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Some Observations on the Effect of Initial Static Shear Stress on Cyclic Response of Natural Silt from Lower Mainland of British Columbia

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ABSTRACT

The effects of initial static shear stress on the cyclic shear response of natural silt was investigated using the constant-volume direct simple shear device. Silt specimens, initially consolidated above the preconsolidation stress with different initial static shear stress levels were subjected to constant volume cyclic shear loading under different applied cyclic stress ratios. All tested specimens displayed a 'cyclic mobility type' strain accumulation. The potential for excess pore water pressure generation and shear strain development during cyclic loading increased with increasing level of initial static shear. Comparing the observed cyclic resistance ratio (CRR) for the silt material tested at different level of static shear stress bias (α) revealed that the value of CRR consistently decreased with increasing α value.

Introduction

The performance of saturated soil deposits during earthquakes is an important geotechnical consideration. Most geotechnical problems involve level-ground as well as sloping-ground configurations. The term "no static shear stress bias" is commonly used to describe the level-ground condition since there is no initial shear stress on the horizontal plane under static conditions corresponding to this case. On the other hand, under sloping-ground conditions, there always is a finite shear stress on the horizontal plane under static conditions, and this stress state is called a condition with "static shear stress bias" (Seed and Peacock, 1971; Vaid and Finn, 1979).

Prior to the onset of earthquake shaking, an element of soil beneath sloping ground has an initial static shear stress (τ_{static}) on the horizontal plane the relative magnitude of which is typically quantified by normalizing it with respect to the initial vertical effective confining stress (σ'_{vo}) (Harder and Boulanger, 1997). The resulting parameter ($\tau_{static} / \sigma'_{vo}$), defined as α, is equal to zero for a level ground configuration. The superposition of cyclic shear stresses (from earthquake loading) on the already existing static shear stress (initial static shear stress bias) can have a major effect on the response of the soil, leading to liquefaction and development of extremely large ground deformations (Chiaro et al., 2012).

To simulate sloping ground conditions during laboratory testing, specimens are typically consolidated with an applied static shear stress τ_{static} prior to cyclic loading. Over the past forty

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years, many researchers have investigated the effect of initial static stress on cyclic resistance of sands and clays (Lee and Seed, 1967; Yoshimi and Oh-Oka, 1975; Vaid and Finn, 1979; Vaid and Chern, 1983; Andersen et al., 1988; Vaid et al., 2001). Early research studies by Lee and Seed (1967), and Lee et al. (1975) have concluded that the presence of initial static stress always improves the cyclic resistance of soil to liquefaction. Continued research has been performed across the world, and it has been concluded that the presence of initial static stress increases the cyclic resistance for moderately dense to dense sandy soil and decreases the cyclic resistance of loose sandy soils regardless of the type of test equipment that has been employed (Yoshimi and Oh-Oka, 1975; Vaid and Finn, 1979; Vaid and Chern, 1983; Vaid et al. 2001).

It should be noted that most of these studies were focused on understanding the liquefaction behavior of sandy soils and only a limited amount of work has been done on understanding the liquefaction behavior of fine-grained silty materials. This is primarily because liquefaction-induced ground failure has been less frequently observed in silt and clay than in sand. However, based on recent case histories (Boulanger et al., 1998; Bray et al., 2004) it is now established that fine-grained soils can undergo deformation and potential failure when subjected to strong ground motion.

In consideration of the above, the effect of initial static shear stress on cyclic response of fine-grained natural silts is studied as a part of a comprehensive experimental research program on the mechanical response of silts undertaken at the University of British Columbia (UBC), Vancouver, Canada. This paper presents some of the initial findings from the tests conducted using the UBC constant-volume cyclic direct simple shear (DSS) device; the DSS device is considered to effectively mimic the anticipated stress conditions the soil would undergo during seismic loading.

Experimental Aspects

Material Tested and Test Apparatus

The silt material for present investigation originates from the Lower Mainland of British Columbia, Canada. The subject site is located on the South Bank of Nicomekle River at the intersection of 40th Avenue and 160th Street in Surrey, B.C. Available data from in-situ cone penetration test indicated the presence of a soft to firm, relatively uniform silty layer within the depth interval between 1 m to 12 m below the ground surface. The close agreement of the particle size distribution curves obtained using hydrometer and sieve analysis for three silt samples from different depth levels, as shown in Figure 1, also confirms the uniformity of the deposit previously indicated by in-situ cone penetration test data. Ground water table at the site was about 1 m. Silt from the depth level of 6.4 – 7.6 m was therefore chosen as a source of test material for the present study. Average soil parameters derived from the index testing is summarized is Table 1.

