Estimation of undrained shear strength of soft soil obtained by cylinder vertical penetration

Estimation de la résistance au cisaillement d’un sol mou en conditions non-drainées obtenue par la pénétration verticale d’un cylindre

Equihua-Anguiano L.N.
UPAEP University, Puebla, Mexico

Orozco-Calderon M.
Geotechnical consultant, Ciudad del Carmen, Campeche, Mexico

Foray P.
Laboratoire 3SR,Grenoble, France

ABSTRACT: Determination of undrained shear strength (s_u) in cohesive soils is essential for the design of the offshore pipelines/flowlines, especially when burial depth is small (in the order of twice of the pipeline diameter). This paper presents experimental results of the undrained shear estimation, obtained by the vertical penetration of a cylinder in a soft normally clay with deep water characteristics. Results obtained were compared with analytical solution for a cylinder embedded in a cohesive soil, as well as with experimental s_u values obtained using laboratory vane test. The results between the two techniques are very close

RÉSUMÉ : La détermination de la résistance au cisaillement en conditions non-drainées des sols est nécessaire dans le design des conduits/*flowlines offshore,* particulièrement dans le cas où profondeur d´enfoncement est de l´ordre de deux fois le diamètre du conduit. Cet article présent les résultats d´une étude expérimentale conduisant à la détermination de la résistance au cisaillement non drainée d´un sol argileux très mous, en utilisant l´enfoncement d´un cylindre. Enfin, concernant l´aspect modélisation, une solution analytique correspondant à l´enfoncement d´un conduit dans un sol cohérent a été utilisée. Les résultats ont été comparés avec ceux obtenues avec un scissomètre du laboratoire et montrent une bonne approximation.

KEYWORDS: undrained shear strength, deep water, offshore geotechnics, pipeline, vane test..

1 INTRODUCTION.

Deep water soils present special characteristics with respect to the other soils. Examples of the particular parameters correspond to undrained of strength and plasticity. In field, high plasticity values (liquidity index close to 1) and low undrained shear strength (s_u) have been found, this last parameter varies approximately from 1 to 3 kPa on the seabed surface.

Undrained shear strength parameters is main in the marine pipeline conception as well as, its variation with depth, especially in the first tens centimeters. In practice, CPT, T-bar and recovery of intact samples with the Box corer and mini-Tbar are used *in situ* (ISSMGE-TC1 2005, Puech et al. 2010) to obtain geotechnical design parameters. In the same way, laboratory test are done for s_u determination to little depth in the soil, using experimental techniques well known as: vane shear laboratory (AFNOR, 1995), fall cone (Hansbo 1957, Orozco Calderon & Mendoza 2002), T-bar penetrometer (Stewart & Randolph 1991), among others. These techniques allow obtaining s_u to the surface level, at a point or continuously with depth. In this context, the article presents an option to measure s_u from testing cylinders in laboratory as is described below.

1.1 *Objective*

An alternative to estimate experimental undrained shear strength variation with depth was developed. Procedure and laboratory tests were done penetrating a cylinder in a soft soil with deep water characteristics. First, the cylinder was placed horizontally in the soil surface and then, it was penetrated vertically into the soil. The vertical displacement (z) was applied with an electromechanical actuator and the vertical force (F_v) was recorded and were compared with a theoretical solution, in order to determine the undrained shear strength. Finally, the results were compared with s_u values obtained with a laboratory vane. Figure 1 shows the schematic cylinder and nomenclature used.

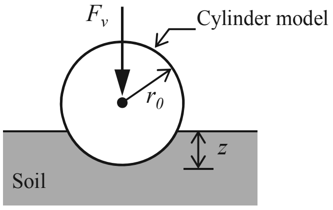

Figure 1. Schematic cylinder penetration.

2 PARTIAL PENETRATION OF A CYLINDER

2.1 *Theoritical solutions*

A theoretical solution to the failure load or collapse for a pipe on the soil was given by Murff et al. (1989) analyzing a pipe partially embedded on the soil and the undrained shear strength (c) uniform with the depth. The solution takes into account the type of surface roughness of the pipe through the concept of adherence $a_d=\alpha c$, and consider a value of α=0 as smooth surface and α=1 as rough surface.

