ROLE OF INTERGRANULAR CONTACTS ON MECHANISMS CAUSING LIQUEFACTION & SLOPE FAILURES IN SILTY SANDS

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Non-technical summary
This research seeks to develop a fundamental understanding of the behavior of silty sands under undrained loading conditions during earthquakes. Particular focus is on post-liquefaction shear strength and liquefaction potential from a microscopic mechanistic point of view. The goal is to improve our ability to evaluate liquefaction potential, flow-deformation potential, seismic slope stability of earth structures, dams and embankments built of natural silty sands and develop design strategies to mitigate earthquake damage and minimize losses.

Introduction

This research seeks to develop a fundamental understanding of the behavior of silty sands under undrained loading conditions during earthquakes. Particular focus is on liquefaction potential and post-liquefaction shear strength from a microscopic mechanistic point of view. The goal is to improve our ability to evaluate liquefaction potential, flow-deformation potential, seismic slope stability of earth structures, dams and embankments built of natural silty sands/sandy silts and develop design strategies to mitigate earthquake damage and minimize losses.

In particular the overall ultimate aim of this research is to:

(a) develop an understanding of the physical nature of inter-fine and inter-granular frictional contacts in silty sands/sandy silts at different void ratio, fines content levels, particle size ratio between coarse and fine grain and their effects on liquefaction resistance and post-liquefaction strength,

(b) develop a new unified method to characterize cyclic and post-liq. strength characteristics,

(c) re-evaluate the current methods of assessing liquefaction potential and liquefaction-related damage potential, based on this new understanding, and

(d) develop an improved method for assessment of liquefaction potential and related damage.

This is a continuation of a prior grant (99HQGR0021, 1999-2000) focusing on task (a). The Annual Report (http://erp-web.er.usgs.gov/reports/annsum/vol42/pt/pt_vol42.htm) summarizes the work performed under the previous grant. Specifically the work performed under the earlier grant focused on the following sub tasks.

- Task I: Development and refinement of a physically sound conceptual and theoretical framework to understand the roles of fines in inter-granular frictional contacts at different "density levels" and different fines content levels, on the undrained behavior of silty soils, and
- Task II: Experimental evaluation of the above framework using new and other available undrained monotonic and cyclic data on gap-graded sand-silt mix soil and refinement of the framework.

Prior experimental studies focused on undrained cyclic and monotonic triaxial tests on a gap-graded soil (Ottawa sand – silt mix). The theoretical studies focused on binary mixes of spherical particles of size D and d (size disparity ratio R_d=D/d) aimed at developing an understanding of the relative roles of coarse and fine grains on the response of the binary mix. Through semi-theoretical arguments, a set of contact density indices was developed for characterization of the undrained cyclic and monotonic strength of the binary mix. The results were promising. The results of that work have been published in a number of conferences and journals (Sec.D.3). Although this work was limited to gap-graded soils, the insights derived from this study prompted further research on reassessing the current techniques for liquefaction potential and development of (new and modification of) current ground improvement techniques suitable for silty soils. References to the latter studies are also presented in Sec.D.3.

The currently ongoing continuation work (Jan.2001-Sept.2001) focuses on extending the above theoretical and experimental work from binary mix to multi-size mixes and from gap-graded soils to more complex silty sand/sandy silt formations. A summary of the results from initial theoretical approaches for characterization of such soils and laboratory test data on broadly graded sand silt mixes are presented. For continuity, the results from the previous work and the current work are presented together. The currently ongoing work is identified appropriately.

A. Work Performed

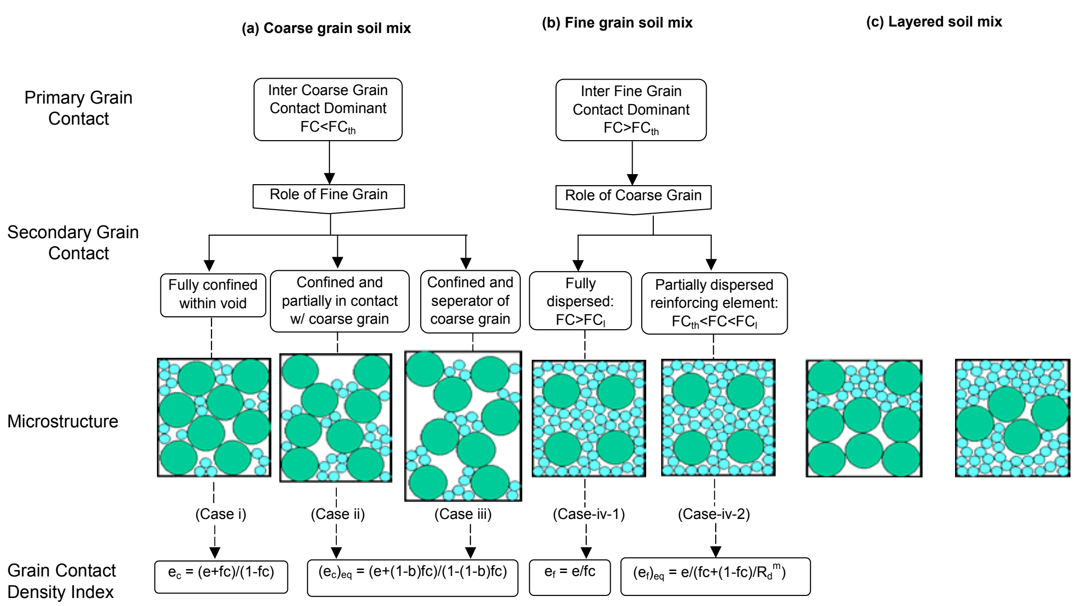
A.1 Development of Framework for Analysis

The hypothesis proposed in the research proposal has been further developed. Based on our prior preliminary research on the nature of soil microstructure, it was *first* realized that silty sand is indeed a soil consisting of "multi-skeleton-structure" with each skeleton having a different compressibility. Its stress-strain behavior is an integrated response of the scale-level dependent response of the different "skeletons" and interactions among them. The traditional approach based on critical state soil mechanics concepts alone using void ratio or state parameter as the primary state variables is insufficient to characterize the measured response. This is so because the relative contributions of the different skeletons differ significantly as the silt content and void ratio of silty sand varies. The mechanisms controlling the stress-strain response are derived from contributions by different skeletons, each offering a different degree of contribution, depending on void ratio and fines content. Furthermore, the size difference between the coarse and fine grain particle also has influence on the degree of contribution. It also depends on the type of fines (plastic or not). A realistic conceptual model should consider appropriate state variables that describe the nature of active grain contacts within each skeleton and the interaction between the skeletons.

A1.1. Approach: A conceptual understanding of the contributions of each grain to the average contact density (per grain) in a silty soil can be progressively developed as follows. First a binary mix containing particles of size D and d was considered and a set of contact density indices were developed with due consideration for geometric compatibility constraints. Then, this work was extended to include particles of three sizes, one for coarse grain (D) and two sizes for fine grains (d_1 and d_2). This process introduces gradation to the fine grains involved in the mix. The results obtained for the binary mix was again extended to include three sizes of particles, two for coarse grains (D_1, D_2) and one for fine grain (d). This was then extended to mix containing multiple sizes of particles (d_1, d_2, d_3,…etc.) and (D_1, D_2, D_3,…etc.). By this process the initial results obtained for a *gap-graded binary mix* was extended to broadly graded soil mixes. The resulting contact density indices are then applicable for a more complex silty sand formation.

A1.2. Work: Initially, as a first-order approximation, a *gap-graded* silty sand was considered and modeled as a composite dual-level skeleton consisting of *single-sized* finer-grain skeleton and a *single-sized* coarse-grain skeleton (Fig.1, Table 1). With due intuition and semi-theoretical consideration for interactions among the coarser grains, the finer grains, and between them, a set of state variables, the intergranular (e_c) and interfine (e_f) was initially introduced as first order indices of active contacts for each skeleton (Fig.2a). Then this was modified, as a second order approximation, to obtain a set of equivalent intergranular [$(e_c)_{eq}= [e+(1-b)fc)]/[1-(1-b)fc]$, $0<b<1$, fc=fractional silt content by weight=FC/100] and interfine [$(e_f)_{eq}=e/[fc+(1-fc)/(R_d)^m]$, where $0<m<1$, and $e_c>e_{max,HC}$] void ratios (Figs.2b-c), introduced as *indices of active grain contact density* for the mix. A threshold fines content [FC_{th}] relationship that prescribes when to use each of the above indices to assess the seismic response of silty soils was developed. The formulation was evaluated using experimental data on a gap-graded Ottawa sand-silt mix (http://erp-web.er.usgs.gov/reports/annsum/vol42/pt/pt_vol42.htm). This was followed by development of phenomenological explanations for the parameters b and m.

