# Comparison of horizontal earth pressure measurements using Ko Stepped Blade, CPTu and DMT in-situ testing in Toronto, Canada

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ABSTRACT
Vertical stress under geostatic conditions can be easily estimated by geotechnical engineers. Horizontal stress cannot be estimated with any degree of accuracy without in-situ testing or interpreted by specialized triaxial testing. In-situ horizontal earth pressure is difficult to measure, and can only be accomplished by self-boring pressuremeter tests or with extrapolation procedures with the Ko stepped blade (KSB) test. KSB testing was carried out at a site along the Toronto waterfront for subsurface modelling in support of geotechnical design. Seismic dilatometer (DMT) and piezocone (CPTu) tests were also carried out adjacent to the KSB locations within the fill, organic soils and silty clay. This paper presents a comparison of the estimated horizontal earth pressures by KSB with interpretations of the DMT and CPTu test results and findings of the geotechnical laboratory testing. Existing correlations are evaluated for CPTu and DMT interpretation for in-situ horizontal earth pressure and a modified correlation proposed.

RÉSUMÉ
La contrainte verticale dans des conditions géostatiques peut être facilement estimée par les ingénieurs géotechniciens. La contrainte horizontale ne peut pas être estimée avec quelque degré de précision sans essai in situ ou interprétée par des essais triaxiaux spécialisés.La pression horizontale in situ des terres est difficile à mesurer, et ne peut être déterminée que par des essais pressiométriques auto foreurs ou par des procédures d'extrapolation des essais ''Ko stepped blade'' (KSB). Des essais KSB ont été réalisés sur le site d'un deux projet de la Commission de Transport de Toronto le long du Lac Ontario, pour la modélisation du sous-sol et l'appui à la conception géotechnique. Les essais de dilatomètre sismique (DMT) et/ou piézocône (CPTu) ont également été menés près de l'emplacement KSB dans le remblai, les sols alluviaux organiques et l'argile limoneuse. Cet article présente une comparaison des pressions horizontales des terres estimées par les essais KSB avec des interprétations des essais de DMT, les résultats des essais CPTu et des essais en laboratoire géotechnique. Les corrélations existantes des pressions horizontales in situ des terres avec l'interprétation des essais de CPTu et de DMT sont évaluées, et une corrélation modifiée est proposée.

## 1 INTRODUCTION

Vertical stress under geostatic conditions can be easily estimated by geotechnical engineers, however horizontal stress cannot be estimated with any degree of accuracy without in-situ testing. In-situ horizontal earth pressure is difficult to measure, and can only be estimated with any confidence using Ko stepped blade (KSB) tests or from self-boring pressuremeter tests (SBPMT). KSB testing was carried out at a site along the Toronto waterfront in order to estimate the horizontal earth pressure, or $K_0$ coefficient. Piezocone (CPTu) and seismic dilatometer (DMT) testing was also carried out adjacent to the KSB testing and the results were analyzed to determine whether site specific correlations can be established for the site.

## 2 HORIZONTAL EARTH PRESSURE

Horizontal earth pressure is typically represented by the $K_0$ coefficient (Jaky, 1948),

$$K_0 = \frac{\sigma'_{ho}}{\sigma'_{vo}} \quad [1]$$

where $\sigma'_{ho}$ = effective horizontal stress
$\sigma'_{vo}$ = effective vertical stress

Vertical stress is easily estimated using the measured/estimated bulk unit weight of the soil and location of the groundwater table. For overconsolidated soils, the following relationship was proposed by Mayne and Kulhawy (1982) for uncemented sands and clays of low to medium sensitivity:

$$K_0 = (1 - \sin\Phi')\ OCR^{\sin\Phi'} \quad [2]$$

Mayne and Kulhawy (1988) also provided a relationship between $K_0$ measured from SBPMT and the soil's overconsolidation ratio (OCR) measured from oedometer tests for clayey soils as follows:

$$K_0 = 0.52\ OCR^{0.51} \quad [3]$$

However these relationships require knowledge of the soil's OCR and effective friction angle (φ'). OCR can generally be readily measured in fine-grained soils, provided undisturbed samples are obtained and tested, but several weeks are needed before the OCR profile can be determined, unless DMT or CPTu testing is carried out to rapidly estimate OCR. In coarse grained soils there is no cost-effective method to measure OCR. The soil's friction angle can be measured in time consuming triaxial and direct shear tests or inferred from other in-situ tests, such as the Standard Penetration, DMT or CPTu tests.