Vertical force on the cylinder (or a pipe) to a certain depth z on a soil with horizontal surface, is given by equation (1):

$$\frac{F_v}{2r_0 c}=\begin{bmatrix}\cos(\Delta+\omega)+2\,\mathrm{sen}\left(\frac{\Delta}{2}\right)+(1+\Delta+2\omega)\cos\omega+\\ +2\cos\left(\frac{\Delta}{2}\right)-2\,\mathrm{sen}\,\omega\end{bmatrix} \quad (1)$$

where: a_d = adhesion at the interface soil-cylinder; c=undrained shear strength; $\Delta=\mathrm{sen}^{-1}\,\alpha$; $\omega=\mathrm{sen}^{-1}\,(1\text{-}z/r_0)$; r_0=cylinder radius; z=penetration depth of the cylinder.

The equation (1) can be represented by an expression of type power, in function of depth penetration z, the radius r_0, coefficient a and exponent b, as follows:

$$\frac{F_v}{2r_0c} = a\left(\frac{z}{2r_0}\right)^b \tag{2}$$

From the above equations, it follows that it is possible to obtain the resistance undrained shear if the vertical force F_v required to penetrate the pipe is known. Considering equation (1) as the theoretical solution, experimental values and resistance undrained shear as the unknown value, namely:

$$\left[\frac{F_v}{2r_0c}\right]_{\text{theoretical}} = \left[\frac{F_v}{2r_0s_u}\right]_{\text{experimental}} \tag{3}$$

The s_u value for each depth of the cylinder penetration is represented by the equation (4). The undrained shear strength average for the entire depth z is represented by equation (5), where N=total values of cylinder penetration during the laboratory test.

$$\left(s_u\right)_i = \frac{\left[\frac{F_v}{2r_0}\right]_{\text{experimental}}}{\left[\frac{F_v}{2r_0c}\right]_{\text{theoretical}}} \tag{4}$$

$$\overline{s_u} = \frac{\sum_{1}^{N}\left(s_u\right)_i}{N} \tag{5}$$

Another alternative to obtain s_u for the entire depth (z) of the cylinder penetration is solving the equation (3), applying numerical methods, for instance the least squares method.

In this case, the adjustment evaluation is minimizing the sum of squared residuals (E), which corresponds to the squared distance of the experimental values and the theoretical curve based on their, as shown in equation (6).

$$E = \sum_{i=1}^{N}\left\{\left[\frac{F_v}{2r_0s_u}\right]_i - \left[\frac{F_v}{2r_0c}\right]_i\right\}^2 \tag{6}$$

where: $\left[F_v / 2r_0s_u\right]$ corresponds to the values obtained experimentally and s_u is an unknown; $\left[F_v / 2r_0c\right]$ is the vertical collapse load normalized by the pipe diameter and the soil shear strength for different values of α (Murff et al. 1989).

Substituting equation (2) into (6) it is possible to obtain E (equation 7) with three unknowns values: the undrained shear strength s_u, coefficient a, and the exponent b.

$$E = \sum_{i=1}^{N}\left\{\left[\frac{F_v}{2r_0}\right]_i - \left[s_u a\left(\frac{F_v}{2r_0}\right)^b\right]_i\right\}^2 \tag{7}$$

Solution of equation (7) represents the value of s_u for the entire depth (z), where the values a and b allow to fit the experimental data to approximate the theoretical solution (equation 1).

Using the expressions (4), (6) and (7) it is possible to obtain s_u. Calculated values of s_u by these equations were compared with experimental values as shown in next sections.

3 CYLINDER MODELS AND SETUP

3.1 *Cylinder models and setup*

Two cylinder models with different geometrical and material characteristics were used: a steel pipe model with a diameter of 100 mm and a length of 335 mm, the second pipe model in PVC with 200 mm diameter and 900 mm length.

Tests were performed in the tank *VisuCuve* of Laboratoire 3S-R in Grenoble. Its internal dimensions are 2m-length, 1m-width and 1m-depth. For the experimental tests it was filled only 0.4 m-depth with the soft soil.

The vertical force F_v was applied on the cylinders using an electromechanical actuator. The vertical force and displacements were recorded during the penetration test via a control and data acquisition system (Fig. 2).

The large rigid tank *VisuCuve* was used in others laboratory studies to visualize in order to visualize the failure mechanism around a mini penetrometer T-bar (Puech et al. 2010) and study models anchor plates (Equihua-Anguiano et al. 2012).

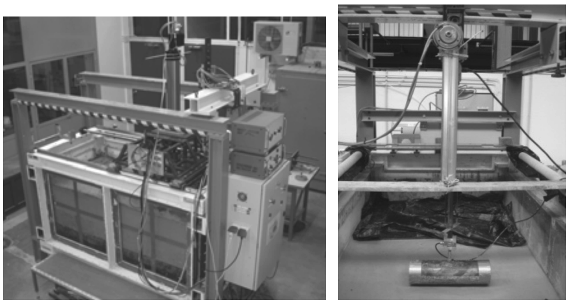

Figure 2. VisuCuve setup and electromechanical actuator used to penetrate a pipeline model vertically into a soft soil.