Relatively undisturbed samples were retrieved from the silt deposits using specially fabricated stainless-steel tubes (~75 mm diameter, 0.9 m long, no inside clearance, 5-degree cutting edge and 1.5mm wall thickness) using conventional mud-rotary drill. Wijewickreme and Sanin (2010) have demonstrated that "fair to good" samples can be obtained using this method of sampling for low-plastic silts from the Fraser River delta. Upon retrieval, thin-walled tubes were sealed and waxed on both sides to prevent the loss of natural moisture content and brought back to the Geotechnical Laboratory of UBC where they were kept in an upright position in the moisture controlled room.

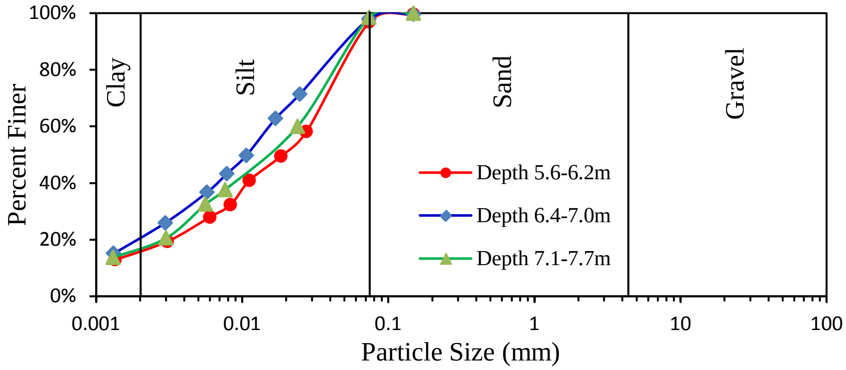


Figure 1. Grain size distribution of the tested material obtained from various depth horizons.

Table 1. Index properties of tested natural silt material.

Soil Property	Values
Depth range below the ground surface (m)	6.4 ~ 7.6
Water content (%)	44 – 52
Liquid limit, LL (%)	34 ~ 36
Plastic limit, PL (%)	26 ~ 27
Plasticity Index, PI	8 ~ 9
Unified Soil Classification	ML
Specific Gravity	2.73
Pre-consolidation Stress (kPa)	50 ~ 60

The modified NGI-type (Bjerrum and Landva, 1966) direct simple shear (DSS) test device at UBC was used to conduct the experimental work in present investigation. The DSS test device can accommodate a cylindrical soil specimen (70-mm diameter and ~20-mm height) inside a steel-wire reinforced rubber membrane which ensures a state of zero lateral strain during consolidation and shear loading. A constant volume condition, if required, can be enforced by clamping top and the bottom platens of the specimen against vertical movement, thus providing a height constraint along with the lateral restraint from the wire reinforced rubber membrane. This is an alternative to the commonly used approach of maintaining constant volume condition by suspending the drainage of a saturated specimen. Dyvik et al. (1987) has shown that the decrease (or increase) of vertical stress in a constant-volume DSS test is essentially equal to the increase (or decrease) of excess pore water pressure in an undrained DSS test where the near constant-volume condition is maintained by not allowing the mass of pore water to change.

Testing Procedures and Test Program

Upon extrusion from the thin-walled sample tubes, the soil specimens were carefully placed within the wire reinforced membrane with the aid of a polished-stainless steel sharpened edge cutting ring. The test specimens were then consolidated to the target vertical effective stress level

(σ'_{vc}) which was above the pre-consolidation stress (σ'_{p-1D}) inferred from one-dimensional consolidation testing. After the end of consolidation phase, the specimens were subjected to a static shear stress (τ_s) to meet the desired initial static shear stress bias ($\alpha = \tau_s / \sigma'_{vc}$). The desired static shear stress (τ_s) was applied slowly and incrementally under drained conditions until both vertical and shear strains were stable. Upon completion of the static bias phase, the specimens were subjected to constant volume cyclic shear loading. The cyclic shear load was applied in the form of symmetric sinusoidal wave with a frequency of 0.1 Hz at a constant cyclic stress ratio ($CSR = \tau_{cy} / \sigma'_{vc}$) amplitude. The cyclic loading was terminated after allowing the specimen to reach ~10% shear strain.

