

Strain-Rate Effects in Mexico City Soil

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Abstract: Mexico City soil has very high specific surface, plasticity and void ratio; its natural structure is preserved until the yield pressure σ'_y , which is typically above the in situ effective stress σ'_o , and the mechanical response changes significantly when the effective confining stress σ'_o exceeds the yield pressure σ'_y . In this study, the effects of strain rate on the undrained response of Mexico City soil are explored using undisturbed specimens subjected to monotonic triaxial compression tests at a constant rate of deformation. Results show that strain-rate effects on undrained strength and mode of failure depend on σ'_y/σ'_o , hence, on the degree of natural structure preserved in the specimen. Undrained strength increase with strain rate, particularly in the more structured specimens (i.e., higher σ'_y/σ'_o). The role of σ'_y/σ'_o on strain-rate effects in this unremolded natural soil resembles the effect of overconsolidation ratio on resedimented specimens. The limitations in using standard triaxial equipment for strain-rate effect studies are discussed.

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Introduction

Mexico City soil formed from volcanic ash that sedimented in a biologically active lacustrine environment. Geochemical weathering took place within the pore space of the original sediment and involved the dissolution of volcanic ash grains, followed by leachage of some hydrated components and the reprecipitation of new minerals. The resulting high-specific surface soil is made of diatoms and minerals such as montmorillonite, opaline silica and ferromagnesian minerals, opal-CT (cristobalite-tridymite), cristobalite, goethite, calcite, and pyrite (Díaz-Rodríguez et al. 1998).

Mexico City soils are unique in the context of most other natural soils (Díaz-Rodríguez et al. 1992; Díaz-Rodríguez 2003). They have very high specific surface ($S_s=40-350 \text{ m}^2/\text{g}$), void ratio ($e=3-9$), plasticity ($w_L=140-380$, $w_P=55-112$), and friction angle ($\phi=43-47^\circ$). The shear wave velocity is relatively constant with depth in the upper 40 m ($V_s=70-90 \text{ m/s}$) and the yield pressure σ'_y is higher than the in situ effective stress σ'_o , in agreement with the stress-independent formation process described above.

The effect of strain rate on mechanical soil properties can have important engineering implications. In particular, parameters inferred from in situ tests (estimated strain rate $\dot{\epsilon}=10^3-10^5 \text{ \% / h}$) and standard laboratory measurements (conducted at $\dot{\epsilon}$

$=0.5-5 \text{ \% / h}$) must be carefully considered during the selection of design parameters for engineering systems where the strain rate is typically between $\dot{\epsilon}=10^{-2}$ and 10^{-3} \% / h (Bjerrum 1972; Prapaharan et al. 1989).

The purpose of this study is to explore strain-rate effects on the load-deformation response of Mexico City soil. The effect of the yield stress on strain-rate sensitivity is explicitly explored. A brief review of strain-rate effects follows.

Strain-Rate Effects—Previous Studies

The strain-rate dependent strength and stiffness of soils has been extensively reported. General trends common to clayey soils are summarized next (note: most previous studies have been conducted on remolded-resedimented specimens).

Stiffness. The higher the strain rate, the higher the normalized stiffness E/σ'_o measured in consolidated undrained test with isotropic consolidation (CIU) triaxial tests (Berre and Bjerrum 1973; Vaid and Campanella 1977; Zhu and Yin 2000).

Undrained Strength. The undrained strength increases at a rate of 5–15% per log cycle of strain rate (Taylor 1943; Casagrande and Wilson 1951; Bjerrum 1972; Kulhawy and Mayne 1990). This general guideline must be qualified. In particular, it has been observed that the effect of strain rate on undrained strength:

- Continues for about three or four orders of strain rate, yet, the soil may reach a constant strength at very low strain rate [Vaid and Campanella (1977); see Leroueil and Tavenas (1979) for a discussion in the context of the Singh and Mitchell (1968) stress-strain-time response].
- Is greater in k_o -consolidated than isotropically consolidated specimens, and in extension than in compression loading [Zhu et al. (1999a); Zhu and Yin (2000)—Graham et al. (1983) found no significant effect of anisotropic consolidation].

