Study on the practices for preconsolidation stress evaluation from oedometer tests

P. Paniagua
Norwegian Geotechnical Institute, Norway, priscilla.paniagua.lopez@ngi.no

J.-S. L'Heureux, S.Y. Yang, T.L. Lunne
Norwegian Geotechnical Institute, Norway

ABSTRACT
The preconsolidation stress (p_c') is determined from high-quality oedometer test results by a variety of interpretation methods. Sample quality in the database varies from very excellent to fair (i.e. class 1-2). Results show that the five methods applied give very similar p_c' values when the samples are of good quality, with p_c' varying up to 14% between the five methods.

Keywords: oedometer test, preconsolidation stress, OCR

1 INTRODUCTION

The standard oedometer tests provide the basis for investigating one-dimensional (1D) soil deformation characteristics and soil stress history. During the tests, soft and compressible soil generally exhibit bilinear stress-displacement behavior when the data are plotted on a semi-logarithmic graph. Below a vertical effective yield stress (σ'_{vy}), the displacements are small; and above that threshold value, the soil strains until it reaches a more compressed structured. The σ'_{vy} is known as preconsolidation stress (p_c'). The ratio between p_c' and the *in-situ* vertical effective stress (σ'_v) is known as overconsolidation ratio (OCR).
Most of the clays included in this study are not mechanically over consolidated but have an apparent over consolidation due to aging: an apparent p_c' considered to be created by delayed consolidation (Bjerrum, 1967) and various chemical processes, i.e. not by mechanical unloading. The apparent p_c' is considered as a yield stress that can be estimated from oedometer test results through a variety of methods like those proposed by e.g. Casagrande (1936), Janbu (1969), Pacheco Silva (1970), Butterfield (1979), Becker et al. (1987), Oikawa (1987), Burland (1990), Karlsrud (1991), Jacobsen (1992), Onitsuka et al. (1995) and Boone (2010).
These methods have in common the assumption of a change in soil stiffness from a stiffer to a softer response near p_c'; however, their procedures vary greatly. Ideally, interpretation of p_c' should not depend on the chosen interpretation method nor require subjectivity.
One of the principal objectives of the ongoing internal Strategic Project "SP8- Soil Parameters in Geotechnical Design" (GEODiP) at the Norwegian Geotechnical Institute (NGI) is to help achieving a more consistent interpretation of laboratory and *in-situ* results, and to test/develop procedures for the choice of characteristic design parameters in soft clay. As part of the project SP8-GEODiP, the present work compares the results of applying some of the abovementioned interpretation methods [i.e. Casagrande (1936), Janbu (1969), Pacheco Silva (1970), Becker et al. (1987) and Karlsrud (1991)] for determination of p_c' and OCR on high quality (i.e. fair to excellent) oedometer test results from clay samples collected both on- and off-shore. The purpose is to evaluate the applicability of these methods in a wide range of clays; in order to suggest a more consistent interpretation of p_c'. A short discussion on the evaluation of p_c' on samples of poor quality is presented. Finally, the paper evaluates the interpretation methods in terms of technicalities, source of errors and practical purposes.

2 METHODS FOR EVALUATING P_C'

2.1 Previous works on this topic

After Casagrande (1936) proposed a method for defining the preconsolidation pressure, alternative approaches have been suggested, mostly based on empirical observations regarding the stress and deformations patterns exhibited by the soil during oedometer tests. Grozic et al. (2003, 2005), Clementino (2005) and Boone (2010) present detailed and graphical summaries of these approaches.

In particular, Grozic et al. (2003, 2005) evaluated multiple methods for interpreting p_c' in low plasticity clays and concluded that uncertainties affect all methods, and that some were more difficult and ambiguous than others in application.

As detailed by Boone (2010), scale effects can clearly influence the Casagrande's method. He details also that the conclusion drawn by Grozic et al. (2003) on recommending Becker et al. (1987) and Onitsuka et al. (1995) methods, in addition to Casagrande (1936) and Janbu (1989) methods, may prove difficult and frustrating in practice, and lead to no better results given the level of uncertainty that exist when using these methods.

2.2 Casagrande (1936)

Casagrande (1936) uses an empirical construction from the void ratio, e, and the logarithm of vertical effective stress, σ_v', curve. To determine p_c', a geometrical approach is followed based on Figure 1a: (i) choose by eye the point of minimum radius (or maximum curvature) on the consolidation curve (point A in Fig. 1), (ii) draw a horizontal line from point A, (iii) draw a line tangent to the curve at point A, iv), bisect the angle made by steps (ii) and (iii), (v) extend the straight-line portion of the virgin compression curve up to where it meets the bisector line obtained in step (iv). The point of intersection of these two lines is the most probable preconsolidation stress (point B of Fig. 1). The maximum possible preconsolidation stress is shown as point D while E represents the minimum possible value of the preconsolidation stress.

