LIQUEFACTION POTENTIAL AND UNDRAINED FRAGILITY OF SILTY SOILS

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SUMMARY

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 detailed study.

INTRODUCTION

Recent earthquake case histories indicate that natural soils and man-made sandy deposits that contain a significant amount of finer-grains (silty sands, clayey sands) and/or gravel do liquefy and cause lateral spreads (Seed et al. 1983, Seed and Harder 1990, JGS 1996). Experience gained from past studies on clean sands does not always directly translate to such broadly graded soils. Recognition of this has lead to several laboratory and field studies to evaluate the effects of increasing silt or gravel content on: (a) cyclic strength, (b) collapse potential, (c) steady state strength, (d) shear wave velocity, etc. Results from laboratory studies on clean sands mixed with non-plastic silts or plastic fines show that, at the same (global) void ratio, the steady state strength and cyclic strength of silty sand decreases with an increase in fines content (Chang 1990, Chameau and Sutterer 1994, Georgiannou et al. 1990,91a-b, Vaid 1994, Koester 1994, Finn et al. 1994, Pitman et al. 1994, Singh 1994, Zlatovic and Ishihara 1995, 1997, Thevanayagam et al. 1996). An example is shown in Fig.1a for a soil prepared by mixing a sand with a silt (PI=4) at nearly constant global void ratio (e=0.558) and confining stress (104 kPa) but at different fines content (0 to 60% by weight). Fig.1b shows the number of cycles to reach initial liquefaction versus fines content for the same sand-silt mix, along with the data for two other sands mixed with the same silt. [Fig.1c which is the same as Fig.1b will be discussed later]. As observed in these figures, beyond a certain transition range the trend in decrease of strength reverses and the strength increases with further increase in fines content. The transition fines content range is about 20 to 30% for non-plastic fines (Vaid 1994, Kuerbis et al. 1988, Singh 1994, Koester 1994). It is less than 20% for clayey fines (Georgiannou et al. 1991a-b). The physical meaning of the transition fines content is not clear. The conclusions in the literature on whether the presence of fines is beneficial or not is contentious. Similar concerns prevail regarding gravely soils (Evans and Zhou 1995).

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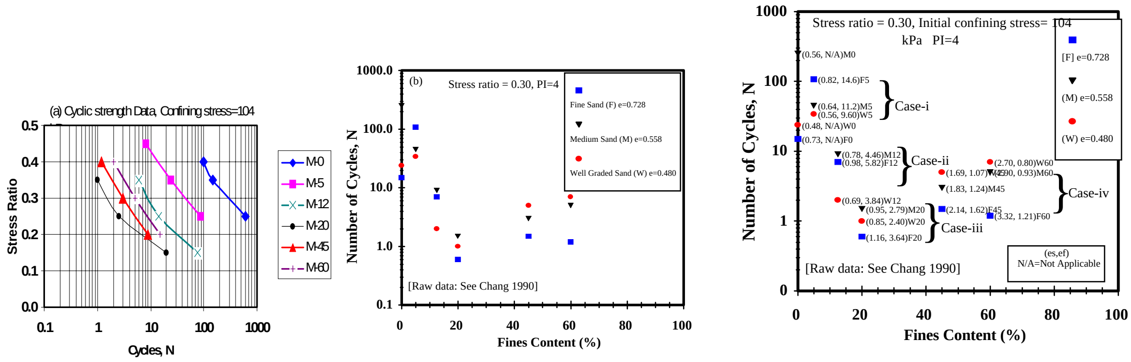

Fig.1. Influence of finer grain content on cyclic strength – (a) Medium Sand, (b,c) Three Sands

Taking a different approach, field performance studies have sought to solve this problem by correlating SPT blow counts, CPT data, and shear wave velocity measurements with liquefaction potential in a binary fashion based on observations of liquefied sites. Such correlations have also been developed for post-liquefaction strength based on back-analysis of failed embankments. Various corrective procedures have been incorporated to account for the influence of fines (Seed et al. 1983, Seed 1987, Seed and Harder 1990, Robertson et al. 1997, Andrews and Stokoe 1997). Their use in practice relies on such intuitive reasoning as the impeding drainage effect of fines on such field measurements and/or their relation with relative density. There are variations as well (Stark and Mesri 1992, Ishihara 1993, Baziar and Dobry 1995) on the nature of such relationships. Questions also prevail among practicing engineers on broad applicability of the field correlations to all (new) sites.