Simplified theoretical expressions were derived for b and m, considering disc-like particles or spherical particles. Physical meaning of 'b' and 'm' were developed. This was extended to include three sizes (D, d_1, d_2) of particles and to identify how the contact density is affected by the presence of the third sized particle in the granular mix. This gave way to introduce the influence of gradation on contact density indices. Considering the pore size distributions of this mix for a few packing formations, and space compatibility constraints for the fine grains to occupy the void spaces and contribute to contact-force-chain formation, it was identified that the parameters b and m are affected by R_{d1} (D/d_1) and R_{d2} $(=D/d_2)$. This was further extended to express the results in terms of $D/(d_1+d_2)$ and d_2/d_1. Similar work was carried out to study particles of size D_1, D_2, and d and the results were expressed in terms of $R_{D1}=D_1/d$ and $R_{D2}=D_2/d$, and later in terms of $(D_1+D_2)/d$ and D_2/D_1. In all cases the studies were limited to $R_d>6.5$. When $R_d<6.5$, the physics of interaction among particles in a mix is further constrained by pore throat size limitations and this was excluded in this initial study. Recognizing that d_2/d_1 and D_2/D_1 are related to the gradation of the fine and coarse grain soils, respectively, this was extended to broadly graded soils by making a leap from three sized particle mix to multi-sized particle mix by expressing the above initial results in terms of the coefficients of uniformities (C_u) the of coarse-grained soil ($C_{uc}=D_{60}/D_{10}$) and the fine-grained soil ($C_{uf}=d_{60}/d_{10}$) and R_{d50} $(=D_{50}/d_{50})$ contained in a broadly graded granular mix. This work facilitated extending the prior work that was developed for binary mix to broadly graded silty sand, sandy silty, gravelly sand, sandy gravel, etc. A rigorous treatment of the subject is beyond the scope for presentation here.



b=portion of the fine grains that contribute to the active intergrain contacts; e=global void ratio; FC=fine grains content; FC_{th}=threshhold fine grains content, $FC_{th}<(100e/e_{max,HF})\%$; FC_l=limit fines content, $FC_l>100(1-\pi(1+e)/(6s^3))\%>FC_{th}$; m: reinforcement factor; $R_d=D/d$=particle size disparity ratio; $s=1+a/R_d$, a=10; $e_{max,HF}$: the maximum void ratio of host fine

Fig.1 Intergranular Soil Mix Classification

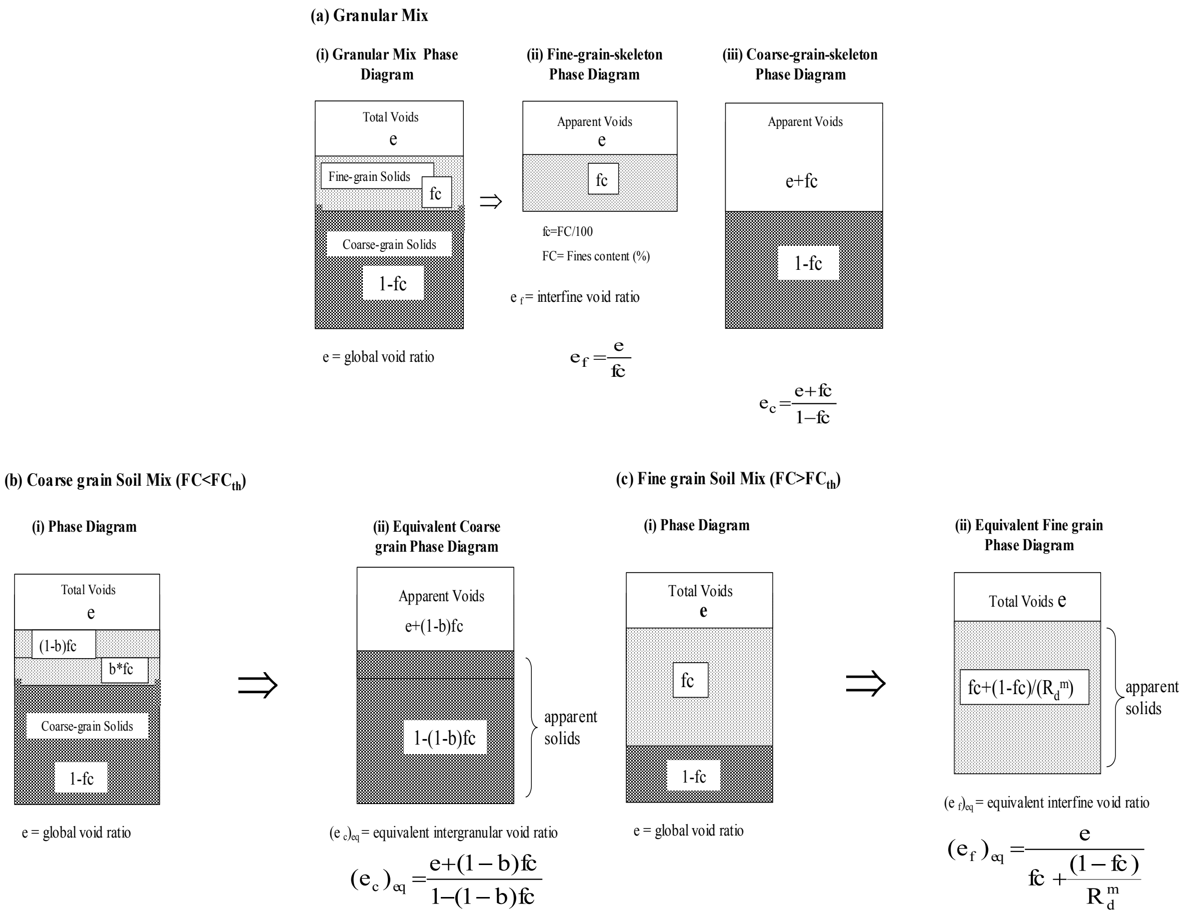


Fig.2 Intergranular Phase Diagram and Contact Index Void Ratios

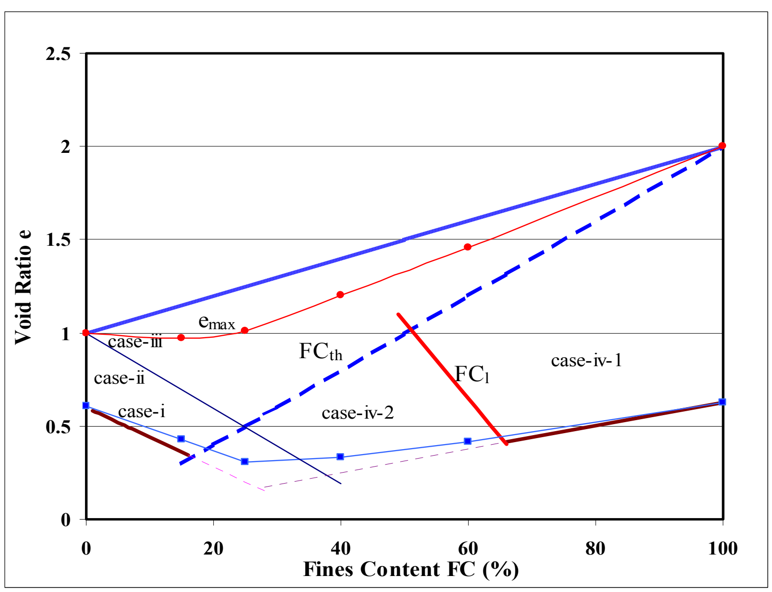


Fig. 3 Granular Mix Classification

Table 1: Granular Mix Classification (Ref. Figs. 1-3)

Case	FC	e_c	e_f	***Roles of coarser-grains and finer-grains***	Contact Index Void Ratio	Fig.
i		$e_c < e_{max,Hc}$	$e_f > e_{max,HF}$	Finer grains are inactive (or secondary) in the transfer of inter particle forces. They may largely play the role of "filler" of intergranular voids. The mechanical behavior is affected primarily by the coarser grain contacts.	$(e_c)_{eq}$	1a
ii	$FC < FC_{th}$	e_c near $e_{max,Hc}$		Finer grains support the coarser-grain skeleton that is otherwise unstable. They act as a load transfer vehicle between "some" of the coarse-grain particles in the soil-matrix while the remainder of the fines play the role of "filler" of voids.	$(e_c)_{eq}$	
iii		$e_c > e_{max,Hc}$		Finer grains play an active role of "separator" between a significant number of coarse-grain contacts and therefore begin to dominate the strength characteristics.	$(e_c)_{eq}$	
iv-2	$FC_{th} < FC < FC_l$		$e_f < e_{max,HF}$	The fines carry the contact and shear forces while the coarser grains may act as reinforcing elements embedded within the finer grain matrix.	$(e_f)_{eq}$	1b
iv-1	$FC_l < FC$	$e_c >> e_{max,Hc}$	$e_f < e_{max,HF}$	The fines carry the contact and shear forces while the coarser grains are fully dispersed.	e_f	

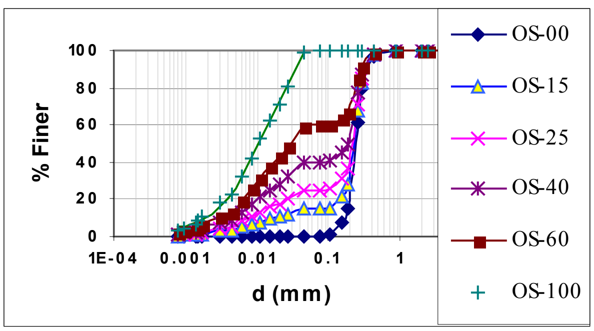
Notes: $e_{max,Hc}$, $e_{max,HF}$ = maximum void ratio of the host sand (coarser grains) and host fines (finer grains) media, respectively. They are the limiting void ratios beyond which each soil (clean coarser grained soil, pure fine grained soil) has no appreciable strength. FC_{th}=Threshold finer grains content, and FC_l = limiting finer grains content. The magnitudes of FC_{th} and FC_l depend on the size disparity ratio (R_d=D/d) of the size of the coarser (D) and finer (d) grains, shape, packing, $e_{max,Hc}$, and $e_{max,HF}$ as shown elsewhere (Thevanayagam 1998-2000). Intergranular void ratio (e_c) =[e+fc]/[1-fc], (fc=FC/100, FC=finer grain content by weight). Interfine void ratio (e_f) =e/fc, s=1+a(d/D)=1+a/R_d, where a=10 (approximately).

$$FC_{th} \leq \frac{100 e_c}{1 + e_c + e_{\max,HF}} \% = \frac{100\, e}{e_{\max,HF}} \% \; ; \qquad FC_l \geq 100\left[1 - \frac{\pi(1+e)}{6 s^3}\right] \% = 100 \left[\frac{\frac{6s^3}{\pi} - 1}{\frac{6 s^3}{\pi} + e_f}\right] \% \geq FC_{th} \, ; \; e_f \leq e_{\max,HF}$$

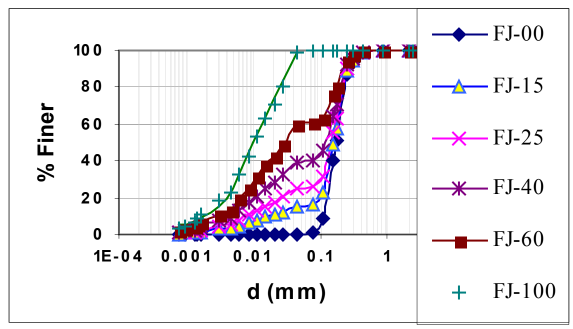
A.2 Experimental Research and Data Base Development

The earlier study focused on gap graded Ottawa sand – silt mix (Fig.4a) at fines contents (non-plastic silt, Sil co sil #40, referred to as GSF#40) from 0 to 100% (denoted os00, os07, os15, os25, os40, os60, os100, os15=15% silt content). This experimental study was extended to include two more sands (a uniform sand FJ#80 mixed with the same silt (GSF#40), Fig.4b; one well-graded sand (WG) made by mixing three kinds of sands (NJ#000, NJ#0, and OS#95 mixed in equal amounts) mixed with the same silt (GSF#40) Fig.4c). This provided soil mixes varying from well graded to poorly graded gradation. More than about 150 undrained monotonic and stress controlled cyclic (at cyclic stress ratio CSR=0.2) tests have been conducted on the above three sand mix specimens, initially isotropically consolidated to an effective stress of 100kPa.

