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Intact, disturbed and reconstituted undrained shear behavior of low plasticity natural silt

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Abstract:	This paper presents a laboratory investigation of undrained triaxial shear behavior of a natural low plasticity silt from Halden, Norway in the intact, disturbed and reconstituted states. Sherbrooke block sample and reconstituted specimens were subjected to simulated tube sampling in a triaxial stress path cell system prior to reconsolidation and undrained shear to assess the effects of disturbance on undrained shear behavior, undrained shear strength and effective stress friction angle. Shear stress and pore pressure development were evaluated relative to that measured for the undisturbed reference state taken as that measured on specimens from the intact block sample. Furthermore, specimens trimmed from fixed piston tube samples collected from the field site were also tested for comparative purposes. Collectively, the results demonstrate that neither the volumetric method of evaluating sample quality for clays nor shear wave velocity track sample disturbance well for this low plasticity silt. Relative to the reference intact block sample tests simulated tube sampling results in an increasingly pronounced dilative type behavior during post-disturbance undrained shear and a general increase in undrained shear strength. Specimens from the block sample that were subjected to simulated tube sample disturbance showed similar stress-strain behavior to that from conventional anisotropically consolidated triaxial compression tests conducted on specimens from the tube samples, suggesting that significant alteration of the intact soil state occurred during tube sampling. Practical suggestions for selection of undrained shear strength for intact low plasticity silts that exhibit dilative behavior such as the Halden silt are proposed.
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If yes, please provide justification in the comments box below. as follow-up to "Authors are expected to present their papers within the page limitations described in <u><i>Publishing in ASCE Journals: A Guide for Authors</u></i>. Technical papers	The manuscript contains about 34 pages when figures and tables are compressed. The authors believe that the topic presented (sample disturbance effects on a natural silt and subsequent practical recommendations for selection of undrained shear strength) are of significant importance to the geotechnical community, and thus merits a thorough discussion even though it exceeds the 30 page limit of JGGE. This way fragmentation of the research results is also avoided. In connection with this objective three pages are tables within which we list all of the important data associated with the research.

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Intact, disturbed and reconstituted undrained shear behavior of low plasticity natural silt

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Keywords: silt, sample disturbance, block sampling, triaxial, oedometer

Abstract

This paper presents a laboratory investigation of undrained triaxial shear behavior of a natural low plasticity silt from Halden, Norway in the intact, disturbed and reconstituted states. Sherbrooke block sample and reconstituted specimens were subjected to simulated tube sampling in a triaxial stress path cell system prior to reconsolidation and undrained shear to assess the effects of disturbance on undrained shear behavior, undrained shear strength and effective stress friction angle. Shear stress and pore pressure development were evaluated relative to that measured for the undisturbed reference state taken as that measured on specimens from the intact block sample. Furthermore, specimens trimmed from fixed piston tube samples collected from the field site were also tested for comparative purposes. Collectively, the results demonstrate that neither the volumetric method of evaluating sample quality for clays nor shear wave velocity track sample disturbance well for this low plasticity silt. Relative to the reference intact block sample tests simulated tube sampling results in an increasingly pronounced dilative type behavior during post-disturbance undrained shear and a general increase in undrained shear strength. Specimens from the block sample that were subjected to simulated tube sample disturbance showed similar stress-strain behavior to that from conventional anisotropically consolidated triaxial compression tests conducted on specimens from the tube samples, suggesting that significant alteration of the intact soil state occurred during tube sampling. Practical suggestions for selection of undrained shear

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strength for intact low plasticity silts that exhibit dilative behavior such as the Halden silt are proposed.

Introduction

While effects of sampling and sample disturbance on undrained shear behavior of clays have been subject to extensive research for decades (La Rochelle and Lefebvre 1971; Lacasse et al. 1985; Hight et al. 1992; Tanaka et al. 1996; Lunne et al. 1997; Santagata and Germaine 2002; Lunne et al. 2006), few studies have investigated how tube sampling of low plasticity silts affects selection of engineering properties compared to those interpreted from companion high quality block samples. Indications are that tube sampling can densify loose silts and sands (e.g. Hight and Leroueil 2003) due to drained or partially drained conditions during sampling. As a result advanced laboratory testing (e.g. direct simple shear or triaxial compression) of these samples can lead to opposite effects of those often observed in naturally occurring structured clays, i.e., higher strength and stiffness properties than in situ values (Carroll and Long 2017; Lukas et al. 2019). The dilative nature of many silts and other intermediate soils (silty sand, sandy silt, clayey silt, silty clay, etc.) also results in strain hardening during undrained shear, and oftentimes, no unique undrained shear strength (peak) is observed (e.g. Fleming and Duncan 1990; Høeg et al. 2000; Sandven 2003; Brandon et al. 2006; Long 2007; Carroll and Long 2017). Consequently, significant uncertainties are associated with predicting the in situ undrained shear strength of silts using laboratory tests on apparently intact, so-called undisturbed samples. Furthermore, only one quantitative framework for assessment of sample quality has been proposed for low plasticity soils (DeJong et al. 2018). This method was developed for 1-D consolidation tests and is based on synthetic soil mixtures that do not exhibit the same sensitivity and structure as many naturally occurring soils. The lack of such practical recommendations has led to use of the clay-based volumetric sample quality assessment indices, e.g., normalized void ratio change, $\Delta e/e_0$, (Lunne et al. 1997) the recompression volumetric strain, ε_{vol} or Sample Quality Designation (SQD, Terzaghi et al. (1996)). While all soils are subject to strains during tube sampling, in clays the shearing can be considered undrained and thus under constant volume conditions (although there can be local redistribution of water content after tube sampling). Silts, however, may be undrained, partially drained, or drained during tube sampling depending on sampling rate, soil composition, type of sampler etc., and any potential volume changes occurring during and after sampling are unknown. The use of clay-based frameworks for silts has recently been shown to be misleading (Long et al. 2010; Carroll and Long 2017; DeJong et al. 2018; Lukas et al. 2019) even though its use has been presented in the literature.

This paper presents an assessment of the undrained triaxial shear behavior of a natural silt in the intact, reconstituted and disturbed states, where the Sherbrooke block sample is considered the best representation of intact soil. It investigates differences observed between tests on material from the block sample and specimens reconstituted using moist tamping and slurry deposition and compares the behavior of block sample material and specimens subjected to experimental sample disturbance simulation (Baligh et al. 1987). Furthermore, the undrained triaxial stress-strain behavior and interpreted undrained shear strength of the block sample and experimentally disturbed specimens are compared with results on specimens from the NGI 54 mm composite fixed piston sampler (Andresen and Kolstad 1979) and Japanese Gel-Push Static fixed piston sampler (Tani and Kaneko 2006; Mori and Sakai 2016).

Current practice in sampling of silts and assessment of undrained shear strength

Tube and block sampling

Sample disturbance results from stress relief during drilling and straining during tube sampling. Other sources of post sampling disturbance include sample extrusion, transportation, sample storage and specimen trimming (Ladd and DeGroot 2003). The magnitude and effect of these factors are functions of soil type, drilling and sampling equipment, operator experience, transportation method, and storage time. For example, Baligh et al. (1987) and Clayton et al. (1998) investigated the effect of tube dimensions and cutting shoe geometry on sample quality and found that increasing area ratio (AR = ratio of the cross-sectional area of the sampler that is solid to that of the inside of the cutting shoe) resulted in a significant increase in the compressive centerline strains ahead of the sampler. Best practice recommendations from such research and that of others (e.g. Hight and Leroueil 2003; Ladd and DeGroot 2003) are that: 1) the area ratio should not exceed 10%, 2) the inside diameter should be greater than around 72 mm, 3) the cutting shoe should be sharp (e.g., around 5° to 10°), 4) the sample tube should have zero inside clearance, and 5) a fixed piston should be used.

Silts and intermediate low plasticity soils have traditionally been sampled using: (i) open drive U100 or split spoon samplers (Bray et al. 2004; Long 2007), both of which have a poor geometry with a large area ratio and cutting angle; (ii) thin-walled samplers with a better geometry, including Shelby tubes of various diameters (Brandon et al. 2006; Nocilla et al. 2006) and; (iii) different fixed piston samplers with thin-walled tubes (Høeg et al. 2000; Bray and Sancio 2006; Long et al. 2010; Solhjell et al. 2017). Although large diameter block type samplers, e.g. Sherbrooke (Lefebvre and Poulin 1979) and Laval samplers (LaRochelle et al. 1981) typically provide high quality samples of clays, there is limited experience with these sampling techniques for low plasticity silts. Examples of collection of hand-carved and downhole Sherbrooke block samples in this material include Bradshaw and Baxter (2007), Carroll and Long (2017) and Blaker et al. (2019).

Because of the challenge in collecting good quality samples of silts, some laboratories prepare advanced test specimens (e.g., triaxial) using reconstitution methods, including: moist and dry tamping (Ladd 1978), and slurry deposition (Wang et al. 2011; Lukas et al. 2019). Under controlled laboratory environments the effects of different variables can be studied, but due to particle reorientation, particle segregation, impact energy, and loss of structure and/or cementation effects, reconstituted soil may not necessarily be an attractive alternative for silts, nor be representative of the in-situ soil state and structure.

Laboratory simulation of tube sampling - Ideal Sampling Approach (ISA)

Tube sample disturbance can be simulated in the laboratory to study the effects on undrained shear behavior and engineering parameters. Baligh et al. (1987) and Clayton et al. (1998) used the Baligh (1985) strain path method to investigate the effects of undrained tube sampling in saturated clays. The result of this work demonstrated that a tube sampler takes a centerline element of soil initially beneath the sampler into a strain cycle including both compression and extension strains during sampler penetration. This can be simulated in the laboratory using the Ideal Sampling Approach (ISA; illustrated for a silt in Figure 1) in which a specimen is consolidated to the estimated in situ stress condition, σ'_{v0} and σ'_{h0} (Step 1) of interest. In Step 2 tube sampling is simulated by shearing the specimen first in undrained compression to a predefined strain level, $+\varepsilon_{zz,max}$ (shown for +1% vertical strain in Figure 1; which is considered a representative value for a standard 76 mm outside diameter US Shelby tube), reversing the direction of loading and bringing the specimen into extension, i.e. to a strain level equal to $-\varepsilon_{zz,max}$, before returning to 0% vertical strain and removing the shear stress $q = 0.5(\sigma_v - \sigma_h)$, under undrained conditions. In Step 3 the "tube-sampled" specimen is reconsolidated back to σ'_{v0} and σ'_{h0} followed by the final Step 4 of undrained compression shearing the soil to failure. In the results section of this paper the final undrained shear results are compared to behavior of a companion test specimen that has not been subjected to the ISA strain cycle.

