Limit Load Analysis of suction anchors for cohesive materials

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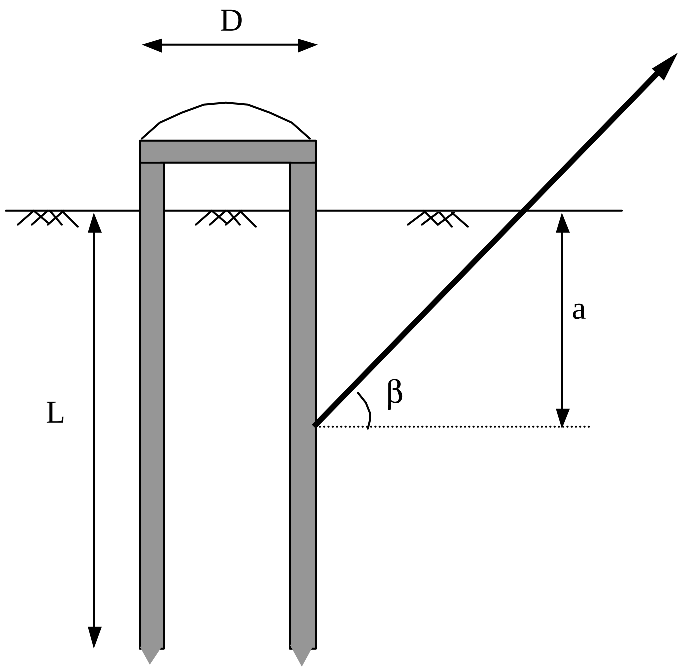
In association with

1. Introduction

Suction anchors (or suction piles) are deep water anchors for floating structures or offshore oil installations. The pile consists of a hallow cylinder which has a top cap and a relatively thin wall.

Installing the pile involves initial penetration into the sea-bed under self weight. The pressure in the water trapped inside the pile, between the mud-line and the top cap, is then lowered by pumping, to cause a positive differential water pressure across the top of the pile, thus forcing the pile further into the soil until its final position is reached.



2. Problem Specifications

Pile diameter, D= 6m
Pile penetration, L=13.5m

Attachment point positions are:
a= 6.75 m (or 1/2 depth L)
a=9m (or 2/3 of depth L)
a=7.785m (just below mid point, considered to be optimum position)

Angle of inclination β is 0^o (horizontal chain), 15^o, 26^o, 30^o, 45^o, 90^o (vertical chain)

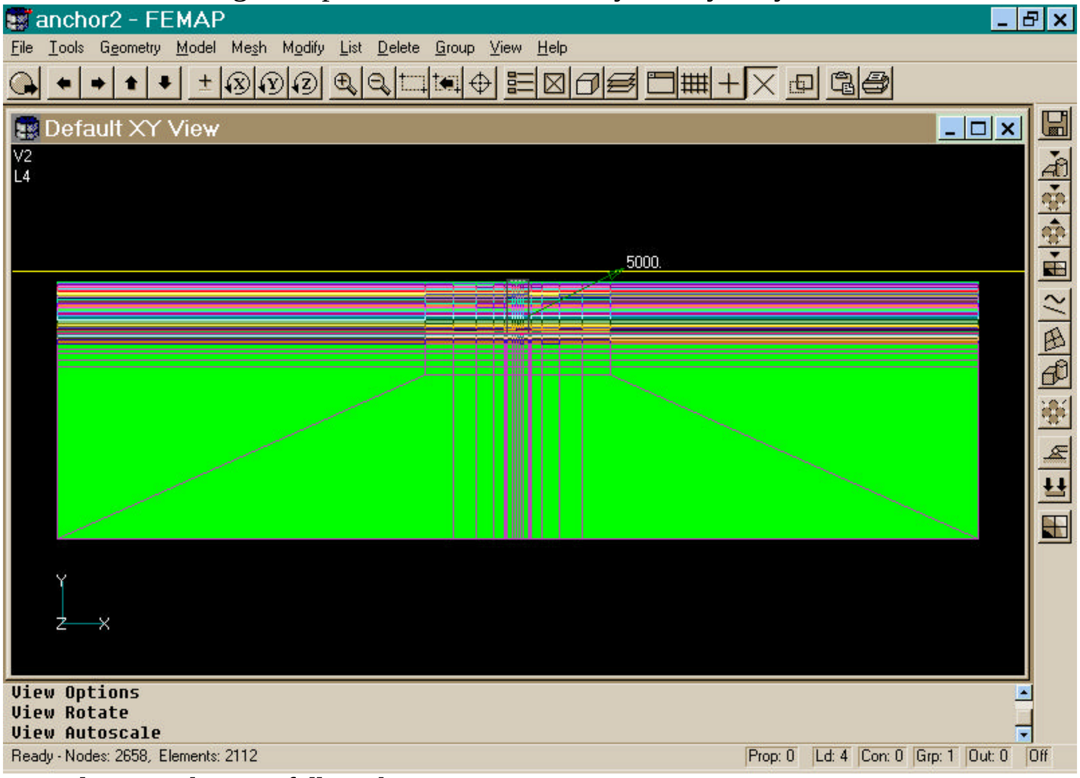
Load applied consists of 50 unequal load increments with maximum load=10000kN