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- May be more pronounced in high plasticity clays (Berre and Bjerrum 1973; Vaid et al. 1979). The effect of plasticity may vanish in natural, structured overconsolidation (OC) clays (Graham et al. 1983).
- Is higher in natural-structured and in remolded-OC clays than in normally consolidated (NC) clays [in terms of S_u/σ'_0 —Lacasse (1979); Richardson and Whitman (1963); Sheahan et al. (1996); Zhu and Yin (2000)].
- The strain at peak resistance does not vary with strain rate (Vaid and Campanella 1977).

Excess Pore Pressure. Changes in strength have been associated to changes in pore pressure (Richardson and Whitman 1963). Indeed, there is a tendency to higher excess pore pressure generation during low strain-rate undrained loading, and the effect is more pronounced in extension than compression loading (Casagrande and Wilson 1951; Bjerrum et al. 1958; Crawford 1959; Richardson and Whitman 1963; Zhu et al. 1999b). Excess pore pressure generation in structured OC clays, $\sigma'_0 < \sigma'_y$, is less sensitive to strain rate than in destructured clays (Lefebvre and LeBeouf 1987).

Effective Stress Parameters. The effect of strain rate on effective stress friction angle ϕ' remains unclear, in part due to experimental difficulties and contradictory data (Bjerrum et al. 1958; Crawford 1959), possible changes in the failure mode (Richardson and Whitman 1963), and data interpretation (Kenney 1959). In general, it appears that higher strain rate leads to higher effective strength envelope (Lo and Morin 1972; Tavenas et al. 1978; Vaid et al. 1979; Leroueil and Tavenas 1979).

Strain-Rate Effects in Mexico City Soil. Previous studies identified a lower limit for the undrained compressive strength of 45 and 55 kPa at very low strain rates (Casagrande and Wilson 1951), an increase in the effective stress friction angle of 2–3° per log cycle of strain rate [Alberro and Santoyo (1973)—friction angles determined assuming $c'=0$], and strain-rate independent value of the strain at the peak deviatoric load (Alberro and Santoyo 1973; Casagrande and Wilson 1951).

Experimental Study—Specimens

An experimental study was conducted to extend the available information for Mexico City soil, with emphasis on the role of initial structure on strain-rate effects. Experimental details are presented next; the complete study is reported in Martínez-Vasquez (2004).

Shelby tubes (OD=128 mm, ID=125 mm, area ratio 4.9%) were recovered from a depth of 17.9 m. The site is within the Alameda Central Park (19.26°N, 99.08°W); nearby areas suffered extensive damage during the Sept. 19, 1985 Mexico City earthquake. Each tube was x-rayed, and no evidence of cracks or edge effects was found. The measured index properties for the tested samples are: natural water content $w=190.24\% \pm 13.65$ SD, void ratio $e=4.40 \pm 0.40$ SD, liquid limit $w_L=211\% \pm 23.37$ SD, plastic limit $w_P=63.90\% \pm 8.03$ SD. The elastic and volumetric threshold strains are $\gamma_{el} \approx 3 \times 10^{-2}\%$ and $\gamma_{ld} \approx 1\%$ respectively (Díaz-Rodríguez and Santamarina 2001). Minimal sampling effects are expected in these high plasticity and high threshold strain soils.

Cylindrical specimens were carefully trimmed (36 mm diam and 75 mm height), placed in a standard triaxial cell with full size

porous stones built in the end caps, and enclosed by two latex membranes separated by a thin film of silicone oil to minimize flow through. All specimens were subjected to isotropic consolidation to the target effective confinement σ'_0 and left under constant effective confining stress for 12 h past the end of consolidation. The back-pressure was maintained at 340 kPa; the measured Skempton B -values exceeded 0.97 in all tests. After consolidation, specimens were subjected to deviatoric compression under undrained conditions.

Two control variables are selected for this study: strain rate $\dot{\epsilon}$ and the ratio σ'_y/σ'_0 between the soil yield stress σ'_y and the imposed effective isotropic confinement stress σ'_0 . Specimens preserve the natural structure when $\sigma'_y/\sigma'_0 > 1.0$ and become gradually destructured as σ'_y/σ'_0 falls below 1.0 (note that $\sigma'_y/\sigma'_0 > 1.0$ corresponds to the overconsolidated OC condition, and σ'_0/σ'_y to the normally consolidated NC state in regular sedimentary soils). Isotropic consolidation data gathered with specimens that span the full void ratio range encountered in this study show that the yield pressure is $\sigma'_y=95.6 \text{ kPa} \pm 5.63$ SD (break noted in both e -log σ' and the linear-linear e - σ' space).

