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The revival of multiple pore pressure measurements in the cone penetration test

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ABSTRACT: In common practice the most usual positioning of the filter location for the piezocone (CPTU) is at the cone shoulder (u_2) which is recommended by ISO 19901-8:2014 and ISO 22476-1:2012. However, these ISO standards allow additionally for pore pressure measurements to be taken at the cone face (u_1) or behind the friction sleeve (u_3). The triple element piezocone (CPTU3) offers a solution whereby measurements of pore pressure can be taken simultaneously at all three locations. By taking these three pore pressure measurements the soil behaviour classification may be enhanced by interpretation in terms of c_h from u_1, u_2 and u_3 and by correlations to overconsolidation ratio (OCR) and lateral stress ratio (K_0). In this paper the correlations to OCR are explored by establishing a database from historical data as presented in international geotechnical literature.

1 INTRODUCTION

The pore pressure measurement taken using the piezocone (CPTU) can be recorded with depth or as dissipation over time when penetration is paused. The most common pore pressure measurement is behind the cone shoulder (u_2), as preferred by ISO 19901-8:2014 and ISO 22476-1:2012. However, these ISO standards allow additionally for penetration pore pressure measurements to be taken on the cone face (u_1) or behind the cone sleeve (u_3) as shown in Figure 1. The so-called triple element piezocone (CPTU3) was used by several researchers in the 1980s and 1990s but has seen very little use in the last 25 years. The available literature indicates that CPTU3 has considerable potential relative to the standard CPTU including:

- Correction of sleeve friction (f_s) for pore pressure effects
- Increased reliability of assessment of horizontal coefficient of consolidation (c_h) from three sets of dissipation tests
- Evaluation of drainage conditions around the cone – especially for intermediate soils where partial drainage occurs
- Improved layering detection using u_1 compared to u_2
- Enhanced correlations to stress history and in situ horizontal stress

This paper explores the last aspect of correlations to stress history by developing a database from available CPTU3 tests published mainly in the 1980s and 1990s. First a review of the earlier reported use of pore pressures in connection with CPT is made.

2 HISTORY OF PORE PRESSURE MEASUREMENT IN THE CPT/CPTU

Pore pressure measurement during penetration of a probe was introduced in the 1970s (Janbu & Senneset, 1974, Torstensson, 1975, Wissa et al., 1975). The pore pressure probe used by Janbu & Senneset (1974) resembled an electrical cone, with the same area at the base of the cone. The other probes had different geometries and dimensions, but all had cylindrical porous elements. From the beginning, the large potential of such probes was recognised. At that time, CPTs and pore pressure probe tests were performed in adjacent deployments, for instance Janbu & Senneset (1974) used a CPT and in parallel a standard NGI piezometer.

Although Parez et al. (1976) had already developed and used equipment able to measure cone resistance (q_c) and pore pressure simultaneously, it was only in the early 1980s that many researchers

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around the world started to use a pore pressure measurement element incorporated in the electrical cone (e.g. Roy et al.,1980, Campanella & Robertson, 1981). Battaglio et al., (1986) presented results from CPTU3 tests carried out in a medium to stiff clay at the Pontida site (Italy). Fugro and McClelland both developed CPTU3 probes in the mid1980s, see Bayne & Tjelta (1987) and Zuidberg et al. (1988).

Based on CPTU data from several clays with a range of overconsolidation ratio (OCR) values, Robertson et al. (1986) presented a conceptual pore pressure distribution along the length of a penetrating

Figure 1. Pore pressure measurement positions.

cone penetrometer for clays, ranging from normally consolidated to heavily overconsolidated clays (Figure 2). The pore pressure distribution is normalised by in-situ hydrostatic pore pressure (u_0).

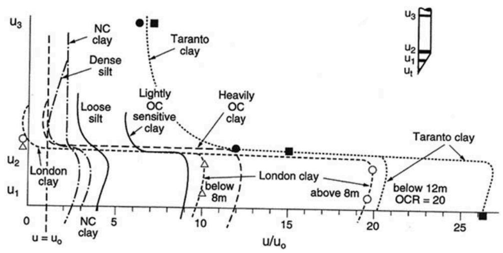

Figure 2. Pore pressure distribution in saturated clays around a penetrating cone based on field measurements (Robertson et al., 1986).

