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Squeezing potential of tunnels in clays and clayshales from normalized undrained shear strength, unconfined compressive strength and seismic velocity

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ABSTRACT: The tunnel squeezing phenomenon was first described by Terzaghi (1946) who associated squeezing mainly with clay-rich rocks. Consistent with Terzaghi's original description, the focus of this paper is on tunnels in clays and clay-rich rocks such as clayshales. The paper develops a simple procedure to predict tunnel squeezing potential using normalized undrained shear strength, unconfined compressive strength and P-wave velocity. A collection of a large amount of undrained triaxial test data is used to show that the undrained shear strength of clay shales can be normalized with respect to the effective vertical stress. The normalized undrained shear strength can then be used to predict the squeezing potential since it can be directly related to Peck's (1969) stability factor N. Values of N provide estimates of the degree of squeezing potential, with values of $N > 1$ indicating potential for squeezing. The normalized undrained shear strength of clay and shales is shown to be related to the apparent overconsolidation ratio *OCR*, which accounts for both mechanical and other diagenetic pre-consolidation, following the SHANSEP procedure for clays (Ladd and Foott, 1977). To facilitate the use of the proposed normalized undrained shear strength vs. *OCR* relationship, empirical equations are established to predict the apparent pre-consolidation stress from unconfined compressive strength σ_c and seismic P-wave velocity. Together with the in situ effective vertical stress prior to excavation at the tunnel location, the apparent pre-consolidation from σ_c or P-wave velocity can be used to estimate the apparent OCR and thence the squeezing potential. The proposed approach is compared with available field data and to existing methods to predict tunnel squeezing potential.

1 INTRODUCTION

Barla (2001) defined squeezing "as the large time-dependent convergence during tunnel excavation. It takes place when a particular combination of induced stresses and material properties pushes some zones around the tunnel beyond the limiting shear stress at which creep starts. Deformation may terminate during construction or continue over a long period of time." Several other definitions of tunnel squeezing have been proposed including those by Gioda (1982), O'Rourke (1984), Kovari (1988), Singh (1988), and Aydan et al. (1993). A full review of the different definitions is given in Barla (2001). In general, squeezing cannot always be distinguished from swelling conditions (Steiner, 1993).

The tunnel squeezing phenomenon was first described by Terzaghi (1946) who associated squeezing mainly with clay-rich rocks. Consistent with Terzaghi's original description, the focus of this paper is on clay-rich rocks such as clayshales, although squeezing can also occur in other rock types. Several procedures have been developed to predict the squeezing potential of tunnels. One of the first stability criteria to predict squeezing was developed by Peck (1969) for tunnels in clays based on Broms and Bennermark's (1967) stability criterion for open excavations. He proposed a stability number N which is expressed as the ratio between the total vertical stress σ_v at the tunnel location and the undrained shear of the clay S_u:

$$N = \frac{\sigma_v}{S_u} \tag{1}$$

Values of N have been correlated with observations of tunnel stability response, and these correlations are

Table 1. Stability criteria for tunnels in cohesive soils (Peck 1969).

N	Problems encountered
1–5	Tunneling without unusual difficulties
5–6	Clay may squeeze rapidly into shield void
6–7	Shear failure ahead of tunnel causes ground movements into the face even in shield tunneling
>7	General shear failures and ground movements around tunnel heading cause shield contact to become difficult; shield tends to dive

summarized in Table 1. Cases where $N > 5$ are considered to have high degrees of rapid squeezing, and higher values of N indicate potential for general shear failure and large tunnel displacements close to the tunnel heading.

For tunnels in rocks, several tunnel squeezing criteria, which are mostly empirical, have also been proposed. Singh et al. (1992) developed a criterion based on the Q-system of rock mass classification (Barton et al. 1974) and the overburden height H (in m) which separates the squeezing cases from the non-squeezing cases:

$$H = 350\,Q^{1/3} \tag{2}$$

Tunnels with overburden height greater than that given in Eq. (2) will experience squeezing.