The undrained shear strength, Cu, at mud-line is 3Kpa and it is assumed to increase with depth by a rate of 1.85.
Young's modulus at mud-line is assumed to be 300 KPa and it is assumed to increase with depth by a rate of 185.

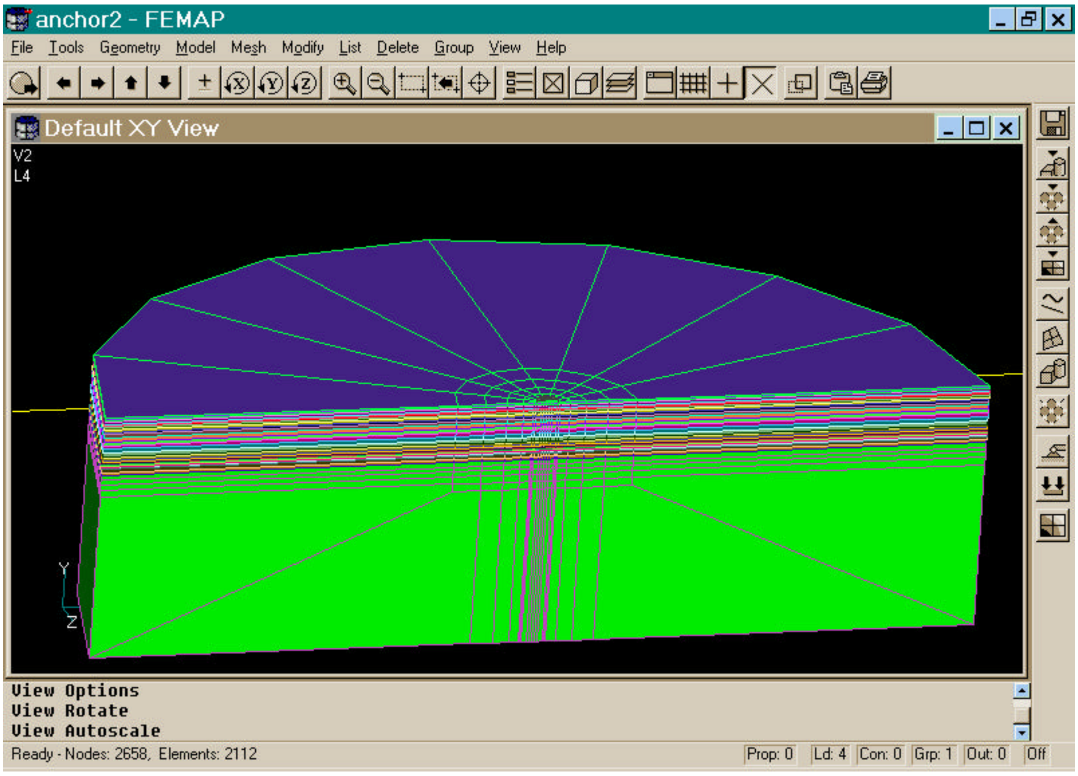
The pile shell's thickness is 3cm. The pile is also assumed to be very stiff, with E=2.1E8