2.3 Janbu (1969)

Janbu (1969, 1989) suggested to base the determination of p_c' on plots of tangent constrained modulus values versus σ_v'. However, he did not specify in detail how to do the p_c'-determination. The procedure used here is explained in the sketch shown in Figure 1b. Janbu's approach uses the resistance concept. He defined the tangent modulus (or constrained modulus), M, as the ratio of the change in effective stress ($\delta\sigma$') to the change in strain ($\delta\varepsilon$) for a particular load increment (i.e. $M = \delta\sigma'/\delta\varepsilon$). For a low stress level, around σ'_{v0}, the resistance against deformation (M_0) is large. When σ' increases, this high resistance decreases appreciably owing to partial collapse of the grain skeleton. Resistance reaches a minimum (M_n) around p_c'. Subsequently when σ' is increased beyond p_c', the resistance increases linearly with increasing σ'. In the overconsolidated range M_1 (the average between M_0 and M_n) is often used in design. Behaviour in the normal consolidation stress range can be approximated by a linear oedometer modulus M. Hence, for $\sigma' > p_c'$, $M = m(\sigma'-\sigma_r')$ where m is the modulus number and σ_r' is the intercept on the σ' axis and it called the reference stress.

2.4 Pacheco Silva (1970)

The method proposed by Pacheco Silva (1970) to determine p_c' is widely used in Brazil. It uses an empirical construction from the e – log σ'_v curve.

The p_c' is determined graphically as shown in Figure 1c and explained as follows: (i) draw a horizontal line (A–B) passing through the initial void ratio (e_o) of the specimen, i.e., the specimen void ratio before any load has been applied; (ii) extend the straight line portion of the virgin compression curve (C–D) until it intercepts line A–B; (iii) from the point of intersection of lines A–B C–D, draw a vertical line down until it intercepts the e – log p′ curve (Point E); (iv) from Point E draw a horizontal line until it intercepts line C–D (Point F); and then (v) the stress value in the horizontal axis associated with Point F is p_c′. Pacheco Silva (1970) method is independent of the drawing scale (Pinto, 1992).

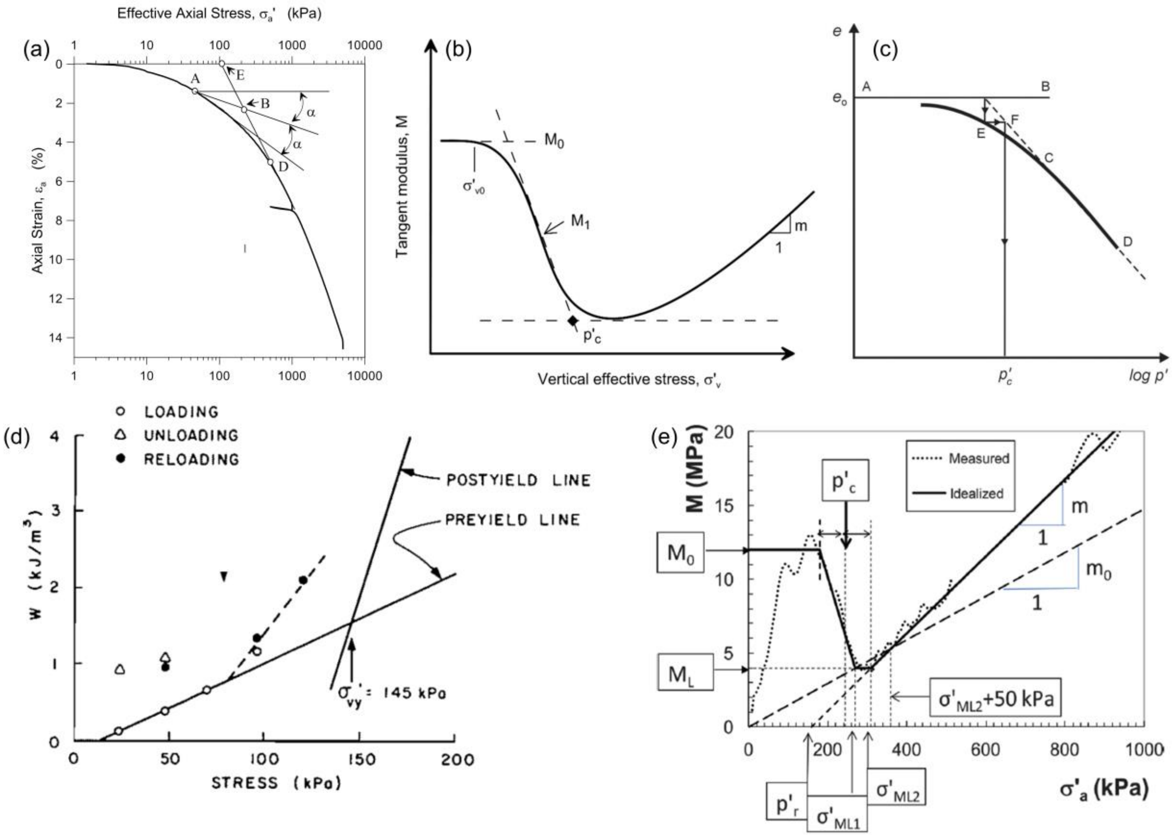

Figure 1. Methods for evaluating p_c': (a) Casagrande (Holtz and Kovacs, 1981), (b) Janbu (Lunne et al. 2008), (c) Pacheco Silva (Grozic et al. 2003), (d) Becker (Becker et al. 1987) and (e) Karlsrud (Karlsrud and Hernandez-Martinez, 2013).