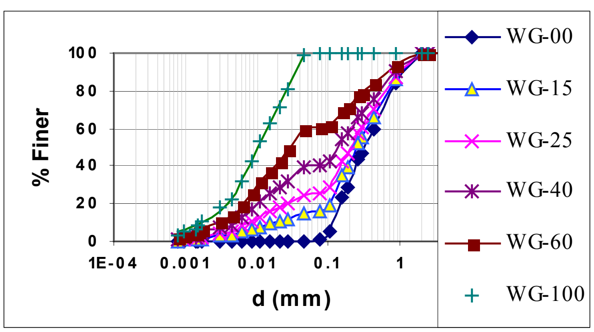
Other available data on monotonic and cyclic behavior of silty sands and gravelly sands from the published literature (e.g. Fig.4d-f) was also collected providing a large database of very broad range of gradation, grain size, shape, angularity, etc. This combined database of new and existing data is continually being updated and analyzed. The analysis of this data is currently underway. Progress made so far is presented next.



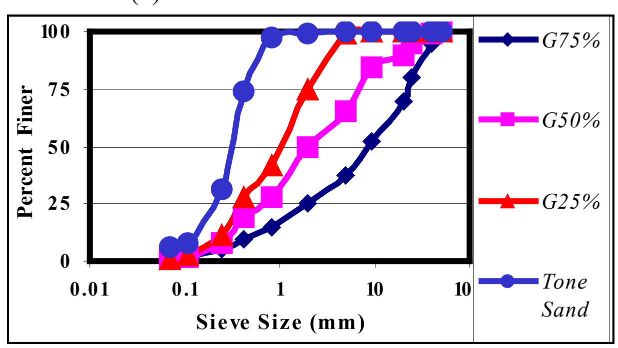
(a) Ottawa sand – silt mix



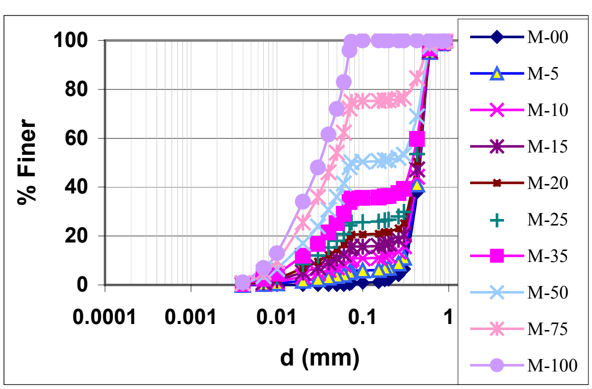
(b) FJ#80 sand-silt mix



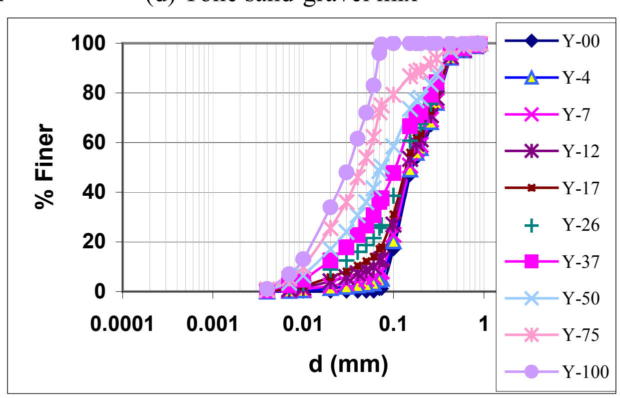
(c) Well-graded (WG) sand – silt mix



(d) Tone sand-gravel mix



(e) Monterey sand-Yatesville silt



(f) Yatesville sand-Yatesville silt

Fig.4 Gradation Data

A.3 Analysis and Results

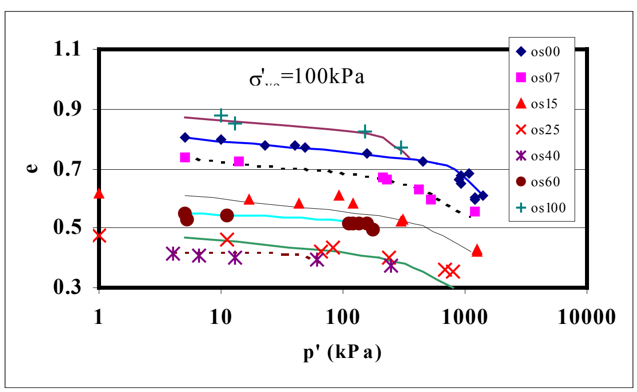
Analyses of the data available in the current database indicate that the newly proposed contact density indices $(e_c)_{eq}$ and $(e_f)_{eq}$ correlate well with (a) cyclic strength, (b) post-liquefaction strength, (c) strain-energy required to trigger liquefaction, (d) post-liquefaction volumetric strain, (e) shear modulus and shear wave velocity, etc. for the soil mixes. The data for each soil is presented next.

A.3.1 OS#55 sand-silt mix series

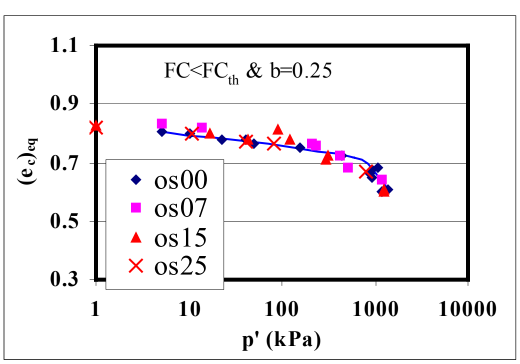
Figs.5a-c and 6a-f show the steady state data and cyclic resistance data, respectively, for the Ottawa sand-silt mix. The N_L in Figs.6a,c, and d refers to number of cycles to cause liquefaction (at a double amplitude strain level of 5% at CSR=0.2). The E_L in Figs.6b, e and f refers to the energy required per unit soil volume to cause liquefaction of the soil.

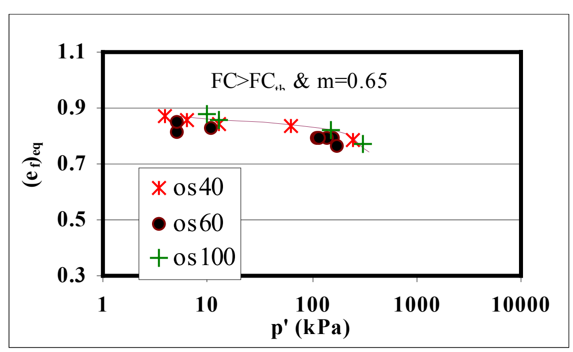
1. Figs.4b, 6c and 6e indicate that the silty sands [at $FC<FC_{th}$] behave similar to the host sand when compared at the same $(e_c)_{eq}$.
2. Sandy silt [at $FC>FC_{th}$] behaves similar to the host silt when compared at the same $(e_f)_{eq}$ (Fig.5c, 6d and 6f).

The corresponding values for b and m are shown in the relevant figures and in Table 2. The behavior of each soil mix is different and no unique correlation is found when compared using global void ratio e (Figs.5a, 6a-b). Further work indicates that these new contact indices also correlated well with shear modulus, shear wave velocity, and stress-strain behavior, and post-liq vol. strain of silty soils and sands alike, in a consistent unified manner (Thevanayagam and Mohan 2000, Thevanayagam 1999, Thevanayagam 2000, Thevanayagam and Martin 2001, Thevanayagam et al. 2001). This illustrates that the equivalent intergrain contact indices $(e_c)_{eq}$ and $(e_f)_{eq}$ are useful parameters to characterize the seismic behavior of gap-graded silty soils.



