer.

The simple pile example is shown in Figure 4-1. The pile is exposed to a vertical (compression) force, which introduces buckling, (because the end bearing capacity is high and the lateral resistance is low in this *designed* case).

The pile plastic utilization as well as the soil utilization is visualized on the deformed pile. In order to easier see the failure modes, the utilization fringes are used as follows:

- Soil utilization dominated by T-Z : Symmetric colours
- Soil utilization dominated by P-Y : Unsymmetrical, Exposed side becomes red.

In addition, the deformation are used as follows:

The soil disc inner circle follows the vertical movements of the pile, but is fixed in the horizontal direction. In connection with lateral failure, a “gap” opens on the unexposed side, to easier see the failure mode.

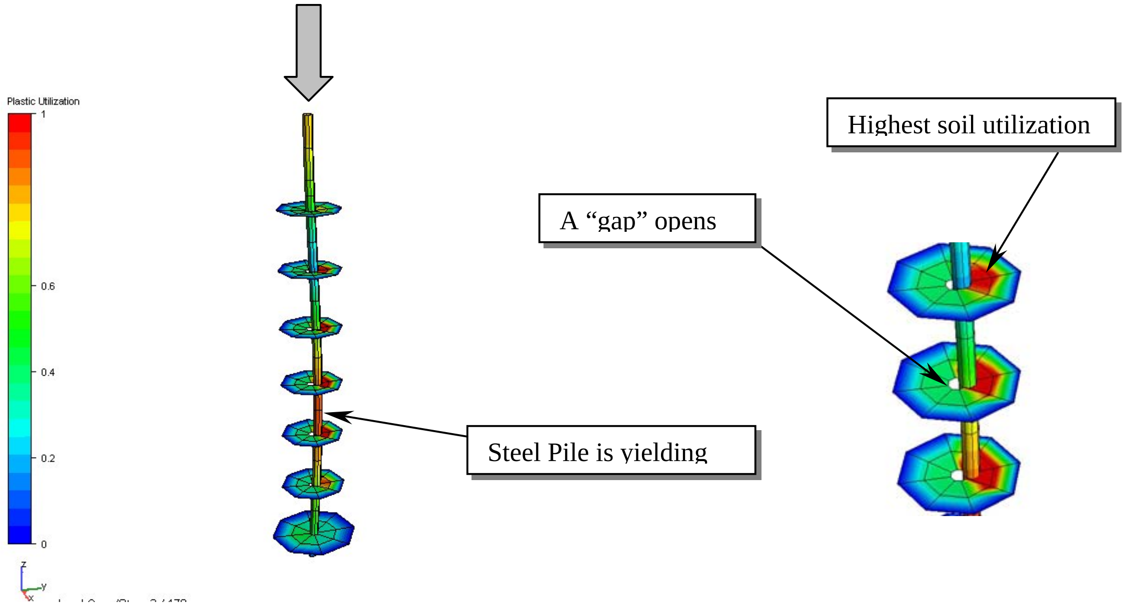

Figure 4-1 Buckling of Single pile. Visualization of utilization and deformations.

The soil strength is defined by the general non-linear curve commands `ElPlCurve` (Elasto-Plastic Curve) and `HypElastic` (Hyper Elastic). These curves are defined by discrete points, Force and Displacement, starting in 3rd quadrant.

- Force : Pile resistance per unit length of the pile [N/m]
- Displacement : Corresponding deformation [m]

The forces are referred to a *certain pile diameter*, and this diameter is specified in the `SOILCHAR` record (D_{REF}). If another pile diameter is used, USFOS will scale the capacity accordingly (linear scaling).

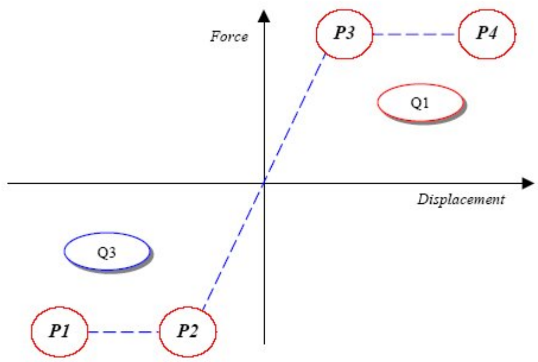

Figure 4-2 Definition of Curves. Specify points from Quadrant 3 towards Q1.