2.5 *Becker et al. (1987)*

Becker et al. (1987) proposed the work method. They defined the incremental work as:

$$\Delta W_{oed} = \left(\frac{\sigma'_{i+1} + \sigma'_i}{2}\right)(\varepsilon_{i+1} - \varepsilon_i) \qquad (1)$$

Where σ'_{i+1} and σ'_i are the effective stresses at the end of i+1 and i loading increments, respectively; and $\varepsilon_{i+1}$and ε_i are the natural strains at the end of i+1 and i loading increments, respectively.

For overconsolidated specimens (Figure 1d), a linear relationship is fitted in the data below *in-situ* stress and the post-yield (i.e. above p_c') data is approximate with a linear relationship. The intersection of those two fitted lines represents p_c'.

2.6 *Karlsrud (1991)*

Karlsrud (1991) and Karlsrud and Hernandez-Martinez (2013) proposed a slightly modified version of the Janbu (1969, 1989) method.

As detailed in Karlsrud and Hernandez-Martinez (2013), the modulus behaves as follows (see Figure 1e):

a) During loading from zero to the *in-situ* σ_v', the modulus generally increase gradually and then tends to reach a plateau defined as the maximum re-loading modulus, M_0. The modulus then drops off more or less linearly to a minimum level defined as M_L (i.e. M_n), with corresponding stress defined as σ'_{ML1}. After this stress is reached the modulus increases linearly, but for some clays the modulus is constant up to a stress level defined as σ'_{ML2} before it starts to increase linearly. Janbu's modulus number, m, defines the rate of increase beyond this point. This line defines an M = 0 intercept on the stress axis defined as p_r', which is the same definition as used by Janbu (1969). Note that for very stiff as well as disturbed clays, p_r' may be negative.

b) The definition of p_c' is taken as the average stress at which the tangent modulus starts to drop off, until it starts to climb up again along the virgin modulus line.

3 APPLICATION OF METHODS TO INTERPRET P$_C$'

3.1 Soil index properties

The 169 oedometer tests results (94% as CRSC and 6% as incremental loading - IL) used in the present study come from 18 different sites. The samples were taken with either 72 mm piston sampler, miniblock sampler or block sampler. Table 1 presents a summary of some index properties of the clay materials tested. In particular, water content (w), unit weight (γ_T), plasticity index (IP), clay content (clay) and sensitivity (S_t).

Table 1. Basic properties of the clays studied

Site	w (%)	γ_T (kN/m³)	IP (%)	Clay (%)	St (-)
Eidsvoll	25-35	19-20	13-19	37-48	2-5
Emmerstad	40-48	17-18	3-12	27-40	77-225
Hvalsdalen	31-39	18-20	9-18	40-49	5-20
Kløfta-Nybakk	32-46	18-19	8-19	33-46	7-135
Leirsund	30-39	19	9-18	36-49	5-20
Nybakk-Slomarka	30-45	17-19	7-28	13-67	1-170
Lierstranda	32-42	18-20	13-19	31-36	7-15
Glava	30-35	18-20	15-30	30-60	7-10
Ellingsrud	34-40	18-19	5-8	37	15-61
Klett	25-35	19-20	4-10	30-35	10-240
Kvenild	30-46	17-19	10-14	31-47	22-63
Stjordal	33-43	17-19	7-8	37-38	200
Klett-Bårdshaug	26-35	19-20	6-13	30-33	10-160
Nykirke	25-35	20	4-9	20-55	65-80
Onsøy	60-65	15-16	32-42	20-60	4,5-6
Ghana	90-145	13-15	70-95	45-65	2-6
Johan castberg	22-38	18-20	20-42	30-45	1-3
Bothkennar	66-72	15-16	42-53	17-35	8-13

Table 2. Evaluation of sample quality, after Lunne et al. (1998).

OCR	$\Delta e/e_0$			
1 to 2	< 0,04	0,04-0,070	0,070-0,14	> 0,14
2 to 4	< 0,03	0,03-0,050	0,020-0,10	> 0,10
4 to 6	< 0,02	0,02-0,035	0,035-0,07	> 0,07
Qua-lity	1: very good to excellent	2: good to fair	3: poor	4: very poor

3.2 Quality of oedometer tests results

The quality of the samples tested is evaluated based on the initial void ratio and the axial strain at the *in-situ* stress according to the classification proposed by the Norwegian Geotechnical Society (NGF, 2013). This classification is based on Lunne et al. (1998). The quality criteria is presented in Table 2. The data is categorized as high quality (i.e. class 1 and class 2) which varies from good to fair and very good to excellent. Figure 2 shows as an example the variation of sample quality with depth for the data included in the analysis.

