### Soil with cohesion (clay)

If the soil surrounding the soil is considered to be an elastic continuum with Young´s modulus $E$ and Poisson´s ratio of 0.5 the lateral soil modulus, $k_u$, can be derived e.g. according to Baguelin (1997). If the Young´s modulus is supposed to be $E=50c_u$, where $c_u$ is the cohesion the lateral soil modulus can be written:

$$k_u = k_0 c_u / b, \qquad 157 \leq k_0 \leq 242 \tag{2}$$

For long term loading the creep effect must be considered. This done approximately by reducing the lateral soil stiffness:

$$k_u = 50 c_u / b \tag{3}$$

The pressure against the pile is described by the expression:

$$p = k_u u \tag{4}$$

Where u is the lateral displacement of the pile. The pressure $p$ is limited to a value $p_y$ that for drained conditions can be calculated by:

$$p_y = N_c c_u \tag{5}$$

Where $N_c$ is a constant that varies between 8-12 for deep soil layers (<3b) and decreases to 2 for layers closer to the surface. For short time loading $N_c=9$can be used and for long time loading the creep is considered by a lower value of $N_c=6$.

### Cohesion-less soil (friction soil)

For cohesion-less soils there are no unambiguous expression that describes the relation between the lateral soil modulus and the strength parameter ´. The relationship between lateral displacement and soil pressure against the pile is therefor based on suggested empirical “p-y” curves based on experimental data. There are numerous suggestions on different “p-y” curves among them are Reese (1994). The “p-y” curves are un-linear and a soil model with linear curve based the initial slope of the “p-y” curve suggested by Reese et. al.(1994) is used here. The lateral soil modulus is half of the initial modulus according to Reese et. al.(1994) and is expressed as follows:

$$K_u = 1/2 k_s z \tag{6}$$

where $k_s$is given in Table III.

TABLE III. VALUES FORTHE CONSTANT $K_s$FOR LATERAL SOIL MODULUS ACCORDING TO REESE ET. AL. (2007)

| | Water[MN/m$^3$] | Sand above water table [MN/m$^3$] |
|---|---|---|
| Loose sand | 5 | 7 |
| Medium dense sand | 16 | 24 |
| Dense sand | 34 | 61 |

For un-drained conditions the limit value is calculated by:

$$p_y = N_{\square} \sigma'_v \quad (7)$$

where $\sigma'_v$is the vertical soil pressure and $N \;\; = 3K_p$. Creep is not considered for friction soils.

**Modelling the pile abutment connection**

The connection between the pile and the abutment can be modelled as fixed or pinned connection. Experiments at Lulea University of Technology (Pétursson et. al. 2013) using full-scale models of clamped piles demonstrated that a steel pipe pile can accommodate large inelastic deformations under strains six times greater than the yield strain for several hundred load cycles. This indicates that by permitting pile strains in excess of the yield strain (which is not permissible under most current design codes), integral abutment bridges could be erected with several hundred meters of bridge length. Considering that the fixity of the pile is somewhere between rigidly fixed and pinned it is practical to consider the connection as pinned and design the pile with normal force, displacement and an external moment at the top of the pile.

**Modelling the pile soil interaction**

In the suggested analytical model to design the pile it is assumed that the largest displacements take place near the pile head and thus the largest soil pressure against the pile also is at the upper part of the pile. As soon as the limit value, $p_y$, of the soil pressure is obtained the lateral soil modulus will behave plastic at further displacement of the pile top (see Figure 9). The pile will behave elastic until a plastic hinge is formed somewhere along the pile and then the pile capacity is reached. To reach this state the pile must be ductile and belong to Class 1 cross-section according to EN 1993-1-1.

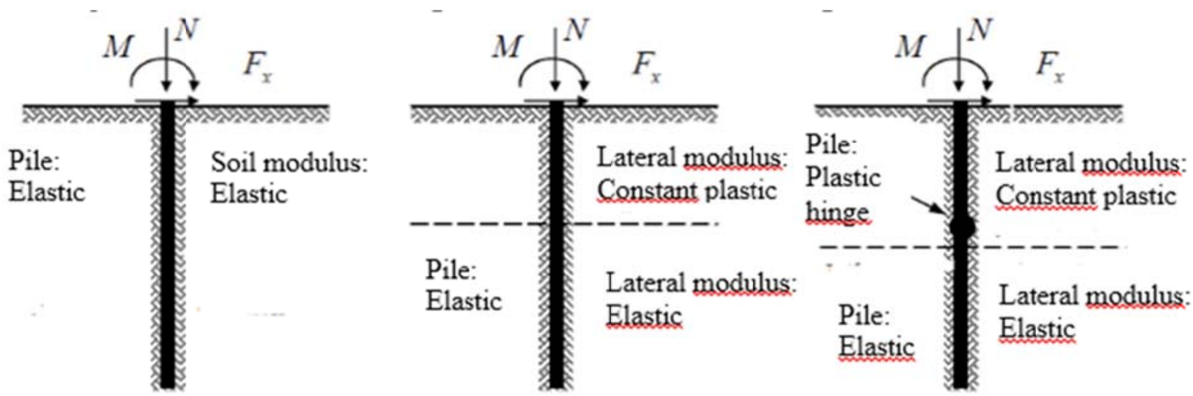


Figure 8. Three stages for the pile analysis, low load at the left, intermediat load in the middle and large load at the right.

The procedure to calculate the moments and shear forces along the pile considering second order effects is a iterative process that is preferable done with computer programs.

## Initial imperfections and second order moments

When designing piles second order effects are taken into consideration. This is done by enlarging moment along the pile and is depending on the initial imperfections of the pile. The initial imperfection of the pile can be assumed according to Table 5.1 in EN 1993-1-1 and is:1/200

$$e_0/l_c=1/200 \qquad (8)$$

for steel pipe piles that are cold formed. For piles with H-profile the value is 1/300 for strong axis bending and 1/250 for weak axis bending.

## Concluding remarks

This paper describes some of issues that have to be dealt with when designing steel piles for integral abutment bridges, but is far from complete. For a more comprehensive material about designing integral abutments according to Eurocodes the reader can look into the design guide from the INTAB project Feldman et. al 2010.

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