Clayton et al. (1992); Santagata and Germaine (2002); Santagata et al. (2006) found that simulated tube sampling of clays results in a reduction in the mean effective stress $p' = 0.5(\sigma'_v + \sigma'_h)$, during ISA cycling, an increase in ε_{vol} or $\Delta e/e_0$ during post-ISA reconsolidation, and decreases in the small strain stiffness, undrained shear strength $s_u = q_f$ (where q_f is the shear stress at failure), and post-peak strain softening. ISA testing on silts have seen limited research efforts until recently but these soils have shown contrasting behavioral effects of disturbance relative to that of clays. For the Irish, intermediate plasticity Letterkenny silt Carroll and Long (2017) demonstrated that increasing the level of ISA strain damage resulted in an increase s_u and stiffness by almost 20%. Greater damage also resulted in an increase in the rate of negative shear induced pore pressure generation of the specimens. Lukas et al. (2019) tested various synthetic intermediate soils and found a decrease in the initial pre-peak stiffness, a decrease in strain-softening response and increases in s_u and vertical strain at failure $\varepsilon_{v,f}$ with increasing ISA strain. Also, the magnitude of these changes increased with decreasing plasticity index. These results are opposite of that found for the effect of tube sample disturbance on the behavior of low to moderately overconsolidated clays.

Selection of undrained shear strength for design

Due to sample disturbance effects, limitations in reconstitution methods, and the strain hardening nature of many silts, there are significant uncertainties associated with estimating the in-situ s_u of silts for design purposes from laboratory tests (Wang et al. 1982; Fleming and Duncan 1990; Høeg et al. 2000; Carroll and Long 2017). Brandon et al. (2006) reviewed six criteria for interpretation of s_u of two natural silts from the Mississippi River Valley. For specimens sheared in triaxial compression, the criteria include: 1) maximum deviator stress, $(\sigma_1 - \sigma_3)_{max}$; 2) an assigned limiting vertical strain, $\varepsilon_{v,f}$; 3) state of zero excess shear induced pore pressure at failure $\Delta u_f = 0$, which is equivalent to Skempton's A parameter at failure equal to zero, $A_f = 0$ for $B = 1$; 4) point at which the effective stress path first reaches the failure envelope, defined by the K_f line; 5) maximum obliquity, $(\sigma'_1 / \sigma'_3)_{max}$; and 6) maximum shear induced pore pressure, u_{max}. Note that with zero cohesion intercept, $c' = 0$, criteria 4 and 5 provide the same undrained shear strength. Long et al. (2010) and Long (2007) found that the use of criterion (1) for anisotropically consolidated undrained triaxial compression (CAUC) tests on the Norwegian Os, and the Irish Sligo and Dunkettle silts gave unusually high s_u values and that other criteria (e.g., criteria 3 and 6) could more effectively reduce the scatter. Long et al. (2010) and Long (2007) concluded that due to the dilative nature of silty soils interpretation of s_u from CAUC tests using criterion (1), which is the traditional approach for clays, gives unrealistically high s_u values and advocated use of criterion (2) with $\varepsilon_{v,f} = 2\%$. Whereas Börgesson (1981); Wang et al. (1982); Fleming and Duncan (1990) used $\varepsilon_{v,f}$ ranging from 5% to 15%. Criterion (6) typically provides the lowest value of s_u as u_{max} often occurs at small strain and thus before full mobilization of the in situ s_u has taken place. While Stark et al. (1994) used both criteria (1) and (6), Brandon et al. (2006) recommended criterion (3). Solhjell et al. (2017) evaluated s_u for a North Sea offshore silty, sandy, clayey soil unit for which the project design basis required both lower and upper bound estimates of s_u. The Authors selected s_u at the onset of dilative behavior (i.e., $\Delta u - \Delta\sigma_{oct} = 0$, where $\Delta\sigma_{oct} = 2\Delta q/3$ and $q = (\sigma_v - \sigma_h)/2$) in CAUC and direct simple shear (DSS) tests as the lower bound while the upper bound was estimated as the lesser value of the conventional peak shear stress (criterion 1) and s_u at $\varepsilon_{v,f} = 10\%$

for CAUC tests or 15% shear strain in DSS tests (criterion 2). Depending on the design conditions, it is evident that s_u for silts exhibiting dilative behavior can be significantly underestimated or overestimated. In sum, limited research is available on how sample disturbance influences the various s_u selection criterion and furthermore how laboratory s_u values for silts defined by the above-mentioned criteria relates to the in-situ s_u for specific design applications.

Methods of Investigation

Soil sampling

Samples were collected at the Halden, Norway research site using the Sherbrooke block sampler (Lefebvre and Poulin 1979), the NGI 54 mm inner diameter (ID) composite piston (NGI 54) sampler (Andresen and Kolstad 1979) and the 71 mm ID Japanese Gel-Push Static (GP-S) sampler (Tani and Kaneko 2006). The latter injects a water-soluble polymeric lubricant (gel) from the sampler shoe to lubricate and reduce friction between the cut sample and sampler wall. The NGI 54 and GP-S samplers have outside diameter to thickness ratios (D_w/t) of 12 and 8, respectively, giving AR of about 44% and 78%. The former sampler has about 0.6% inside clearance and the latter about 1.5%. The Sherbrooke block samples are considered in this paper the best representation of intact soil and used as the reference laboratory behavior for the Halden silt.

Specimen preparation

Both consolidated triaxial and incremental load oedometer test specimens were prepared in the laboratory. Three specimen preparation methods were used: trimming of block and tube samples and two variations of soil reconstitution. Reconstituted specimens were prepared from a batch of air-dried untested material from the same depth as the collected samples and had essentially identical grain size distributions as the block sample. The individual reconstituted specimens were prepared either by moist tamping (MT) or slurry deposition (SD). In the MT method the amount of dry silt that provided the desired density for the specimens was mixed with about 3% (by mass) de-aired water. The specimens were prepared on the triaxial pedestal in six separate equal-volume lifts using a split mold. The lower layers were under compacted (Ladd 1978) such that the energy applied to the successive layers would produce a specimen of approximately uniform density throughout when the preparation was finished. The top cap and membrane were sealed using O-rings and an internal under pressure of 20 - 30 kPa applied. The SD method was similar to the approach described by Wang et al. (2011) and Lukas et al. (2019) for which 200 - 400 g of air dried silt was thoroughly mixed with de-aired water at 1.5 - 2.0 times the liquid limit, and left overnight to hydrate. Then the slurry was mixed further and poured into an oedometer ring or, in the case of triaxial specimens, a split mold with an extension collar (ID = 54 mm) and the membrane already in place. All slurry specimens were left 4 - 10 hours to self-weight consolidate before free water was removed. Oedometer specimens were incrementally loaded to the estimated in situ vertical effective stress for the block sample σ'_{v0} = 125 kPa using dead weights, left overnight to consolidate, then unloaded and mounted in the oedometer load frame. Triaxial specimens were incrementally loaded to 50 kPa while still in the split mold, also using dead weights. The specimens were unloaded, the top cap and membrane sealed using O-rings and an internal underpressure of 30 kPa was applied for about 30 minutes prior to removal of the split mold. For both the MT and SD methods the specimen dimensions were measured while still under vacuum which was not released until the triaxial cell was filled with water and oil, and a cell pressure of about 30 kPa was applied. Both MT and SD specimens produced specimens with almost identical void ratio after consolidation as specimens prepared from the Sherbrooke block sample (Table 1). Furthermore, replicate specimens prepared using the same method demonstrated repeatable undrained triaxial compression behavior, as presented in the results section.

Triaxial testing

The triaxial specimens were prepared to diameter, d = 54 mm and height, h = 108 mm and tested using the procedures described by Lacasse and Berre (1988). During the saturation process the test specimens were first subjected to an isotropic effective stress (cell pressure) equal to the estimated value of the initial negative pore pressure (suction) within the specimen. The porous filter stones were initially dry except for the SD specimens. At the initial isotropic stress, de-aired water was flushed through the porous stones and any tendency for volume change was prevented by adjusting the cell pressure until a stable condition was reached. Following this stage, backpressure was applied using a pressure volume controller and all B values, which were measured at the end of the consolidation phase, were ≥ 97% except for one MT reconstituted specimen with a measured B value of 91%. All specimens were anisotropically consolidated to the best estimate σ'_{v0} and horizontal effective stress σ'_{h0} using an assumed K_0 = 0.5 (Blaker et al. 2019). All specimens were allowed to creep for 12 to 24 hours prior to undrained shear. ISA triaxial tests were performed with peak ISA vertical strains of ±0.5%, ±1.0%, and ±3.0% except for one test which was performed inadvertently with asymmetric vertical strains of +1%/–0.5%. The ISA strain cycles were followed by undrained removal of the deviator stress (reducing σ_v to $\sigma_v \approx \sigma_h$), the back pressure was re-set to the end-of-ISA pore pressure, and the specimen was reconsolidated back to σ'_{v0} and σ'_{h0} as shown for example in Figure 1. All monotonic and ISA undrained shear tests were strain-controlled at a strain rate of 0.5 %/hr. The total radial stress was kept constant while the total axial stress was increased in compression (CAUC) and decreased in extension (CAUE). All stress measurements were corrected for membrane resistance and changes in specimen area (Berre 1982).

Incremental loading oedometer testing

Incremental loading (IL) oedometer tests were performed as per Sandbækken et al. (1986) using specimens trimmed from the block sample with a cross-sectional area of 20 cm^2 and height 20 mm and mounted with dry porous filter stones. Slurry specimens were prepared in a 50 cm^2 oedometer ring to a specimen height of 26 mm. Each load increment was maintained for 60 min, except for one test on the block sample specimen, on which a 24 hour increment duration was used. A load increment ratio of approximately one was used in all tests.

Bender element testing

Piezo ceramic bender elements (Dyvik and Madshus 1985) were used to measure the shear wave velocity of the triaxial specimens. The bender element at one end of the specimen was used to transmit a vertically (v) propagating horizontally (h) polarized sinusoidal shear wave. The receiver bender element detected the arrival of this shear wave at the opposite end of the specimen, and the velocity of the shear wave (V_{vh}) was determined. The transmitting signal was generated by a Wavetek model 29 10 MHz Direct Digital Synthesis (DDS) Function Generator, exciting the transmitting bender with a single ±10 V amplitude sine wave triggered at a 10 Hz delay. The transmitted and received signals were both recorded using a LDS-Nicolet Sigma 30 digital oscilloscope with 12-bit resolution and up to 10 Ms/s sampling rate.