3.2 *Tested soil*

The reconstituted soil used in this study was composed of a mixture of bentonite and kaolin in equal proportions (50B/50K) with w=110% and 200%, w_L=163% and PI=132%. Its characteristics are very similar of deep water (Gulf of Guinea w=150-200%, w_L=170% and PI=125%). In the same way, this reconstituted soil has been used in other researches, for example a study of T-bar penetrometer and soil-pipeline interaction (Orozco-Calderon 2009).

3.3 *Experimental program*

Table 1 shows nine experimental tests program. For the pipe model of 100 mm diameter two soils were tested (s_u=6 kPa and 3 kPa). In the case of pipe 200 mm diameter only two penetration tests were performed in a soil with s_u=3 kPa.

Table 1. Dimensions of the pipe models used in the experiments.

Test No.	Pipe model	Pipe diameter (mm)	Material pipe model	Soil No.	w (%)	s_u (kPa)
1	10-110-1	100	Steel	1	110	6
2	10-110-2	100	Steel	1	110	6
3	10-110-3	100	Steel	1	110	6
4	10-110-4	100	Steel	1	110	6
5	10-150-5	100	Steel	2	150	3
6	10-150-6	100	Steel	2	150	3
7	10-150-7	100	Steel	2	150	3
8	20-150-8	200	PVC	2	150	3
9	20-150-9	200	PVC	2	150	3

4 RESULTS

Results for numerical and experimental testing are presented in the next sections.

4.1 *Force vertical and depth penetration of pipe model tests*

Figure 3 shows some typical experimental results and a comparison with those calculated from equations (4), (6) and (7).

Results presented in Figure 3(a) correspond to the curves of type s_u-z/r_0 (solution of equation 4) which represent undrained shear strength for each depth of the penetration. The results of Figure 3a the equation (5) could be used to obtain an average value of the s_u throughout the depth analyzed.

The second type of curves, Figures 3(b) and 3(c), corresponds to the vertical force F_v normalized respect to the diameter of the pipe and the undrained shear strength ($F_v/2r_0s_u$) versus the penetration normalized respect to the radius or diameter. The use of these curves represents the solution of the equations (6) and (7).

In the case of Figures 3(a) and 3(b) the calculated values correspond to depths of $z/2r_0 \leq 0.5$, since the theoretical solution is used for normalized force (Murff et al. 1989, equation 1), valid for a penetration less than or equal to the radius of the pipe. Values of the undrained strength calculated considering two types of surface, while the surface of the laboratory model was the same during the tests, and that can be interpreted as the minimum and maximum values.

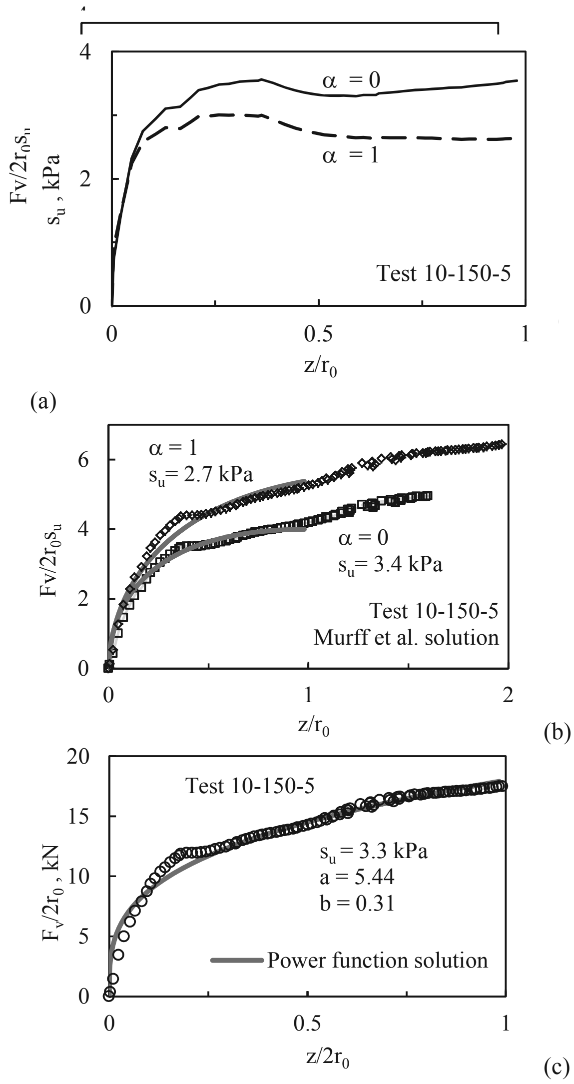

Figure 3. Estimating of undrained shear strength using a vertical penetration of a cylinder (Test No. 5). Solution using the equation (4) in (a). Calculated values of s_u considering the solution Murff et al. for α=0 and α=1 (equation 4) in (b). Value of s_u by fitting set of experimental data with a power function solution (equation 7) in (c).