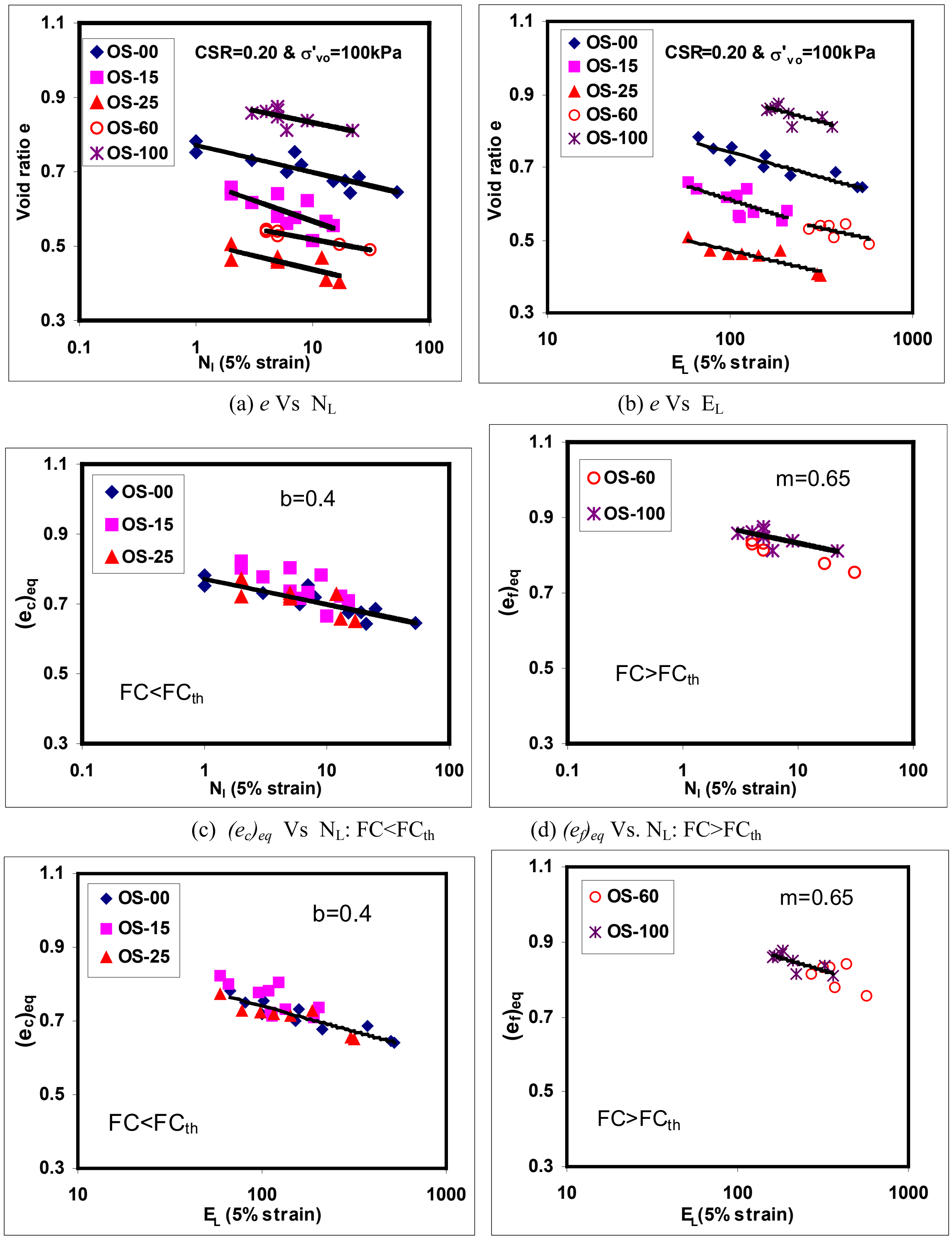
(a) e vs. p





(b) $(e_c)_{eq}$ versus p': $FC<FC_{th}$ (c) *$(e_f)_{eq}$* Vs. p': $FC>FC_{th}$

Fig.5: Steady state data: OS sand-silt mix ($p'=(\sigma'_1+2\sigma'_3)/3$)



(a) *e* Vs N_L (b) *e* Vs E_L

(c) $(e_c)_{eq}$ Vs N_L: FC<FC$_{th}$ (d) $(e_f)_{eq}$ Vs. N_L: FC>FC$_{th}$

(e) $(e_c)_{eq}$ Vs. E_L: FC<FC$_{th}$ (f) $(e_f)_{eq}$ Vs. E_L: FC>FC$_{th}$

Fig.6: Cyclic resistance data: OS sand-silt mix

A.3.2 FJ#80 sand-silt mix series

Tests on FJ#80 sand-silt were carried out to verify the applicability of the contact indices used to study the behavior of OS#55 sand-silt mix to other gap-graded soil mixes. Figs.7a-b show the undrained monotonic steady state data for FJ#80 sand-silt mix, plotted against e and $(e_c)_{eq}$ (for

$FC<FC_{th}$), respectively. Figs.8a-f show the cyclic resistance (N_L and E_L) plotted against e, $(e_c)_{eq}$ (for $FC<FC_{th}$), and $(e_f)_{eq}$ (for $FC>FC_{th}$). The corresponding values for b and m are shown in the relevant figures and in Table 2. The observations are similar to those for the Ottawa sand-silt mix.

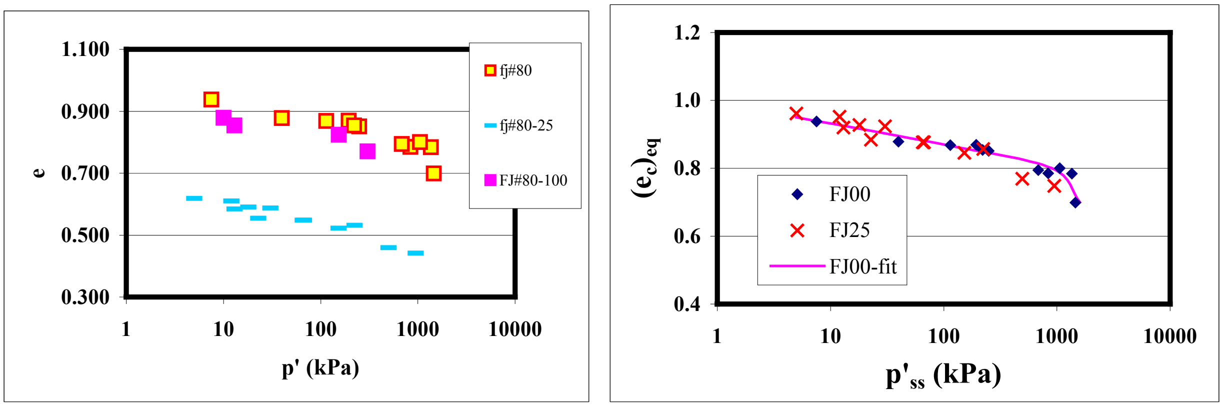
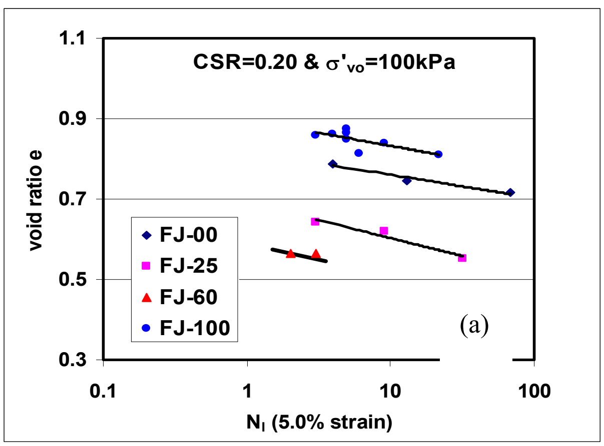
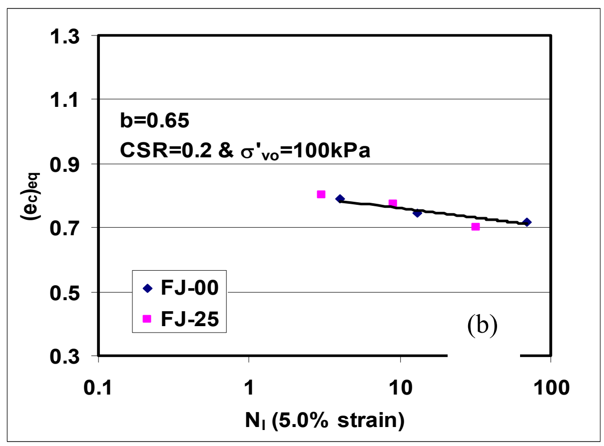


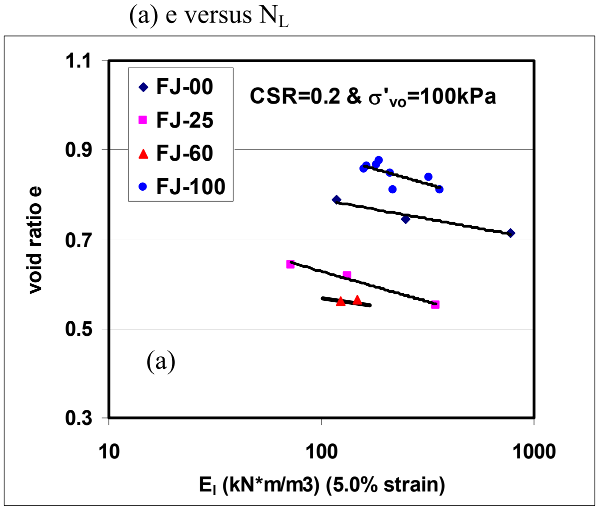
Fig.7 Steady state data: FJ#80 sand-silt mix: (b) e versus p', and (b) $(e_c)_{eq}$ versus p': $FC<FC_{th}$