Results

Tested specimens and conditions are summarized in Table 1; each test is named using the letter T followed by test number, the ratio σ'_y/σ'_0 (2.4, 1.2, 0.60, 0.32) and the strain rate $\dot{\epsilon}$ (1, 5, 100, and 800%/h). Stress-strain data are plotted in Fig. 1. The strength increases with the applied effective confinement σ'_0 and strain rate. However, the axial strain at the peak deviatoric stress is almost constant ($\epsilon_f=3.40\% \pm 0.22$ SD in structured OC specimens and $\epsilon_f=4.0\% \pm 0.16$ SD in destructured NC specimens) and independent of the strain rate, even as $\dot{\epsilon}$ varies in ~ 3 orders of magnitude.

Fig. 2 shows the undrained shear strength normalized with respect to the initial effective confining stress S_u/σ'_0 plotted versus the strain rate $\dot{\epsilon}$. The normalized undrained shear resistance S_u/σ'_0 increases with strain rate, and the rate of increase is more pronounced in structured specimens [$\sigma'_y/\sigma'_0 > 1$ —analogous observations were made by Sheahan et al. (1996) for reconstituted overconsolidation ratio clays]. Furthermore, trends appear to converge at some very low strain rate.

The failure mode identified for each specimen is sketched in Fig. 3 as a function of strain rate $\dot{\epsilon}$ and σ'_y/σ'_0 . Destructured NC specimens ($\sigma'_y/\sigma'_0 < 1.0$) subjected to low strain rates ($\dot{\epsilon} < 100\%/h$) exhibit barreling deformation at the time of failure (barreling is a consequence of end constraint due to the rough end caps used). On the other hand, strain localization and shear band formation are readily observed in structured OC specimens ($\sigma'_y/\sigma'_0 < 1.0$) and/or at high strain rates. There is agreement between specimens that localize and those that exhibit postpeak strain softening in Fig. 1.

Analyses and Discussion

The experimental study was designed to minimize the potential impact of time-dependent biases such as electronic drift in long duration tests (the baseline oscillation in load cell and pressure transducers is $< 0.2\%/day$), time for pore pressure homogenization within the specimen (strips of filter paper run along the length of the specimen to accelerate drainage), and the conse-

Table 1. Results of CIU Tests on Mexico City Soil

Test number	σ'_o (kPa)	$\dot{\epsilon}$ (%/h)	σ'_y/σ'_o	ϵ_f (%)	$(\sigma_1-\sigma_3)_{max}$ (kPa)	u_f (kPa)	S_u/σ'_o
Series 1							
T1-2.4-1%	40	1	2.4	3.20	68.80	32.50	0.86
T2-2.4-5%		5		3.80	122.57	35.80	1.53
T3-2.4-100%		100		3.56	142.64	36.20	1.78
T4-2.4-800%		800		3.33	147.25	37.30	1.84
Series 2							
T5-1.2-1%	80	1	1.2	3.59	115.87	61.00	0.72
T6-1.2-5%		5		3.47	139.27	66.40	0.87
T7-1.2-100%		100		3.15	154.18	67.50	0.96
T8-1.2-800%		800		3.30	178.40	76.80	1.12
Series 3							
T9-0.60-1%	160	1	0.60	3.89	146.29	120.30	0.46
T10-0.60-5%		5		3.77	149.67	118.90	0.47
T11-0.60-100%		100		3.94	180.19	138.60	0.56
T12-0.60-800%		800		4.31	215.18	153.10	0.67
Series 4							
T13-0.32-1%	300	1	0.32	3.93	216.34	220.70	0.36
T14-0.32-5%		5		4.04	216.63	196.50	0.36
T15-0.32-100%		100		4.10	332.27	246.60	0.55
T16-0.32-800%		800		3.96	314.73	252.90	0.52
Series 5							
T-2.4-0.1%	40	0.1	2.4	3.27	65.92	32.70	0.82
T-2.4-0.5%		0.5		3.80	78.43	37.20	0.98
T-2.4-1%		1		2.05	85.06	28.30	1.06
T-2.4-2.5%		2.5		2.84	92.14	36.70	1.15