No consensus exists on how to characterize liquefaction resistance, collapse resistance, and post-liquefaction strength of silty sands, sandy silts, and gravely soils.

In this regard, recently, it has been brought to the attention that physical nature of silty sands and gravely sands is entirely different from clean sand (Thevanayagam 1998a-b, 1999, Thevanayagam and Mohan 1998). As the void ratio and proportion of the coarser and finer grains content of these soils change the nature of their microstructure also changes. The relative participation of the particles of very different sizes in the *internal interparticle contact force chain* also changes. Due to particle size disparity and availability of pores larger than some particles, at low finer grains content some of the finer particles may remain inactive or move between pores without significantly affecting or contributing to the force chain. Yet they contribute to the global void ratio. Alternately when there are sufficient amount of finer grains the coarser grains become dispersed contributing much less to the force chain than to the global void ratio. Global void ratio e ceases to be an index to represent the nature of contact density of active particles. The traditional use of e to compare the behavior of soils containing different amounts of fines content ceases to be valid. The same holds for relative density.

In general the stress-strain behavior, liquefaction potential, and fragility of granular mixes are affected by a critical combination of *intergranular and interfine contacts* and the physical and physico-chemical interactions thereof. The combined effects of intergranular and interfine contacts must be delineated in dealing with silty sands and gravely soils in understanding the mechanisms leading to liquefaction and post-liquefaction deformation, and the mechanical response of the media in general. New indices of active contacts are needed to represent the nature of intergrain contacts inorder to characterize the behavior of such soils. It is thought that recognition of these factors may help to bring about a rational method for liquefaction potential assessment of silty and gravely soils.

Using a two-sized particle mix as a model, this paper highlights the nature of the microstructure of granular mixes. Based on this such granular mixes are classified into certain groups (Fig.2) depending on the relative frictional contributions at the intergranular and interfine grain contact level. Intergranular (e_c) (Mitchell 1993), interfine (e_f) (Thevanayagm 1998a), and equivalent interfine $(e_f)_{eq}$ (Thevanayagm 1998b) void ratios (Fig.3) are introduced as primary indices of contact density for the various groups. Global void ratio is introduced as a secondary index. The range of void ratio and fines content where each group (Fig.2) belongs to is conveniently shown in a global void ratio versus fines content diagram (Fig.4). This is followed by reanalysis of observed cyclic behavior of silty soils at various silt contents using the above indices. Detailed theoretical developments and experimental evaluations are presented elsewhere (Thevanayagam et al. 1999, Thevanayagam 1998a-b, 1999).

CONCEPTUAL FRAMEWORK

Microstructure

Consider a two-sized granular mix. The microstructure of this granular mix can be constituted by infinite different ways. Each one of them leads to a different internal force chain network among particles and hence each exhibits a different stress-strain response during shear. Among infinite variations, a few extreme limiting categories of microstructure and the relevant roles of coarser and finer grains are as follows.

Case-i: The first category (Fig.2a) is when the finer grains are fully confined within the void spaces between the coarser-grains with no contribution whatsoever in supporting the coarser grain skeleton. 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. During deformation the finer grains may move from one pore space to another without significantly contributing to the mechanical response of the soil. This requires that the finer grain particle size (d) is much smaller than the pore size between the coarser grains and that the intergranular pore space is not completely filled with the finer grains. Typically this requires that the coarser grain size (D) is atleast 6.5 times larger than the finer grain size, and that the finer grain content (FC) is less than a certain threshold value (FC_{th}). This category is called *case-i*. Even at low FC, if the size disparity R_d (=D/d) is not very large, the finer grains cannot freely move through the inter-coarser granular voids; They also tend to participate in the force chain and actively contribute to the stress-strain response.