Results – block samples and reconstituted specimens

The block and tube samples were collected in separate boreholes but all from the depth interval of 11.0 to 11.8 m below grade, and maximum horizontal distance of 3.3 m apart. Typical index and classification properties were: water content w = 27 %, fall cone liquid limit w_L = 29 %, plastic limit w_P = 21 %, plasticity index I_P = 8%, liquidity index I_L = 0.7, silt fraction (% > 2 μm and < 63 μm) = 89 %, and clay fraction (% < 2μm) = 9 % (Blaker et al. 2019). As noted above the liquid limit of 29 % was determined using the fall cone method (ISO 2018) but was also determined using the Casagrande Cup (ASTM 2017) which gave, as expected (e.g. DeGroot et al. 2019) , a much lower liquid limit $w_{L,CC}$ = 23% resulting in an $I_{P,CC}$ = 2 %. These Casagrande values classify the Halden silt as ML in the Unified Soil Classification System (ASTM 2017).

1-D compression behavior

Figure 2 presents the 1-D IL results for two Sherbrook block sample specimens and one slurry consolidated specimen. Volumetric strains of 1.3% and 1.4% were measured for the two block specimens at σ'_{v0} corresponding to $\Delta e/e_0$ of 0.031 and 0.032. The strain energy based compression ratio, $C_{rw,i}/C_{cw}$ (DeJong et al. 2018) for the two block specimens was in the range of 0.16 - 0.20. Interpretation of the initial portion of the time-deformation curves using conventional root-time and log-time methods was not possible but it was evident that end of primary was reached well within 4 minutes and all data points in Figure 2 are plotted at t_c = 4 minutes. Figure 2a shows no evidence of a yield or preconsolidation stress (σ'_p) and even if plotted in semi-log space the rounded nature of the compression curves are such that any Casagrande (1936) or Becker et al. (1987) interpretation of σ'_p is considered unreliable. Based on the geologic history of the site as summarized by Blaker et al. (2019) the deposit is believed to be geologically normally consolidated but likely exists in a lightly overconsolidated state due to aging. The recompression ratio ($C_{r\varepsilon} = \Delta\varepsilon/\Delta\log\sigma'_v$) and maximum compression ratio ($C_{c\varepsilon,max}$) for the block specimens were 0.006 and 0.075, respectively, and the Janbu (1963) constrained modulus (M) at the in situ effective stress (σ'_{v0}) was about 11 MPa. The average unload-reload constrained modulus (M_{ur}) was about 130 MPa. Secondary consolidation effects were rather small, with $C_{\alpha\varepsilon}/ C_{c\varepsilon}$ approximately equal to 0.035, and thus, consistent with the range suggested by Terzaghi et al. (1996) for inorganic clays and silts. The slurry consolidated specimen started at the same initial void ratio as the block samples but exhibited much greater compressibility, as anticipated, and the e - logσ'_v curve did not converge with that of the block samples within the maximum σ'_v values applied (Figure 2c).

Block and reconstituted undrained stress-strain behavior

Volumetric strain at σ'_{v0}, for the consolidation phase of all the CAUC/E tests ranged from 0.8% to 1.3% and the corresponding $\Delta e/e_0$ values ranged from 0.014 to 0.031 (Table 1). The shear wave velocity values normalized by the in situ value, as measured downhole using a seismic flat dilatometer, SDMT (Blaker et al. 2019), $V_{vh,0}/V_{vh,SDMT}$, ranged from 0.83 to 0.87 (Table 1). Overall the measures of ε_{vol}, $\Delta e/e_0$ and $V_{vh,0}/V_{vh,SDMT}$ were uniform for the seven specimens trimmed from the block sample.

Figures 3a and 3b show that for CAUC testing the block sample specimens exhibited an initial contractive behavior up to 1 - 2% vertical strain but thereafter switched to dilative behavior and strain hardening response. This behavior is clearly observed in Figure 3c which shows the effective stress paths turn towards and eventually run along the K_f line. All tests, including the CAUE test exhibited an effective stress friction angle at maximum obliquity of ϕ'_{mo} = 36°. This friction angle, which is the same as that measured for the SD and MT specimens, implies a normally consolidated $K_0 = (1 - \sin\phi')OCR^{\sin\phi'}$ (Mesri and Hayat 1993) of 0.41. With the Halden deposit considered to be lightly overconsolidated suggests an estimated in situ K_0 value somewhat greater than 0.41 and thus the value of 0.50 assumed at the start of the test program seems reasonable.

The reconstituted specimens prepared either by MT or SD had essentially the same initial and end of consolidation void ratios as the block sample specimens (Table 1) but exhibited significantly different undrained stress-strain behavior. Peak shear stresses of about 35 kPa occurred at around ε_v = 0.1% and the specimens developed u_{max} values of around 40 kPa as depicted in Figure 3d and 3e. Both MT and SD specimens showed post-peak strain softening behavior but from about ε_v = 3% the stress-strain characteristics switch towards dilative behavior and strain hardening as the stress path reaches the K_f line at essentially the same maximum obliquity friction angle of 36° as the block sample specimens (Figure 3f).

The significant difference in the block and reconstituted undrained shear behavior is believed to be due to differences in structure. The reconstitution procedure most likely does not replicate the depositional environment of the natural soil. Furthermore, the in situ soil had undergone significant aging, i.e., multiple log cycles of secondary compression (Blaker et al. 2019). In contrast, reconstituted laboratory specimens were aged for only a short period after end of primary consolidation. While physical handling and trimming of the block sample was possible without support, the SD specimens (with essentially the same void ratio and silt and clay content) had to be supported during preparation and even after dead-weight consolidation to 50 kPa. As no evidence of cementation has been found for the Halden silt (Blaker et al. 2019) this implies that an inherent structure of the block sample prevented collapse of the unconfined soil matrix and was likely also responsible for the stiffer strain hardening observed in CAUC tests and likewise for the 1D consolidation behavior. This intact structure could not be replicated by reconstitution in the laboratory by either of the two reconstitution methods without any form of aging of the soil. Figures 4a to 4c show how the stress-strain, stress-path and secant shear modulus ($G_u = \Delta(\sigma'_v - \sigma'_h)/3\Delta\varepsilon_v$) of reconstituted Halden silt (SD) changes after only 7 days (10^4 minutes) of drained creep in the triaxial cell. The lower void ratio after consolidation (e_c = 0.67 for 7 days creep versus 0.71 for 2 hours creep) cannot alone explain the 15% increase in peak shear stress of the "aged" SD specimen. The secant shear modulus at small shear strains of the unaged SD specimen was also lower for all levels of shear strain compared to the SD specimen subjected to 7 days of drained creep. Mesri et al. (1990) and Schmertmann (1991) hypothesized that drained creep is the dominant mechanism of aging of granular soils on an engineering timescale and that the increase in stiffness and strength during drained creep results from both increased density and continued particle rearrangement creating an increase in macrointerlocking of particles and microinterlocking of surface roughness. Furthermore, angular particles, like those present in the Halden silt (Blaker et al. 2019), can result in a greater aging effect since they have a larger range of stable contacts and more particle interlocking (Mitchell and Soga 2005).

ISA strain cycling behavior

Positive shear induced pore pressure continuously developed during ISA shearing of the block sample specimens which caused a significant reduction in p' as shown in Figure 5. For the ±3.0% ISA test, the effective stress path towards the end of the ISA strain cycle eventually tracked the CAUC/E K_f lines. The change in mean effective stress $\Delta p'_c$ expressed as percentage of the pre-ISA mean effective stress after consolidation p'_c (Santagata and Germaine 2002) ranged from 74% and 98% (Figure 5c.). ISA shearing of the SD specimens with strain cycles of ±1% and ±3% also caused a significant decrease in p' with $\Delta p'/p'_c$ equal to 95% and 98% (Figure 5f) with the effective stress path towards the end of the ISA cycle also tracking the same K_f line as the block sample specimens. These effective stress path excursions for both the block and SD specimens towards very low p' values are consistent with that reported by Lukas et al. (2019) for synthetic silt mixtures. However, this significant loss of p' during ISA simulation of tube sampling is much greater than that measured for clays (e.g., Santagata and Germaine 2002).

Post-ISA reconsolidation and disturbed undrained shear behavior

The post-ISA recompression ε_{vol} and $\Delta e/e_0$ values required to bring the disturbed silt specimens back to the pre-ISA effective stress state increased with increasing magnitude of the ISA strain cycle (Table 1). For all post-ISA tests, e_0 was taken as the pre-ISA void ratio e_c. $\Delta e/e_0$ and ε_{vol} were both higher for the reconstituted specimens than the companion tests on block samples. Lunne et al. (2006) cautioned that the $\Delta e/e_0$ method may not be applicable for low plasticity silts. This appears to be the case here as the $\Delta e/e_0$ values in Table 1 show that even after being subjected to significant strain induced disturbance, the samples still rated within the "Very good to excellent" and "Good to fair" clay-based sample quality ratings (Lunne et al. 1997) or quality A or B using the SQD system (Terzaghi et al. 1996). It also confirms recently published findings of Carroll and Long (2017), DeJong et al. (2018) and Lukas et al. (2019). Furthermore, bender element tests demonstrated a significant decrease in V_{vh} during ISA (from $V_{vh,0}$ to $V_{vh,ISA}$) - corresponding to large decrease in p'. $V_{vh,ISA}$, however, showed complete recovery to $V_{vh,0}$ upon post-ISA reconsolidation (Table 1). Yet, post-ISA undrained shear behavior was very different for ISA disturbed specimens compared to the reference block sample specimens, indicating, in this case, V_{vh} does not track sample disturbance well.

Increasing ISA-imposed strain damage from ±0.5% to ±3.0% increased the rate of shear stress development with strain in the block sample specimens as shown in Figure 6a, especially for the ±3.0% test. This corresponds to an increasing rate of negative shear induced pore pressure with an increase in ISA strain (Figure 6b). However, as strain continues both the undisturbed specimen and the ISA disturbed specimens all converged to the same failure envelope (Figure 6c). Figures 6d to 6f present results of the post-ISA undrained shear behavior of the SD specimen and show similar trends to that of the block sample specimens although with more dramatic effect. At an ISA strain of ±3.0%, the strain softening observed in the reference undisturbed SD specimen is completely removed, a much lower Δu is developed, and the effective stress path significantly shifts to the right (Figure 6f). Indeed, an interesting outcome of these tests is that with an increase in ISA disturbance strain level the behavior of the reconstituted soil progressively migrates towards that of the block sample.