Note: Each test is named using the letter T followed by test number, the ratio σ'_y/σ'_o (2.4, 1.2, 0.60, 0.32), and the strain rate $\dot{\epsilon}$ (1, 5, 100 and 800%/h). $\sigma'_y=95.6$ kPa \pm 5.63 SD (yielding stress). $S_u=(\sigma_1-\sigma_3)/2$.

quences of thermal fluctuations (the daily thermal fluctuation was restricted to $\pm 1.5^\circ\text{C}$ in the laboratory—smaller fluctuations are expected inside the cell given the thermal inertia of the device).

However, the more compressible boundary layer against end caps causes higher pore pressure generation at the end caps (where fluid pressure is measured) than at midheight of the specimen during fast undrained loading. The time for internal pore pressure homogenization within the soil mass can be estimated as $t=L^2/c_v$ where L =drainage length; and c_v =coefficient of consolidation. Let us consider a value of $c_v=0.55$ mm²/s for Mexico City soil (Diaz-Rodriguez 2003); then, it would take 42 min for longitudinal drainage ($H=75$ mm), and 10 min for drainage across the radius of the specimen ($d=36$ mm—in the case of effective filter paper on the periphery). For comparison, the time to reach a nominal failure strain of $\sim 4\%$ is 240 min for $\dot{\epsilon}=1\%$ /h, 48 min for $\dot{\epsilon}=5\%$ /h, 2.4 min for $\dot{\epsilon}=100\%$ /h, 18 sec for $\dot{\epsilon}=800\%$ /h. The comparison between these internally and externally imposed time scales renders pore pressures measured at end caps uncertain for the two high-strain-rate series $\dot{\epsilon}=100$ and 800% /h. This analysis explains the higher pore pressures measured in this study during the two high strain-rates undrained loading tests than during low strain-rate tests. It is recognized that the problem is related to end effects by stress and strain nonuniformity combined with system compliance and pore-pressure diffusion as mentioned by Carter (1982). Sheahan et al. (1996) lessened this bias by making measurements at midheight and Blight (1965) by using lubricated ends.

While the specimen failure mode and undrained strength may not be affected by this boundary phenomenon, the inferred effective

stress path computed with the measured pore pressure shifts to the left in the $p'-q$ space. Therefore, higher effective stress strength parameters may be obtained for high strain rates due to experimental bias. Credible effective stress paths for the low strain-rate tests $\dot{\epsilon}=1\%$ /h and 5% /h are similar and show an effective stress friction angle that varies between $\phi=42^\circ$ for the structured specimens ($c'>0$) and $\phi=35^\circ$ for the destructured specimens ($c'=0$).

Fig. 2 includes additional low strain-rate data gathered as part of this study ($\dot{\epsilon}=0.1$ to 2.5% /h, at $\sigma'_y/\sigma'_o=2.2$), and the data reported by Alberro and Santoyo (1973)—Texcoco basin—test conditions: $\dot{\epsilon}=0.045$ to 94% /h, and $\sigma'_y/\sigma'_o=1.8-0.45$. The general trend in the data can be captured using an expression similar to the one used in Zhu and Yin (2000) and shown as dashed lines in Fig. 2

$$\frac{S_u}{\sigma'_o} = 0.2 + 0.1 \left(\frac{\sigma'_y}{\sigma'_o} \right) \log \frac{\dot{\epsilon}}{\left(10^{-5} \frac{\%}{h} \right)}$$

for $\dot{\epsilon} > \dot{\epsilon}_t$ and $\sigma'_y/\sigma'_o = 0.3 - 2.4$ (1)

$$\frac{S_u}{\sigma'_o} = 0.2 \quad \text{assumed for } \dot{\epsilon} < \dot{\epsilon}_t \quad (2)$$

where all trends converge at $S_u/\sigma'_o=0.2$ and $\dot{\epsilon}_t=10^{-5}\%$ /h. The existence of a minimum strength at very small strain rates below a threshold value requires further validation. Published threshold strain rates include: $\dot{\epsilon}_t=5 \times 10^{-2}\%$ /h for plastic Drammen clay