### 2.1 KSB

Horizontal stress can be directly measured by SBPMT or estimated by KSB testing. The KSB test consists of a series of concentric pressure cells distributed over a thin steel blade of narrowing thickness, as shown on Figure 1. The KSB, or Iowa Stepped Blade, is pushed into the bottom of an open borehole and lift-off pressures recorded. Plots of the lift-off pressures versus blade thickness are analyzed and extrapolated to a zero thickness blade to obtain the interpreted in-situ horizontal stress. The disadvantages of this testing is that (i) the blade can only be pushed into weaker soils, (ii) the extrapolation assumes that the soil conditions are uniform over the length of the blade, which is not always the case in layered soil deposits, and (iii) pushing the blade into plastic clays may generate excess pore pressures resulting in an overestimation of horizontal pressures.

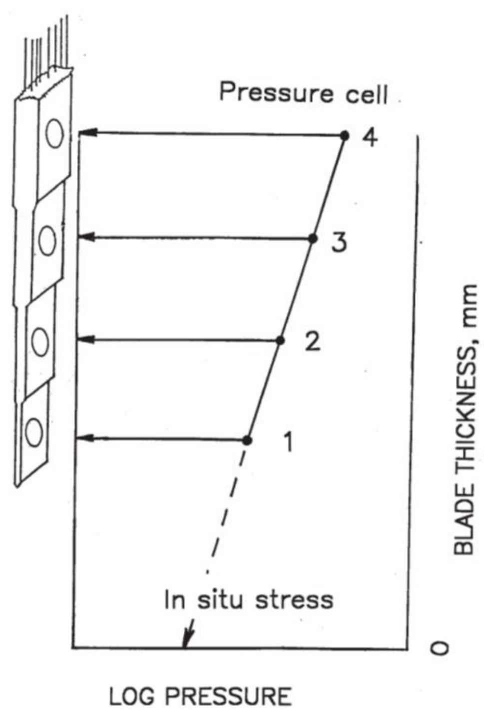


Figure 1. Example of KSB and extrapolation method (from Handy *et al* 1990).

## 3 PUBLISHED IN-SITU CORRELATIONS

Literature indicates that horizontal pressure interpreted from pre-bored pressuremeter testing or DMT should be used with caution due to disturbance effects of installation by boring or DMT insertion. CPTu interpretation should only be used as a rough estimate in fine grained soils due to the scatter in published results. However DMT and especially CPTu testing provides rapid results compared to pressuremeter or KSB testing. Correlation of $K_0$ values with CPTu and DMT testing are further explored in this paper.

### 3.1 DMT

Literature suggests DMT as a good tool for measuring $K_0$ values. The dilatometer horizontal stress index, $K_D$, was used by Marchetti (1980) to evaluate $K_0$ for uncemented clays in the following equation,

$$K_0 = \left(\frac{K_D}{1.5}\right)^{0.47} - 0.6 \qquad [4]$$

Other papers (Powell and Uglow, 1988; Larsson and Eskilson, 1989; Nash et al, 1992; Burghignoli et al, 1991) have examined the relationship between $K_0$ and $K_D$ based on comparisons of DMT and self-boring pressuremeter data. These papers generally indicate that Marchetti's original correlation, noted above, provides a reasonable estimate of $K_0$ in clays.

### 3.2 CPTu

Review of published results suggest that there is no reliable method to determine $K_0$ from CPTu. The following correlation by Kulhawy and Mayne (1990) provides an estimate of $K_0$ in fine-grained soils,

$$K_0 = 0.1\left(\frac{q_t - \sigma_{v0}}{\sigma'_{v0}}\right) \qquad [5]$$

where $q_t$ = corrected cone resistance

The following equation, based on calibration chamber database regression, proposed by Mayne (1995) provides an estimate of $K_0$ for use in sands.

$$K_o = 0.00133\, q_t^{0.22} (\sigma_{v0}')^{-0.31}\, OCR^{0.27} \qquad [6]$$

However, the above equation requires an estimate of the OCR in sands, which as previously stated cannot be readily measured. OCR in sands can be estimated by iteration equating Equation 2 and 6 simultaneously.