Figure 2 indicates that the pore pressure measured at the tip or face of the cone (u_{1t} or u_{1f}, designated u_{uc} and u_1 respectively on inset of Figure 2) is higher than that measured at u_2, which again is higher than that measured at u_3. Figure 2 also illustrates the potential to use relative values of u_{1t} or u_{1f}, u_2 and u_3 to estimate OCR and possibly lateral stress ratio (K_0).

Early studies based on limited data, reported by Sully et al. (1988), Sully & Campanella (1991) and others showed the potential of correlations among Pore Pressure Difference (PPD) = $(u_1-u_2)/u_0$ vs OCR and suggested that they will vary with soil type as shown in Figure 3, this was later confirmed by Powell and Lunne (2005).

3 LEARNINGS FROM DATABASE

Based on the potential use of the CPTU3 seen from the literature review, it was decided to collect available data from previously published field test results to

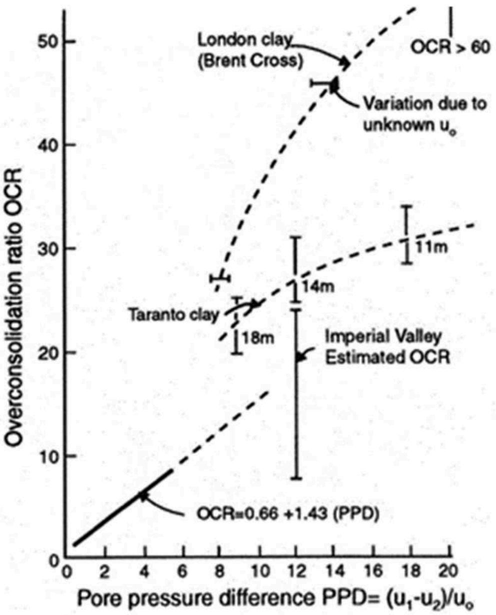

Figure 3. PPD vs OCR for OCR > 10 (Sully et al., 1988).

create a database of pore pressure measurements, index properties and stress history values. The objective of the database was to evaluate reported correlations between the measured pore pressures and reported correlations between geotechnical engineering parameters and parameters derived from pore pressure measurements, referred to hereafter as pore pressure parameters.

The data used to create the database represent a range of clays from Europe and the USA, taken mainly from Chen & Mayne (1994), Larsson & Mulabdic (1991), Sandven (1991), Powell & Lunne (2005), and from unpublished data from offshore soil investigations in the North Sea where NGI was the consultant and some recent NGI projects. When possible, datasets were checked by studying the original source. Uncertain or poor-quality data were removed from the originally prepared database where appropriate.

Altogether, the final database contained 546 datasets from 63 sites (both offshore and onshore). OCR values, based on oedometer tests, are available for all 63 sites, whereas K_0 values are available from 5 UK and 2 Norwegian clays, mainly based on results of self-boring pressuremeter tests.

Table 1. Details of relevant datasets in final database.

Parameter	u_{1t}	u_{1f}	u_{1f}*	u_2	u_3
Data points	56	381	36	512	413
Parameter	OCR	K_0			
Data points	313	112			

* Calculated from u_{1t} (as explained later in the paper)

In addition to PPD (defined above) other derived pore pressure parameters utilising u_1 and u_2, are found in literature:

1. Pore pressure ratio (PPR) = u_1/u_2 (Sully et al., 1988)
2. Excess pore pressure ratio (PPR1) = $(u_1-u_0)/(u_2-u_0)$ (Sully et al., 1988)
3. Normalized Pore Pressure Difference (PPSV) = $(u_1-u_2)/\sigma'_{v0}$

Since the present database contained a reasonably good number of datasets for u_3 also, similar parameters involving u_1 and u_3, and u_2 and u_3 were also derived. Parameters derived using u_1 and u_2 were designated with suffix 'a', using u_1 and u_3 with suffix 'b' and using u_2 and u_3 with suffix 'c'.