Summary of cyclic direct simple shear tests (CDSS) conducted for this study (identified by different test series names) are summarized in Table 2. The CDSS tests were conducted on undisturbed specimens at varying static shear bias level ($\alpha \leq 0.15$) and CSRs (0.14 – 0.22). All the specimens were initially normally consolidated to vertical effective stress level of approximately 100 kPa. Test series A was initially conducted at $\alpha = 0$, followed by test series B, C, and D performed with $\alpha = 0.05$, 0.10 and 0.15 respectively.

Table 2. Test parameters and summary of test results.

Test Series	Test ID	WC (%)	e_i	σ'_{vc} (kPa)	e_c	α (τ_s/σ'_{vc})	Cyclic Shearing CSR (τ_{cyc}/σ'_{vc})	Cyclic Shearing N_{cyc} [γ=3.75%]
A	NS 100-00-15	50.85	1.388	100.62	1.263	0.00	0.143	N/A
	NS 100-00-20	48.15	1.314	101.11	1.161	0.00	0.191	22.75
	NS 100-00-23	51.81	1.414	98.32	1.237	0.00	0.226	5.75
B	NS 100-05-15	49.60	1.354	100.54	1.159	0.05	0.148	87.25
	NS 100-05-20	48.48	1.323	100.76	1.147	0.05	0.191	12.25
	NS 100-05-22	44.75	1.222	99.34	1.073	0.05	0.213	6.25
C	NS 100-10-15	44.91	1.226	101.99	1.060	0.10	0.146	24.25
	NS 100-10-17	44.37	1.211	99.97	1.045	0.10	0.163	12.25
	NS 100-10-13	44.53	1.216	102.93	1.060	0.10	0.126	90.25
D	NS 100-15-15	46.63	1.273	103.78	1.100	0.15	0.145	8.25
	NS 100-15-11	48.61	1.327	97.99	1.215	0.15	0.117	76.25
	NS 100-15-10	50.53	1.379	101.78	1.249	0.15	0.094	N/A