Influence of tube sampling

Figure 7 presents results from two CAUC tests conducted on samples collected using the NGI 54 and GP-S fixed piston samplers. The values of ε_{vol} and $\Delta e/e_0$ during reconsolidation were 1.1 % and 0.024 for the NGI 54 and 1.1 % and 0.026 for the GP-S samples which is essentially the same as that of the two CAUC block sample specimens (Table 1). These values suggest similar sample quality for the tube samples as that of the block samples and yet the undrained shear behavior is markedly different. The specimens from the tube samples have a much a greater rate of shear stress and negative pore pressure development with increasing vertical strain. Although at large strains all the tests converge to the same failure envelope at about ϕ'_{mo} = 36°. Results from the ± 1 and 3% ISA tests performed on the block sample specimens are also plotted for reference in Figure 7. These results indicate a general similarity in the effect on undrained shear behavior of actual tube sampling disturbance (NGI 54 and GP-S) and simulated tube sampling disturbance (ISA tests on the block sample). Both tube samplers have a poor area ratio with the GP-S sampler being the worse of the two and yet the results in Figure 7 indicate greater disturbance for the NGI 54 sampler. It is hypothesized that some compensation occurred due to the reduction in friction between the sampler wall and soil by the polymer gel.

Discussion of results

The field work described by Blaker et al. (2019), and the results presented above demonstrate that, although challenging, an intact Sherbrooke block sample in this case was successfully collected in a I_p = 2 % soil with 89% silt and 9% clay. Recompression metrics, ε_{vol} and $\Delta e/e_0$, for the block and tube samples were low and similar, yet the undrained stress-strain behavior of the tube samples was markedly different, reaching much higher shear stress at lower strains. The post-ISA reconsolidation phase suggested that for Halden silt neither ε_{vol}, $\Delta e/e_0$, nor V_{vh} track sample disturbance for the ISA specimens; even after significant ISA induced disturbance post-ISA $\Delta e/e_0$ values were very low and $V_{vh,ISA}$ completely recovered to $V_{vh,0}$.

The low compressibility and dilative type behavior during undrained shear of the block sample specimens, and high compressibility and contractive type undrained shear behavior of the reconstituted specimens confirm the differences also observed by Høeg et al. (2000) for the Swedish Börlange silt. It appears that the natural soil structure and undrained response to triaxial compression loading of Halden silt cannot be replicated using reconstitution methods even when prepared to the same void ratio as the block sample specimens (Figure 3). One test did show that aging during 7 days of laboratory drained creep stiffened a slurry reconstituted specimen, but it still did not behave close to that of the block sample (Figure 4). At a minimum a significantly greater duration of drained creep would be required. Furthermore, natural seismic ground motion over the years could have also resulted in stiffening and strengthening of the natural silt deposit.

The significant effects of simulated tube sampling (ISA) were confirmed by the observed stress-strain behavior of collected NGI 54 and GP-S tube samples. Increasing degree of disturbance generally resulted in increasingly pronounced dilative type behavior and consequently higher mobilized shear stresses at almost all strength criteria (Table 2 and Table 3). The effective stress friction angle, however, were essentially the same for all tests, independent of sampling or preparation method (block, tube or reconstitution) and degree of disturbance. If undrained shear strength is required for design, selection of a representative value is highly dependent on the state of the laboratory test specimens, strength criterion and the design application, i.e. whether lower bound or higher bound values are required. Figure 8 illustrates how the combination of the Brandon et al. (2006) 1 to 6 undrained shear strength criteria and sampler type can have a significant effect on the selected undrained shear strength. The block sample is considered to be a more accurate representation of the intact soil than the tube samples, given difference in the stress-strain behavior. For such a silt that exhibits dilative type behavior criterion 6 (u_{max}) nevertheless gives close to the same s_u value for all three samplers. At this point, the soil is not dilating yet and the differences in measured behavior are small. Furthermore, selection of a representative design value of A_f (e.g. 0.0 or 0.25) will give near the same s_u for all tests as the Halden silt converges onto the same K_f line, independent of sample type, and at the same time typically limit ε_{vf} < 10%. It is noted, however, that in Figure 8c the starting point (end of consolidation stress, i.e. p'_c and q_c) of the three tests show small differences and values of s_u at A_f = 0 and 0.25 are thus somewhat different. For the other criteria, s_u of the tube sample specimens were generally well above that of the block, by up to 159% (Table 2). In the extreme case, a selected representative value of s_u from 11.5 m depth at Halden can range from about 50 kPa (block sample at criterion 6 - u_{max}) to 120 kPa (NGI 54 at criterion 2 - ε_{vf} = 10%), giving a factor of 2.4. Figure 9 shows that, except for the u_{max} and A_f = 0 criteria, the undrained shear strength estimates increase with increasing magnitude of ISA induced strain for all other criteria. Relative to the reference monotonic block sample results (plotted at ε_{zz} = 0%) the increase in s_u, is the largest for q_{max} and ε_{vf} = 10% criteria. These findings imply that undrained triaxial testing of tube sampled silt specimens can lead to selection of an artificially high undrained shear strength for design. These effects are opposite of that observed for low to moderate overconsolidation clays, where disturbance typically results in a softer stress-strain response and lower peak undrained shear strength.

The selection of undrained shear strength is an important issue for design of structures in silt where loading regime, structure geometry or drainage properties of the soil are such that undrained, or partially drained conditions prevail. From CAUC results for the Halden silt it appears that the shear stress at u_{max} represents the lower bound, and at $\varepsilon_{v,f}$ = 10% the upper bound undrained shear strengths, respectively. Selection of the relevant s_u for design will need to assess if the field application will be undrained, fully drained, or partially drained. Applying A_f in the range of 0.0 to 0.25 as upper bound strength criterion; (i) reduces the range between the upper and lower bound undrained shear strength; (ii) allows the design to rely on dilative type behavior, but not on the shear induced pore pressure actually going negative or excessive values of strain; and (iii) minimizes the adverse effect of sample disturbance on design parameter selection. At a minimum $A_f = 0$ provides a valuable reference undrained shear strength equal to the drained shear strength. For strongly dilative soils like the Halden silt any strength criterion yielding $A_f < 0$ needs careful consideration unless higher values of undrained shear strength are conservative, e.g. for extraction assessments, skirt penetration, pile driving etc. For stability problems, lower values of s_u are more conservative and consideration should be given to estimated strain levels and pore pressure dissipation in the field.

Summary and conclusions

This paper presents a laboratory investigation of the undrained shear behavior of a natural low plasticity silt from Halden, Norway in the intact, disturbed and reconstituted states. Specimens trimmed from a Sherbrooke block and reconstituted specimens were tested using the ideal sampling approach (ISA) framework in a triaxial stress path cell system. Three levels of ISA vertical strain cycles, ±0.5%, ±1% and ±3%, were applied to simulate different degrees of tube sampling disturbance. The sample quality recompression metrics, demonstrated that neither $\Delta e/e_0$, ε_{vol}, nor shear wave velocity, V_{vh}, track sample disturbance well for this low plasticity silt unlike that for moderate to low OCR clays. Relative to the reference block sample specimens ISA strain cycles, and subsequent reconsolidation to the best estimate in situ effectives stress conditions, resulted in an increasingly pronounced dilative type behavior during post-ISA undrained triaxial shear, and a general increase in s_u. The ISA disturbed block sample specimens also showed similar stress-strain behavior as that measured in conventional CAUC tests conducted on specimens from the NGI 54 mm composite and GP-S fixed piston tube samplers. These results indicate that tube sampling can cause significant alteration of the intact soil state. However, in all cases the intact, disturbed and reconstituted specimens reached the same effective stress failure envelope. For design applications an assessment of whether the field application will involve drainage is an important consideration. Applying undrained shear strength criteria for soils that exhibit dilative behavior the u_{max} and $0.25 \geq A_f \geq 0$ as lower and upper bound strength criteria reduces the range in characteristic undrained shear strength; ensures that s_u does not rely on net negative pore pressures or excessive strains; and mitigates the adverse effect of sample disturbance on design parameter selection.

Data availability statement

Some or all data, models, or code that support the findings of this study are available from the corresponding author upon reasonable request.

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Figure Titles

Fig. 1. Ideal sampling approach (ISA, Baligh et al. 1987) concept illustrated by (a) shear stress versus vertical strain, and (b) stress path plots. – data for block sample specimen of Halden silt.

Fig. 2. 1D consolidation of Sherbrooke block and reconstituted (slurry) Halden silt. Vertical effective stress versus vertical strain on (a) linear and (b) semi - log axis, and (c) void ratio versus log stress.

Fig. 3. Undrained shear behavior of (a to c) Sherbrooke block and (d to f) reconstituted Halden silt.

Fig. 4. "Aging" effect on undrained triaxial compression shear behavior of reconstituted (slurry) Halden silt. (a) Stress - strain, (b) stress - path, and (c) shear modulus reduction with shear strain.

Fig. 5. ISA strain cycling behavior from triaxial tests on (a to c) block, and (d to f) reconstituted (slurry) Halden silt.

Fig. 6. Post-ISA undrained shear behavior from triaxial tests on (a to c) block, and (d to f) reconstituted (slurry) Halden silt.

Fig. 7. Effect of simulated (ISA, Baligh et al., 1987) and true sample disturbance on undrained shear behavior. (a) Stress – strain, (b) pore pressure - strain, and (c) stress - path.

Fig. 8. Undrained shear strength criteria (Brandon et al.2006) illustrated for CAUC tests on three types of Halden silt samples (NGI 54, GP-S and Sherbrooke block). (a) Stress – strain, (b) pore pressure - strain, and (c) stress - path.

Fig. 9. Effects of simulated sampling disturbance (ISA, Baligh et al., 1987) on selection of undrained shear strength from CAUC tests on Sherbrooke block samples of Halden silt for various criteria (data in Table 2).

Tables

Table 1: Key initial, after consolidation and post-ISA data from IL oedometer and CAUC tests on block, disturbed and reconstituted Halden silt.