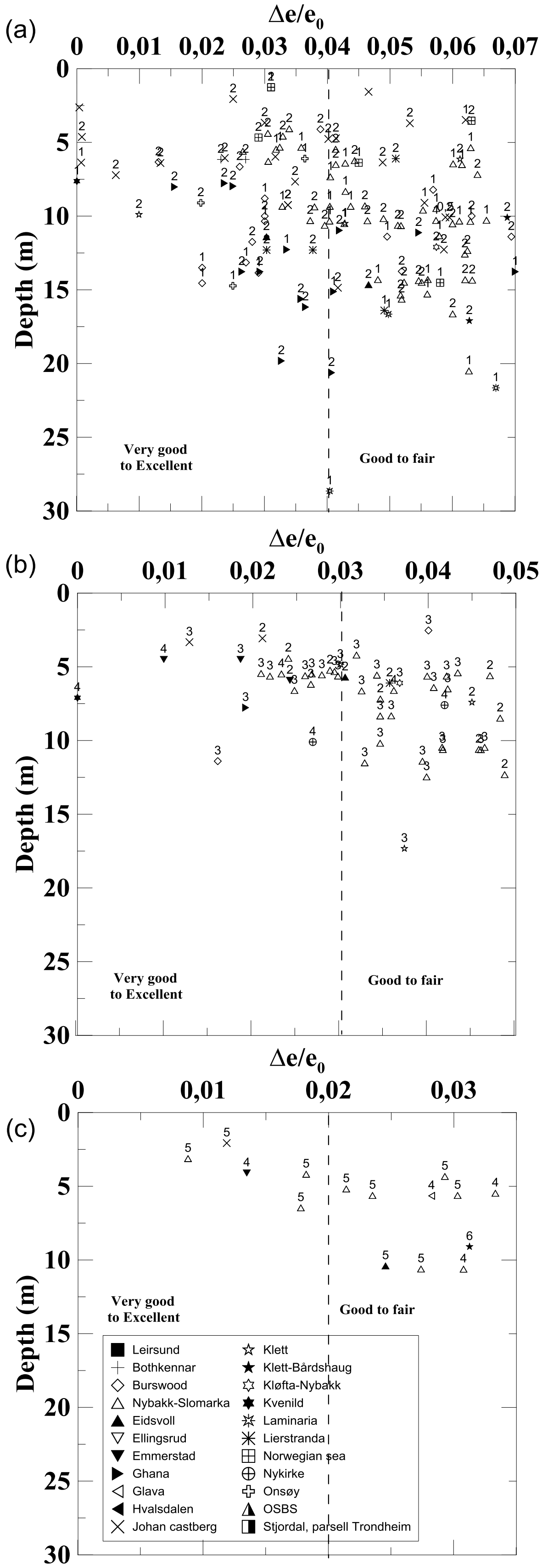

Figure 2. Sample quality for oedometer tests, for OCR between a) 1 and 2, b) 2 and 4 and c) 4 and 6. The OCR is shown over the symbols.

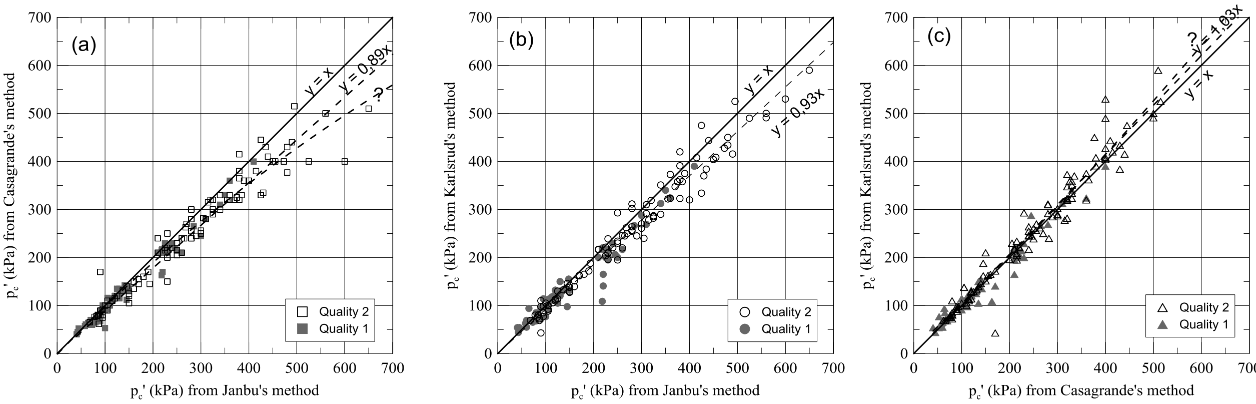

Figure 3. Comparison of p_c' obtained by: a) Janbu's and Casagrande's methods, b) Janbu's and Karlsrud's methods and c) Casagrande's and Karlsrud's methods.