Excellent correlation was found between u_{1t} and u_{1f} (Figure 4). Using this relationship u_{1f} was calculated for 36 datasets where only u_{1t} values were measured. For subsequent analyses

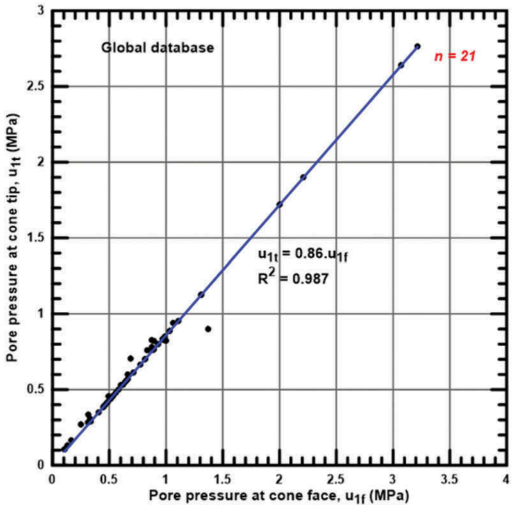

Figure 4. Relationship between u_{1t} and u_{1f} for global data base.

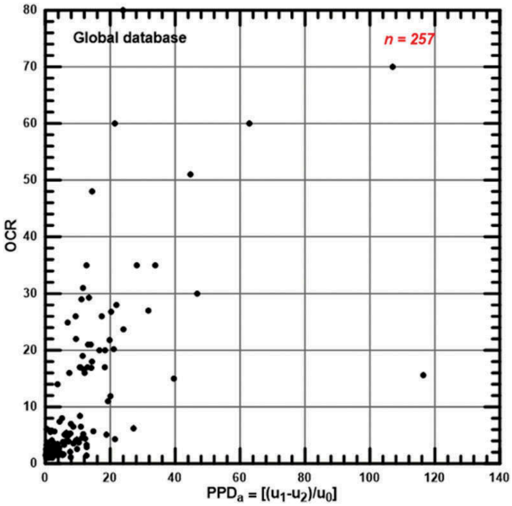

Figure 5. PPDa vs OCR for global data base.

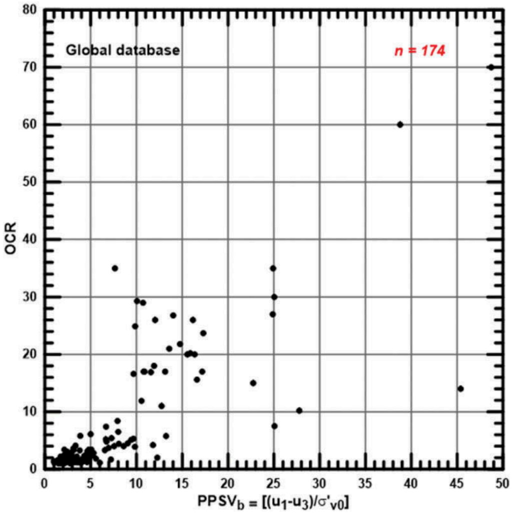

Figure 6. PPSVb vs OCR for global data base.

only u_{1f} was used and for simplicity called u_1. However, ratios involving u_1 and u_2, u_1 and u_3 or u_2 and u_3 did not show good correlations when all data were plotted. With reference to Figure 2 this is as expected.

The database contains OCR ranging from 1 to 80, evaluated mainly from oedometer test results. OCR data plotted against PPRa, PPRb and PPRc, and against PPR1a, PPR1b and PPR1c did not show any clear trends. PPDa, PPDb, PPDc, PPSVa, PPSVb and PPSVc showed only a weak trend of increasing with increasing OCR but no clear relationship could be established due to

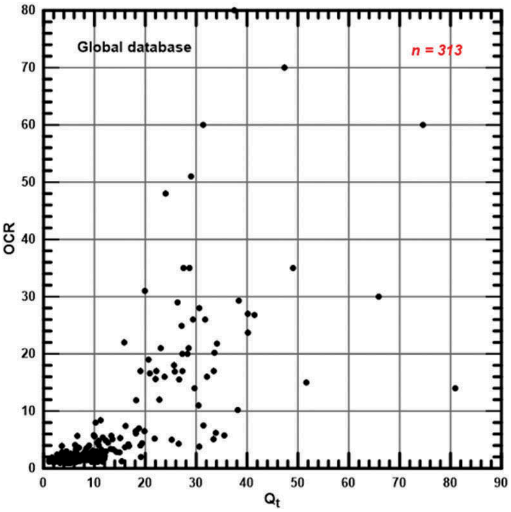

Figure 7. Relationship between Q_t vs OCR for global data base.