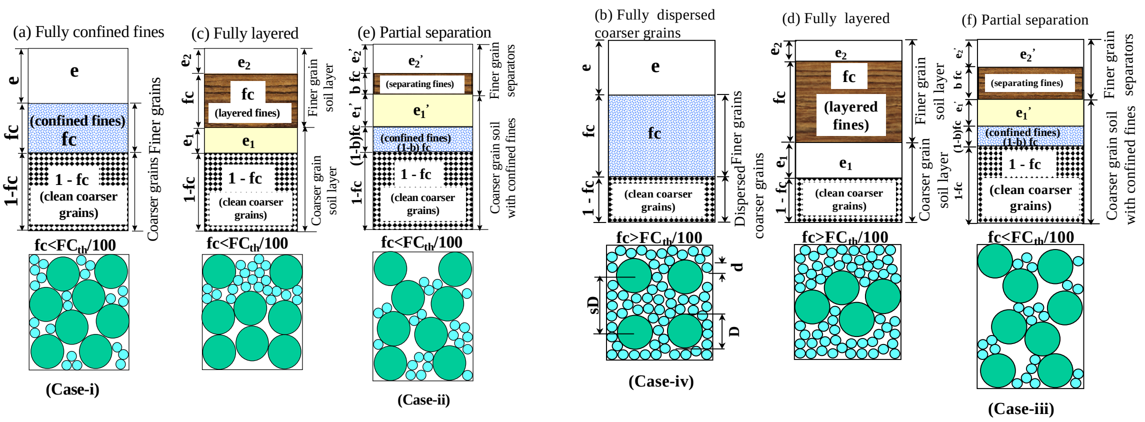

Fig.2 Microstructure and intergranular matrix phase diagram

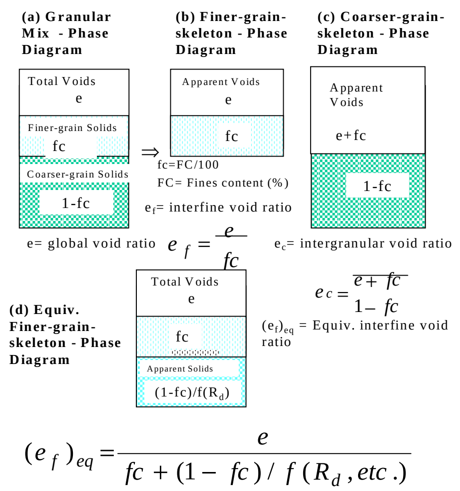

Fig.3 Intergranular contact indices

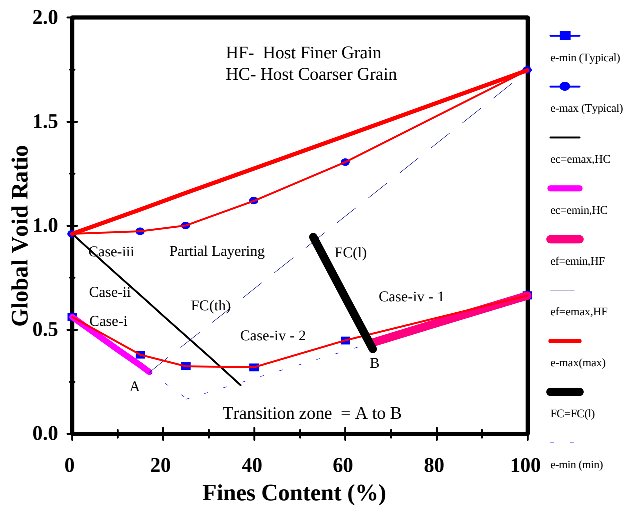

Fig.4 Intergranular matrix diagram – Mix Classification

Cases-ii and iii: Consider changing the microstructure shown in Fig.2a in two ways: (1) alter the position of some of the finer grains, or (2) add more finer grains. The consequences are significant. If one alters the position of some of the finer grains, while maintaining the finer grain content the same, the microstructure corresponding to the second and third categories shown in Figs.2e and f are obtained with a concurrent increase in global void ratio. Essentially, the microstructure in Figs.2e-f is made up of partial layering and partial separation of coarser grains by the finer grains along with confined finer grains within the voids between the coarser grains. Some of the finer grains become active participants in the internal force chain. These finer grains are termed the *'separating fines*' in Figs.2e and f. In Fig.2e, the finer grains may be supporting 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. They may dominate the initial stress-strain behavior depending on the type of finer grains (plastic or non-plastic). In Fig.2f, the finer grains may play an active role of *"separator"* between a significant number of coarse-grain contacts and therefore begin to dominate the strength characteristics. Coarser grain skeleton is virtually unstable without the finer grains. These two categories of microstructure are called cases ii and iii, respectively. Case-ii is a transition between cases i and iii. Theoretically case-iii occurs at an intergranular void ratio exceeding the maximum void ratio (emax.HC) achievable for the 'pure' coarser grain soil.