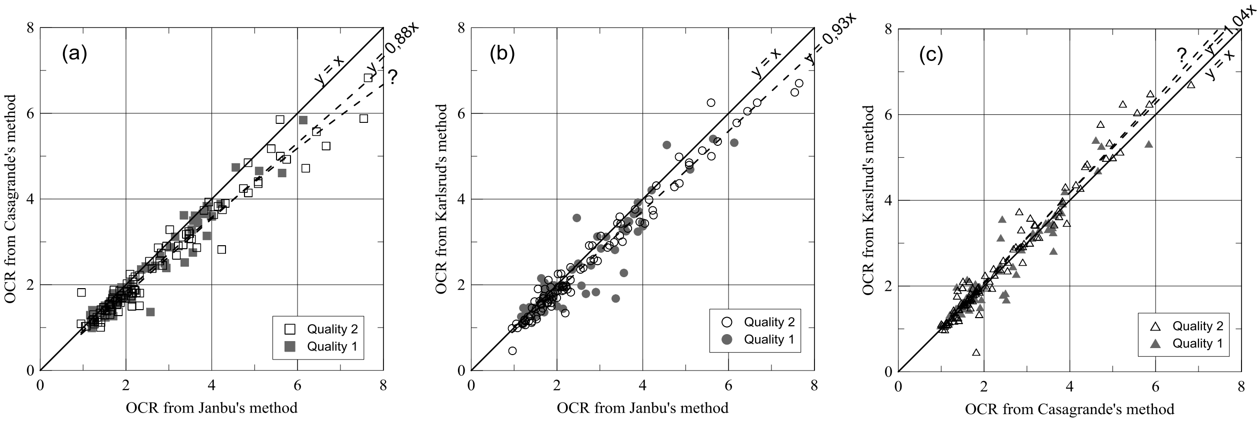

Figure 4. Comparison of OCR' obtained by: a) Janbu's and Casagrande's methods, b) Janbu's and Karlsrud's methods and c) Casagrande's and Karlsrud's methods.

3.3 Results and interpretation

Figure 3 and Figure 4 show the values of p_c' and OCR obtained with Casagrande's, Janbu's and Karlsrud's approaches. These methods give very similar values. Janbu values tend to be slightly higher than Casagrande (as observed by Grozic et al. 2003) and Karlsrud values. Karlsrud's and Casagrande's methods seem to result in similar values.

The values show more scatter for high p_c'and higher OCR that adds uncertainties to the data. It seems that the data with quality 2 tend to add more deviation to the expected trend. Some exceptions are observed for data with quality 1, that come from Johan Castberg and Kvenild sites. Data from Johan Castberg site was difficult to interpret regarding the definition of the tangents in the graphical methods. Kvenild data is reported as quality 1 data, however, this couldn't be confirmed by $\Delta e/e_o$ values. The p_c' and OCR values vary between 4-12%. These differences are more visible for high values of p_c' (i.e. p_c' > 400-500 kPa) and OCR (i.e. OCR > 4).

In particular, the differences up to 12% are between Janbu's and Casagrande's methods, and Janbu's and Karlsrud's methods. This result is somehow surprising considering that the Janbu's and Karlsrud's methods are based on the same assumptions. However, in Karlsrud's method, p_c' is calculated as an average from two single values whereas in Janbu's method p_c' is a single point.

Since all of them are graphical methods, the interpreter must have good plot resolution (large enough scale in the range of analysis) in order to clearly define tangents and choose the values with high accuracy.

Karlsrud and Hernandez-Martinez (2013) comment that a comparative study of different other methods for defining p_c' from oedometer tests was applied to 15 of the oedometer tests in the database used by them. Karlsrud's method comes out just about equal to the average of the other methods (0,8% on the high side). Our data shows a higher deviation (i.e. up to 7,5%) when the quality of the sample decreases, and the p_c' and OCR increases.