### 3.3 CPT – DMT Correlations

In sands, Baldi et al. (1986) presented the following algebraic equation to calculate $K_0$, which is based on a combination of both DMT and CPT testing:

$$K_0 = 0.376 + 0.095\, K_D - \alpha \frac{q_c}{\sigma'_{v0}} \qquad [7]$$

where $q_c$ = measured cone resistance

In this equation, $\alpha$ varied from 0.0017 for artificial sands and 0.0046 for natural Po River sands.

## 4 INVESTIGATION SITE

A geotechnical investigation was carried out at the site of a proposed Toronto Transit Commission LRT storage and maintenance facility at Ashbridges Bay, adjacent to the Toronto waterfront. This area of Toronto consists of reclaimed land composed generally of silty sand to sandy silt fill to a depth of 5 m below grade, overlying organic soils (organic silts, clays and peat), sands, silty clay, glacial till and shale bedrock. The groundwater table was encountered at a depth of about 3 m below grade.

At three locations on the site (BH 1, 2, and 3) KSB, DMT and CPTu testing was carried out adjacent to one another, along with sampled boreholes for geotechnical laboratory testing. Figure Nos. 2 and 3 graphically present the DMT and CPTu measurements, derived geotechnical parameters and measured laboratory index test results. It should be noted that BH 6 was advanced adjacent to an existing 12 m high fill mound.

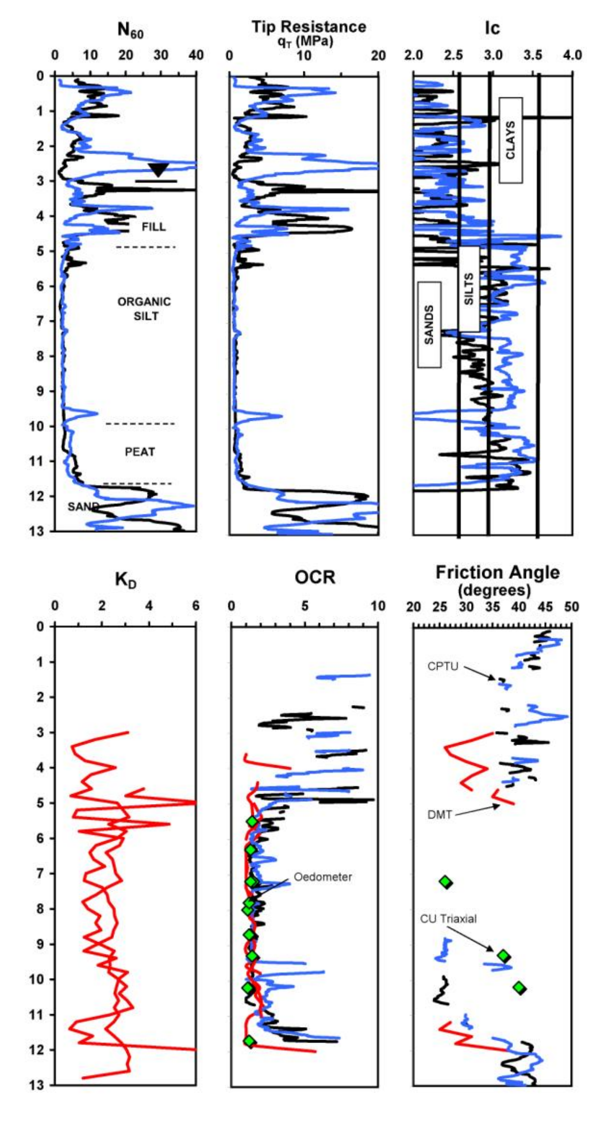


Figure No. 2. DMT, CPTu and laboratory test results for BH 2 and 3 at Ashbridges Bay.