Cases-iv-1 and iv-2: On the other hand if one increases the finer grains content sufficiently, one gets the fourth category (Fig.2b). It occurs naturally when sufficient finer grains are present making active contacts among themselves. The coarser grains begin to disperse in the finer grain matrix. Transition from Fig.2a to Fig.2b occurs when the finer grains content (FC) exceeds beyond the threshold fines content (FC_{th}). When $FC>FC_{th}$ the finer grains begin to play a rather important role while the role of coarser grains begin to diminish. The fines may carry the contact and shear forces while the coarser grains may act as *reinforcing elements* embedded within the finer grain matrix. The effect of coarser grains cannot be completely neglected until they are separated sufficiently apart. This imposes a limiting fines content FC_l. There exists a transition zone between FC_{th} and FC_l before the behavior of the soil mix is entirely governed by the finer grains. This is called case-iv-2 whereas the case corresponding to $FC>FC_l$ is called case-iv-1. The size disparity constraint discussed before for cases i to iii needs not be satisfied for case-iv.

The fifth category (Figs.2c-d) is when the coarser and finer grains constitute a fully layered system where the coarser grain layers have no fines contained in them and vice versa. This is called case-v. It is also possible to create a composite system that contains some of the cases i through v. The figures 2a, c, e and f are more relevant at low finer grains content. Figs. 2b and d are relevant at high finer grains content.

Contact Indices

Case-i: Up to $FC=FC_{th}$ the finer grains can, but not necessarily, remain within the intergranular voids. Provided that the size disparity is large and the coarser granular skeleton is dense whether or not some of the finer grains fall between the coarser grain contacts or remain fully confined within the intergranular voids does not significantly affect the shear strength of the soil. Primarily the intergranular contacts between the coarser grains affect the mechanical behavior with secondary effects by the finer grains. Hence, neglecting the effects of fines, the *inter-coarser grain void ratio* e_c (=[e+fc]/[1-fc], fc=FC/100, Fig.3c) may be used as an index of active contacts. The magnitude of e_f (=e/fc) may be used as an index to assess the secondary effects by the finer grains.

Cases-ii and iii: For these cases, still the inter-coarser grain contact plays a significant role. However, the influence of finer grains supporting the coarser grains must also be accounted for in devising an index of active contacts. The relevant contact index void ratio would be [e+(1-b)fc)]/[1-fc+bfc] (Fig.2). Hence, although it may be possible to use e_c as an index of active contacts for these cases, it is expected the mechanical behavior of such mixes would be different and generally stronger than that of the host coarser grain soil at the same *ec*.

Case-iv: When $FC>FC_l$, for case-iv-1, neglecting the effects of dispersed coarser grains, the *interfine void ratio* e_f (=e/fc, Fig.3b) may be used as an index of active contacts. At $FC_{th}<FC<FC_l$, neither e, e_c, nor e_f can sufficiently represent the active contacts, alone, although all of them together can be used to deduce the mechanical response. Devising a primary index of active contacts in this range is useful, however.

For a granular mix in this range the global void ratio e overestimates the actual density of active contacts in the granular mix. This is so because the dispersed coarser grains in the mix do not contribute as many active contacts as if the soil was prepared at the same void ratio by substituting each coarser grain by an equal (solid) volume of finer grains. The reason is that solid volume of a dispersed coarser grain, which directly influences the global void ratio, grows in proportion to the power of three of size. Whereas its surface area, which influences the nature of contacts with the surrounding finer grains, grows in proportion to the power of only two. For equal solid volume, the substituted finer grains have a larger surface for contact than a dispersed coarser grain of equal (solid) volume embedded in the finer grain medium. The density of contacts in the mix is smaller than that in the finer grain soil at the same e. Hence e overestimates the active contacts in the mix.

The use of e_c as an index of active contacts is not valid since it ignores entirely the existence of interfiner grain contacts. It grossly underestimates the active contacts. Similarly, the interfine void ratio e_f also underestimates the active contacts, since it completely ignores the presence of the dispersed coarser grains. The latter do make contact with the surrounding finer grains and participate in the force chain. The effects of such contacts may not be negligible unless the spacing between the dispersed coarser grains is very large. The reinforcement effect by the coarser grains must also be introduced to obtain an equivalent interfine void ratio $(e_f)_{eq}$ as the index of active contacts. The equation for e_f must be modified accordingly.