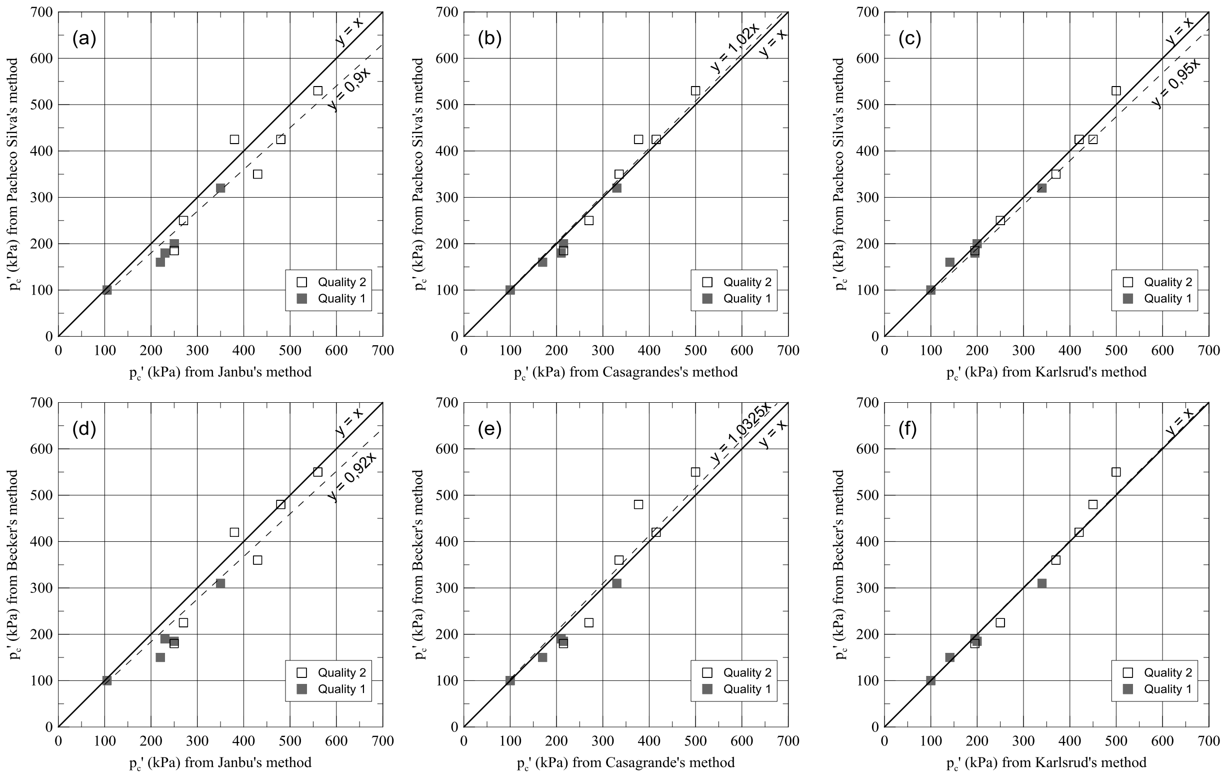

Figure 5. Comparison of p_c' obtained by: a) Pacheco Silva's and Janbu's methods, b) Pacheco Silva's and Casagrande's methods, c) Pacheco Silva's and Karlsrud's methods, d) Becker's and Janbu's methods, e) Becker's and Casagrande's and f) Becker's and Karlsrud's methods.

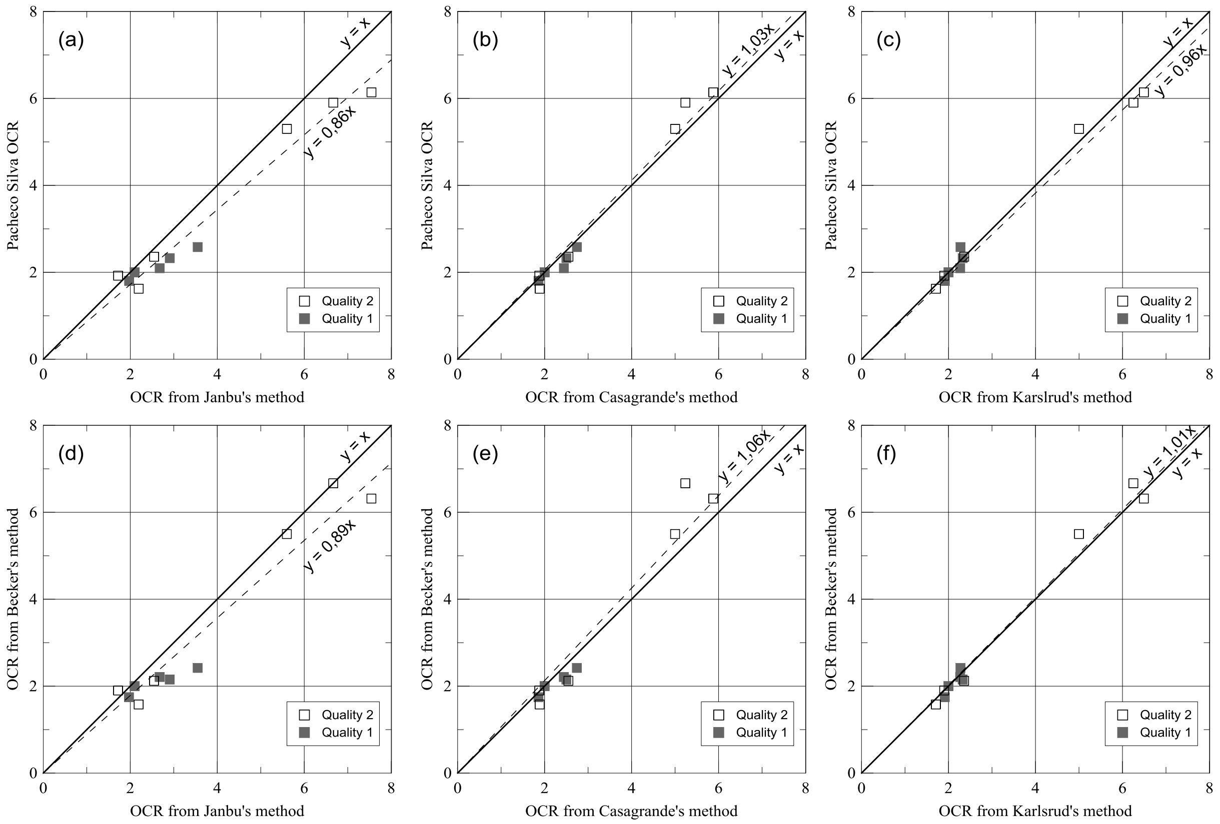

Figure 6. Comparison of OCR obtained by: a) Pacheco Silva's and Janbu's methods, b) Pacheco Silva's and Casagrande's methods, c) Pacheco Silva's and Karlsrud's methods, d) Becker's and Janbu's methods, e) Becker's and Casagrande's and f) Becker's and Karlsrud's methods.