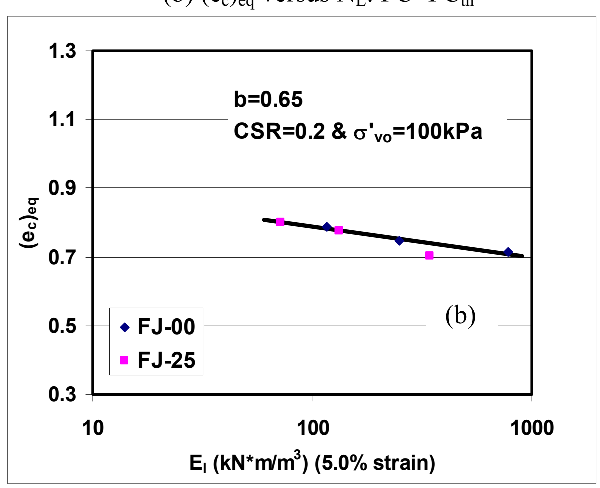
(a) e versus N_L



(b) $(e_c)_{eq}$ versus N_L: $FC<FC_{th}$

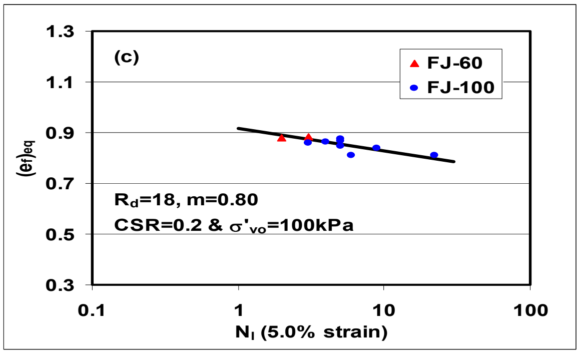


(c) e versus E_L

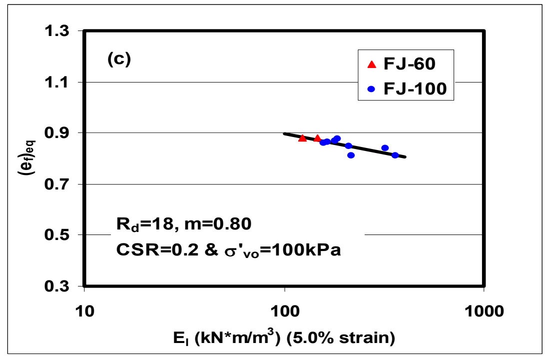


(d) $(e_c)_{eq}$ versus E_L: $FC<FC_{th}$

Fig.8 Cyclic Resistance: FJ#80 sand-silt mix

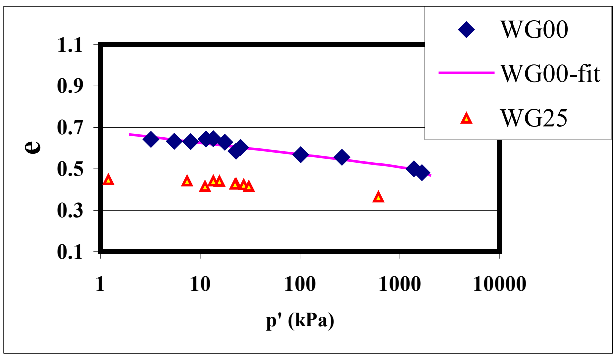


(e) $(e_f)_{eq}$ versus N_L: $FC>FC_{th}$



(f) $(e_f)_{eq}$ versus E_L: $FC>FC_{th}$

Fig.8 Cyclic Resistance: FJ#80 sand-silt mix (cont'd)



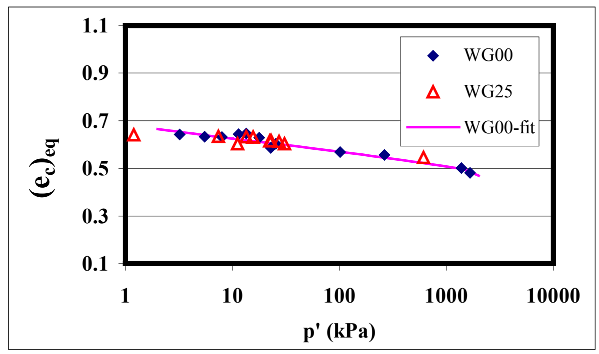
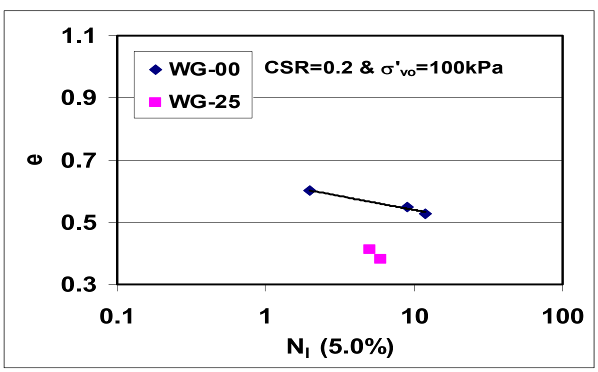
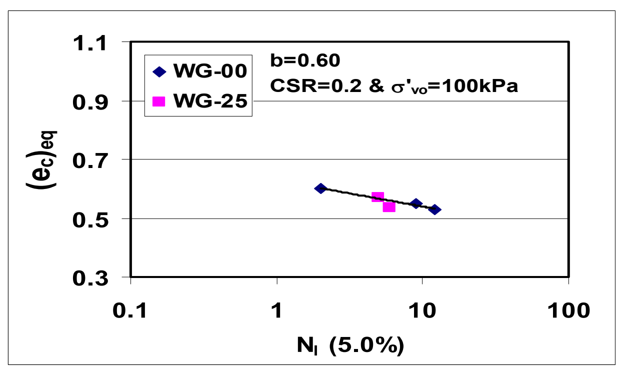


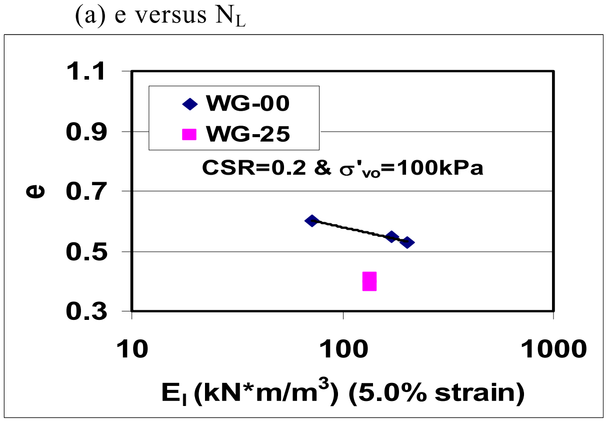
Fig.9 Steady state data: WG sand-silt mix (a) e versus p' and (b) $(e_c)_{eq}$ versus p': $FC<FC_{th}$



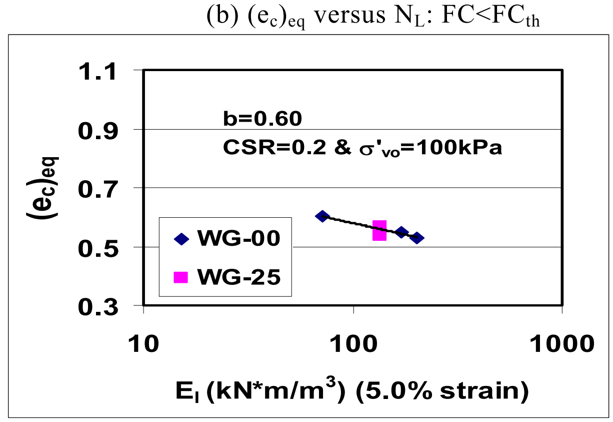
(a) e versus N_L



(b) $(e_c)_{eq}$ versus N_L: $FC<FC_{th}$



(c) e versus E_L



(d) $(e_c)_{eq}$ versus E_L: $FC<FC_{th}$

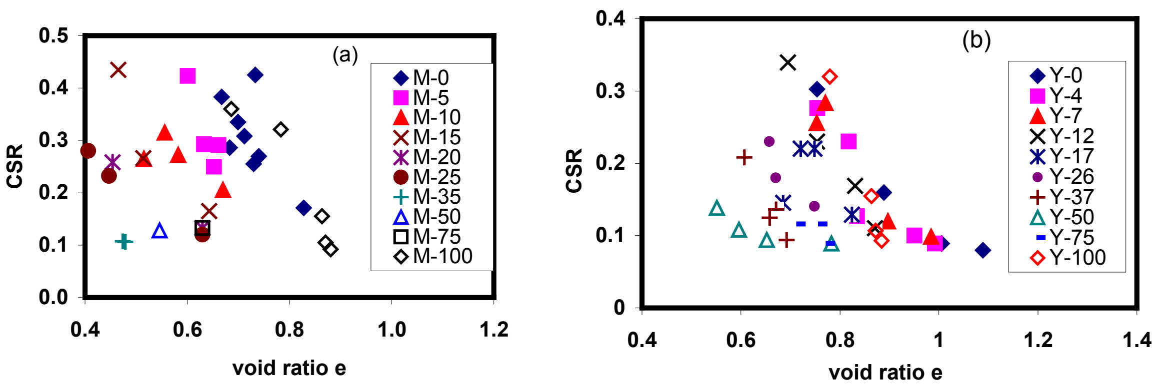
Fig.10 Cyclic Resistance: WG sand-silt mix

A.3.3 Well-graded sand-silt mix series

The tests on WG sand-silt mixes were done to examine the applicability of the contact indices $(e_c)_{eq}$ and $(e_f)_{eq}$ for well-graded sand mixed with silt. Figs.9a-b show the monotonic undrained steady state data. Figs.10a-d show the cyclic resistance data (N_L and E_L). The corresponding values for b and m are shown in these figures and in Table 2. The observations are similar to the previous two soil mixes. The data agree well when compared against $(e_c)_{eq}$ and $(e_f)_{eq}$ at $FC<FC_{th}$ and $FC>FC_{th}$, respectively.