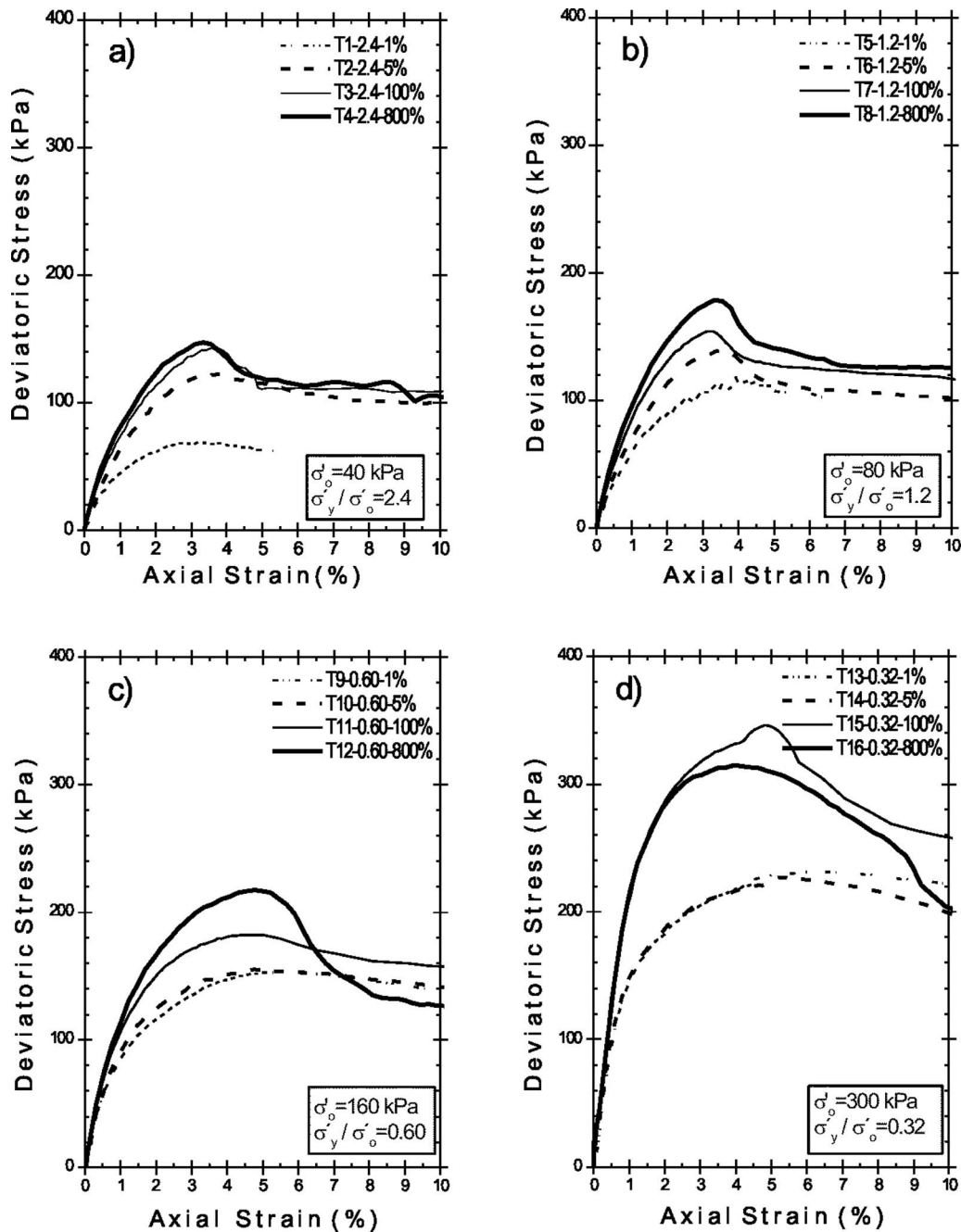


Fig. 1. Stress-strain curves for triaxial compression tests on Mexico City soil

(Berre and Bjerrum 1973), $\dot{\epsilon}_t = 15 \times 10^{-2} \% / \text{h}$ for Haney clay (Vaid and Campanella 1977), $\dot{\epsilon}_t \approx 10^{-3} \% / \text{h}$ for various postglacial clays [Graham et al. (1983)—weak evidence]; $\dot{\epsilon}_t = 10^{-5} \% / \text{h}$ for Mexico City soil (this study).