Semi-empirical approaches have also been proposed by Goel et al. (1995, 2000), Jethwa et al. (1984), Aydan et al. (1993), and Hoek and Marinos (2000). The last three criteria use a stability number, which is a reciprocal of Peck's stability. Almost all these squeezing criteria summarized are empirically or semi-empirically based on direct observations of tunnel response. In the semi-empirical approaches of Jethwa et al., Aydan et al., and Hoek and Marinos, the ratio of capacity and load (or strength and stress) is analogous to the factor of safety FS (or the reciprocal if the load to capacity ratio is used). In addition to linking the degree of squeezing to the factor of safety, the advantage of using stress and strength is that these can be related to strain levels, provided the full stress-strain curve are known, which in turn can be related to degree of squeezing in the tunnel.

The main challenge in the use of these semi-empirical approaches is in the determination of the rock mass strength. In Peck's approach, the strength is expressed in terms of the undrained shear strength, while in Jethwa et al., Aydan et al., and Hoek and Marinos, the strength is expressed in terms of the unconfined compressive strength of either the intact rock or the rock mass. It should also be noted that the proposed methodologies have been developed mainly for clays or hard rocks. Fewer studies have investigated the applicability of the above mentioned criteria to intermediate materials such as hard soils or soft rocks (e.g. Hoek and Marinos, 2000). Based on these observations, the main objective of this paper is to propose simple methods to estimate the shear strength of intermediate soil-rock materials, particularly cemented clays and shales, and to use the simple methods to estimate squeezing potential in tunnels. Estimates of the shear strength of shales are obtained from a database of triaxial test data on several clayshales. These estimates of shear strengths are then linked to field observations of squeezing to develop simple procedures for the preliminary investigation of squeezing in tunnels in clays and shales.

2 NORMALIZED UNDRAINED SHEAR BEHAVIOR OF CLAY AND SHALES

A procedure that is widely used to characterize the undrained shear strength of clays is the SHANSEP (Stress History and Normalized Soil Engineering Properties) procedure developed by Ladd and Foott (1977). According to this procedure, the undrained shear strength S_u of normally consolidated (NC) clays normalized with respect to the current effective vertical stress σ'_v is unique, and for overconsolidated (OC) clays, the following relationship adequately represents the normalized undrained shear strength:

$$\frac{S_u}{\sigma'_v} = a(OCR)^b \tag{3}$$

where OCR is the overconsolidation ratio defined as the ratio between the maximum past effective vertical stress σ'_p and the current effective vertical stress σ'_v, that is:

$$OCR = \frac{\sigma'_p}{\sigma'_v} \tag{4}$$

The parameter b is an empirical exponent, and $a = (S_u/\sigma'_v)_{NC}$ is the normalized undrained shear strength of NC clay, i.e., the value of S_u/σ'_v for $OCR = 1$.

Numerous studies in the literature have shown the applicability of SHANSEP in representing the undrained shear strength of many types of clays, including marine, residual and glacial soils. Although some studies have shown the successful use of SHANSEP for clays with some degree of cementation (e.g. Bo et al. 2003), the applicability of SHANSEP to lithified materials like shales has not been fully established.

SHANSEP has been successfully used in practice in geotechnical analysis and design, and it would

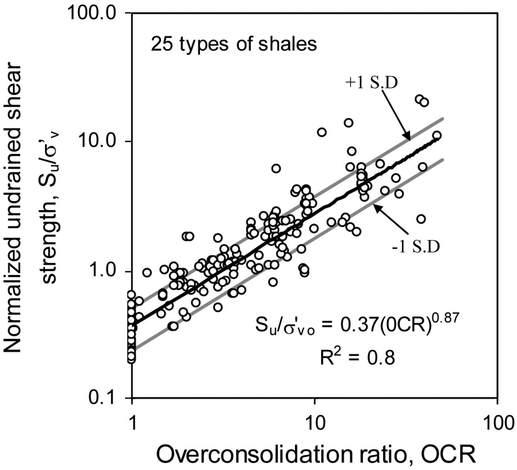

Figure 1. Normalized undrained shear strength as function of apparent OCR for 25 different types of shales.