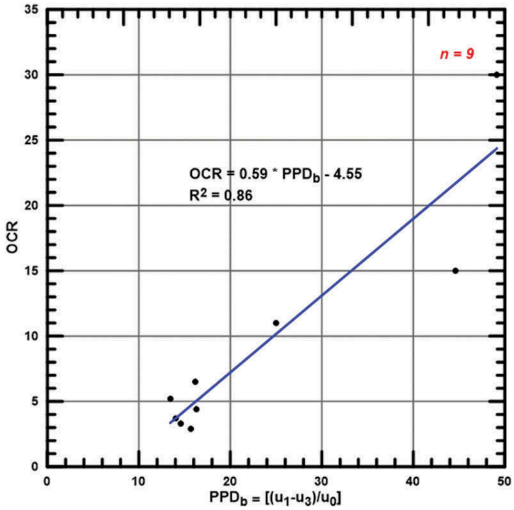

Figure 8. Correlation of PPDb vs OCR for Cowden glacial till.

very large scatter, as shown by the examples in Figure 5 and 6. Figure 7 shows that the most frequently used correlation between OCR and Q_t (= $(q_c - \sigma_{v0})/\ \sigma_{v0'}$), also shows a very large scatter where it was not meaningful to fit a trendline.

The findings from the database indicate that it may not be possible to establish a strong correlation between pore pressure parameters and OCR that are valid for all cohesive soils. This status is similar to the correlation factor N_{kt}, the ratio of net cone resistance to undrained shear strength, where after decades of attempts by researchers and industry reported N_{kt} values are still wide ranging. With this example in mind, it will therefore be necessary to establish local correlations between pore pressure parameters and OCR as is commonly the practice for N_{kt}.

4 ATTEMPTS AT LOCAL CORRELATIONS

4.1 *General*

Two data sets that are believed to be of good and reliable quality have been selected for an illustration of local correlations.

- The glacial till at Cowden, UK, thoroughly tested in the 1990s as documented by Powell and Butcher (2003).
- Two Norwegian moderately overconsolidated stiff marine clays tested by Sandven (1991).

4.2 *Glacial till at Cowden*

Part of the programme was to carry out new CPTU3 tests at Cowden. However, the pore

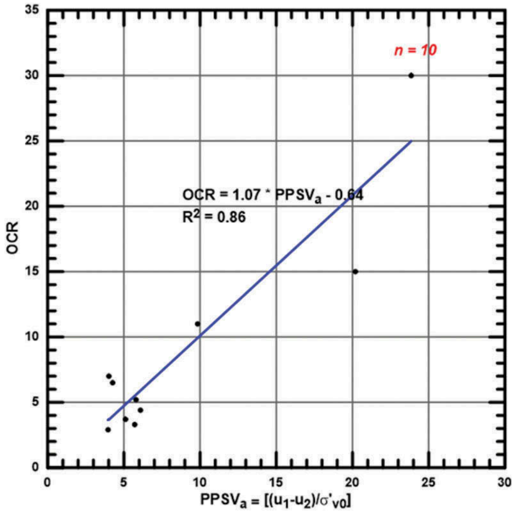

Figure 9. Correlation of PPSVa vs OCR for Cowden glacial till.

pressures measured suffered from unsatisfactory saturation and historic measurements given by Powell and Lunne (2005) were used, since these were considered to be of good quality. Correlations to PPD parameters showed equally good results when based on $u_1 - u_2$ (PPDa) and $u_1 - u_3$ (PPDb). An example of the latter is shown in Figure 8. The same conclusion can be drawn regarding OCR to PPSV where, as an example, PPSVa is shown in Figure 9. All four PPD and PPVS correlations had R^2 values in the range 0.83 -to 0.87.