A.3.4 Reanalysis of Data from Literature

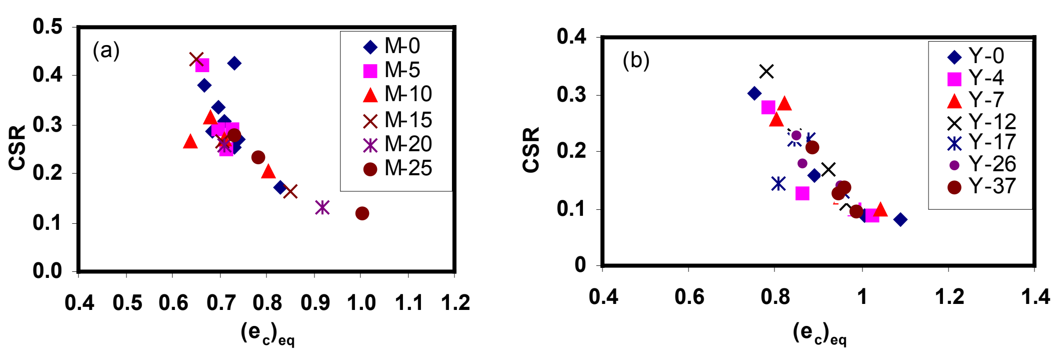
This section presents a summary of results obtained from a reanalysis of other data available in the literature using the framework presented herein (Also see Thevanayagam et al. 2001). As an example, the cyclic resistance data (Fig.11a-b) for two soil mixes (Monterey sand-Yatesville silt mix and Yatesville sand-Yatesville silt mix) reported by Polito and Martin (2001) were reinterpreted using this framework. The applicability of the framework for these soils is very clear. Figs.12-13 show the cyclic resistance data (CSR) required to cause liquefaction in 10 cycles plotted against equivalent void ratios $(e_c)_{eq}$ and $(e_f)_{eq}$, respectively. The data agree well with equivalent index void ratios. The corresponding values for b and m are also shown in these figures and in Table 2. Such an analysis has been carried out for other soils as well. Again the data agree well with contact indices when reinterpreted using the framework presented herein.



(a) Monterey sand-silt mix (b) Yatesville sand-silt mix

(M-20=Monterey sand with 20% silt)

Fig.11 Cyclic resistance CSR versus e (after Polito and Martin 2001)



(a) Monterey sand-silt mix (b) Yatesville sand-silt mix

Fig.12 CSR versus $(e_c)_{eq}$: $FC<FC_{th}$ (after Thevanayagam et al. 2001)

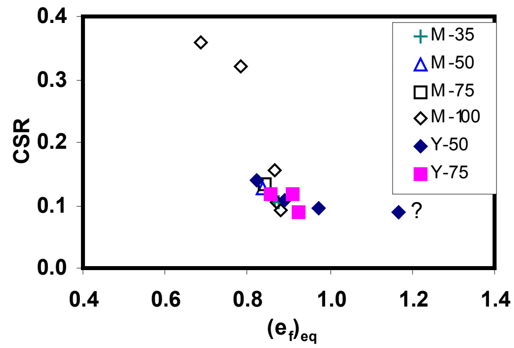


Fig.13 CSR versus $(e_f)_{eq}$ - Monterey sandy silt and Yatesville sandy silt: FC>F_{Cth}
(after Thevanayagam et al. 2001)

B. Research Highlights – Breakthrough

Significant new understanding of the behavior of silty soils was developed during this research period. A few highlights of the results to date are summarized in some detail in the following.

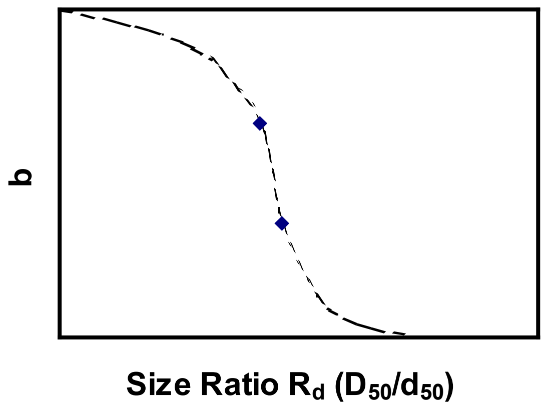
B.1 Granular Mix at FC<FC_{th}

B1.1 Applicability of $(e_c)_{eq}$

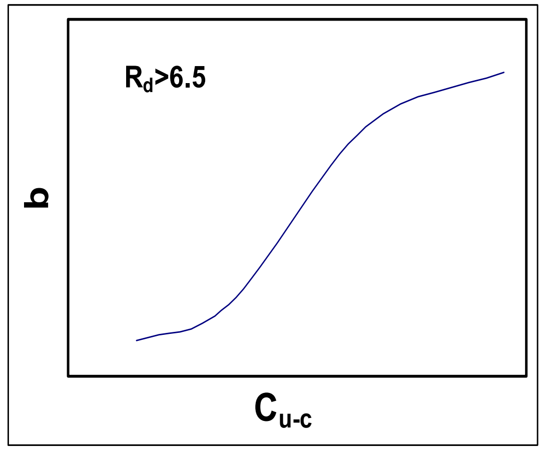
The above experimental data indicate that, for silty soils at FC<FC_{th}, its mechanical behavior, including steady-state strength, cyclic strength, and required energy to cause liquefaction can be well-related to equivalent intergranular void ratio $(e_c)_{eq}$. In each case the behavior of the mix is similar to the host sand when compared at the same contact density index. This conclusion is clearly supported by Figs. 5b, 6c, 6e, 7b, 8b, 8d, 9b, 10b, 10d, and 12a-b for a variety of soil of very broad range of gradation, particle size, shape, angularity, etc. The meaning of b needs further evaluation, as shown next, before this framework can be applied to broad classes of soils.

B.1.2 Secondary Contact Density Parameter b

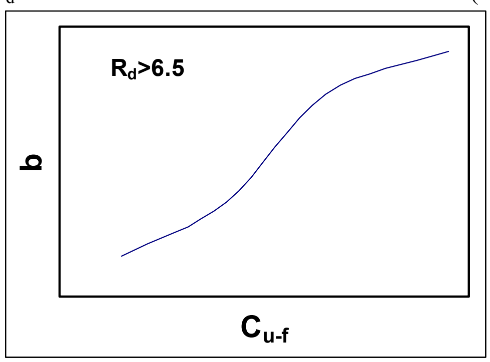
For silty soil with fines content FC<FC_{th} (threshold fines content), the mechanical behavior of the silty soil is governed by coarse grain matrix. The fine grain matrix has a secondary contribution. For a binary mix, theoretical considerations (see A1.2) indicate that the degree of contribution by the finer grains, which is reflected on the parameter b, depends on R_d. For broadly graded soil mixes, the initial theoretical consideration indicate that b depends on the size disparities R_{d1}, R_{d2}, etc. and R_{D1}, R_{D2}, etc. The results from this initial theoretical work for a few cases of packing of discs or spheres can be collectively reflected by C_{uc} and C_{uf} and R_d= D_{50}/d_{50}. The results are schematically shown in Figs.14a-c. The effect of each of these three variables, while the remaining two remain the same is as follows. When R_d decreases, pore throat/d_{50} ratio decreases allowing participation by more number of fine grains in the contact force chain. Hence, b increases. When C_{uc} increases, pore throat/d_{50} ratio decreases, and hence b increases. When C_{uf} increases, for the same d_{50}, the fine-grained soil contains a greater number of large particles than a case where C_{uf} is small, and hence, the contribution of the finer grains to the contact force chain increases. *A similar set of relationships like those shown for b is expected for m (for FC>FC_{th})*. A complete theoretical treatment of this is beyond the scope of this work.



(a) b versus R_d



(b) b versus C_{uc}



(c) b versus C_{uf}

Fig.14 Schematic relationship: Effect of R_d, C_{uc} and C_{uf} on b and m

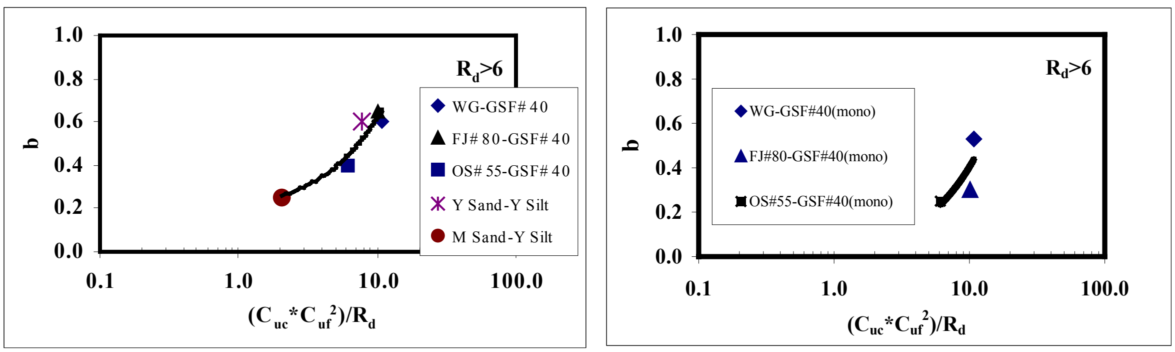
The above conceptual understanding can be tested further and the physical meaning of b can be discerned if all the b values for the various soils are combined and analyzed together. Table 2 summarizes the relevant gradation data for each soil mix and the corresponding b and m values. The minimum value of R_d was 6.

Figs.15a-b shows the relationships between b and (C_{uc}, C_{uf} and R_d) for test data obtained from cyclic triaxial and monotonic triaxial tests, respectively. The soil mixes are identified in these figures. Judicious caution is called for in extrapolating this relationship beyond a reasonable limit of R_d of about 6.5. For soils with R_d's below 6.5 the physics of particle interaction is further constrained by further compatibility restrictions between pore throat size and fine grain size and therefore R_d further affects the contact-force-chains (see Sec.A1.2) beyond the cases studied herein. Nevertheless, the existence of a unifying relationship for b in Fig.15a-b for many seemingly unrelated soils of very different gradations (and shapes, angularity, etc.), including those soils tested by others, is a positive step forward. It indicates the general applicability of the framework presented herein. Furthermore, the relationship shown in Fig.15a-b agrees with the trend (Fig.14) deduced from the initial theoretical considerations.