3. Finite Element Mesh

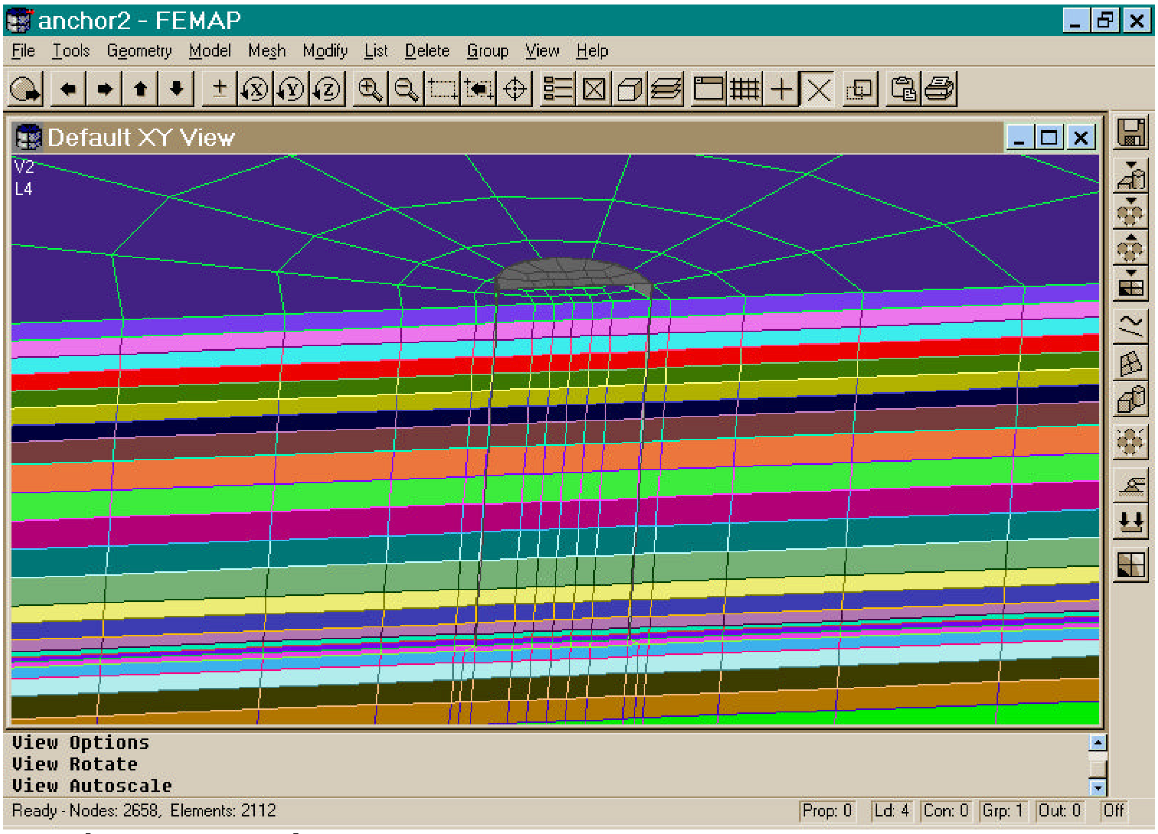
This was done using Femap Basic edition. Due to symmetry, only half the model was considered due