Test	Depth	Test type	Sample [1]	w_i	γ_t	e_i [2]	e_c [2]	ε_{vc} [2]	ε_{vol} [2]	$\Delta e/e_0$	$V_{vh,0}/V_{vh,SDMT}$ [3]	$V_{vh,ISA}/V_{vh,0}$ [3]	$V_{vh,p\text{-}ISA}/V_{vh,0}$ [3]	$\Delta e/e_0$ [4] p-ISA
(-)	(m)	(-)	(-)	(%)	(kN/m^3)	(-)	(-)	(%)	(%)	(-)	(-)	(-)		
HALB04-10-2-A1	11.5	IL	SB	27.8	19.25	0.76	0.74	1.38	1.38	0.032				
HALB04-10-2-A2	11.5	IL	SB	25.3	19.22	0.73	0.71	1.29	1.29	0.031				
HALB04-Batch3-1	-	IL	SD	30.1	19.53	0.77	0.68	5.18	5.18	0.119				
HALB04-10-1-A2	11.5	CAUC	SB	28.0	19.37	0.74	0.72	0.72	0.99	0.024	0.83			
HALB04-10-1-B1	11.5	CAUC	SB	27.3	19.39	0.73	0.71	0.78	1.10	0.026	0.83			
HALB04-10-1-D2	11.5	CAUE	SB	26.8	19.47	0.72	0.71	0.54	0.56	0.014	0.85			
HALB04-10-1-C2	11.5	ISA±0.5%	SB	25.9	19.32	0.72	0.70	0.65	1.12	0.026	0.86	0.70	1.01	*0.010*
HALB04-10-1-B2	11.5	ISA±1%	SB	27.7	19.39	0.73	0.71	0.70	1.15	0.027	0.84		1.03	*0.017*
HALB04-10-1-C1	11.5	ISA±1%	SB	26.5	19.44	0.71	0.69	0.86	1.29	0.031	0.87	0.56	1.01	*0.017*
HALB04-10-1-D1	11.5	ISA±3%	SB	27.4	19.47	0.72	0.71	0.55	0.79	0.018	0.85	0.41	0.99	*0.039*
HALB03-9-A1	11.6	CAUC	NGI54	27.9	19.55	0.72	0.71	0.90	1.08	0.026	0.83			
HALB06-4-D1	11.4	CAUC	GP-S	28.2	20.34	0.65	0.65	1.11	1.06	0.024	0.84			
HALB04-Batch1-1	-	CAUC	MT	28.0	19.32	0.75	0.70	2.08	2.40	0.056				
HALB04-Batch1-2	-	CAUC	MT	28.1	19.30	0.75	0.73	2.00	1.33	0.031				
HALB04-Batch1-3	-	CAUC	SD	28.1	19.30	0.75	0.71	2.55	2.14	0.049				
HALB04-Batch1-4	-	CAUC	SD	27.2	19.43	0.73	0.70	1.77	1.33	0.032				
HALB04-Batch1-5	-	ISA±1%	SD	27.5	19.40	0.73	0.70	2.65	2.02	0.048				0.026
HALB04-Batch1-6	-	ISA±3%	SD	28.0	19.31	0.75	0.70	3.28	2.52	0.059				0.066
HALB04-Batch2-1	-	CAUC (w/creep)	SD	26.6	19.51	0.71	0.67	3.02	2.36	0.056				

Note: [1] SB = Sherbrooke Block, NGI54 = NGI 54mm composite piston sampler, GP-S = Gel Push sampler, MT= Reconstituted, Moist Tamping, SD = Reconstituted, Slurry Deposition; [2] Void ratio after preparation (e_i) and after consolidation to best estimate in situ stress conditions (e_c), vertical (ε_{vc}) and volumetric (ε_{vol}) strains after consolidation; [3] Shear wave velocity from bender elements after consolidation ($V_{vh,0}$), after ISA imposed strain ($V_{vh,ISA}$), post-ISA reconsolidation ($V_{vh,p\text{-}ISA}$) and in situ shear wave velocity from seismic flat dilatometer, SDMT ($V_{vh,SDMT}$ = 178 m/s), (Blaker et al. 2019). $V_{vh,0}$ averaged 151.3 m/s for all bender element tests on block sample specimens (n = 8, SD = 2.56 m/s); [4] e_0 was taken as the pre-ISA void ratio, e_c.

Table 2: Undrained shear strength of Halden silt Block 10 (11.5m) tests using Brandon et al. (2006) failure criteria for dilating soils.

Sample or Test Type	$A_f = 0$		$A_f = 0.25$		$(\sigma'_1/\sigma'_3)_{max}$		u_{max}		K_f line		$\varepsilon_{v,f} = 5.0\%$	$\varepsilon_{v,f} = 10\%$	$(\sigma'_1\text{-}\sigma'_3)_{max}$
	q_f (kPa)	ε_f (%)	q_f (kPa)	ε_f (%)	q_f (kPa)	ε_f (%)	q_f (kPa)	ε_f (%)	q_f (kPa)	ε_f (%)	q_f (kPa)	q_f (kPa)	q_f (kPa)
Sherbrooke block and tube samples													
Sherbrooke Block	83.7	10.4	61.6	2.9	69.6	4.8	50.3	0.9	69.8	4.8	69.7	83.8	93.6
Sherbrooke Block	83.1	11.0	62.3	3.3	76.9	7.2	49.1	1.0	76.4	7.1	71.5	82.3	90.0
Tube (NGI 54)	89.6	5.2	62.8	2.0	85.9	4.7	52.1	1.0	84.7	4.7	88.0	120.8	148.7
Tube (GP-S)	94.1	8.1	67.9	3.5	67.0	3.4	53.5	1.6	66.7	3.4	77.4	102.1	118.5
Ideal Sampling Approach (ISA)													
± 0.5% ISA	*87.2*	*6.8*	57.8	1.0	87.8	7.0	56.1	0.8	85.6	6.9	79.8	93.0	98.6*
± ~1.0% ISA	*85.9*	*5.5*	52.1	0.5	89.6	6.0	59.7	1.0	88.7	6.0	83.5	98.9	111.8
± 1.0% ISA	*86.8*	*5.1*	54.4	0.4	94.5	6.9	57.2	0.6	90.9	5.9	85.2	101.4	110.9*
± 3.0% ISA	88.6	3.3	59.5	1.2	105.8	5.2	48.4	0.6	106.2	5.2	105.0	131.3	153.0

Note: $(\sigma'_1\text{-}\sigma'_3)_{max}$ at end of test, i.e. at about 20% vertical strain. * Specimen did not reach 20% vertical strain but stopped at about 15%.

Table 3: Undrained shear strength of Halden silt MT and SD (11.5m) tests using Brandon et al. (2006) failure criteria for dilating soils

Sample or Test Type	$A_f = 0$		$(\sigma'_1/\sigma'_3)_{max}$		u_{max}		K_f line		$\varepsilon_{v,f} = 5.0\%$	$(\sigma'_1\text{-}\sigma'_3)_{max}$	
	q_f (kPa)	ε_f (%)	q_f (kPa)	ε_f (%)	q_f (kPa)	ε_f (%)	q_f (kPa)	ε_f (%)	q_f (kPa)	q_f (kPa)	ε_f (%)
Reconstituted specimens											
MT Undisturbed	-	-	33.0	7.5	31.4	5.7	33.0	7.5	30.8	40.5 (36.1)*	15.4 (0.1)*
MT Undisturbed	-	-	23.2	6.5	23.2	6.8	23.3	6.7	23.5	36.0*	0.1*
SD Undisturbed	-	-	30.4	9.3	26.4	5.0	31.2	9.9	26.4	41.5 (34.2)*	19.9 (0.1)*
SD Undisturbed	-	-	27.7	8.8	25.4	5.5	27.8	8.9	25.3	36.5 (34.6)*	19.5 (0.04)*
Ideal Sampling Approach (ISA)											
SD ± 0.5% ISA	-	-	39.5	8.4	37.1	5.1	39.6	8.4	37.0	49.5 (38.7)*	19.9 (0.4)*
SD ± 3.0% ISA	78.1	13.8	59.0	6.9	44.1	2.1	59.2	6.9	53.3	88.5	19.9

Note: * Low strain peak shear stresses, i.e. peak shear stress prior to strain hardening behavior.

Figure 1 (revised)