Conclusions

The exceptional properties of Mexico City soil provide a unique opportunity to test current concepts related to strain-rate effects, with emphasis on the role of the natural soil structure. This study was based on isotropically consolidated, undrained triaxial compression tests, where undisturbed specimens were consolidated to initial effective confinements σ'_0 below and above the yield stress of the soil σ'_y to attain different degrees of destructuration. Con-

solidated specimens were then sheared at constant strain rates $\dot{\epsilon}$. It is concluded that Mexico City soil exhibits significant time-dependent stress-strain effects, with the following characteristics:

- High strain rates result in higher undrained strength S_u/σ'_0 . Furthermore, more structured specimens (high σ'_y/σ'_0) exhibit higher strength S_u/σ'_0 sensitivity to the strain rate $\dot{\epsilon}$. This result resembles observations gathered with remolded-resedimented specimens sheared from NC and OC states. Strength trends for different strain rates tend to converge towards $\dot{\epsilon} < 10^{-5} \% / \text{h}$ at a minimum undrained strength of $S_u/\sigma'_0 \approx 0.2$.
- The axial strain at peak deviatoric stress is independent of the strain rate.
- The tendency to shear strain localization in conventional triaxial compression loading increases with high strain rates and degree of remnant structure.

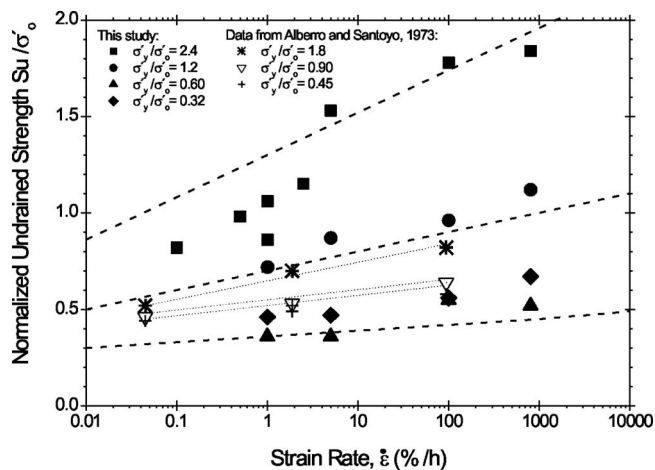


Fig. 2. Relationship of normalized undrained shear strength versus strain rate (log-scale) for triaxial compression tests on Mexico City soil

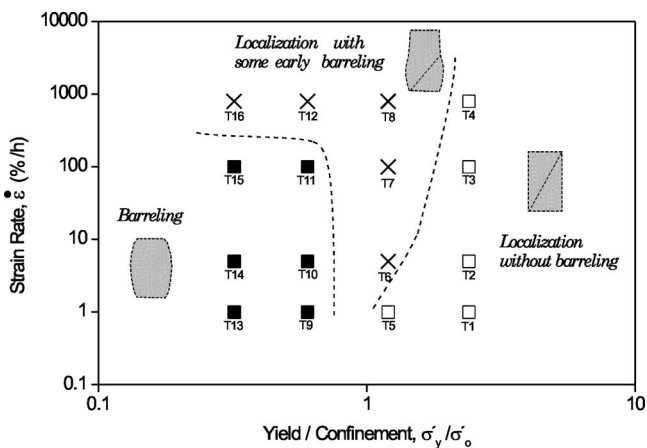


Fig. 3. Mode of failure for triaxial compression tests on Mexico City soil (from visual observations at the time of failure)

- Experimental biases can play a critical role in the study of strain-rate effects. In particular, relative time scales between internal pressure diffusion and externally imposed deformation rates need careful consideration. Local conditions at the specimen-cap interface affect the measurement of longitudinal stiffness, constrain lateral deformation, and cause higher local pore pressure during fast undrained loading; the latter biases the interpretation of effective stress parameters in high strain-rate tests.

Published results suggest greater strain-rate effects in k_o -consolidated specimens (and in extension loading) than in the isotropically consolidated specimens tested in this study. Research in progress extends this study to k_o consolidated specimens using local measurements of deformation and pore pressure.

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