For the results in Figure 3(c) the adjustment takes into account the values of $z/2r_0 \geq 0.5$, which represents an advantage over the equations (4) and (6), and the solution corresponds to a unique value of s_u, also at the same time, *a* and *b* values were calculated.

4.2 *Calculated undrained shear strength*

Results of undrained shear strength of all tests are summarized in Figure 4. Figure 4(a) represents the mean value of the s_u calculated with equation (5) for the typical results included in Figure 3(a). Interpretation of the results takes into account the variation of pipe surface. It can be noticed immediately the difference in the results for soils with different undrained shear strength.

Results are concentrated around the soil resistance obtained with miniature vane shear test. In case of analysis with α=0 the estimated values s_u are higher than corresponding to a rough surface (α=1). Horizontal lines included in the Figure 4(a) represent the average value of considering all the values of each soil and roughness. The experimental pipe models used had a surface intermediate, therefore it is expected that the corresponding s_u value is between two limits.

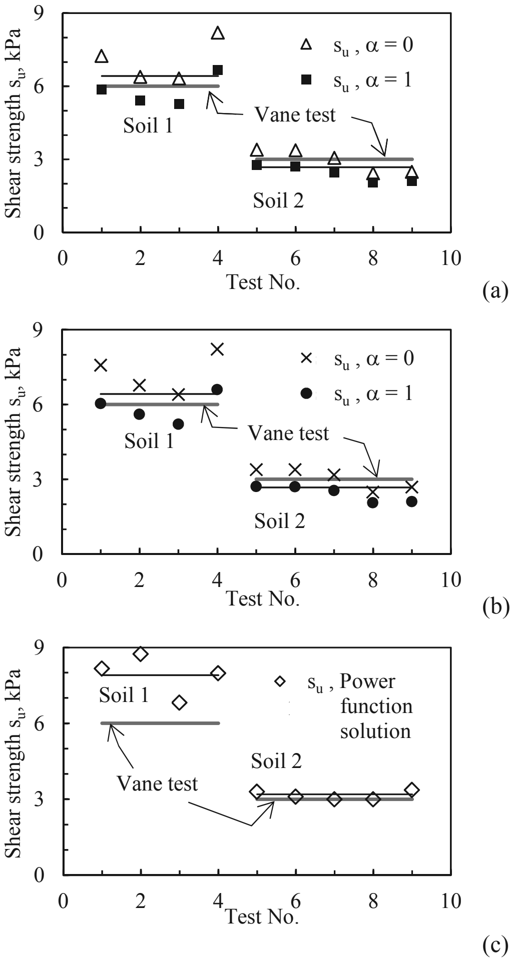

Figure 4. Undrained shear strength obtained from the equation (5) for a penetration depth of $z/2r_0 \leq 0.5$ (a). Values of s_u calculated from the equation (6) and the solution Murff et al. (equation 1) for α=0, α=1 and $z/2r_0 \leq 0.5$ (b). Values of s_u calculated from the equation (7) whereas the total depth of penetration of the pipe model (c).

Figure 4(b) shows the results for the case of the estimated value from the equation (6). Their values are grouped for each soil and the tendency of behavior is similar to the results of Figure 4(a), the difference is clearly distinct between the two undrained shear strength. Similarly, the horizontal line represents the mean value s_u estimated of each soil.

The calculated results from Equation (7) are included in Figure 4(c). Values are generally higher than those of the preceding Figures 4(a) and 4(b), this can be understood as such calculation does not take into account the theoretical solution (Equation 1), and the roughness of the pipeline is implied by the value of the coefficient *a* and the exponent *b* of the numerical curve fitting. In this case, the average value of the coefficient is a=5.12 with a standard deviation of σ=±0.48, to the exponent average value of b=0.32 and σ=±0.09. Figure 5 shows the variation of *a* and *b* values.

The estimated values of the undrained strength and standard deviation for each soil are included in Table 2. There are similarity of the values calculated from equations (4) and (6) and roughness respectively. For the type of power adjustment, which represents a simple solution compared to the strict theoretical equation, the values are generally higher. It is important to note that the value of the standard deviation is high, which encourages to study this alternative to estimate experimental undrained shear strength with a large number of experimental test for different soils with different undrained shear strength.