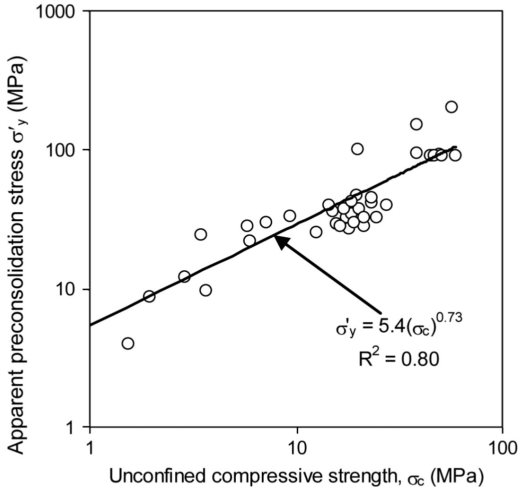

Figure 2. Correlation between apparent preconsolidation and unconfined compressive strength for different shales.

be valuable to extend the procedure to shales and highly cemented cohesive materials. The main difference with clays is that overconsolidation and shear strength in shales are effected not only by mechanical loading-unloading, but also by the other diagenetic processes particularly cementation at the clay particle contacts. The increase in overconsolidation due to non-mechanical processes is called apparent or quasi preconsolidation (e.g. Bjerrum and Wu, 1960).

To investigate the applicability of SHANSEP to shales, a database of triaxial test results on 25 types of clayshales from different locations was assembled. Included in this database are consolidated undrained (CU) triaxial test results on shales with different consolidation stresses. The normalized undrained shear strength of 25 types of materials are plotted against apparent *OCR* in Fig. 1. Only clayshales, which are shales containing more than 50% clay particles by weight, and stiff cemented clays are included in the study. The apparent *OCR* is defined as ratio of the current effective vertical stress and the apparent preconsolidation stress, i.e. $OCR = \sigma'_y/\sigma'_v$, where σ'_y is simply the effective vertical stress at which yielding can be observed from the experimental consolidation stress-strain curve. In case of uncemented materials, $\sigma'_y = \sigma'_p$.

The results show a linear relationship between the $\log(S_u/\sigma'_v)$ and $\log(OCR)$, which agrees with the power function given in Eq. (3). The reasonably good correlation between S_u/σ'_v and *OCR* for 25 types of materials is very promising, and indicates that SHANSEP can provide a reliable approach to predicting the undrained shear strength of shales. The average values of a and b for the 25 different materials are equal to 0.37 and 0.87, respectively. In comparison, Ladd and Foott (1977) obtained values of $a = 0.20$ and $b = 0.77$ for several clays from CU triaxial tests. It is important to note that the data shown in Fig. 1 are for clayshales with different degrees of diagenesis and cementation. Although the normalized undrained shear strength of shale samples are similar, more lithified samples are actually stronger (i.e., have higher undrained shear strength S_u) than younger uncemented samples because of higher values of the apparent preconsolidation stress.

3 DETERMINATION OF THE APPARENT PRECONSOLIDATION STRESS IN SHALES

The most widely used laboratory approach to determine σ'_y experimentally is Casagrande's (1936) procedure where σ'_y corresponds to the sharpest bend in consolidation plot. In addition to this approach, it is useful to develop procedures to estimate the apparent preconsolidation stress from simple index tests to facilitate the application of SHANSEP to shales. One parameter that can be obtained with relative ease in the field or in the laboratory is the unconfined compressive strength σ_c. In the following, it is assumed that the intact rock and rock mass σ_c are the same, as was done by Aydan et al. (1993), and Hoek and Marinos (2000). Figure 2 presents a plot of σ'_y vs. σ_c (both in MPa) for different clayshales, which shows a reasonable correlation between the two parameters of the following form:

$$\sigma'_y = 5.4\left(\sigma_c\right)^{0.73} \tag{5}$$

Although there is some scatter in the data, they are in the range of typical σ_c values of about 1 to

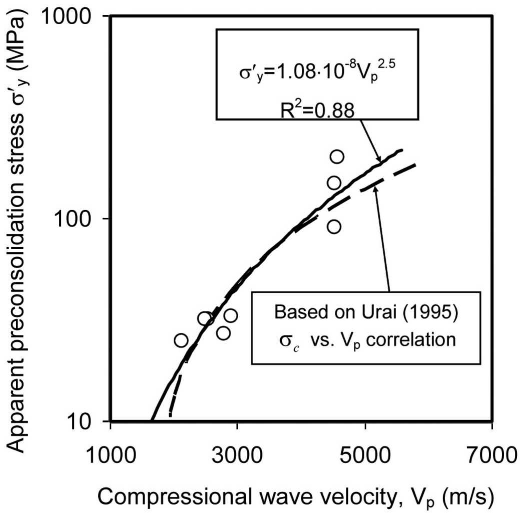

Figure 3. Correlation between apparent preconsolidation and compressional wave velocity for different shales.