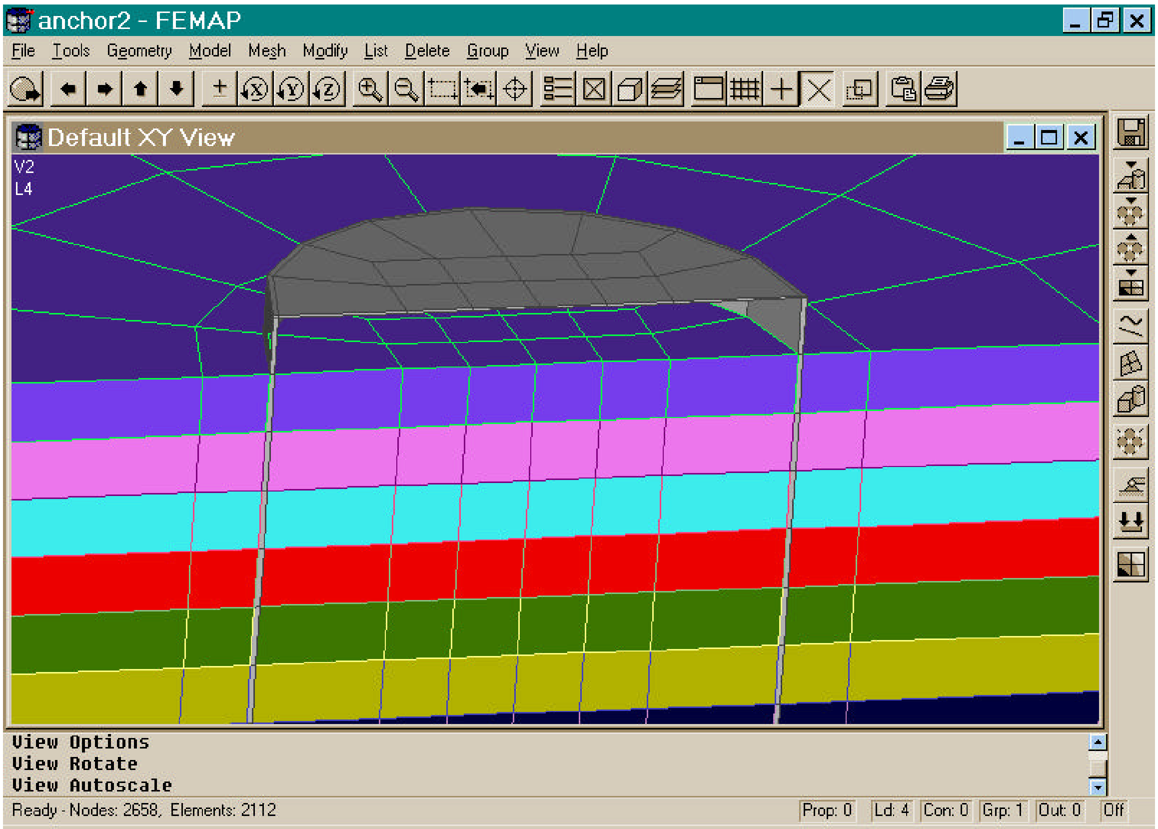
X-Y elevation showing full mesh



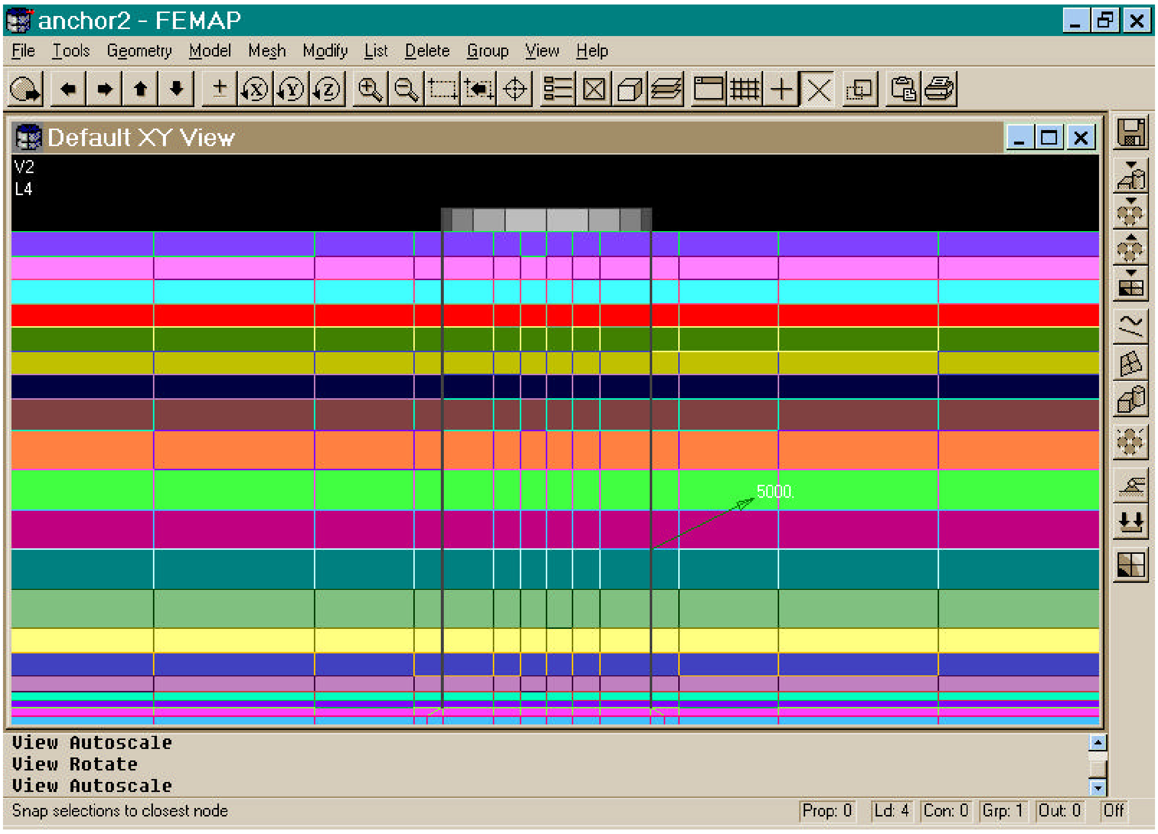
3D view of full mesh



View showing suction pile