Internationally, most oedometer tests are performed as IL tests (with 24 h load steps). The test in the database used in the present study are mostly CRSC tests. It is generally observed that, p_c' from IL tests will be 15 - 20% lower than CRSC tests.

3.4 Additional methods applied to samples with variable quality

Twelve tests results of the ones studied with Casagrande (1936), Janbu (1969) and Karlsrud (1991) methods (i.e. tests with quality 1 and quality 2, six of each one) were chosen to apply Pacheco Silva (1970) and Becker et al. (1987) methods. In addition, six tests results with quality 3 were included to study the effect of sample quality in the application and determination of p_c'.
Figure 5 and Figure 6 shows the values of p_c' and OCR obtained with these approaches for the different specimens evaluated. As observed before, Janbu's method tends to have higher values of p_c' than the other methods. When compare to Pacheco Silva's method, Janbu's method results up to 14% difference in OCR and 10% difference in p_c'. Pacheco Silva's and Becker's methods fit pretty well with Casagrande's and Karlsrud's methods. Some differences up to 5% are observed between the estimated values of p_c' and OCR. More deviation from the expected trend is observed for high p_c' (i.e. p_c' > 500 kPa) and OCR (i.e. OCR > 4-5) values, and in particular for samples with quality 2 and 3. The difference between Pacheco Silva's and Becker's methods reach 6% for p_c' and OCR.

4 EVALUATION OF METHODS

After these results, no strong p_c' and OCR variations are observed for high quality samples interpreted using Casagrande's, Karlsrud's, Pacheco Silva's and Becker's methods. Janbu's method gives the highest deviations. One reason could give at Janbu's method does not clearly specify the steps to follow for a graphical interpretation, therefore, it depends on the own user experience and judgement. The observation that more scatter is observed for high p_c' and OCR values might be due to the fact that a soil specimen undergoes higher reloading behaviour after sampling and unloading, or recompression, up to the point at which it reaches first the *in-situ* condition and then the apparent p_c' it has experienced in the past, and then the "virgin" compression beyond p_c'. This unloading-reloading process might cause more disturbance in the skeleton and therefore quality reduction.
When comparing all methods, a very significant difference is that Casagrande's method and Pacheco-Silva's method as well as most international methods use double logarithmic scales. Whereas Janbu's method suggests that a linear scale should be used to avoid misinterpretations since double logarithmic scales can hide large scatter in the data.
One of the main difficulties in applying the graphical methods is the definition of the tangents to the data. Usually a stress-deformation curve from a CRSC odometer test has more data points than traditional incremental loading methods and the "best-fit" lines require some judgement and subjectivity.

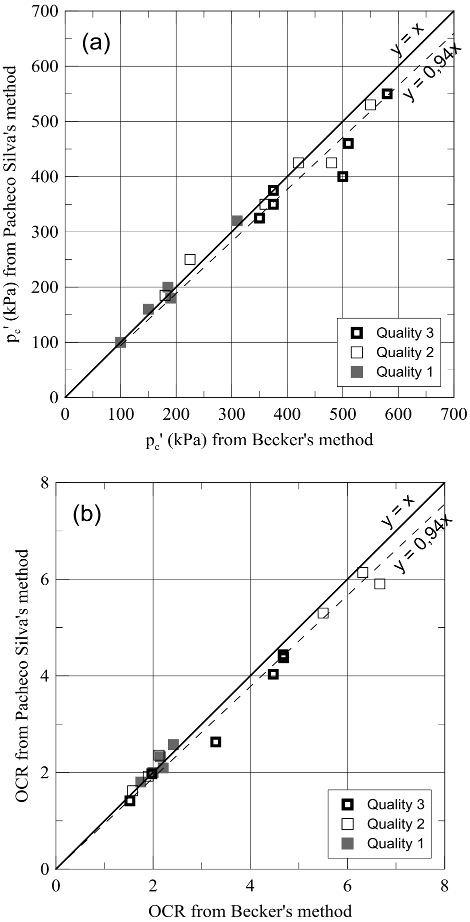

Figure 7. Comparison between a) p_c' and b) OCR from Pacheco Silva's and Becker's methods.

Table 3. Final evaluation of the p_c' interpretation methods applied in the present study

Method	Technicalities	Source of errors	Practicalities	
All the methods	Tangent or "best-fit" lines definition	Subjectivity Scale of the plot (type)	Easy if scale is large	Difficult if scale is small
	Calculation / reading of p_c'	Scale of the plot (size)	Difficult if scale is large	Easy if scale is small
Janbu Becker Karlsrud	Additional calculations (i.e. incremental work or deformation modulus)	Calculation mistakes	Extra time and effort required	
Casagrande	Definition of highest curvature point	Subjectivity	Difficult, it requires judgement	
Janbu	Undefined procedure	Subjectivity	Difficult, it requires judgement and experience	

In particular, it was experienced during the application of the methods, that a small change in the slope of the tangents produced significant changes in p_c'. In addition, the scale type of the plot might increase the difficulties regarding reading the stress values.