70 MPa for shales. It should be reasonable to expect that a correlation exists between σ'_y and σ_c since both can be considered as material parameters, which depend on the degree of mechanical consolidation and cementation.

A more convenient procedure is to relate σ_c with data that can be directly measured in the field using in situ tests such as the compressional wave velocity V_p. One such correlation obtained by curve-fitting through experimental data, shown in Fig. 3 in terms of σ'_y (in MPa) and compressional wave velocity V_p (in m/s), also assumed the same for the intact rock and the rock mass, is obtained as

$$\sigma'_y = 1.08 \cdot 10^{-8} \left(V_p\right)^{2.5} \tag{6}$$

Again, data are limited but are within the typical range of V_p of 2 to 5 km/s for shales. To support the reliability of Eq. (6), an additional relationship is formulated via the following correlation for shales developed by Urai (1995) between σ_c (in MPa) and V_p (in m/s):

$$\log\left(\sigma_c\right) = -6.36 + 2.45 \log(0.86\, V_p - 1172) \tag{7}$$

Substituting Eq. (7) in (5) provides the second σ'_y vs. σ_c curve shown in Fig. 3, which is in close agreement with Eq. (6). The similarity of the two curves shown in Fig. 3 appears to support the correlation between σ'_y and V_p. Obviously more data are needed, but Eqs. (5) to (7) can provide preliminary estimates of the apparent preconsolidation stress in the field.

4 SQUEEZING POTENTIAL OF TUNNELS IN CLAYS AND SHALES

Substituting Eq. (3) in Eq. (1) yields the following expression for the stability number:

$$N = \frac{\sigma_v}{S_u} = \frac{\sigma_v}{a\sigma'_v (OCR)^b} \tag{8}$$

The total and effective vertical stresses are related to the depth to the tunnel H and the total unit weight γ and the effective unit weight γ' of the material above the tunnel, i.e. $\sigma_v = \gamma H$ and $\sigma'_v = \gamma' H$. Both these unit weights depend on the specific gravity of the solids G_s, the porosity n of the material, and the degree of saturation. Assuming fully saturated conditions, the ratio σ_v/σ'_v can be expressed as:

$$\frac{\sigma_v}{\sigma'_v} = \frac{\gamma}{\gamma'} = F(n) = \frac{G_s\left(1-n\right)+n}{\left(G_s-1\right)(1-n)} \tag{9}$$

Re-writing Eq. (8)

$$N = \frac{F(n)}{a(\sigma'_y/\sigma'_v)^b} \tag{10}$$

and solving for the effective vertical stress gives a relationship between the effective vertical stress and the apparent yield stress:

$$\sigma'_v = \left(\frac{F(n)}{aN}\right)^{(-1/b)} \sigma'_y \tag{11}$$

In turn, substituting Eqs. (5) and (6) in the above equation results in the following relationships between the effective vertical stress, and the unconfined compressive strength and the P-wave velocity:

$$\sigma'_v = \left(\frac{F(n)}{aN}\right)^{(-1/b)} \left(5.4\sigma_c^{\,0.73}\right) \tag{12}$$

$$\sigma'_v = \left(\frac{F(n)}{aN}\right)^{(-1/b)} \left(1 \cdot 08 \cdot 10^{-8} V_p^{\,2.5}\right) \tag{13}$$

Equations (12) and (13) may be viewed as stability criteria which relate the effective vertical stress corresponding to the tunnel depth σ'_v, the unconfined compressive strength σ_c or P-wave velocity V_p, the stability number N, the porosity function $F(n)$, and the empirical constants a and b. Tunnels with σ'_v, larger than those given in Eqs. (12) and (13) have high potential for squeezing.