Combining the above arguments e_f should be modified by accounting for the contacts made by the coarser grains with the surrounding finer grains. Theoretically, after simplifications, this leads to a form of the type, $(e_f)_{eq} = e/[fc+(1-fc)/(R_d)^m]$ (Figs.2b and 3d, exponential m), and m=a coefficient satisfying $0<m<1$, $e_c>e_{max,HC}$ (Thevanayagam 1998b). The value of m ranges between about 0.4 to 0.5 for non-plastic granular mixes.

Intergranular Matrix Diagram: Conceptually Fig.4 shows the regions belonging to the four cases i through iv confined by various transition boundaries. The transition lines corresponding to the threshold and limiting fines contents are given by:

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

where $s=1+a(d/D)=1+a/R_d$ where a=10 (approximately). The rationale behind the equation for FC_{th} is that once the interfiner grain void ratio drops below $e_{max,HF}$ (the maximum void ratio achievable for the 'pure' finer grain soil) the finer grains begin to make active contacts among themselves and contribute to the force chain. The reasons leading to the derivation of the expression for FC_l may be attributed to the observations of Roscoe (1970) that the zone of influence of shear is about 10 times the diameter of particles. The various other boundaries refer to the maximum and minimum void ratio profiles: $e=e_{max,HC}+(e_{max,HF}-e_{max,HC})\,fc$; $e_c=e_{max,HC}$; $e_f=e_{max,HF}$; $e_c=e_{min,HC}$; and $e_f=e_{min,HF}$.

Mechanical Behavior

The aforementioned contact indices and the location of a soil mix in Fig.4 can be used as aids to predict the trends of the stress-strain characteristics, liquefaction potential, and fragility of silty or gravely soils (prepared by the same method at the same confining stress) *relative* to that of the host coarser grain soil or the finer grain soil. Fig.5 shows a schematic diagram for *hypothetical* specimens satisfying the following specific constraints: (1) an increase in global void ratio e at the same fines content [specimens 1,2,3], (2) an increase in fines content at a constant global void ratio e [4,2,5,6,7,13], (3) an increase in fines content at the same intergranular void ratio e_c [8,1,9 or 3,10 or 14,2,15; $FC<FC_{th}$], or (4) an increase in coarser grain content at the same interfine void ratio e_f [11,7,12; $FC>FC_{th}$].

Relative Trends -- Cyclic Strength and Fragility: The anticipated trends in number of cycles (N) required to cause initial liquefaction at the same cyclic stress ratio are *schematically* shown in Fig.5 [N versus FC]. In (1) both intergranular and interfine void ratios increase with concurrent reduction in inter-coarser grain contacts. Therefore the soil becomes weaker. In (2) while e_c increases e_f decreases. Viz. the inter-coarser granular contacts decrease while the interfine contacts increase. Hence initially the soil is expected to weaken [4,2,5] followed by a transition in the vicinity of $e_f=e_{max,HF}$ ($FC=FC_{th}$). The soil becomes stronger beyond that [6,7,13]. In (3), the increase in cushioning effect by the fines is manifested leading to a slight increase in strength [3,10, case-iii]. The specimen 10 is expected to be somewhat more resistant to collpase than the specimen 3. This effect, however, diminishes gradually if the soil becomes denser in terms of e_c [case-ii]. The reason is that when e_c is small (dense coarser grains) the relative effect of fines is less appreciable compared to the direct coarser-coarser grain contact resistance until e_f becomes sufficiently low. In (4) when the soil is at a fines content less than FC_l but greater than FC_{th} [11,7,12] the reinforcement effect of the coarser grain 'inclusions' may affect the stress strain behavior. The specimen 11 is expected to be stronger than 7. Again this reinforcement effect may become relatively small compared to the direct finer-grain-to-finer-grain contact resistance when e_f is small (dense interfine contacts). Once FC exceeds FC_l the reinforcement effect is expected to be small. Primarily the interfine contacts and e_f are expected to affect the soil behavior [7,12]. Without elaboration, the remaining figures show the relative trends for N for various cases i through iv plotted against the relevant contact indices (e_c, e_f, and $(e_f)_{eq}$).