The technique using cylinders penetration in order to obtain the soil shear strength provides good results, one limitation is consider the undrained strength constant with depth.

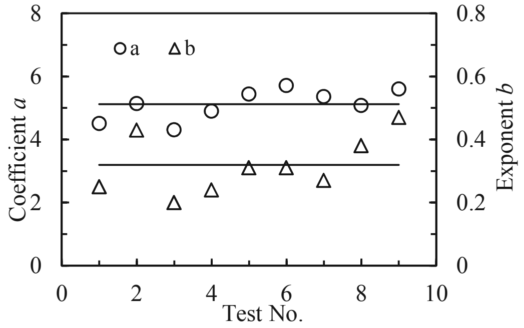

Figure 5. Variation coefficient *a* and exponent *b* for all experimental tests, obtained from fitting of experimental values with equation (2).

Table 2. Values of the average undrained shear strength calculated from vertical penetration tests cylinder models.

Soil No.	Values*	Equations					
		(4)		(6)		(4) & (6)	(7)
		α=0	α=1	α=0	α=1	α=0 and 1	...
1	$\overline{s_u}$ (kPa)	7.0	5.8	7.3	5.9	6.5	7.9
	±σ (kPa)	0.9	0.6	0.8	0.6	1.0	0.8
2	$\overline{s_u}$ (kPa)	2.9	2.4	3.0	2.4	2.7	3.2
	±σ (kPa)	0.5	0.3	0.4	0.3	0.3	0.2

* $\overline{s_u}$: average undrained shear strength, σ: standard deviation.

5 CONCLUSIONS

This article presents experimental tests, as an option to obtain the undrained shear strength of soft soils using vertical penetration of a cylinder into the soil.

Experimental results takes into account theoretical solution for a pipe penetrated in a homogeneous medium, characterized by a constant undrained strength with depth.

Experimental tests were performed on two soils with different undrained shear strength, the results are close to the value of s_u obtained with a laboratory miniature vane.

The standard deviation of the experimental results of this paper is relatively high, which encourages study with a larger number of soils.

One limitation of the test is the depth shallow for soil characterization, however it is considered appropriate for the case of marine pipeline design.

6 ACKNOWLEDGEMENTS

The authors acknowledge the *GéO* team of the *Laboratoire 3S-R* at Grenoble, France, for the facilities and support to perform the experiments.

7 REFERENCES

AFNOR. 1990. *Essai scissométrique en laboratoire, sols: reconnaissance et essais*, Norme NF P 94-072, Association Française de Normalisation, Paris, La Défense, 325-337.

Aubeny C.P., Shi H. and Murff J.D. 2005. Collapse load for cylinder embedded in trench in cohesive soil, *International Journal of Geomechanics*, Vol. 5(4), 320-325.

Equihua-Anguiano L.N., Orozco-Calderon M. and Foray P. 2012. Numerical finite element method and experimental study of uplift capacity anchors, *Seventh International Conference on Offshore Site Investigation and Geotechnics, OSIG 2012*, London, U.K.

Hansbo S. 1957. A new approach to the determination of the shear strength of clay by the fall-cone test, Stockholm: Royal Swedish Geotechnical Institute, Proceedings 14.

ISSMGE-TC1 2005. Geotechnical and geophysical investigations for offshore and near shore developments, TC1, ISSMGE.

Murff J.D., Wagner D.A. & Randolph M.F. 1989. Pipe penetration in cohesive soil, *Géotechnique* Vol. 39(2), 213-229.

Orozco-Calderon M. 2009. *Etude de l'interaction cyclique sol-pipe dans les grands fonds marins*. Thèse, Institut Polytechnique de Grenoble, Laboratoire Sols, Solides, Structures – Risques, France.

Orozco-Calderon M. and Mendoza M.J. 2002. Quick and reliable determinations of water content, liquid limit and undrained shear strength for fine-grained soils (in Spanish), *XX National Meeting of Soil Mechanics*, SMMS, Oaxaca, Mexico, Vol. 2, 53-62.

Puech A., Orozco-Calderon M. and Foray P. 2010. Mini Tbar testing at shallow penetration, *Proceedings Frontiers in Offshore Geotechnics II*, Perth, W.A., Australia, 305-310.

Stewart D.P. and Randolph M.F. 1991. A new site investigation tool for the centrifuge, *Proceedings of CENTRIFUGE 91*, 531-538.