View showing suction pile cap

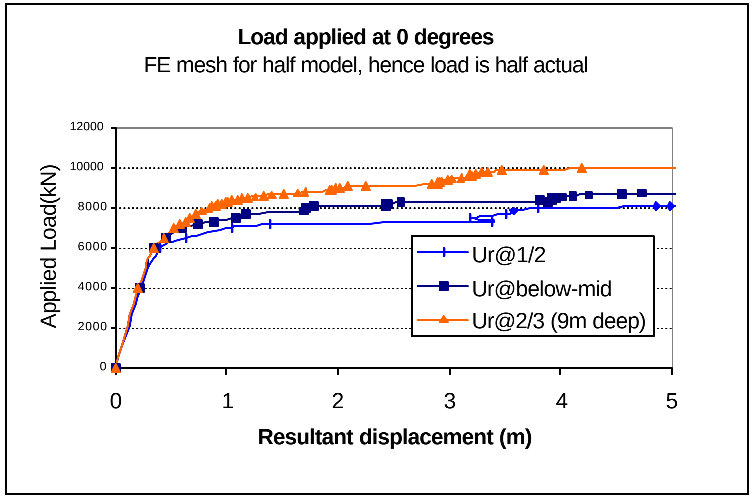


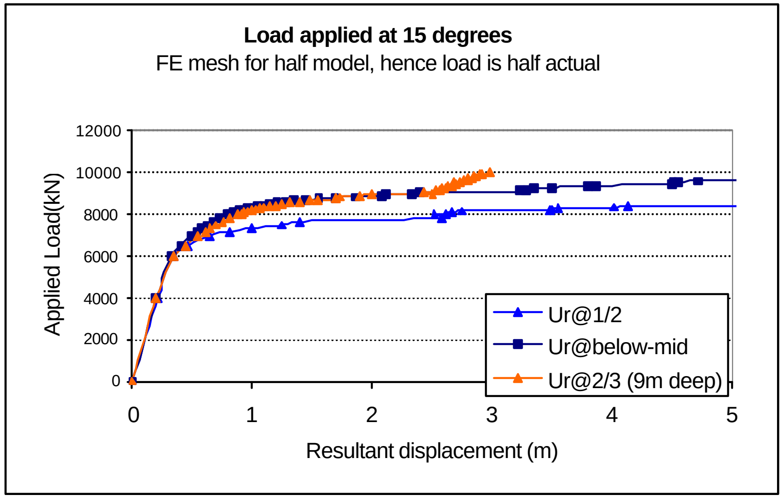
X-Y elevation view showing pile and loading point