Table 3 presents a final evaluation of the methods in terms of technicalities (i.e. small details of the procedure), source of errors and practical purposes (i.e. according to the experience of its application for p_c' determination).

5 CONCLUSIONS

Interpretation of 129 oedometer test results show that, in general, the value of p_c' and OCR does not depend on the interpretation method used when evaluating high quality samples. This is especially true for low values of preconsolidation stress and overconsolidation ratio.

For samples having high values of p_c' and OCR, differences in interpretation methods can lead up to 14% in estimates of p_c' and/or OCR.

In practice, we recommend to employ at least three different methods for evaluating p_c' and OCR. This will guarantee a more consistent choice of parameters for a given user and project. In case of doubts and to reduce uncertainties, evaluation of p_c' and OCR should be performed and/or checked by a colleague.

This work does no pretend to conclude which method is correct. As Becker et al. (1988) mentioned "... the issue is which technique provides the most repeatable result and is least ambiguous."

6 REFERENCES

Becker, D.B., Crooks, J.H.A., Been, K., & Jefferies, M.G. (1988). Work as a criterion for determining *in-situ* and yield stresses in clays: Reply. Can. Geotech. J. 25, 848-850.

Becker, D.R., Crooks, J.H.A, Been, K. & Jefferies, M.G. (1987). Work as criterion for determining *in-situ* & yield stresses clays. Can. Geotech. J. 24: 549-564.

Bjerrum, L. (1967). Engineering Geology of Norwegian Normally-Consolidated Marine Clays as Related to Settlements of Buildings. Géotechnique 17: 83-118.

Boone, S.J. (2010). A critical reappraisal of "preconsolidation pressure" interpretations using the oedometer test. Can. Geotech. J. 47, 281-296.

Burland, J.B. (1990). On the compressibility & shear strength of nat. clays. Géotechnique 40: 329-378.

Butterfield, R. (1979). A natural compression law for soils. Géotechnique 24: 469-479.

Casagrande, A. (1936). The determination of the preconsolidation load and its practical significance. Proc. First Intern. Conf. on Soil Mech. & Found. Eng., Cambridge, 60-64.

Clementino, R.V. (2005). Discussion: An oedometer test study on the preconsolidation stress of glaciomarine clays. Can. Geotech. J. 42, 972-974.

Grozic, J.L.H., Lunne, T. & Pande, S. (2003). An oedometer test study on the preconsolidation stress of glaciomarine clays. Can. Geotech. J 40, 857-872.

Grozic, J.L.H., Lunne, T. & Pande, S. (2005). Reply to the discussion by Clementino on: "An oedometer test study on the preconsolidation stress of glaciomarine clays". Can. Geotech. J 42, 975-976.

Holtz, R.D. & Kovacs, W.D. (1981). An Introduction to Geotechnical Engineering. Prentice-Hall, Inc., New Jersey, 733.

Jacobsen, H.M. (1992). Bestemmelse af forbelastningstryk i laboratoriet. Proceedings of Nordiske Geotechnikermonde NGM-92. Danish Geotechnical Society, Bulletin 9, 455-460.

Janbu, N. (1963). Soil compressibility as determined by oedometer and triaxial tests. Proc. Euro. Conf. on Soil Mech. and Found. Eng. 1, 19-25.

Janbu, N. (1989). Grunnlag i Geoteknikk, Trondheim: Tapir.

Karlsrud, K. & Hernandez-Martinez, F.G. (2013). Strength and deformation properties of Norwegian clays from laboratory tests on high-quality block samples. Can. Geotech. J. 50, 1273-1293.

Karlsrud, K. (1991). Sammenstilling av noen erfaringer med prøvetaking og effekt av prøveforstyrrelse i norske marine leire. NGI report 521500-6.

Lunne, T., Berre, T. & Strandvik, S. (1998). Sample disturbance effects in deepwater soil investigations. Conf. Soil Invest. Found. Behav., London.

Lunne, T., Berre, T., Andersen, K.H., Sjursen, M., & Mortensen, N. (2008). Effects of sample disturbance on consolidation behaviour of soft marine Norwegian clays. Proc. 3rd Int. Conf. on Site Charact. ISC'3, Taipei, 1471-1479.

NGF (2013). Veiledning for prøvetaking, melding nr. 11.

Oikawa, H. (1987). Compression curve of soft soils. Soils and Foundations 27, 99–104.

Onitsuka, K., Z. Hong, Y. Hara, & S. Yoshitake. (1995). Interpretation of oedometer test data for natural clays. Soils and Foundations 35, 61–70.

Pacheco Silva, F. (1970). A new graphical construction for determination of the pre-consolidation stress of a soil sample. Proceedings 4th Brazilian Conference Soil Mechanincs and Foundation Engineering, Rio de Janeiro, 225-232.

Pinto, C.S. (1992). First Pacheco's Silva conference – Part I: Distinguished aspect of Pacheco Silva's activities. Brazilian Geotechnical Journal (Solos e Rochas), ABMS-ABGE. 15 (2), 49–87.