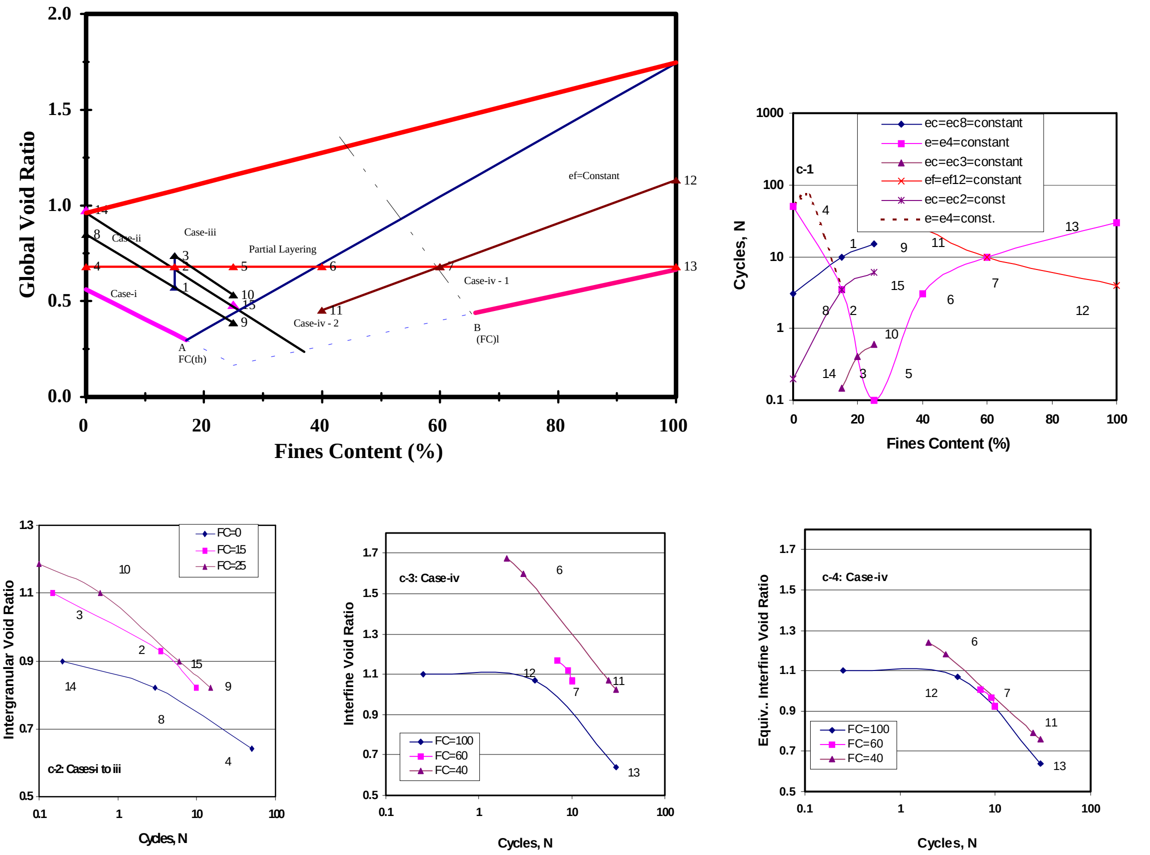

Fig.5 Relative trend in cyclic strength – Schematic.

EXPERIMENTAL EVALUATION

A limited set of experimental data is available in support of the above conceptual framework. In order to save space, only the data shown in Fig.1b is recalled again in Fig.1c, 6 and 7 to illustrate the various roles of coarser and finer grains on the behavior of granular mixes. A series of other papers (Thevanayagam et al. 1999, Thevanayagam 1999) present the results of detailed analyses of other experimental data.