Figure 4-3 describes typical pile-soil capacity curves. The P-Y and T-Z curves are typically symmetric (equal capacity in both directions), while the Q-Z typically has no resistance for pile tension. Curve points in Quadrant-3 represent the tension and Q1 represents compression, (relevant for QZ and TZ). The P-Y data are uni-directional, but are always given as a symmetric curve. Table 4-1, describes the complete pile-soil input for this simple example.

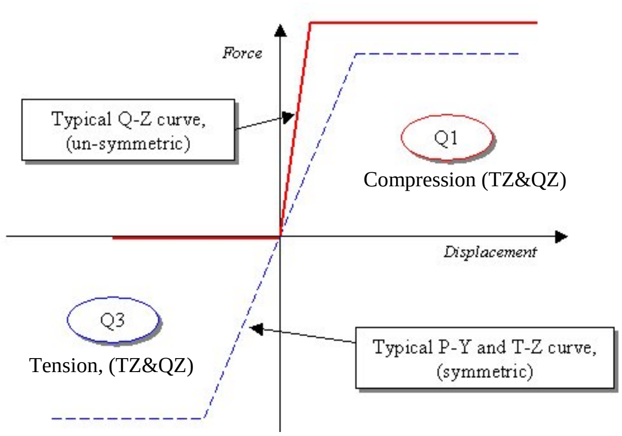

Figure 4-3 Typical T-Z, P-Y and Q-Z curves.

```
' -------------------------------------------------------------------
'     Define Pile and Soil Properties.
' -------------------------------------------------------------------
'        Pile_id     Node1    Node2   Soil_id Pile_mat  Pile_geo  Lcoor Imper
PILE       9100        2        3      762        248   762032      0
'
'
'
'        Pile_geo      type        Do       T
PILEGEO   762032      Single     0.150   0.070
'
'
'          ID   Type  Z_mud   D_ref  F_Fac  L_Fac  Z_top  Z_bott  PY  TZ   QZ
SOILCHAR  762   Curve  0.0    0.150  1.0    1.0    0.0    -1.0    1   2    0
                                                  -1.0    -2.0    1   2    0
                                                  -2.0    -3.0    1   2    0
                                                  -3.0    -4.0    1   2    0
                                                  -4.0    -4.9    1   2    0
                                                  -4.9    -6.0    9   3  101
                                                  -6.0   -10.0   19   4  101
'          ID     P          d
ELPLCURV    1  -6.30E3 -100.0E-2
               -6.30E3  -10.0E-2
               -1.45E3   -1.0E-2
                1.45E3    1.0E-2
                6.30E3   10.0E-2
                6.30E3  100.0E-2
'
'          ID     P          d
ELPLCURV    2  -6.20E3 -100.0E-2
               -6.20E3  -10.0E-2
               -1.25E3   -1.0E-2
                1.25E3    1.0E-2
                6.20E3   10.0E-2
                6.20E3  100.0E-2
'          ID     P          d
ELPLCURV    3  -6.40E3 -100.0E-2
               -6.40E3  -10.0E-2
               -1.65E3   -1.0E-2
                1.65E3    1.0E-2
                6.40E3   10.0E-2
                6.40E3  100.0E-2

'          ID     P          d
ELPLCURV    4  -6.50E3 -100.0E-2
               -6.50E3  -10.0E-2
               -1.65E3   -1.0E-2
                1.65E3    1.0E-2
                6.50E3   10.0E-2
                6.50E3  100.0E-2

'          ID     P          d
ELPLCURV    9  -6.50E4 -100.0E-2
               -6.50E4  -10.0E-2
               -1.65E4   -1.0E-2
                1.65E4    1.0E-2
                6.50E4   10.0E-2
                6.50E4  100.0E-2
'          ID     P          d
ELPLCURV   19  -6.50E5 -100.0E-2
               -6.50E5  -10.0E-2
               -1.65E5   -1.0E-2
                1.65E5    1.0E-2
                6.50E5   10.0E-2
                6.50E5  100.0E-2
'
'          ID     P          d
HypElastic 101
               -1.65E2   -1.0
               -1.65E2   -1.0E-6
                1.65E6    1.0E-2
                6.50E6   10.0E-2
                6.50E6  100.0E-2
'
```

Table 4-1 USFOS commands defining a single pile + user-defined soil.