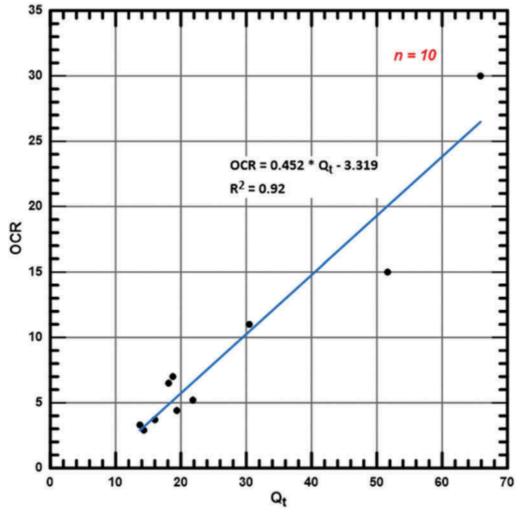

Figure 10. Correlation of Q_t vs OCR for Cowden glacial till.

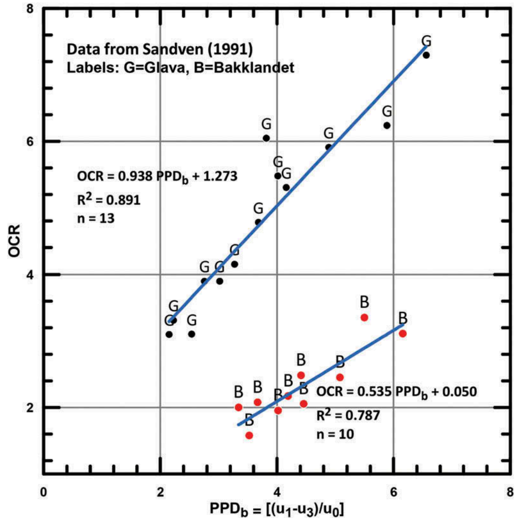

Figure 12. Correlation of PPDb to OCR for Bakklandet and Glava clays.

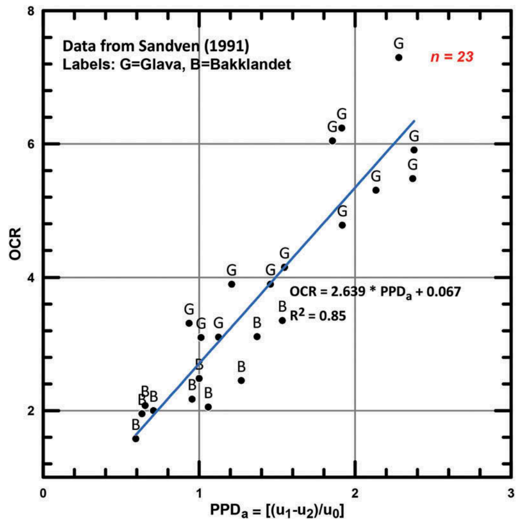

Figure 11. Correlation of PPDa vs OCR for Bakklandet and Glava clays.

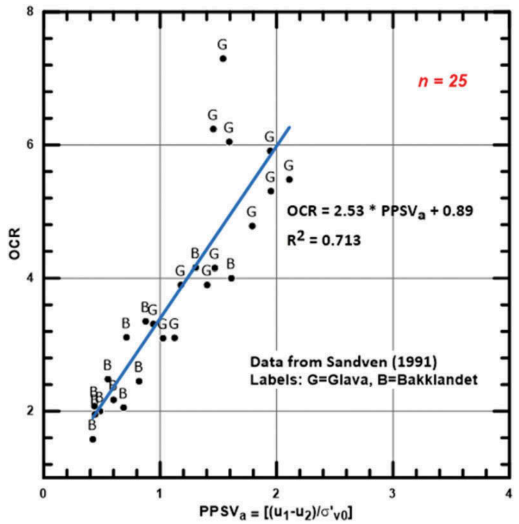

Figure 13. PPSVa vs OCR for Bakklandet and Glava clays.

Figure 10 shows that the most frequently used correlation between OCR and Q_t is actually showing less scatter, with an R^2 value of 0.92, compared to the PPD and PPSV correlations.

4.3 *Trondheim area clays*

Sandven reported results of CPTU3 tests from two sites in the Trondheim area of Norway: Glava and Bakklandet. Both sites are described as moderately overconsolidated stiff marine clays. Figure 11 show that for PPDa a reasonably good correlation can be found with the Bakklandet data generally plot somewhat lower compared to Glava data. However, when plotting OCR vs PPDb as shown in Figure 12 the Bakklandet data plot significantly lower compared to Glava data, but both the sites show local and reasonably good linear trends.