Intergranular Matrix Diagram: Figs.6a-c show the intergranular matrix diagram for three host sands [(1) Fine (F), (2) Medium (M), and (3) Well graded (W)] mixed with a low plasticity fines (PI=4) tested by Chang (1990), reported in Fig.1. The locations of the specimens are also shown. Each sand mix was tested at 0, 5, 12, 20, 45, and 60% fines content. The specimens were prepared by moist tamping method. All specimens were consolidated to the same initial confining stress (104kPa). The specimens for each soil mix were tested at nearly constant global void ratio: e=0.728 for F, e=0.558 for M, and e=0.480 for W, respectively. These void ratios correspond to about 50% relative density of the respective parent sands. No data were available for $e_{max,HF}$ and $e_{min,HF}$ for the silt. For qualitative discussion purposes the threshold boundary may be estimated assuming typical values of $e_{max,HF}$ =1.5 and $e_{min,HF}$ =0.6. Also for illustration purposes the R_d (defined as D50/d50) values for the soils F, M, and W were estimated to be about 15, 40, and 40 based on a typical value for d50 of silts. An examination of Fig.6 and calculated index void ratios would readily reveal the cases each specimen belongs to and the expected behavior of each granular mix relative to one another.

Cyclic Strength variation with Increase in FC: Fig.1c shows the same cyclic strength data shown in Fig.1b. The e_c and e_f values for each specimen and the respective cases each specimen belongs to are also shown in this figure. As the fines content increases, at the same global void ratio e, the e_c increases and e_f decreases. Initially the ef remains high to be of any significance, alone. With increase in FC the soil mixes move gradually from

Case-i to Case-ii to Case-iii and then cross over to Case-iv-2. So is the behavior of the soils. Initially the strength decreases due to reduced intergranular contacts with increase in e_c with little or secondary contribution from the fines. As the soil moves beyond the threshold transition zone (FC_{th} at $e_f = e_{max,HF}$) and enters the zone for Case-iv-2 the influence of e_f becomes important with some reinforcement effect by the coarser grains. The $(e_f)_{eq}$ becomes the primary contact index void ratio. The trend reverses and the strength begins to increase with further increase in fines content.

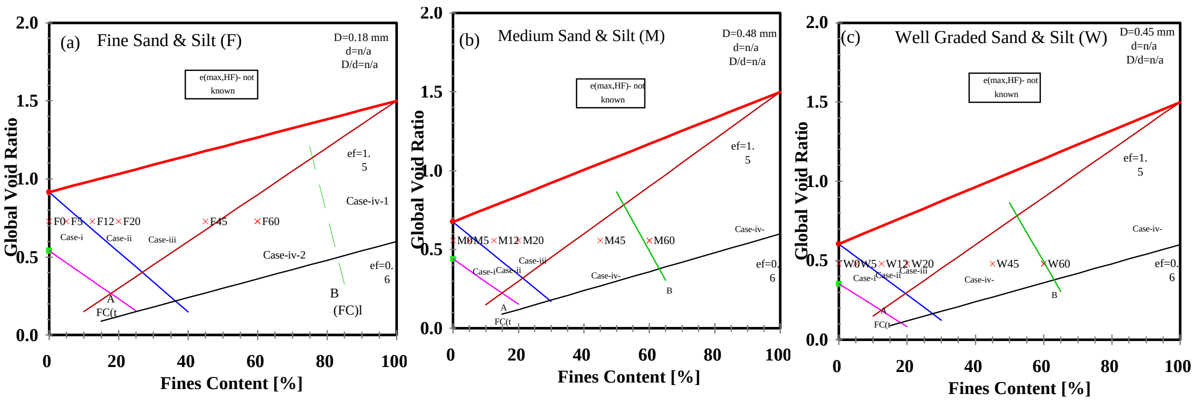

Fig.6 Intergranular matrix diagrams – Three Sand – Silt Mixes

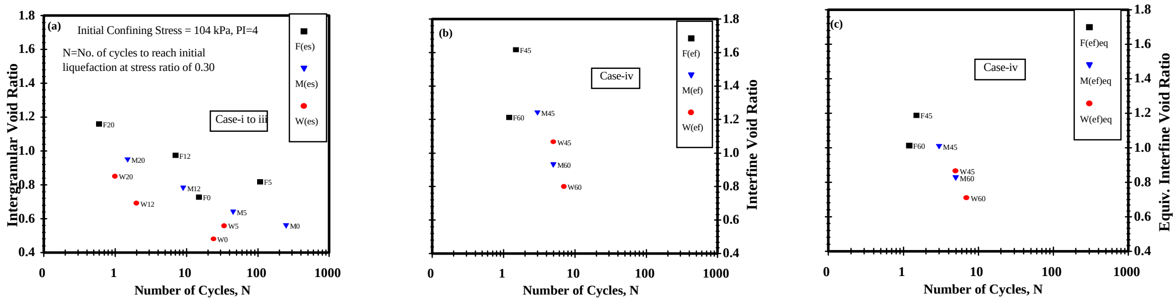

Fig.7 Influence of intergrain contacts on cyclic strength: (a) e_c, (b) e_f, and (c) $(e_f)_{eq}$