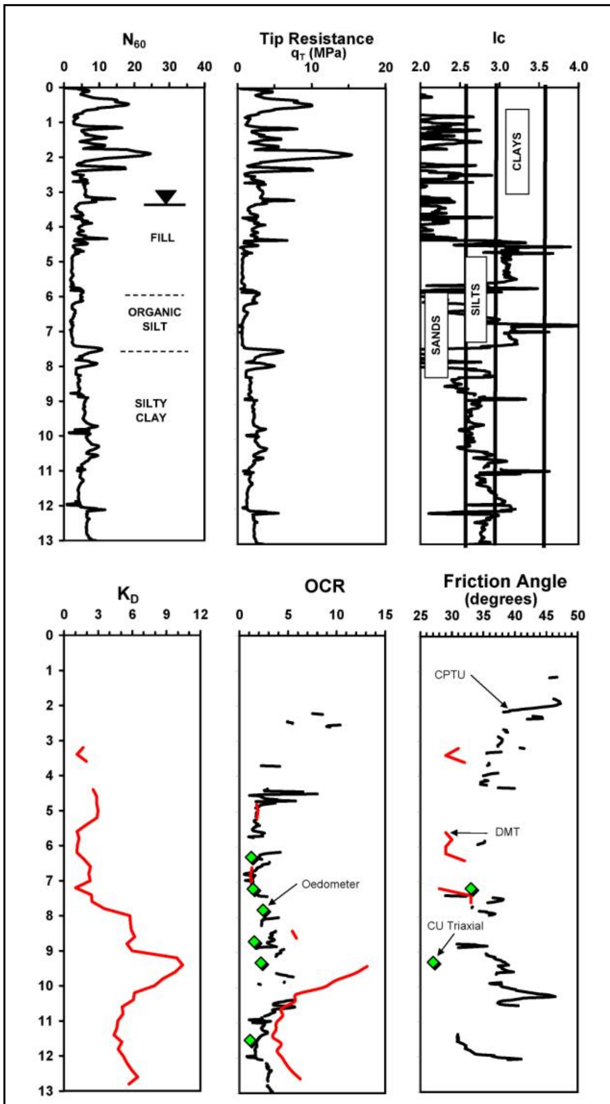


Figure No. 3 . DMT, CPTu and laboratory test results for BH 1 at Ashbridges Bay.

## 5 COMPARISON OF RESULTS

The Ashbridges Bay site provides a range of soil types for comparison of KSB, CPTu, DMT and sampled boreholes when evaluating $K_o$. There is concern that the KSB measurements in clays are dominated by the excess pore pressure generated during insertion. In order to check the validity of the results, the KSB measurements were compared to available triaxial and oedometer test results carried out on relatively undisturbed samples. The comparison is presented in Figure No. 4 and shows reasonable correlation with the laboratory test results. The upper bound $K_o$ results in the silty clay may represent influence from excess pore pressure generated during insertion or from surcharge effects from the adjacent fill mound.

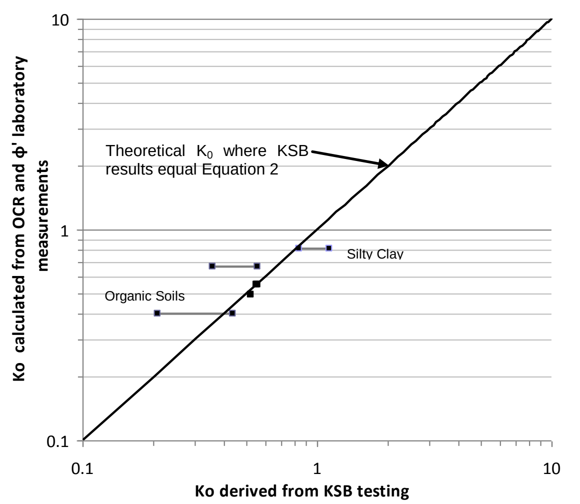


Figure No. 4 Range of KSB results and calculated $K_0$ from triaxial and oedometer testing.

The KSB results and published correlations were analysed and compared with Equations 4, 5 and 7, as well as a proposed modification to Equation 6 for fine grained soils. The comparisons are presented graphically in Figure Nos. 5 to 7.

The DMT correlation proposed by Marchetti (1980) in Equation 4 generally provided good correlation with the KSB testing in the organic soils, although within the lower bound range of $K_o$. The DMT results did not correlate well within the overconsolidated silty clay as Equation 4 overestimated $K_o$, possibly due to excess pore pressure effects due to installation or from surcharge effects of the adjacent soil mound. The disadvantage of this correlation is that it is limited to where $I_D < 1.2$ (clays).