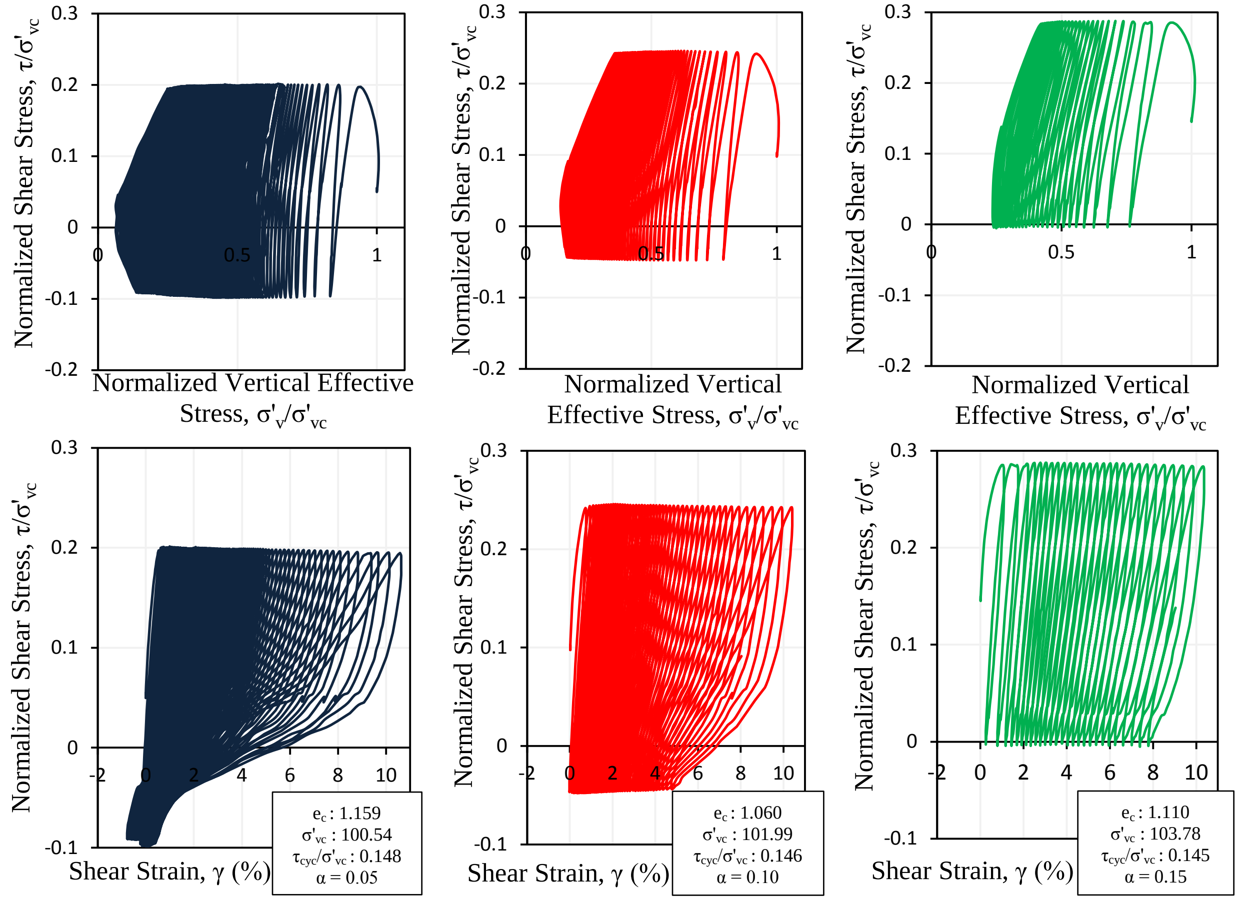
WC : Average water content of the test specimen.
CSR [τ_{cyc}/σ'_{vc}] : Cyclic stress ratio.
σ'_{vc} : Vertical consolidation stress prior to the application of shearing.
e_c : Post-consolidation void ratio prior to the application of shearing.
$N_{cyc[\gamma=3.75\%]}$: Number of uniform loading cycles to reach single amplitude shear strain of 3.75 %.
α : Initial static shear bias.
e_i : Initial void ratio.
N/A : Did not reach γ=3.75% in 200 cycles

Test Results and Discussion

General Cyclic Stress – Strain Response

The typical stress path (top) and stress-strain response (bottom) from constant volume CDSS tests performed on undisturbed silt specimens initially consolidated to a vertical effective confining stress (σ'_{vc}) of ~100 kPa with an initial static shear bias of 0.05, 0.10 and 0.15 and then subjected to a cyclic shear loading under similar CSR values (~0.15) are presented in Figure 2.

The stress-strain and stress-path relationship for specimen initially consolidated at σ'_{vc} ~ 100 kPa without any static shear bias and then subjected to cyclic shear loading of CSR of 0.143 is shown in Figure 3 for comparison purposes.



(A) (B) (C)

Figure 2. Typical normalized stress path (top) and normalized shear stress-strain responses (bottom) for three specimens tested at initial static shear bias of 0.05, 0.10 and 0.15 with σ'_{vc} of ~100 kPa under CDSS loading with CSR of ~ 0.15.

As may be noted from Figures 2 and 3, all the specimens displayed a prominent contractive behavior (i.e., reduction in vertical effective stress) during the initial loading cycle; this was followed by contractive and dilative responses during respective unloading and loading phases of the cyclic shear stress.

The development of equivalent excess pore water pressure and accumulated shear strains with increasing number of cycles during the cyclic shear test are presented in Figures 4 and 5, respectively. As mentioned earlier, the decrease (or increase) in vertical stress during a constant volume DSS test is considered equivalent to the increase (or decrease) in excess pore water pressure (Δu) in an undrained test. It can be observed from the figures that the potential for build-up of equivalent excess pore water pressure and accumulated shear strains (with increasing number of cycles) seems to increase with increasing initial static shear bias level up to the tested α level of 0.15.