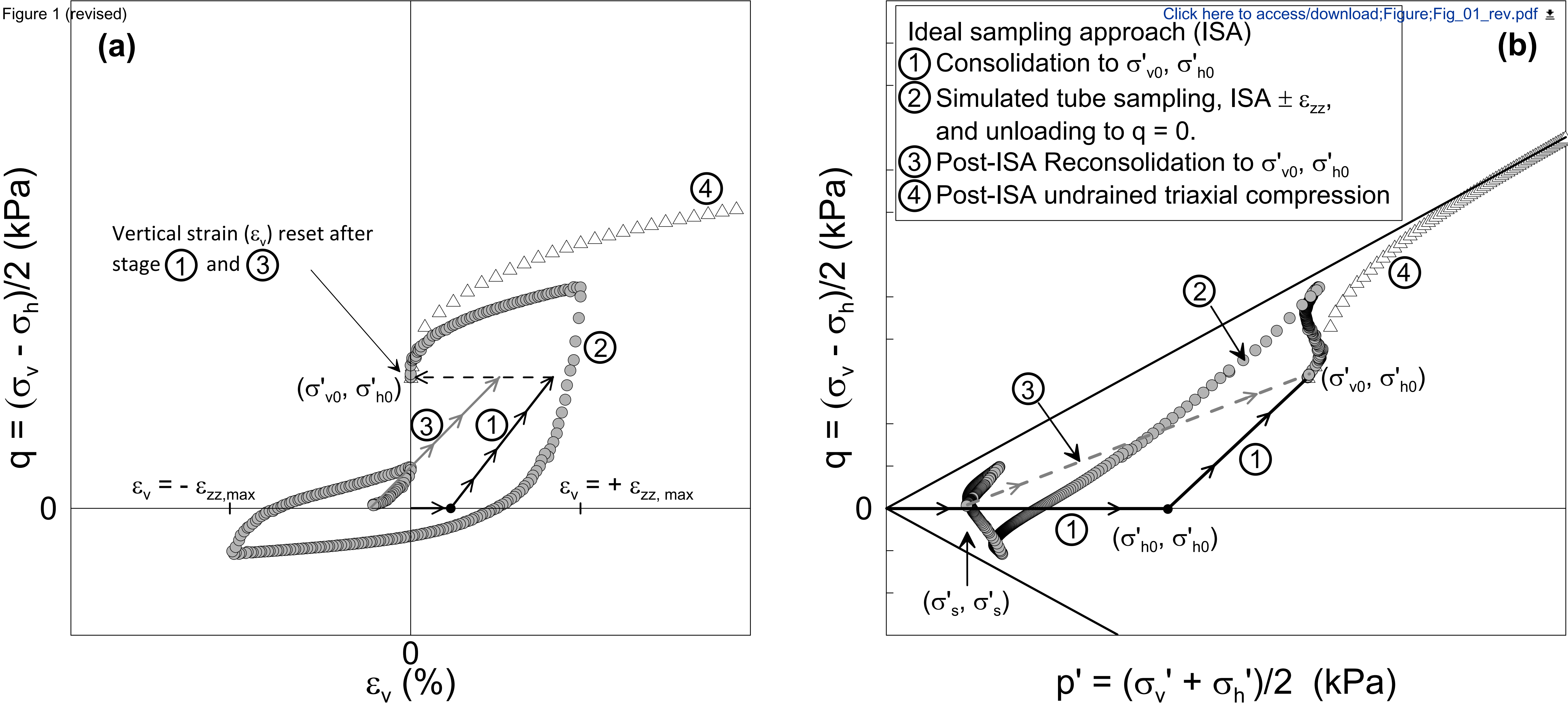
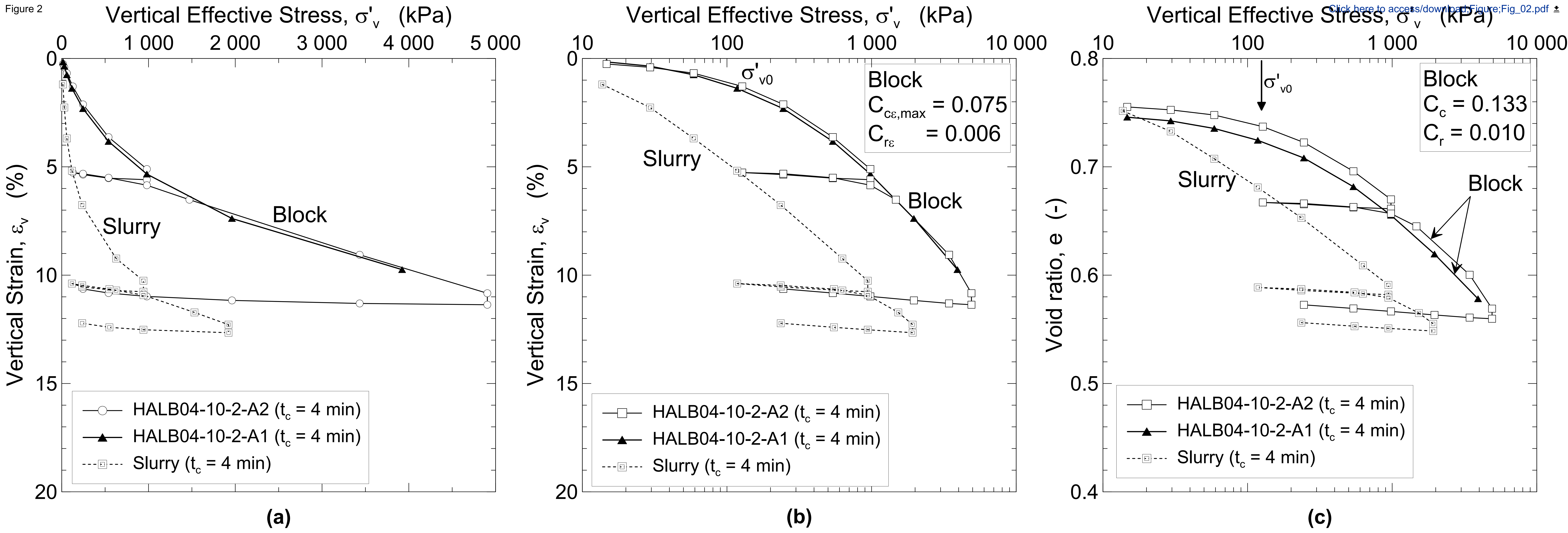
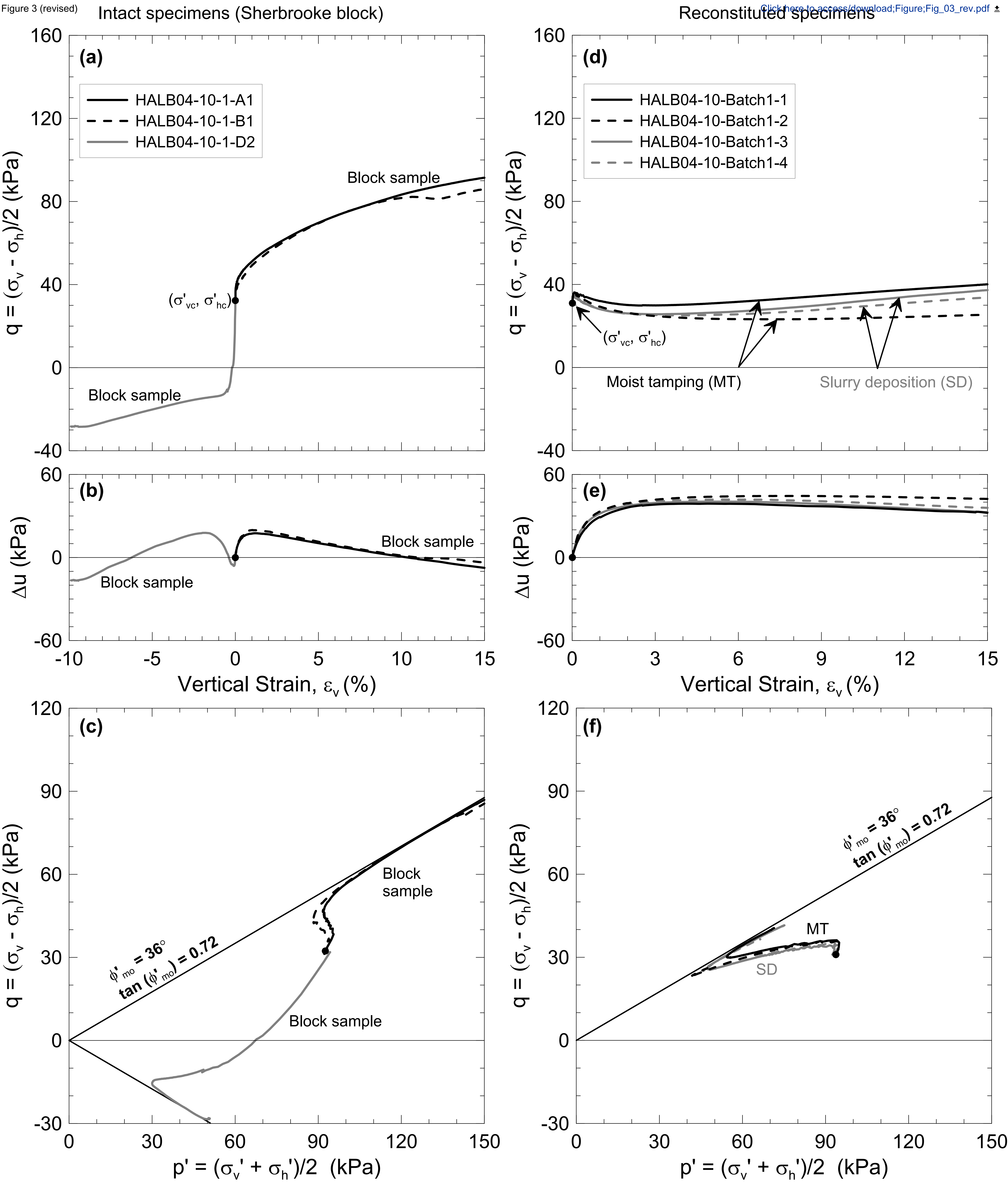


Figure 2



Vertical Effective Stress, σ'v (kPa)
0
1 000
2 000
3 000
4 000
5 000
Vertical Strain, εv (%)
Slurry
Block
HALB04-10-2-A2 (tc = 4 min)
HALB04-10-2-A1 (tc = 4 min)
Slurry (tc = 4 min)
(a)
Vertical Effective Stress, σ'v (kPa)
10
100
1 000
10 000
σ'v0
Block
Ccε,max = 0.075
Crε = 0.006
Slurry
Block
Vertical Strain, εv (%)
HALB04-10-2-A2 (tc = 4 min)
HALB04-10-2-A1 (tc = 4 min)
Slurry (tc = 4 min)
(b)
Vertical Effective Stress, σ'v (kPa)
σ'v0
Block
Cc = 0.133
Cr = 0.010
Slurry
Block
Void ratio, e (-)
HALB04-10-2-A2 (tc = 4 min)
HALB04-10-2-A1 (tc = 4 min)
Slurry (tc = 4 min)
(c)

Figure 3 (revised)



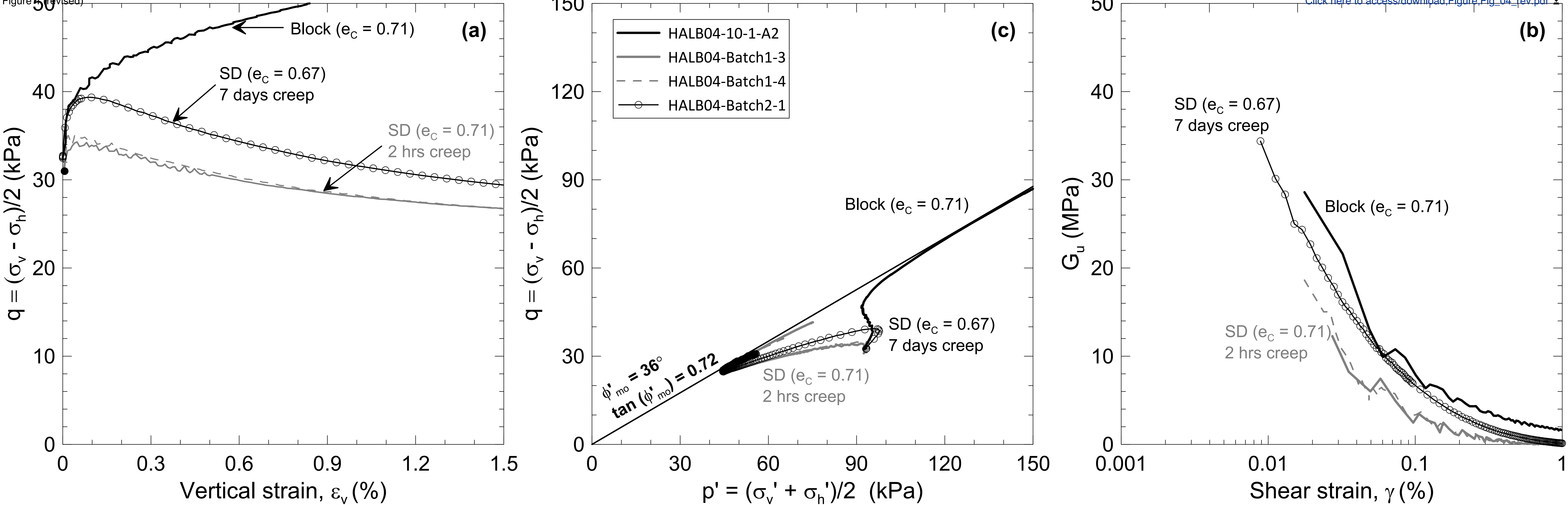

(a)
Block (e_C = 0.71)
SD (e_C = 0.67)
7 days creep
SD (e_C = 0.71)
2 hrs creep
q = (σ_v - σ_h)/2 (kPa)
Vertical strain, ε_v (%)
0
10
20
30
40
50
0
0.3
0.6
0.9
1.2
1.5
(c)
HALB04-10-1-A2
HALB04-Batch1-3
HALB04-Batch1-4
HALB04-Batch2-1
Block (e_C = 0.71)
SD (e_C = 0.67)
7 days creep
SD (e_C = 0.71)
2 hrs creep
ϕ'_{mo} = 36°
tan (ϕ'_{mo}) = 0.72
q = (σ_v - σ_h)/2 (kPa)
p' = (σ_v' + σ_h')/2 (kPa)
0
30
60
90
120
150
0
30
60
90
120
150
(b)
SD (e_C = 0.67)
7 days creep
Block (e_C = 0.71)
SD (e_C = 0.71)
2 hrs creep
G_u (MPa)
Shear strain, γ (%)
0
10
20
30
40
50
0.001
0.01
0.1
1