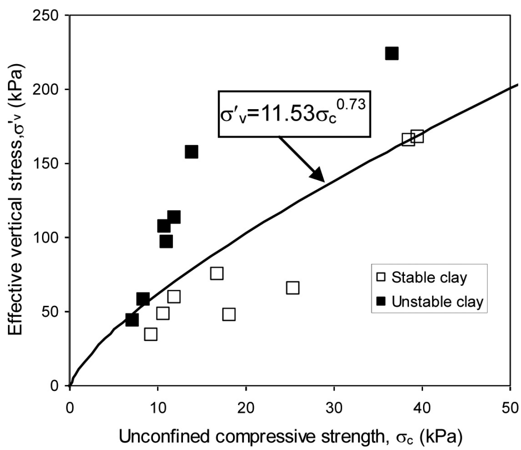

Figure 4. Comparison of the stability criterion given in Eq. (14) with observed cases of squeezing and non-squeezing in tunnels in clays (data from Broms and Bennermark, 1967).

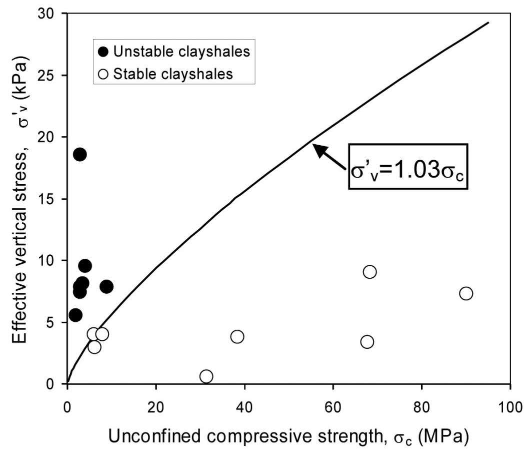

Figure 5. Comparison of the stability criterion given in Eq. (15) with observed cases of squeezing and non-squeezing in tunnels in clayshales (data from Bhasin, 1991).

5 COMPARISON WITH FIELD DATA AND OTHER EMPIRICAL TUNNEL SQUEEZING CRITERIA

To show their validity, the stability criteria given in Eqs. (12) and (13) are compared with field data on response of tunnels in clays and clayshales. The validity of Eq. (12) for tunnels in clays is shown in Fig. 4, which shows data taken from Broms and Bennermark (1967). The data have been re-plotted in terms of the effective vertical stress and unconfined compressive strength. A boundary curve between the non-squeezing and squeezing cases is established using Eq. (12) in conjunction with a value of $F(n) \approx 2.5$ (based on typical values of $n \approx 60\%$ and $G_s = 2.7$ for clays), and a stability of number of $N = 5.3$. Also, values of $a = 0.20$ and $b = 0.77$ were used, which are representative values for clays given by Ladd and Foott (1977). Substituting these values in Eq. (12) gives the following criterion which demarcates cases of squeezing and non-squeezing for tunnels in clays:

$$\sigma'_v = 11.53\sigma_c^{0.73} \qquad (\sigma'_v \text{ and } \sigma_c \text{ in kPa}) \qquad (14)$$

It can be seen that Eq. (14) provides a clear boundary between cases of squeezing and non-squeezing in tunnels in clays.

For clayshales, the validity of Eq. (12) is validated by comparison with data on Himalayan tunnels collected by Bhasin (1991). The data of Bhasin (1991) have been re-plotted as for the data for clay and are shown in Fig. 5. A boundary curve between the non-squeezing and squeezing cases is established using Eq. (12) with values of $F(n) \approx 1.8$ (for typical values of $n \approx 30\%$ and $G_s = 2.7$ for shales), $N = 2.5$, and $a = 0.37$ and $b = 0.87$ taken from Fig. 1. Substituting these values in Eq. (12) gives the following equation:

$$\sigma'_v = 1.05\sigma_c^{0.73} \qquad (\sigma'_v \text{ and } \sigma_c \text{ in MPa}) \qquad (15)$$

It can be seen that Eq. (15) provides a clear boundary between cases of squeezing and non-squeezing in tunnels in shales.