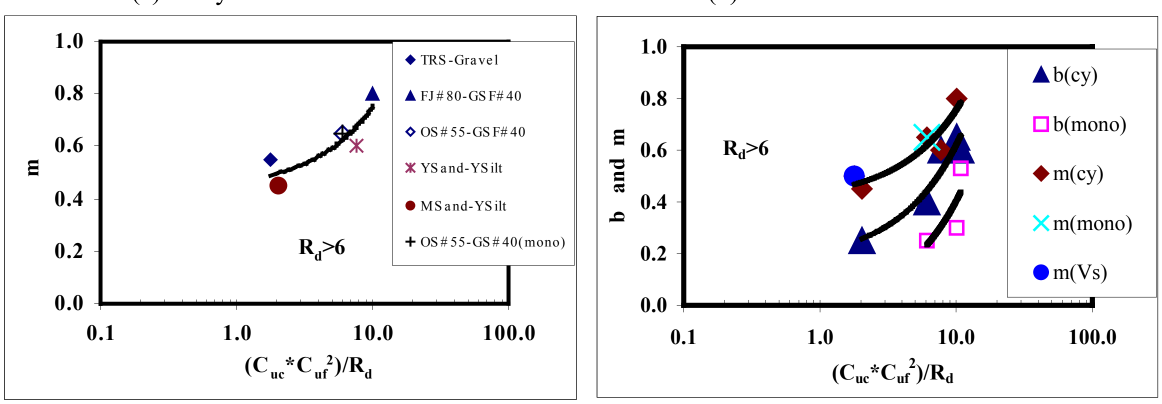
Another notable observation in Figs.15a-b is that the relationship for b with C_{uc}, C_{uf} and R_d relevant for monotonic steady state is not the same as the relationship for cyclic resistance. Although this aspect has not been studied with due theoretical considerations, the reason for this difference may stem from the slight difference between the physics of steady state behavior and physics of liquefaction. The latter involves a complete collapse of the soil structure, and therefore, even the fines that do not necessarily participate in the active contact-force-chains do contribute to the resistance to collapse of the coarse grain skeleton. The inactive fine grains within the intercoarse grain voids hinder the tendency of the coarse grains falling into those voids and hence resist the collapse of the coarse grain skeleton.

Table 2: Soil parameters

Soil Mix	Coarse Grain	Fine Grain	C_{uc}	C_{uf}	R_d	b	m
OS sand-silt	OS#55 Sand	GSF#40	1.7	10	25	0.4	0.65
FJ#80 sand-silt	FJ#80 Sand	GSF#40	1.8	10	18	0.65	0.80
WG sand-silt	WG Sand	GSF#40	3.6	10	33	0.60	N/A
M-Y	Monterey Sand	Yatesville silt	1.5	4.4	14.3	0.25	0.45
Y-Y	Yatesville	Yatesville silt	2.4	4.4	6	0.60	0.60
Grevelly sand	Gravel	TRS sand	5.7	2.8	25	N/A	0.55



(a) b - cyclic triaxial tests (b) b - monotonic triaxial tests



(c) m -cyclic triaxial, monotoni triaxial and shear wave velocity tests (d) b and m – All tests

Fig.15 b and m versus $C_{uc}C_{uf}^2/R_d$ (test type and soil mix type are shown in each figure)

B.2 Granular Mix at FC>FC$_{th}$

B2.1 Applicability of $(e_f)_{eq}$

For silty soil with fines content $FC>FC_{th}$, its mechanical behavior including steady-state strength, cyclic resistance, and energy to cause liquefaction is governed by the fine grain matrix with secondary reinforcement effect by the dispersed coarse grains. The mechanical response correlates well with $(e_f)_{eq}$. This conclusion is clearly supported by Figs. 5c, 6d, 6f, 8e, 8f, 13 and

16 for a variety of soil of very different gradations, particle size, shape, etc. This is particularly highlighted in Fig.16 in which three different soil mixes each prepared by mixing GSF#40 with a different sand agree well with $(e_f)_{eq}$. The meaning of m needs further evaluation, as shown next, before this framework can be applied to a broad class of soils.

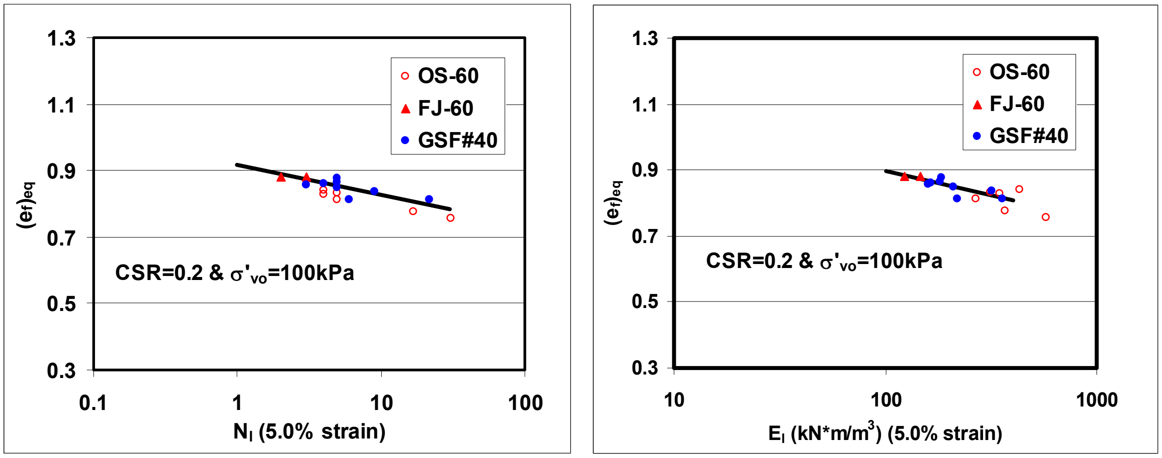


Fig.16 Cyclic resistance: $FC>FC_{th}$

B2.2 Secondary Reinforcement Parameter m

Based on semi-theoretical considerations, Figs.14a-d show the relationship trend for m with C_{uc}, C_{uf} and R_d. Fig.15c shows the actual values for m for five different soils involving different tests (OS-GSF#40, FJ#80-GSF#40, M-Y, Y-Y, and a gravel-sand mix). The m values for OS-GSF#40 mix pertain to cyclic resistance data and undrained steady state strength data, for M-Y and Y-Y mixes pertain to cyclic resistance, and for the gravel-sand mix pertain to shear wave velocity tests. Despite the differences in soil types and tests involved with the soils, a well-behaved trend is observed for the m.

B.3 Significance

The above findings are significant breakthroughs. It indicates the existence of a contact index, simple enough, to characterize the behavior of silty soils in a unified manner. The new index consistently correlates well with the various strength characteristics (steady state, collapse potential, cyclic strength, strain energy, shear wave velocity, post-liq vol. strain, etc.). This is an indication that it is possible to explain the behavior of silty soils in a consistent and fundamental way and develop rational methods for liquefaction potential assessment and related damage potential.

C. Outlook

Based on the results so far, it is expected that this research will produce new understanding of the behavior of silty soils during earthquakes and lead to development of rational methods for mitigation design. While the above findings are promising, at the present time, the main limitation is due to the lack of a complete theoretical underpinning, beyond initial semi-theoretical work used to derive the relationships presented herein, as well as lack of sufficient data involving natural silty soils. Further research is needed to go beyond these limitations and develop a general understanding of the behavior that pertains to all silty soils, and treat all non-plastic silty soils and sands alike under a single formulation. Further research addressing the above issues is ongoing.

D. Dissemination: Reports and Papers

D.1 Development of Framework for Analysis

A report entitled "*Relative roles of coarser and finer grains on undrained behavior of granular mixes*" that summarizes this has been prepared. A technical paper on the same title has been submitted for publication, ASCE J. Geotech. Eng. The abstract of this is presented below.

- *ABSTRACT:* The stress-strain behavior of granular mixes containing coarser and finer grains is derived from a combination of inter-coarser grain and interfiner grain contacts and interactions thereof. Simple analysis of a two-sized particle system with large size disparity is presented to highlight when coarser or finer grain contacts become dominant. The intergranular (e_c), interfine (e_f), and a set of newly introduced equivalent intergranular [$(e_c)_{eq}$], interfine $(e_f)_{eq}$ contact index void ratios are identified as primary indices of intergrain contact density (per grain). Global void ratio is identified as the secondary index. Depending on e_c, e_f, and $(e_f)_{eq}$, the mechanical behavior of a granular mix can be categorized into five subgroups. Each index is dominant for a certain group. The threshold finer grain contents and threshold intergranular void ratios delineating the transition boundaries between these subgroups are presented. Using these indices, the behavior of the mix in each group is qualitatively further characterized in terms of the behavior of either the host coarser grain or the finer grain medium. Exceptions are also identified. Trends in undrained monotonic and cyclic stress-strain and strength behavior of the mix relative to the host coarser or finer grain medium are presented for each group. This is experimentally evaluated for gap-graded silty soils. Detailed evaluation is presented elsewhere. The results provide a mechanistic understanding of possible microscopic mechanisms that affect the liquefaction and post-liquefaction response of man made and natural deposits of silty and gravely sands. It can also be used to develop guidelines for liquefaction mitigation design. *Judicious caution is called for when this is extrapolated to well graded or layered soils.*

D.2 Experimentation and Analysis

A database of existing data on monotonic and cyclic behavior of silty sands has been developed. It is continually being updated and analyzed. In addition, an experimental program was also developed and monotonic and cyclic triaxial tests were conducted on host sand mixed with *non-plastic* silt in different proportions. This data and other available data were analyzed in light of the hypothesis presented in Fig.1 and Table 1. The findings are presented in a series of papers. A few abstracts as follows.