The CPTu correlation by Kulhawy and Mayne (1990) in Equation 5 generally overestimates $K_o$ when compared to the KSB results. The correlation should not be used as it does not take into account the effect of overconsolidation and cannot be used in coarse grained soils.

The DMT-CPT correlation by Baldi et al (1986) in Equation 7 at the Ashbridges Bay site also provided good correlation within the organic soils and silty clay, although limited data points are only available due to reliance of both DMT and CPT tests. The correlation is not practical for most sites due to the number of tests required.

The correlation proposed in Equation 6 by Mayne (1995) was used for the coarser zones using estimated OCR values determined by iteration by equating Equations 2 and 6 simultaneously. Although Equation 6 was derived from calibration chamber database regression for sands, the general shape of the resulting equation fits for fine grained soils when compared to Equations 2 and 3, as well as KSB testing. In order to use Equation 6 within fine grained soils, the equation was modified to model the results of Equations 2 and 3. The following empirical correlation was used for fine and coarse grained soils at the site.

$$K_o = \alpha\, q_t^{0.22}\, (\sigma_{v0}')^{-0.31}\, OCR^{0.27} \quad [8]$$

Where α equals 0.00133 for coarse grained soils and for fine grained soils values of 0.0019 to 0.0024 were derived. Using α of 0.0021 for fine-grained soils, Equation 8 appears to correspond with the KSB results within the organic soils, cohesive fill and silty clay. Evaluation at other sites should improve the above correlation.

One of the potential benefits of developing Equation 8 for fine grained soils is that the same approach to determine OCR for sands may also be carried out for φ' for clays using Equation 2 and 8. The two equations could be solved simultaneously providing an estimate of φ', thus reducing time consuming and expensive triaxial testing, as well as the difficulty in obtaining relatively undisturbed samples for testing. However based on comparison of Equation 8 and the triaxial test results, α varies between 0.0019 to 0.0024 with depth at this site which provides an average φ' over the entire depth.

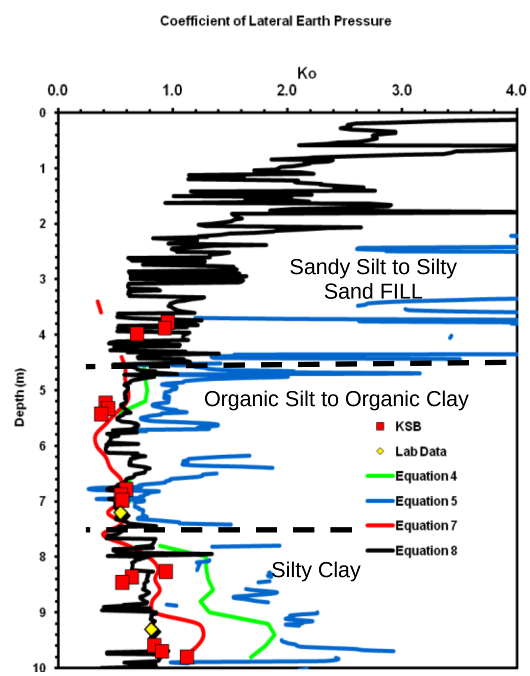


Figure No. 5 KSB results and CPTu, DMT and laboratory data correlations for $K_o$ at BH 1 location at Ashbridges Bay.

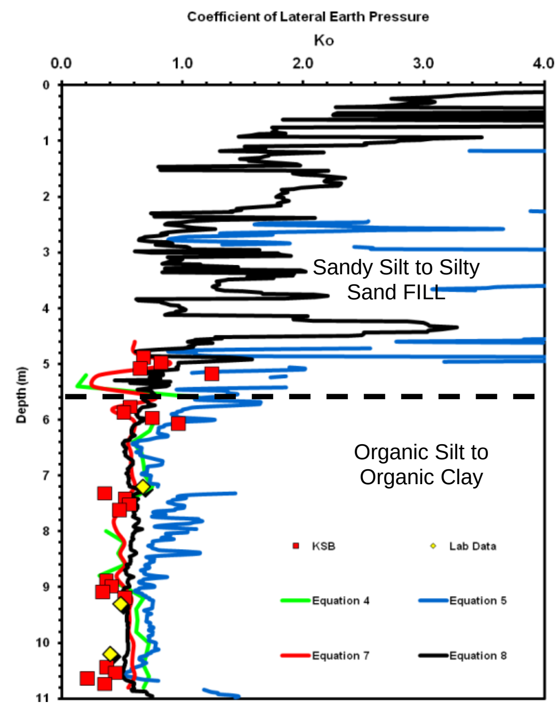


Figure No. 6 KSB results and CPTu and DMT correlations for $K_o$ at BH 2 location at Ashbridges Bay.