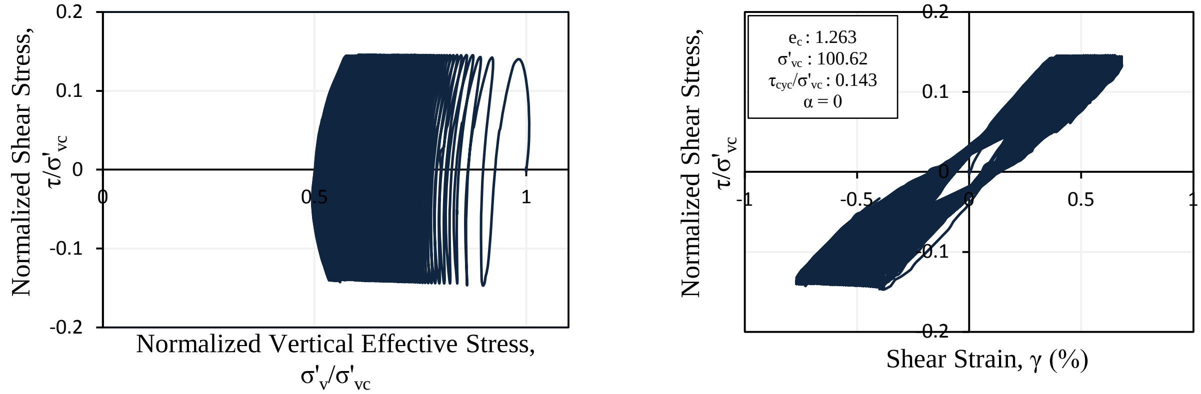


Figure 3. Normalized stress path and normalized shear stress strain responses for a specimen initially consolidated at σ'_{vc} ~ 100 kPa with no static shear bias under CDSS loading with CSR of 0.143.

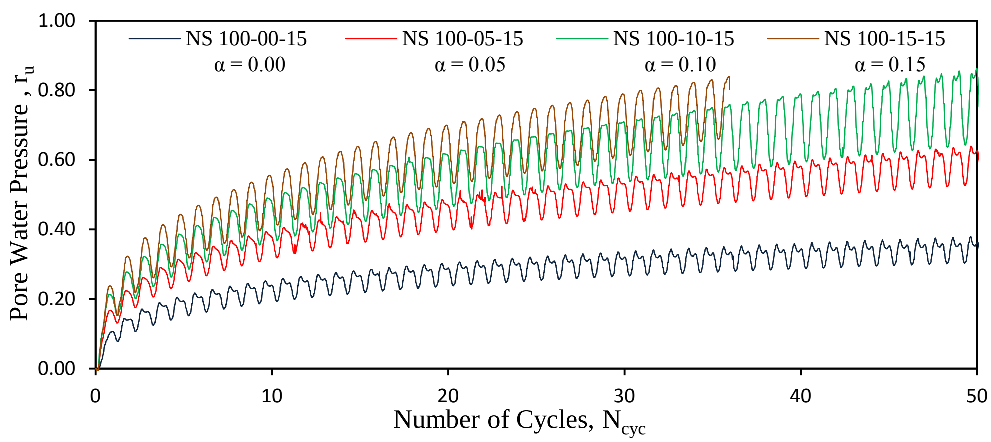


Figure 4. Excess pore-water pressure development at different initial static shear values and constant CSR ~ 0.15.

It is also important to note that 'cyclic mobility type' strain development was observed in all the tests. Liquefaction in the form of strain softening accompanied by loss of shear strength did not manifest regardless of the applied CSR and the initial static shear bias levels, or the degree of the excess pore water pressure developed. In other words, the observed behavior suggests that the tested silt material is unlikely to experience flow failure under cyclic loading (for test conducted at $\alpha \leq 0.15$). The observed cyclic behavior from this experimental investigation is also in agreement with the response from low plastic Fraser River Delta silt tested by Sanin (2010).