- "*Liquefaction potential and undrained fragility of silty sands*", 12th *World Conf. on Earthq. Eng., New Zealand, 2000*: *ABSTRACT* - Observations from recent earthquake case histories indicate that natural and man made fills containing a mix sands, silt, and/or gravel do liquefy and cause lateral spreads, defying conventional wisdom. The knowledge gained from past three decades of research on clean sands does not directly translate to such soils. Whether the presence of silt adversely or beneficially affects liquefaction and the collapse potential of silty soils is a contentious issue. The mechanisms leading to liquefaction and large deformation in such soils are more complex. This requires a greater understanding of the soil microstructure and the contributions of soil particles of different sizes to its mechanical response. A framework for analysis of the undrained stress-strain behavior, shear strength and collapse potential of granular mixes ranging from clean sands to pure silts (or gravel) in terms of intergranular and interfine friction is presented. The primary mechanisms affecting the mechanical response of silty (or gravely) soils are identified. New intergrain contact indices are presented to evaluate the liquefaction potential and large undrained deformation characteristics at various silt/gravel contents. This is followed by experimental evaluation of the framework. *The behavior of such granular mixes deserves a greater further detailed study before they can be reliably applied to natural soils.*

- *"Contact Index and Liquefaction Potential of Silty and Gravely Soils": 14th ASCE Engineering Mechanics Conference, Austin, Texas, May 2000:* Abstract -- A framework for analysis of liquefaction potential of granular mixes ranging from clean sands to pure silts (or gravel) with due consideration for intergranular and interfine friction within a granular mix is presented. New intergrain contact density indices $(e_c)_{eq}$ and $(e_f)_{eq}$ are presented to evaluate their liquefaction potential. The usefulness of these indices is evaluated using stress controlled undrained cyclic triaxial tests conducted on specimens prepared by mixing a silt and clean sand in different proportions. The new indices correlate well with cyclic strength and strain-energy required to trigger liquefaction.

- *"Effect of Non-Plastic Fines on Undrained Cyclic Strength of Silty Sands": ASCE Conf. GeoDenver 2000. Abstract* - Whether the presence of silt adversely or beneficially affects liquefaction and the collapse potential of silty soils and how to evaluate cyclic strength behavior of sand containing different silt contents are contentious issues. The purpose of this work is to investigate this question. Stress controlled undrained cyclic triaxial tests were conducted on specimen prepared by mixing a sand with silt in different proportions. The cyclic stress ratio (CSR=0.2) and confining pressure (100 kPa) were maintained constant. Relationship between no. of cycles required to cause liquefaction (at 5% axial strain) versus void ratio, and newly introduced equivalent void ratio indices based on intergrain contact density considerations are presented. Cyclic strength correlates well with the latter indices.

- *"Liquefaction in Silty Soils – Considerations for Screening and Retrofit Strategies", 2nd International Workshop on Mitigation of Seismic Effects on Transportation Structures Sept.13-15, 2000, Taipei, Taiwan: Abstract* - Current techniques for liquefaction screening, ground modification for liquefaction mitigation, and post-improvement verification rely on knowledge gained from extensive research on *clean sands*, field observations of liquefied ground, and judicial correlation of normalized penetration resistance $[(N_1)_{60}, q_{c1N}]$ or shear wave velocity (v_{s1}) data with field liquefaction observations. Uncertainties prevail on the direct extrapolation of such techniques for silty soil sites. Many silty soil sites in Kobe, Turkey, and Taiwan did liquefy. They offer a test bed opportunity to study these questions. This paper examines laboratory data on liquefaction resistance, strength, and v_{s1} of sands and silty soils using grain contact density as the basis. Effect of silt content on cyclic resistance, strength, $(N_1)_{60}$, q_{c1N}, v_{s1}, m_v, and c_v is examined in this light. Rational insights for extrapolation of the current screening techniques to silty soils are offered. Thoughts on modifications necessary to the traditional densification, drainage, and permeation grouting techniques to make them viable for silty soils are offered.

- *"Cyclic resistance of sands, silty sands, and sandy silt", Technical paper,* ASCE J. Geotech and Geoenv. Eng., submitted for review. *Abstract* – Whether the presence of non plastic silt in a granular mix soil adversely or beneficially affects its liquefaction potential and how to evaluate cyclic strength behavior of a sand containing different silt contents are contentious issues. This paper presents an experimental evaluation of these questions. Two parameters, namely, equivalent intergranular void ratio $(e_c)_{eq}$ and equivalent interfine void ratio $(e_f)_{eq}$, are proposed as indices of active grain contacts in a granular mix. The theoretical basis for these indices are presented elsewhere (Thevanayagam 1998b). These parameters are used to address the above issues. Results indicate that, at the same global void ratio (e), the liquefaction potential of silty sand increases with an increase in fines content (FC) up to a threshold value (FC_{th}) due to reduction in intergranular contact between the coarse grains. At $FC<FC_{th}$, intergranular contact friction plays the primary role. Fines are either confined within the intergranular voids or partially contribute to active contact. Beyond FC_{th}, with further addition of fines, the interfine contact friction becomes significant while the inter-coarse grain contacts diminish and become dispersed. The dispersed coarse grains provide a beneficial secondary reinforcement effect. At the same e, the liquefaction potential decreases and the soil becomes stronger with further increase in silt content. Beyond a certain limiting fines content (FC_L) the above reinforcement effect diminishes and the soil behavior is controlled by interfine contacts only. The FC_{th} and FC_L depend on the void ratio and the characteristics of fines and coarse grains. A meaningful comparison can be made if a granular mix is subdivided into groups depending on $FC<FC_{th}$, $FC_{th}<FC<FC_L$, and $FC>FC_L$, with relevant contact indices $(e_c)_{eq}$, $(e_f)_{eq}$, and interfine void ratio ef, respectively. When $FC<FC_{th}$, at the same $(e_c)_{eq}$, the cyclic strength of silty sand is comparable to that of the host clean sand. When $FC>FC_{th}$, at the same $(e_f)_{eq}$, the cyclic strength of a sandy silt is comparable to that of the host silt. Similar observation holds for $FC>FC_L$. Analyses on effect of non plastic silt content on cyclic strength should be made based on grain contact density.

- *"Strain-energy to cause liquefaction in silty soils" Technical paper, in preparation,* ASCE J. Geotech and Geoenv. Eng., under review. *Abstract* – A framework for analysis of liquefaction potential of granular mixes ranging from clean sands to pure silts (or gravel) with due consideration for intergranular and interfine friction within a granular mix is presented. New intergrain contact density indices $(e_c)_{eq}$ and $(e_f)_{eq}$ are presented to evaluate their liquefaction potential. An experimental program including both monotonic and cyclic triaxial tests conducted on specimens prepared by mixing a silt and clean sand in different proportions is developed to investigate the usefulness of these indices. Energy approach (E_L, the energy required to reach the initial liquefaction of soil), as well as the traditional cyclic strength method (N_L, the number of cycles to reach the initial liquefaction of soil), is applied to measure the liquefaction resistance of soil. $(e_c)_{eq}$ and $(e_f)_{eq}$ are found to correlate better with both N_L and E_L than traditional global void ratio e.

- *"Liquefaction in Silty Soils – Screening and Remediation Issues"*, presented at the 12th Conf. Soil dynamics & earthquake Eng., Philadelphia, Sept.9, 2001; Also to be published in J. Earthquake Engineering and Soil Dynamics. Abstract - Current techniques for liquefaction screening, ground modification for liquefaction mitigation, and post-improvement verification rely on knowledge gained from extensive research on *clean sands*, field observations of liquefied ground, and judicial correlation of normalized penetration resistance $[(N_1)_{60}, q_{c1N}]$ or shear wave velocity (v_{s1}) data with field liquefaction observations. Uncertainties prevail on the direct extrapolation of such techniques for silty soil sites. This paper examines laboratory data on liquefaction resistance, strength, and v_{s1} of sands and silty soils using grain contact density as the basis. Effect of silt content on cyclic resistance, strength, m_v, and c_v is examined in this light. Rational insights on effects of silt content on the current screening techniques based on $(N_1)_{60}$, q_{c1N}, and v_{s1} to silty soils are offered. Recent advances and modifications to the traditional densification, drainage, and permeation grouting techniques to make them viable for silty soils are discussed.
- *"Contact Density – Confining Stress – Energy to Liquefaction Relations"*, Submitted to 15th ASCE Engineering Mechanics Conference, New York City, New York, June 2002. *Abstract* - Liquefaction phenomenon involves loss of contacts among particles. Liquefaction potential of a soil is dependent on the nature and density of active intergrain contacts. Higher the density of active contacts more resistant is the soil to liquefaction. This paper examines this idea analytically and experimentally. A theoretical framework for estimation of active contact density index of soils ranging from clean sand to silt is developed. Undrained cyclic resistance data in terms of energy required to cause liquefaction in three different sands, each mixed with a non-plastic silt, is analyzed to assess the influence of contact density on liquefaction resistance. The energy required to cause liquefaction is found to be dependent on effective confining stress and contact density, regardless of silt content of the soil. Implication of this on liquefaction potential evaluation of soils is addressed.

- "*Shear wave velocity relations for silty and gravely soils*", Technical paper, 4th International Conf. Recent Adv. On Geotech. Earthq. Eng. And Soils Dynamics. 2001. *Abstract* - Shear wave velocity v_s, dynamic shear modulus G_{max}, and damping characteristics are important parameters required for both static and dynamic response analyses of earth structures. Traditional indirect methods for estimation of these parameters based on void ratio, relative density, and mean effective stress have been successful for rather narrowly graded soils, but not for the most commonly found silty and gravelly soils. Their direct application to determine the above characteristics for silty and gravely soils are not satisfactory. A primary reason for this is that global void ratio is not a good measure of intergrain contact density for granular mixes. A simple array of two-sized particle system with large size disparity is presented to highlight the relative roles of intercoarse and interfine grain contacts on mechanical response parameters of such granular mixes. New parameters, namely equivalent intergranular void ratio $(e_c)_{eq}$, and equivalent interfine void ratio $(e_f)_{eq}$ are introduced as indices of active intergrain contacts. They are related to shear modulus and vs of silty and gravely soils.

D.3 Related References and Reports

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