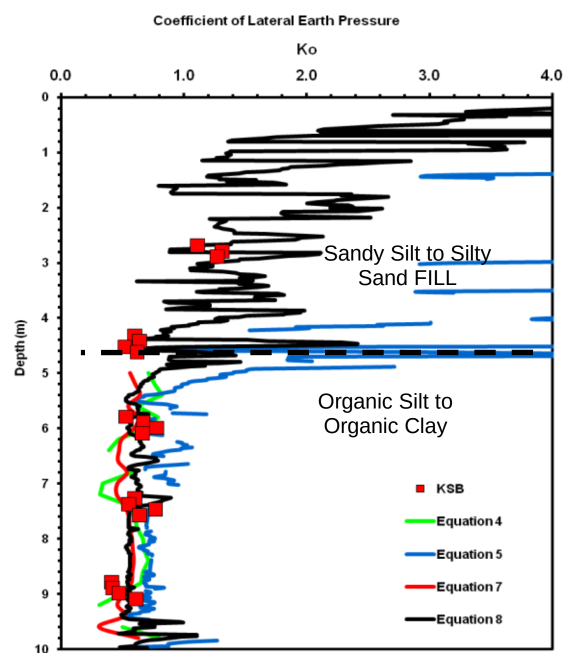


Figure No. 7 KSB results and CPTu DMT and laboratory data correlations for $K_o$ at BH 3 location at Ashbridges Bay.

# 6 CONCLUSIONS

Horizontal stress can be reasonably estimated using DMT and CPTu in-situ test results. DMT and especially CPTu testing provides rapid results compared to self-boring pressuremeter or KSB testing. Based on the analyses above, the following conclusions are offered.

- Equation 4 provides a good correlation with the KSB results in the organic soils, but overestimates $K_o$ in the silty clay.
- Equation 5 should not be used to estimate $K_o$ as it overestimates the value.
- Equation 7 provides a good correlation within the organic soils and silty clay but its use is limited where DMT and CPTu testing are both used, and therefore would not be cost effective for most sites.
- Equation 6 provides an excellent correlation in coarse grained soils.
- Equation 8 is proposed as a modification of Equation 6 to allow its use in coarse and fine grained soils by introducing a constant $\alpha$ (0.00133 for sands and 0.0019 to 0.0024 for clays). The proposed correlation fits well with the KSB test results and Equations 2 and 3. Figure No. 9 provides a $K_o$ profile derived for the Ashbridges Bay site through the full depth of the boreholes using this proposed correlation.

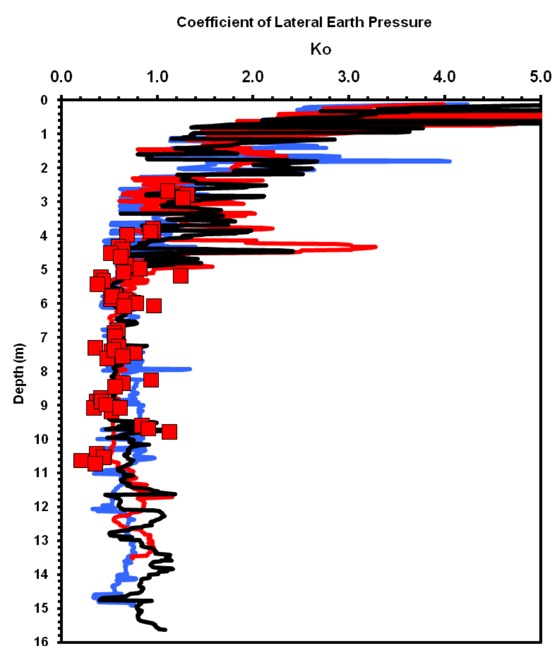


Figure No. 8 Full depth $K_o$ profile inferred at Ashbridges Bay site based on Equation 8.

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