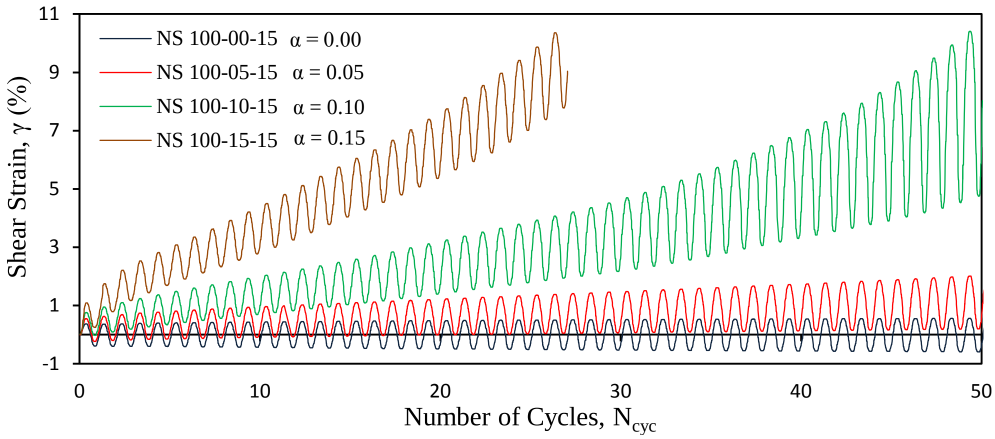


Figure 5. Accumulation of shear strain at different initial static shear values and constant CSR ~ 0.15.

Effect of Increasing Initial Static Shear Bias on Cyclic Shear Resistance

To assess the effect of α on the cyclic shear resistance of the tested silt specimens, the applied CSR is plotted against number of loading cycles to reach single-amplitude horizontal shear strain (γ) of 3.75% (see Figure 6). This strain criterion was considered reasonable as γ = 3.75% in a DSS specimen is equivalent to 2.5% single-amplitude axial strain in a triaxial specimen, which is also a definition for "liquefaction" (NRC 1985). This criterion has also been used in many previous liquefaction studies at UBC.

From Figure 6, it is observed that the cyclic resistance ratio of the material decreases with increasing initial static shear bias, for the tested range of $0 \leq \alpha \leq 0.15$.

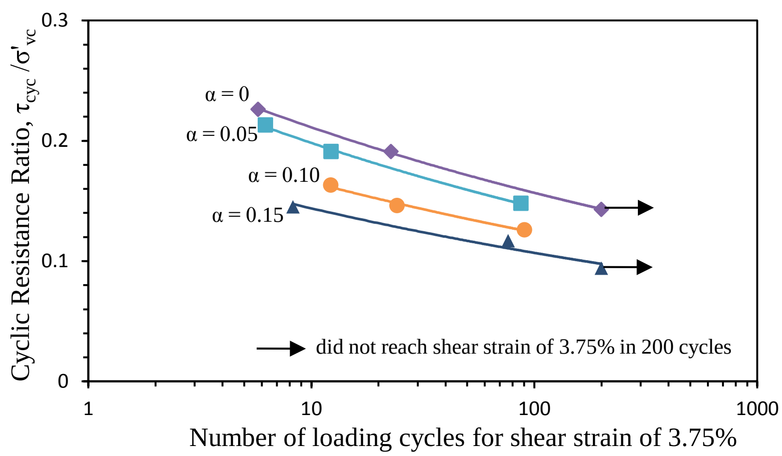


Figure 6. Cyclic resistance ratio (CRR) from constant volume DSS tests performed on undisturbed silt specimens at varying initial static shear bias.

Conclusions

The effect of initial static shear bias on cyclic shear response of natural silts obtained from the Lower Mainland of British Columbia, Canada was investigated using cyclic direct simple shear (CDSS) testing. Undisturbed silt specimens initially normally consolidated to vertical effective confining stress of 100 kPa with an initial static shear bias of 0.0, 0.05, 0.10, and 0.15 were subjected to cyclic shear loading under different CSRs. Under constant volume CDSS loading, the specimens exhibited a 'cyclic mobility type' strain accumulation for all the tests regardless of applied CSRs and initial static shear bias. The data also revealed that the build-up of equivalent excess pore water pressure and accumulated shear strains (with increasing number of cycles) increases with increasing initial static shear bias (α) values up to 0.15. The cyclic resistance ratio of normally consolidated silt specimens were found to decrease with increasing initial static shear bias (α). The observed behavior suggested that the tested silt is unlikely to experience flow failure under cyclic loading for various α values less than 0.15.

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