In Figure 13 PPSVa show a reasonably good correlation to OCR, whereas Figure 14 shows that for

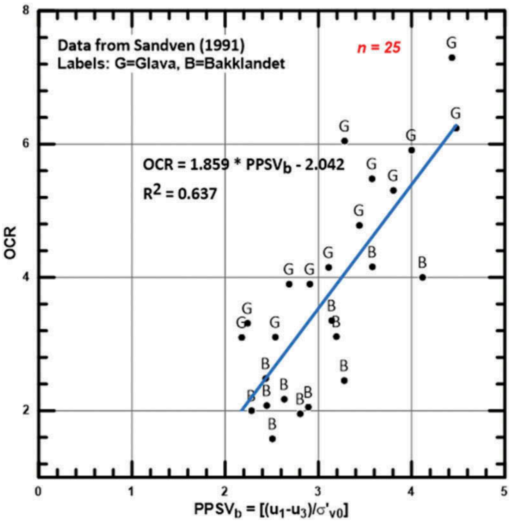

Figure 14. PPSVb vs OCR for Bakklandet and Glava clays.

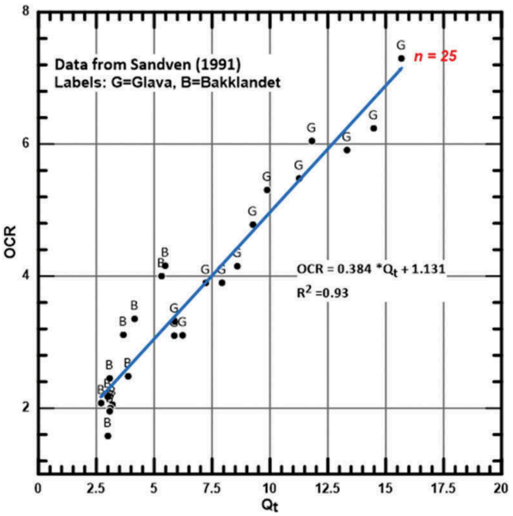

Figure 15. Q_t vs OCR for Bakklandet and Glava clays.

PPSVb Bakklandet data plot somewhat lower than the Glava data.

Figures 12 and 14 really show that the difference between u_2 and u_3 is much lower for the tests at Bakklandet compared to Glava. Sandven (1991) does not make any comments about this difference.

Figure 15 shows that the correlation that is mostly used for standard CPTUs based on Q_t (e.g. by Lunne et al., 1997) actually gives a better correlation than PPD or PPSV illustrating with this example that there may not be any additional benefit using CPTU3 OCR correlations compared to correlations with a standard CPTU.

5 DISCUSSION ON CORRELATIONS

The correlation attempts described in this paper are relatively simple.

Since the data base includes soil classification parameters like water content liquid and plastic limits, future work could explore multiparameter regression analyses to see if this can result in any better correlations. Since K_0 estimates are also available at 7 (out of 63) sites, correlations to this parameter could also be explored.

6 SUMMARY AND CONCLUSIONS

Based on geotechnical literature and unpublished material a data base has been established with CPTU3 parameters (q_c, f_s, u_2, u_1 and u_3) as well as laboratory data giving index parameters and stress history values in terms of overconsolidation parameters. After removing some uncertain data in quality assessment process, the data contain data sets from 63 sites representing a range of clays from Europe and the USA.

The simple correlation study reported in this paper indicates that using all the data available it is not really possible to show any reliable correlation between pore pressure parameters and OCR.

When choosing two sets of local data from the data base (Cowden glacial till and Trondeim area moderately over consolidated marine clays) reasonably good correlations have been found with pore pressure parameters PPD and PPSV. However, for the two sub-data sets even better correlations are obtained when using correlations to Q_t which can be obtained from standards CPTU tests. This indicates that regarding correlations to OCR the inclusion of u_1 and/or u_3 in the CPTU may not improve the accuracy/reliability of the OCR values over the values obtained from standard CPTU.

Other advantages of the CPTU3 relative to the standard CPTU, including results of dissipation tests, are not evaluated in this paper.

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