4.2 How to define soil capacity curves

This example describes how to create the pile-soil curves based on available Geotechnical data. Each curve must be given a unique Material ID no, and it is recommended to use a simple system, (to avoid chaos). In the example below, the following system is used:

- P-Y curves : 1,000 series, 1001, 1002, 1003,…etc
- T-Z curves : 2,000 series, 2001, 2002, 2003,…etc
- Q-Z curves : 3,000 series, 3001, 3002, 3003,…etc

1001 is P-Y data for soil layer no 1, 1002 for layer no 2 etc.

4.2.1 P-Y curve, (Lateral Pile Resistance)

Table 4-2 describes typical lateral pile resistance data (P-Y) as they are received from geotechnical consultants. The lateral resistance, P is given as kN per unit length of a pile with diameter 2.438m. The corresponding lateral displacements, Y, are given in millimetre. Seven points are defined.

The P-Y data are given for some depths in this example, an one arbitrarily chosen layer is described in detail.

USFOS is using force per unit length of pile as input, and in the example, data should be given to USFOS in pure SI units (N, m). The scaling of the data then becomes:

- Forces (P) : Multiply the tabulated values with 1000 to obtain Newton
- Displacement (Y) : Divide the tabulated values with 1000 to obtain meter.

Depth	***P1***	***P2***	***P3***	***P4***	***P5***	***P6***	***P7***
(m)	***Y1***	***Y2***	***Y3***	***Y4***	***Y5***	***Y6***	***Y7***
0.00	*0.00*	*3.36*	*4.83*	*7.31*	*10.53*	*14.63*	*14.63*
	0	12.19	36.57	121.9	365.7	975.2	2438
7.50	*0.00*	*53.86*	*77.28*	*117.09*	*168.61*	*234.18*	*234.18*
	0	12.19	36.57	121.9	365.7	975.2	2438
22.50	***0.00***	***239.72***	***343.94***	***521.12***	***750.42***	***1042.25***	***1042.25***
	0	**6.095**	**18.285**	**60.95**	**182.85**	**487.6**	**2438**
27.00	*0.00*	*277.57*	*398.25*	*603.41*	*868.90*	*1206.81*	*1206.81*
	0	6.095	18.285	60.95	182.85	487.6	2438
34.50	*0.00*	*371.82*	*533.48*	*808.30*	*1163.95*	*1616.60*	*1616.60*
	0	4.2665	12.7995	42.665	127.995	341.32	2438

Table 4-2 P-Y Data. Lateral Strength, P [kN/m] and Displacement, Y [mm] for a D=2.438m pile.

USFOS assumes that the specified curve data is valid for a soil *layer*, specified with the top/bottom Z-coordinate (see page 4), It is therefore important to check how the geotechnical data should be used.

In the present example, it is assumed that the strength for $Depth_I$ is valid to $Depth_{I+1}$. For example that P values in the row for depth 22.50 is valid for the layer between depth 22.50 and 27.00.

```
 ''             MatID      P [N/m]        Y[m]
 ElPlCurve      1003  -1042*1000      -2438/1000
                      -1042*1000       -488/1000
                       -750*1000       -183/1000
                       -521*1000        -61/1000
                       -344*1000        -19/1000
                       -240*1000         -6/1000
                        0.0              0.0
                        240*1000         6/1000
                        344*1000        19/1000
                        521*1000        61/1000
                        750*1000       183/1000
                       1042*1000       488/1000
                       1042*1000      2438/1000
 '
```

Table 4-3 Curve definition for Shear Strength for layer with Z=-15.00 to Z=-19.22.

```
 '
 '           Soil_ID   Type  Z_mud      D_ref     F_Fac     L_Fac
 SOILCHAR       1    Curves   0.000     2.438     1.000     1.000
 '
 '
                               Z_top      Z_bott      P-Y      T-Z       Q-Z
                               0.00       -7.50      1001        0         0
                              -7.50      -22.50      1002     2002         0
                             -22.50      -27.00      1003     2003         0
                             -27.00      -34.50      1004     2004         0

 .............
```

Table 4-4 Highlight reference to P-Y curve 1003.