Figure 5 (revised)

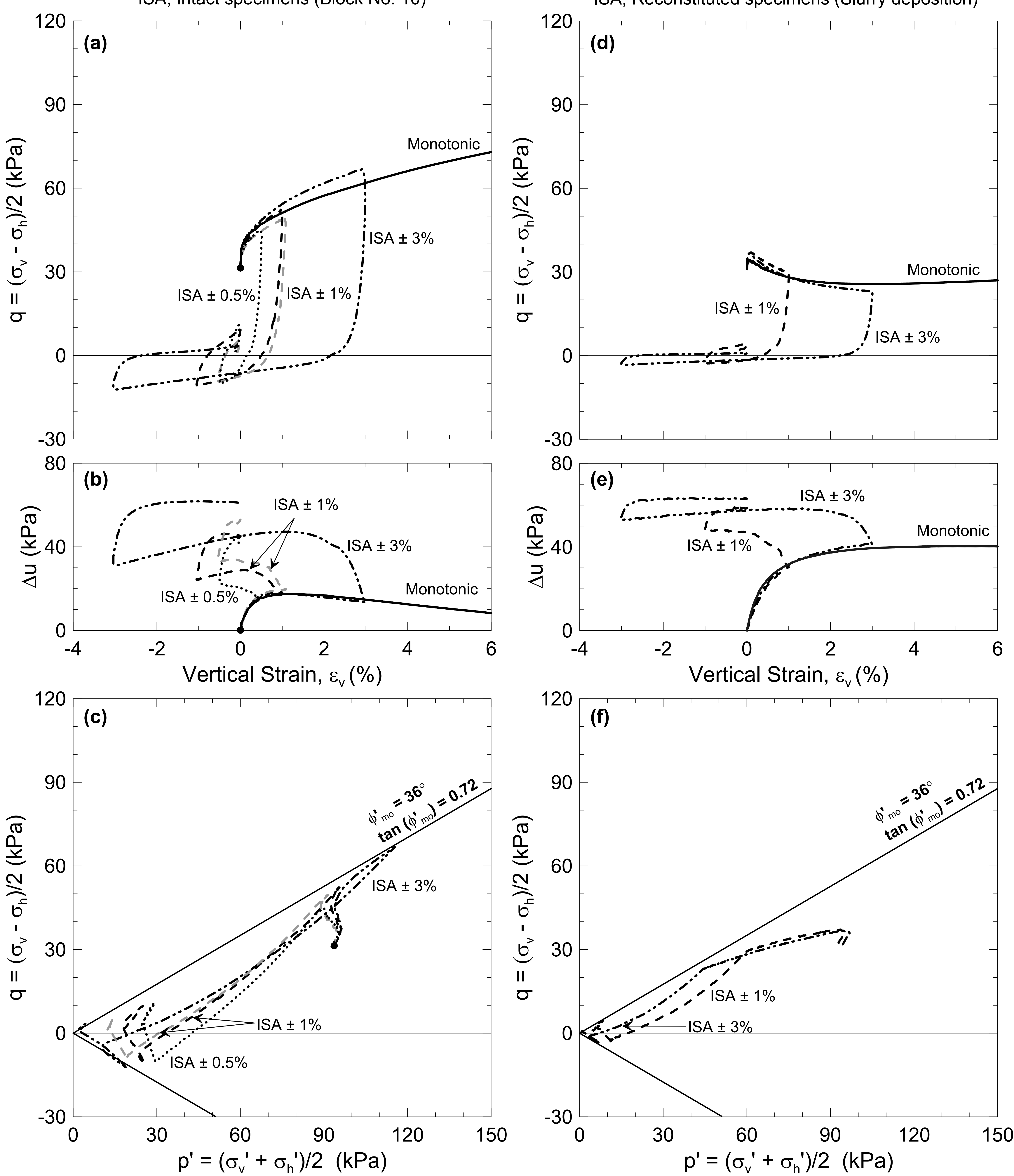
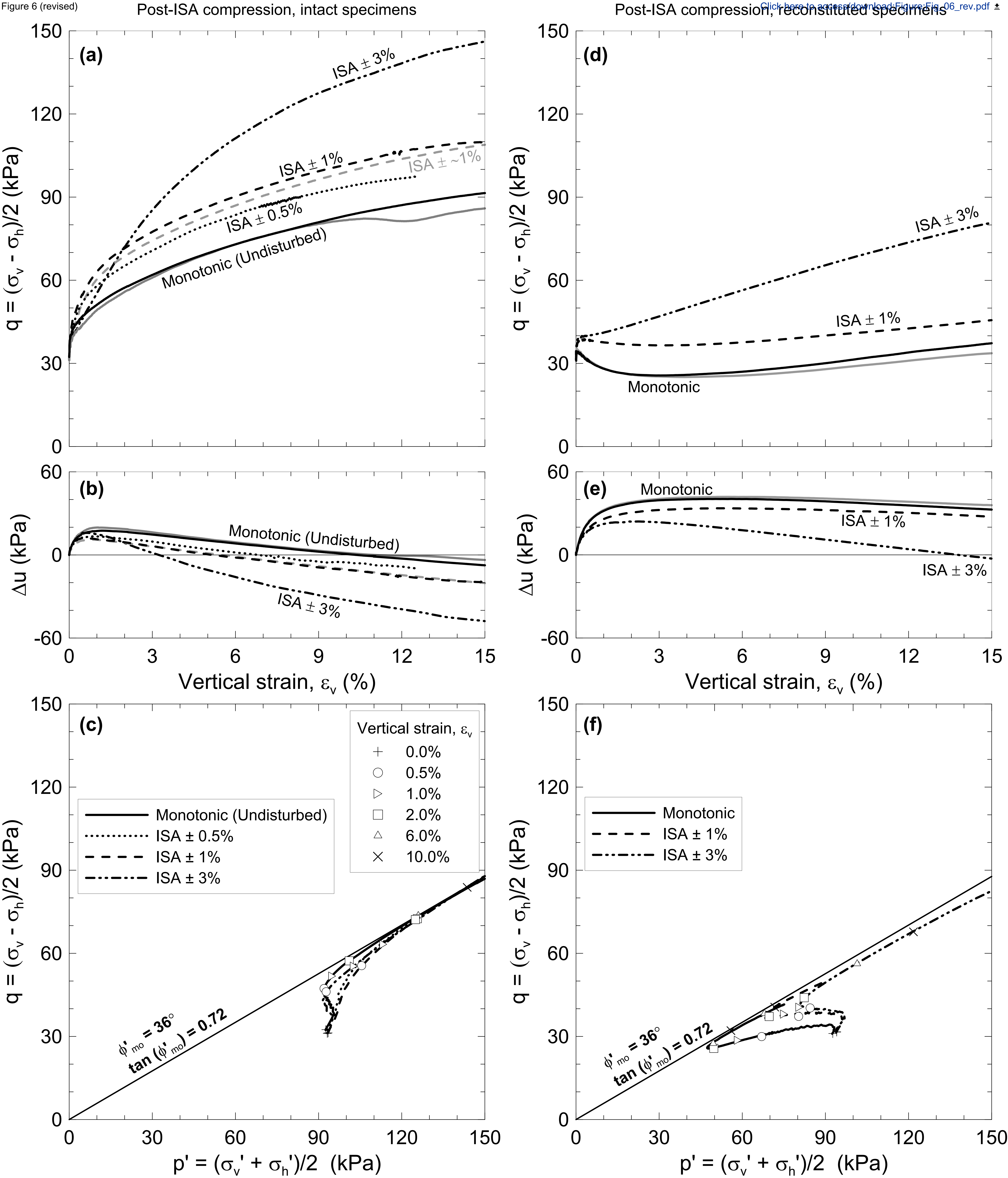


Figure 6 (revised)



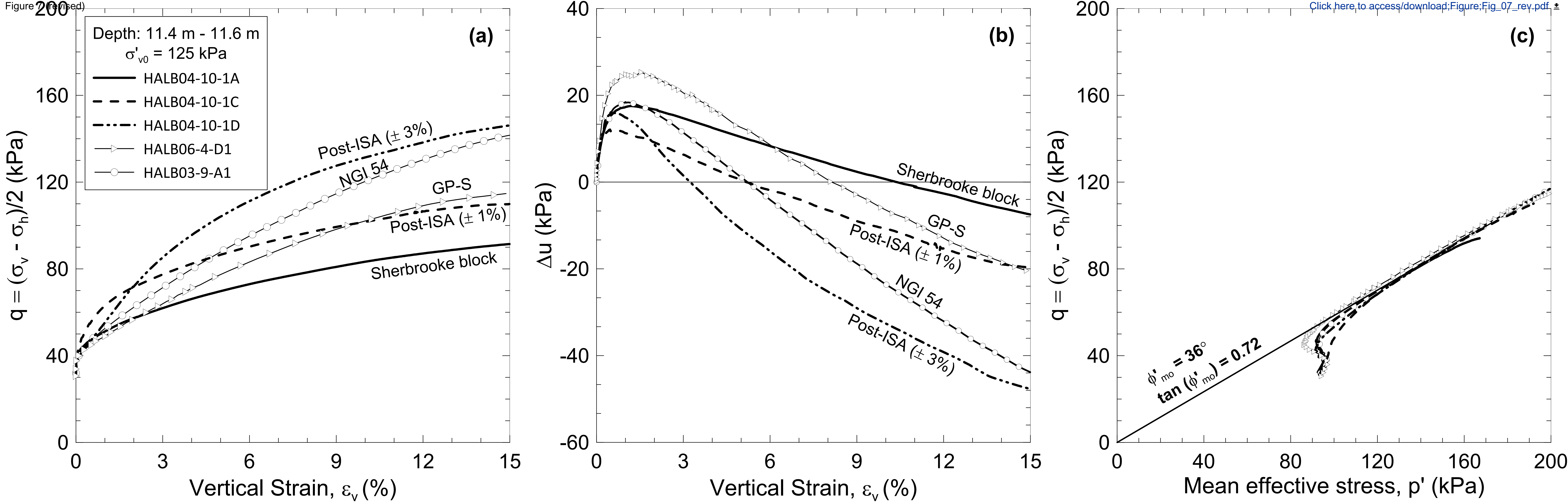

Depth: 11.4 m - 11.6 m
σ'v0 = 125 kPa
HALB04-10-1A
HALB04-10-1C
HALB04-10-1D
HALB06-4-D1
HALB03-9-A1
(a)
Post-ISA (± 3%)
NGI 54
GP-S
Post-ISA (± 1%)
Sherbrooke block
q = (σv - σh)/2 (kPa)
Vertical Strain, εv (%)
(b)
Δu (kPa)
Sherbrooke block
GP-S
Post-ISA (± 1%)
NGI 54
Post-ISA (± 3%)
Vertical Strain, εv (%)
(c)
φ'mo = 36°
tan (φ'mo) = 0.72
q = (σv - σh)/2 (kPa)
Mean effective stress, p' (kPa)