Figure 6 shows the combined data from clays and clayshales. A boundary curve demarcating the case of squeezing from non-squeezing for tunnels in both clays and shales is established from the average of the stability criteria given in Eqs. (14) and (15). This curve is shown in Fig. (6), which shows that Eq. (15) can adequately separate the case histories of squeezing and non-squeezing for tunnel in both clays and clayshales.

$$\sigma'_v = 0.0145\sigma_c^{0.6} \qquad (\sigma'_v \text{ and } \sigma_c \text{ in MPa}) \qquad (16)$$

Figure 6 also shows the stability criterion of Singh et al. (1992) combining Eq. (2) with the empirical relationship between σ_c and Q-value also from Singh et al. (1992). It can be seen from Fig. 6 that the Singh's criterion significantly underestimates the boundary between squeezing and no-squeezing for both clays and shales.

The final comparison with field data is shown in Fig. 7 to show the validity of the criterion given in Eq. (13). The unconfined compressive strength data of Bhasin (1991) were converted to V_p using Eq. (7). Using similar parameters used for Eq. (15), the following stability criterion is obtained in terms of σ'_v and V_p:

$$\sigma'_v = 1.22 \cdot 10^{-8} V_p^{\,2.5} \qquad (17)$$

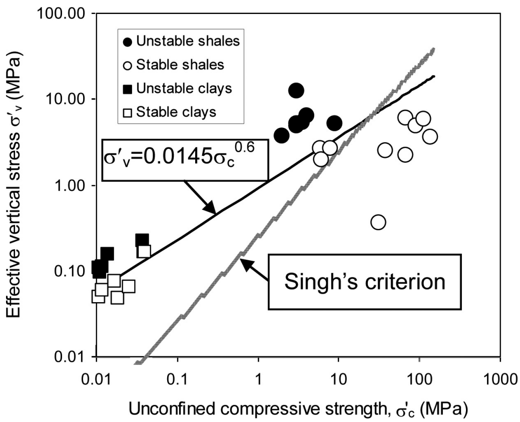

Figure 6. Comparison of the stability criterion given in Eqs. (16) and (18) with observed cases of squeezing and non-squeezing in tunnels in clays and shales (data from Broms and Bennermark, 1967; and Bhasin, 1991).

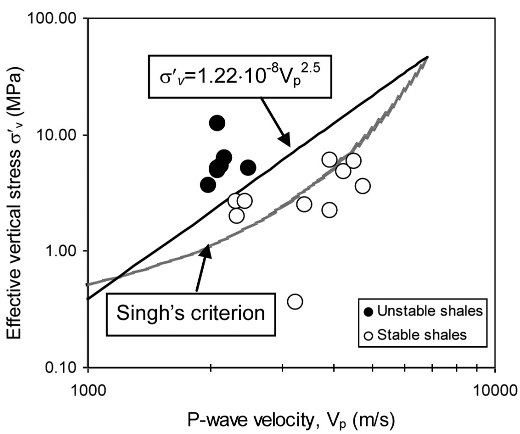

Figure 7. Comparison of the stability criterion given in Eq. (17) with observed cases of squeezing and non-squeezing in tunnels in shales (data from Bhasin, 1991).

As can be seen, Eq. (17) provides an adequate criterion for separating case histories of squeezing and non-squeezing in tunnels in clay and shales. Also shown is the criterion of Singh et al. (1992) re-plotted in terms of V_p by using the relationship between V_p and Q-value developed by Barton (2002). It can be seen that Singh's criterion expressed in terms of V_p underestimates the boundary between cases of squeezing and non-squeezing.

6 CONCLUSIONS

Squeezing criteria for materials that range from clays to clayshales were proposed. The criteria were based on normalized undrained shear strength as embodied in the SHANSEP procedure for clays. It was shown that the undrained shear strength of clayshales also exhibit normalized behavior similar to unlithified clays. In addition to relating stability to overconsolidation ratio, squeezing criteria in terms of unconfined compressive strength and P-wave velocity were proposed.

The validity of the proposed criteria was demonstrated by comparison with field observed squeezing in tunnels in clays and shales. It was shown that the proposed criteria are capable of delineating cases of squeezing and non-squeezing in tunnels in clays and clay shales. The proposed criteria provide better predictions of squeezing in clays and clayshales than other empirical criteria for hard rocks such as the one proposed by Singh et al. (1992).

The proposed criteria can be used for preliminary analysis of squeezing in tunnels in clays and clayshales where there are limited data. For tunnels with sufficient shear strength data, the paper has demonstrated the possibility of using SHANSEP procedure in conjunction with project specific soil parameters to estimate tunnel stability.

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