In the example, the 1,000 series is used for P-Y data, and since the selected layer is the 3rd , the material ID becomes 100***3***

The P-Y data are symmetric, and the Elasto-Plastic Curve data (ElPlCurve) is therefore given with same data in 1st and 3rd quadrant, (see also Figure 4-3).

It should be noted that USFOS input reader may executed simple mathematical expressions, which, in this case means increased readability vs. the original soil data.

The Material ***1003*** should be referred to in the SoilChar as P-Y curve, see Table 4-4.

4.2.2 T-Z curve, (Shear Capacity)

Shear strength data (T-Z) could be available in different formats: Resultant strength per unit length of a given pile, or as shear strength per unit surface area of a pile.

The first alternative could be used directly (if necessary, convert units to N and m), while the 2nd alternative needs some computation.

Below, some typical shear strength data is specified in the tables. The shear strength is given for same displacement levels for all depths, (see Table 4-5). Table 4-6 describes the corresponding shear strength for the different depths. Data are derived from a pile with diameter 2.438m

The displacement is given in millimetre, while the shear strength is given in kPa.

	Z1	**Z2**	**Z3**	**Z4**	**Z5**	**Z6**	**Z7**	**Z8**
	0.0	3.9	7.6	13.9	19.5	24.4	48.8	73.1

Table 4-5 Displacement, Z, [mm].

Depth	**T1**	**T2**	**T3**	**T4**	**T5**	**T6**	**T7**	**T8**
0.00	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
1.22	0.0	0.5	0.9	1.3	1.5	1.7	1.2	1.2
13.78	0.0	3.5	5.9	8.8	10.5	11.7	8.2	8.2
15.00	0.0	3.8	6.4	9.5	11.4	12.7	8.9	8.9
19.22	0.0	6.9	11.5	17.2	20.6	22.9	16.0	16.0
25.78	0.0	9.0	15.0	22.4	26.9	29.9	20.9	20.9

Table 4-6 Shear Strength, T, [kPa].

Since USFOS requires force per length unit of a pile, the T data have to be converted as follows:

$$T_{PerLength} = T \pi D$$

Where D is the outer diameter of the actual pile. In the actual case, the reference diameter is 2.438m and T is given in kPa. Since the strength curves should be given in force [N] per unit length of the pile [m], the computation is as follows:

$$T_{PerLength} = T \pi 2.428 \times 1000 \text{ [N/m]}.$$

Further, USFOS assumes that the specified curve data is valid for a soil *layer*, specified with the top/bottom Z-coordinate (see above). It is therefore important to check how the geotechnical data should be used.

In the example, it is assumed that the strength for $Depth_I$ is valid to $Depth_{I+1}$. For example that T values in the row for depth 15.00 is valid for the layer between depth 15.00 and 19.22, (the layer is arbitrarily chosen).

```
'            MatID     T [N/m]               z[m]
 ElPlCurve   2004   -8.9*1000*PI*2.438      -73.1/1000
                    -8.9*1000*PI*2.438      -48.8/1000
                   -12.7*1000*PI*2.438      -24.4/1000
                   -11.4*1000*PI*2.438      -19.5/1000
                    -9.5*1000*PI*2.438      -13.9/1000
                    -6.4*1000*PI*2.438       -7.6/1000
                    -3.8*1000*PI*2.438       -3.9/1000
                     0.0                    0.0
                     3.8*1000*PI*2.438        3.9/1000
                     6.4*1000*PI*2.438        7.6/1000
                     9.5*1000*PI*2.438       13.9/1000
                    11.4*1000*PI*2.438       19.5/1000
                    12.7*1000*PI*2.438       24.4/1000
                     8.9*1000*PI*2.438       48.8/1000
                     8.9*1000*PI*2.438       73.1/1000
'
```

Table 4-7 Curve definition for Lateral Strength for layer with Z=-22.50 to Z=-27.00.

In the example, the 2,000 series is used for T-Z data, and since the selected layer is the 4th, the material ID becomes 200***4***

It is assumed that the T-Z data are equal for up/down movements of the pile (tension/compression), and the curve is therefore symmetric.

It should be noted that USFOS input reader may executed simple mathematical expressions, which, in this case means increased readability vs. the original soil data.