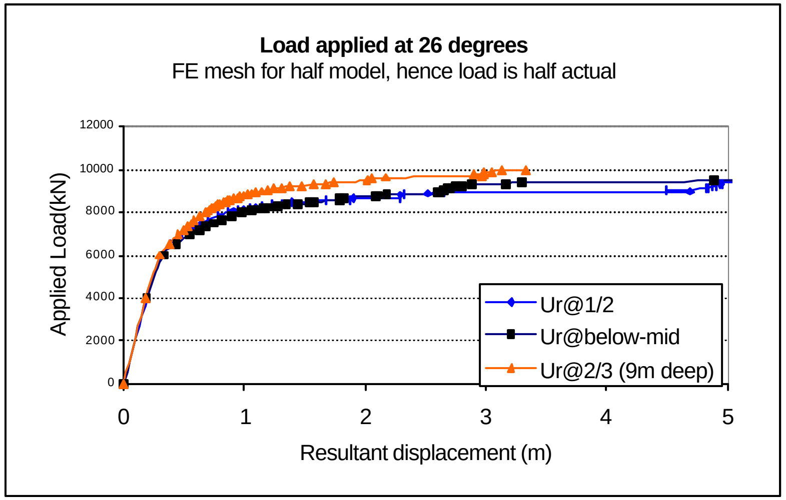
The properties given in the Problem Specification section above are used. A von Mises undrained material is used for the soil, with Poisson's ratio=0.49.

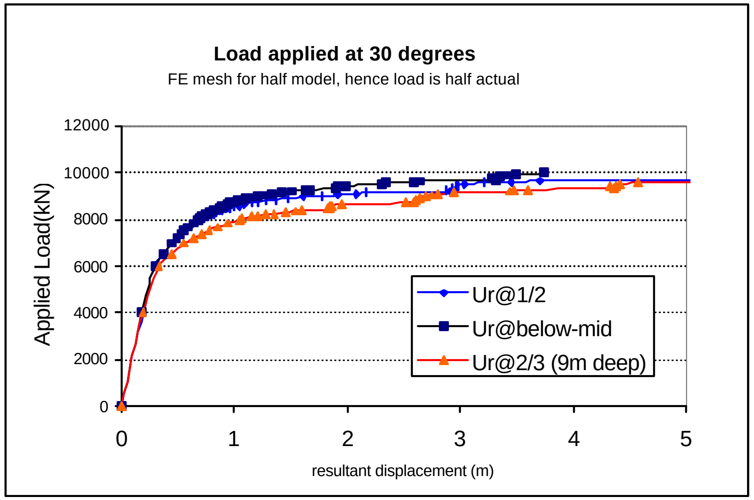
4. Finite Element Results

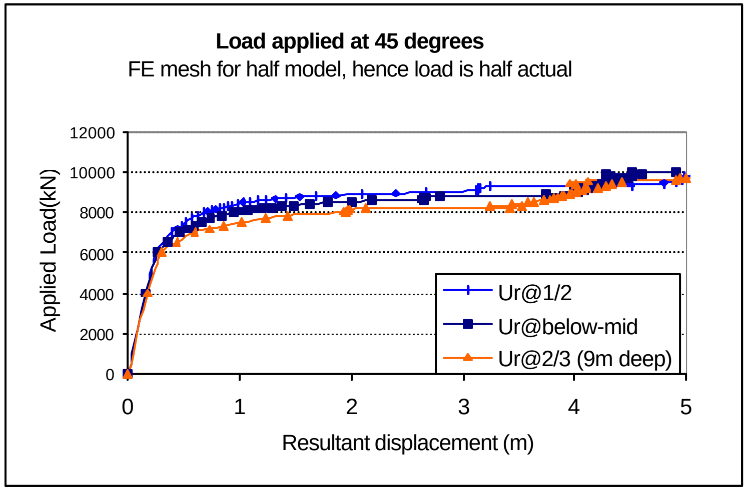
The following charts show FE results for cases with different load attachment point and angle. A von Mises material is used for all of these cases