Figure 8 (revised)

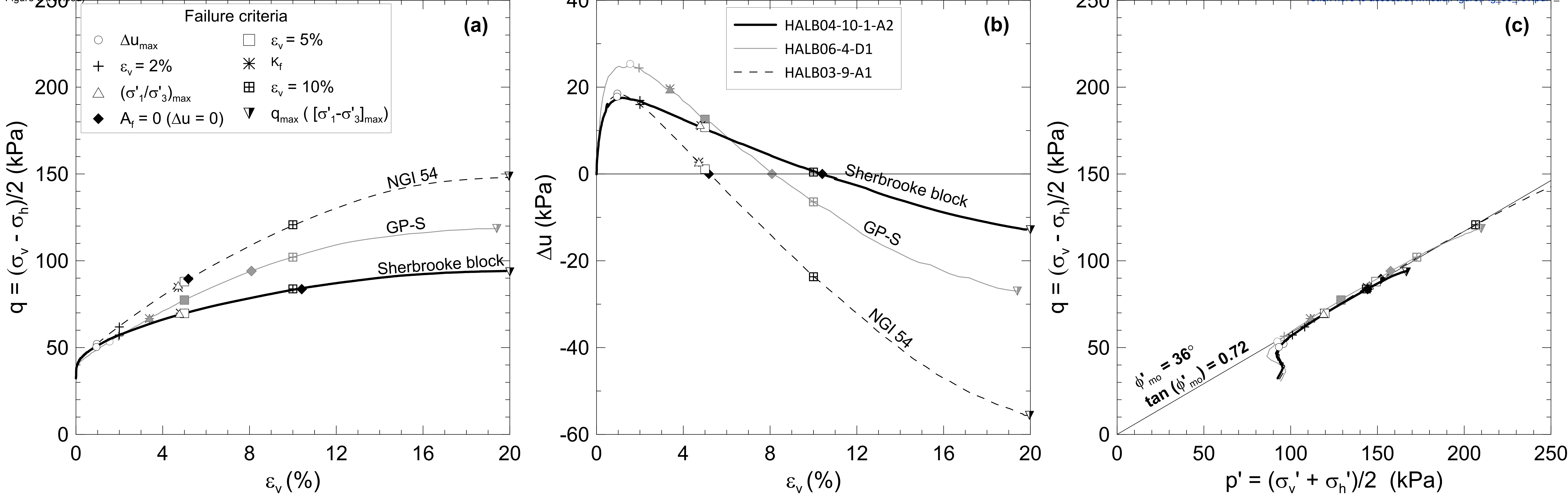


Figure 9 (revised)

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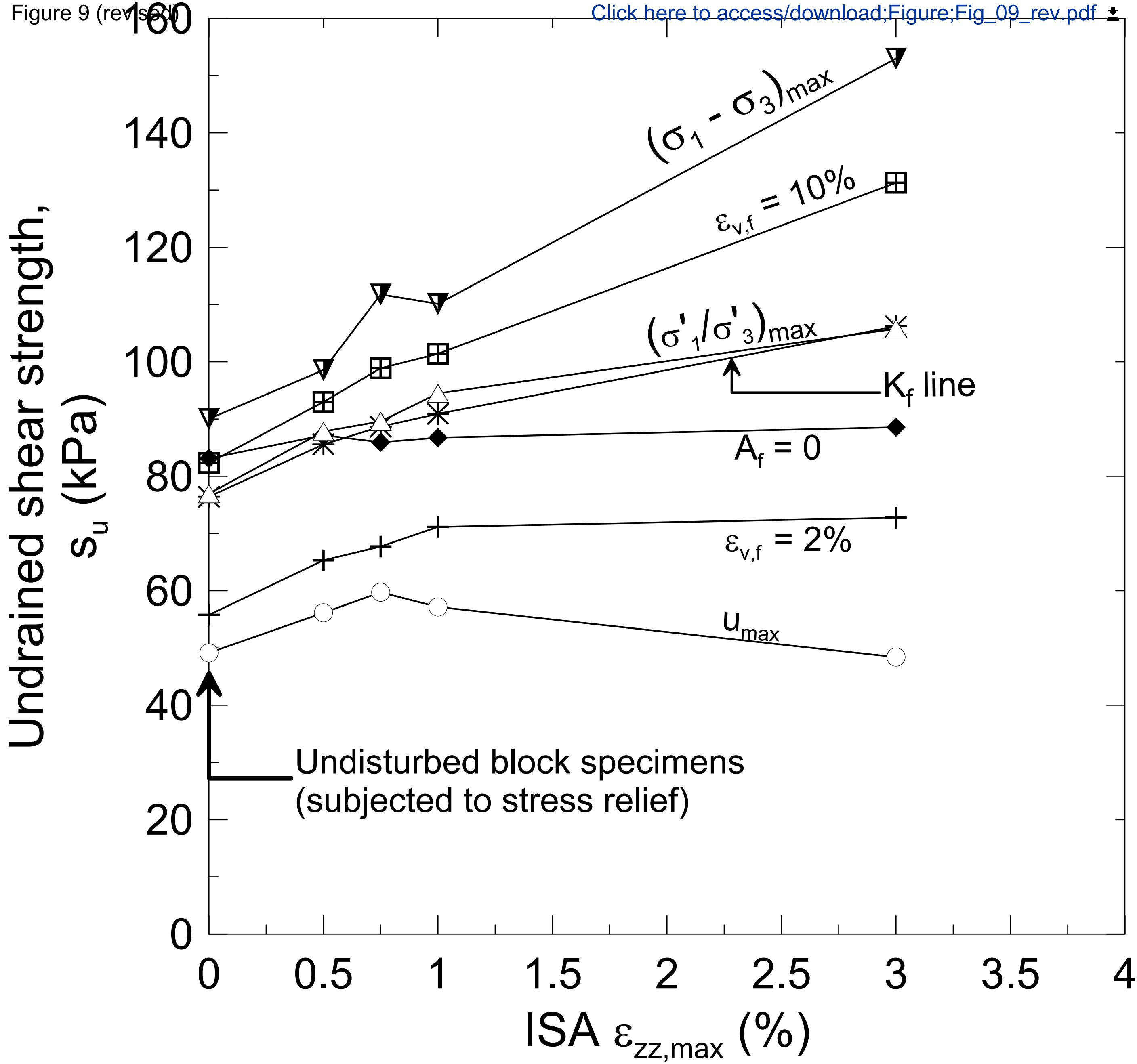

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Øyvind Blaker, M.S.; Don J. DeGroot, Sc.D.

No.	Comment	Authors' response
Editor		
	Thank you for submitting your manuscript to the ASCE. The reviewers are happy that their major concerns have been addressed, however some less significant concerns remain. As you can see from the AE report below, the conclusion is that you should address these concerns and submit a revised version of the manuscript for editorial review. As I know you are aware you should include a short summary outlining how you have addressed these comments.	The authors agree to all comments and have addressed each one in an item-by-item response below. The manuscript has been revised accordingly. We thank you for a swift and seamless review process.
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General	The revised manuscript was reviewed by two original reviewers and both reviewers agree that the authors satisfactorily addressed their major concerns in the revised manuscript. However, reviewer 1 identified a few editorial corrections needed before the manuscripts be accepted for publication. I also reviewed the revised manuscript with interest and somehow concur with the reviewers that the revised manuscript addressed most of the previous concerns. As the revision requested by the reviewer 1 are minor and editorial, I don't think it should go to the reviewers again. AE will make sure that those comments are reflected in the revised manuscript. As such, I recommend the authors to revise the manuscript following reviewer 1's suggestion and resubmit for the final round of review.	The authors agree to all comments and have addressed each one in an item-by-item response below. The manuscript has been revised accordingly.
Reviewer #1		
General	The authors are provided with the following minor (editorial) comments to further improve the quality of their paper:	Thank you for your detailed 2nd review and for improving the paper further. We thank you for a swift and seamless review process. All comments are addressed below.

1	Line 33 should read, "partially drained conditions"	We agree and have made the suggested change.
2	In Lines 81, 4 should be 5	Yes. Typo has been corrected.
3	The sentence in Lines 82 to 87 is unclear. Please re-write in a better way.	We have clarified the sentence by including a three-items list (i) to (iii), as follows: "Silts and intermediate low plasticity soils have traditionally been sampled using: (i) open drive U100 or split spoon samplers (Bray et al. 2004; Long 2007), both of which have a poor geometry with a large area ratio and cutting angle; (ii) thin-walled samplers with a better geometry, including Shelby tubes of various diameters (Brandon et al. 2006; Nocilla et al. 2006) and; (iii) different fixed piston samplers with thin-walled tubes (Høeg et al. 2000; Bray and Sancio 2006; Long et al. 2010; Solhjell et al. 2017)."
4	Please insert "and" before "Blaker" in Line 91	We agree and have made the suggested change.
5	Please change Line 161 to read, "Depending on the design conditions, it is evident ..."	We agree and have made the suggested change.
6	In Line 223, there is a division sign instead of a minus sign. Please correct.	Yes. Typo has been corrected.
7	In Line 227, please delete "performed"	The word "performed" is now deleted.
8	Figures should be cited in numerical order. It appears that Figure 4 is cited before Figure 3.	This was a typo and should read "Figure 2a" rather than "Figure 4a". Typo corrected.
9	In Line 306, "to" after "due"	Yes. Missing word "to" now included.
10	In Line 327, microinterlocking is misspelled.	"Macrointerlocking" was misspelled and has now been corrected.
11	In Line 330, please delete "there is"	We agree and have made the suggested change.

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