The Material ***2004*** should be referred to in the Soilchar as T-Z curve, see Table 4-8.

```
'
'           Soil_ID  Type  Z_mud      D_ref     F_Fac     L_Fac
 SOILCHAR      1    Curves   0.000     2.438     1.000     1.000
'
'                            Z_top      Z_bott      P-Y       T-Z       Q-Z
                             0.00      -1.22       1001         0         0
                            -1.22     -13.78       1002      2002         0
                           -13.78     -15.00       1003      2003         0
                           -15.00     -19.22       1004      2004         0

.............
```

Table 4-8 Highlight reference to T-Z curve 2004..

4.2.3 Q-Z curve, (End Bearing)

Table 4-9 and Table 4-10 describe typical end bearing data for a pile with diameter 2.438m, (96”). The first table gives the displacements for the 7 points (Z1-Z7) while Table 4-10 gives the corresponding end bearing capacity for different depths, (from depth=68 –90.50).

The displacements are given in millimetre, while the end bearing is given in kN. It is recommended to use pure SI units, (m, N, kg), and the generated curve will be given in SI-units.

Since Q-Z data only are relevant for the soil layers where the pile tip is located, the first Q-Z curve is defined for depth = 68m (or Z = -68 in the USFOS soil coordinate system). The *suggested* Material ID to use for this soil layer is ***3052***, (Q-Z, 52th layer).

	Z1	Z2	Z3	Z4	Z5	Z6	Z7
	0.0	5	32	102	178	244	731

Table 4-9 Displacements [mm].

Depth	Q1	Q2	Q3	Q4	Q5	Q6	Q7
68.00	*0.0*	*1260.4*	*2520.9*	*3529.2*	*4537.6*	*5041.7*	*5041.7*
69.22	0.0	1286.0	2572.1	3600.9	4629.8	5144.2	5144.2
76.78	0.0	1444.9	2889.8	4045.7	5201.6	5779.6	5779.6
78.00	0.0	1470.5	2941.0	4117.4	5293.8	5882.0	5882.0
79.22	0.0	1496.1	2992.2	4189.1	5386.0	5984.5	5984.5
89.28	0.0	1707.5	3415.0	4781.0	6147.0	6830.0	6830.0
90.50	0.0	1733.1	3466.2	4852.7	6239.2	6932.4	6932.4

Table 4-10 End Bearing [kN].

The Q-Z data are valid for pile compression only, and the curve therefore becomes *un-symmetric*. The curves are always defined from the very left side, (Q3, ref Figure 4-2 and Figure 4-3 for general description).

The Q-Z data are defined in Newton and meter. Curve 3052 is referred to from SOILCHAR as shown below.

```
                 ID      Force[N]   Disp[m]
 HypElastic  3052       0.0     -1.000    ! No Tension Capacity for Q-Z.
                        0.0      0.000    ! Zero
                      1260E3     0.005
                      2521E3     0.032
                      3529E3     0.102
                      4538E3     0.178
                      5042E3     0.244    ! Ultimate Strength
                      5042E3     0.731    ! Horizontal Curve
'
'
```

Table 4-11 Q-Z curve definition for soil layer no 52. Data in N and m.

```
'
'           Soil_ID   Type   Z_mud      D_ref     F_Fac     L_Fac
 SOILCHAR      1     Curves   0.000      2.438     1.000     1.000
'
'
                              Z_top      Z_bott     P-Y       T-Z       Q-Z
                              0.00      -0.05      1001         0         0
                             -0.05      -0.55      1002         0         0
                             -0.55      -1.22      1003         0         0
                             -1.22      -1.50      1004      2004         0
                             -1.50      -2.50      1005      2005         0
                             -2.50      -3.50      1006      2006         0

.............

                            -66.78     -68.00      1050      2050         0
                            -68.00     -69.22      1052      2052      3052
                            -69.22     -70.50      1053      2053      3053

.............
                           -151.22    -158.78      1056      2080      3080
                           -158.78    -161.00      1056      2081      3081
'
```

Table 4-12 Creating User Defined Pile-Soil Curves. Definition of Q-Z curve with ID 3052.

The same system is repeated for all relevant Q-Z layers. For layers without pile tip, just insert a zero (0).