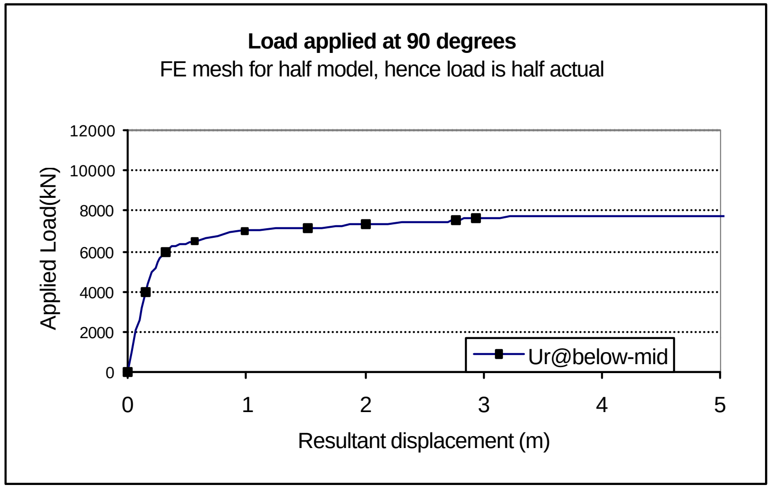


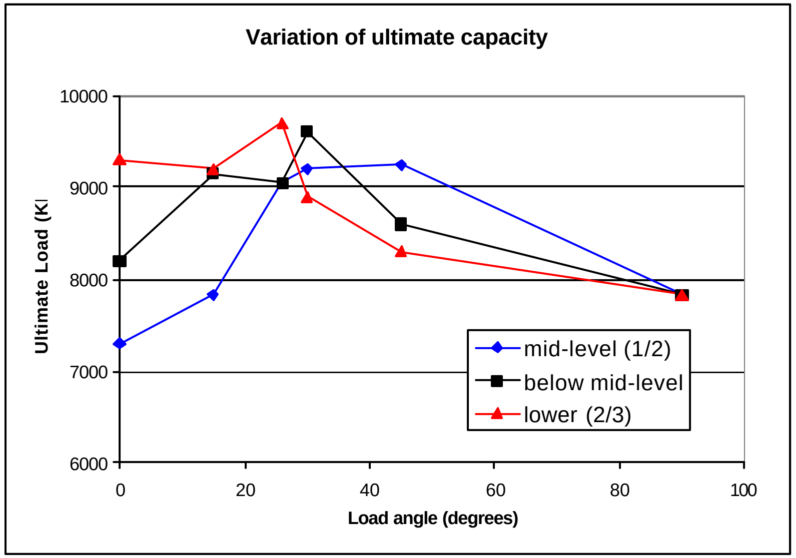




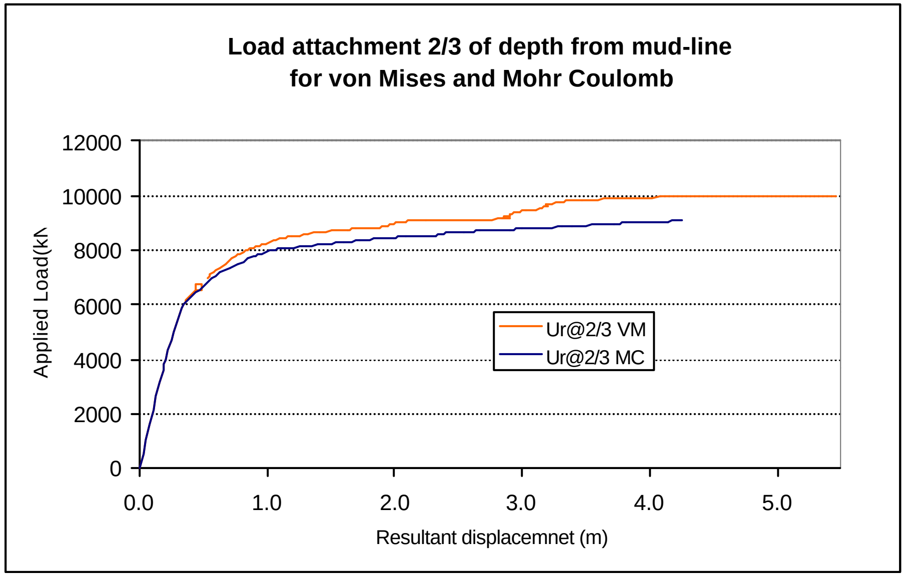








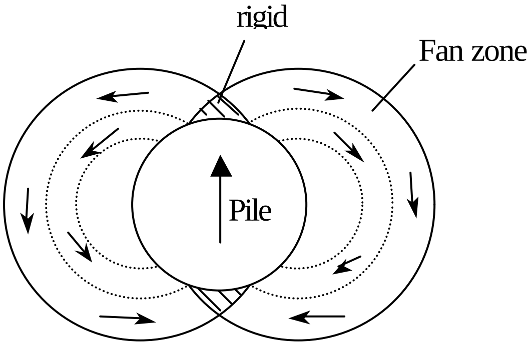
Comparison of ultimate anchor pull-out force
for different anchoring points and angles.



Comparison between von Mises results and Mohr Coulomb results,
for the case of horizontal pull at 2/3 of penetration depth

5. Analytical solution using upper bound theory

According to Randolph and Houlsby (1984)[1] , the plastic flow around a pile loaded laterally, may be described as follows:



The equation for the limiting load for the above mechanism is given as:

$$P_u = c_u d[\pi + 2\Delta + 4\cos\{(\pi - \Delta)/4\}[\sqrt{2} + \sin\{(\pi - \Delta)/4\}]] \quad (1)$$

where d is the pile diameter, and c_u is the undrained shear strength

The pile soil adhesion is defined by:

$$\sin\Delta = f_s / c_u \quad (2)$$

where fs is the limiting pile friction which is less than or equal to the shear strength of the soil. Assuming full adhesion, we get

$$\sin\Delta = 1 \qquad \therefore \Delta = \frac{\pi}{2} \quad (3)$$

Substituting to solve equation we get

$P_u = c_u d \times 12.924$ KN per meter depth

The average Cu for this problem is 15.5 Kpa (linear variation of Cu=3Kpa at the top of pile to 27.98 Kpa at the bottom), and as the diameter is 6m, we get,

P_u=1202 KN per meter depth

The depth of the pile is 13.5m, therefore the total force is

P_u(total)=16225 KN

We could also add the resistance at the base of the pile, which is simply the area times Cu, (or $\pi r^2 \times c_u$). We could use the maximum shear strength at the base, which is Cu=27.98 Kpa. This gives a total force of

P_u(total)=16225+791=17017 KN

The FE solution for lateral loading (ie $\beta=0^o$), we have

P (for 1/2 depth)= 14600 KN

P (for below mid-depth)= 16400 KN

P(for 2/3 of depth)= 18600 KN

[1] Geotechnique 4 of 1984 "The limiting pressure on a circular pile loaded laterally"

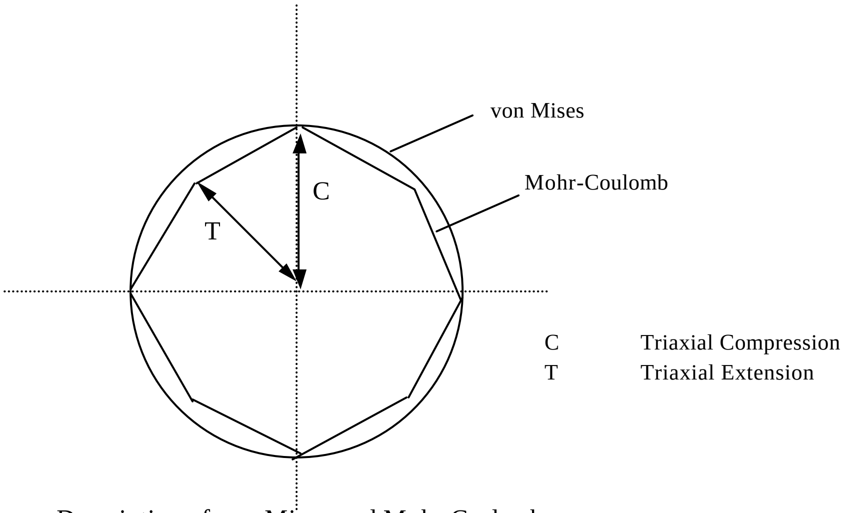
6. Conclusions

- The FE solution for a middle attachment point loaded horizontally can be compared with the upper bound solution of laterally loaded pile. For this analysis the FE solution of =0o at a point below mid-depth is about 4% lower than the upper bound solution.
- A more complex upper bound solution is necessary for cases in which the load is applied at an angle, due to the rotation of the pile.

- Pull out capacity tends to reduce when the angle of load attachment approaches a horizontal level. This indicates that the vertical resistance is the predominant component for such deep piles.

- All the analyses above were carried out using reduced integration (ie 2x2x2 Gauss points). Use of full integration produced a slightly higher collapse load.

- Use of Mohr Coulomb is preferred over use of von Mises material. The Mohr-Coulomb yield surface in the π-plane is slightly smaller giving a lower collapse load.



Description of von-Mises and Mohr-Coulomb yield surfaces in the π-plane