The transition fines content FC_{th} is slightly different for each soil mix. Theoretically it corresponds to the intersection of the constant global void ratio line with the $e_{max,HF}$ line. For the same host fines, typically a soil mix at a smaller global void ratio (Fig.6c) will cross the $e_{max,HF}$ line and reach Case-iv-2 at a smaller fines content than a soil mix at a higher global void ratio (Fig.6a). Hence, the soil W (at e=0.480) reaches this transition at smaller fines content than the soil F (at e=0.728).

$FC<FC_{th}$: Fig.7a show the same data in a different format: Number of cycles to initial liquefaction versus e_c for Cases-i to iii [$FC<FC_{th}$]. For this case, a different cyclic strength profile is obtained for each mix depending on the parent sand type (F,M,W). N is affected primarily by the parent sand type. e_c becomes the primary index of active contacts. The fines have a secondary role. It would be more revealing if (if available) the data for each host sand are superimposed in this figure permitting a comparison of the kind shown in Fig.5 (e_c versus N).

$FC>FC_{th}$: Fig.7b show the N versus e_f data for Case-iv. N data show significant dependency on interfine void ratio e_f. The data for each fines content (45% and 60% separately) correlates well with e_f and fall in a (separate for 45% and 60%) narrow band regardless of the parent sand type. The separate narrow bands for the soils mixed with 45% fines and 60% fines are due to the differences in the degree of reinforcement effect. At the same e_f, the cyclic strength is higher for the soil with higher sands content. The reinforcement effect is higher at 45% fines content than at 60% which is approaching the limiting fines content FC_l. Nevertheless, at low e_f (dense interfine contacts) the relative effect of reinforcement becomes less appreciable compared to direct interfine contact friction. The separate bands for 45 and 60% merge together at low e_f. Fig.7c shows the same data, plotted against equivalent interfine void ratio $(e_f)_{eq}$ [calculated assuming m=0.45). Interestingly the number of cycles required to cause liquefaction correlates with $(e_f)_{eq}$ for all cases of iv. The reason for this is that all sands were mixed with the *same silt*. Hence, once FC exceeds the threshold value, all soil mixes are affected by the same silt except for the minor differences due to the presence of different size coarser grains (F,M,W). Hence a single narrow band is obtained in Fig.7c. It would be more revealing if (if available) the data for the silt is superimposed in this figure permitting a comparison of the kind shown in Fig.5 [$(e_f)_{eq}$ versus N].

CONCLUDING REMARKS

A simple framework for analysis of the relative effects of inter-coarser granular and interfine contacts on the undrained behavior of granular mixes is presented. Intergranular and interfine void ratios are introduced as indices of active contacts. For a granular mix with large size disparities between grain sizes, at low finer grains content less than a threhold value, if and when the finer-grains are fully confined to the void spaces without providing any support to the coarser grain skeleton the stress-strain behavior of that soil can be deduced using the coarser-grain skeleton void ratio (e_c) as an index with secondary beneficial effects derived from the fines. FC_{th} occurs when the intergranular voids are filled with finer grains at the loosest possible packing of the fines. At $e_c << e_{max,HC}$ and FC<FC th the soil mix is categorized as case-i. The secondary beneficial effect of fines is the least when the soil is dense (low e_c). The beneficial effect is the highest when the intergranular skeleton is loose and the intergranular void ratio is close to its maximum void ratio possible for the host coarser grains ($e_{max,HC}$). This is categorized as case-ii behavior. In reality, however, even at $FC<FC_{th}$ the finer grains are not confined strictly within the intergranular voids. The fines can also play the role of separator of coarser grain contacts and constitute a loose and metastable structure. This occurs typically when $e_c>e_{max,HC}$. This is denoted as Case-iii behavior. When FC exceeds FC_{th} the finer grains begin to exert a major role on the stress-strain response of the soil. The coarser grains act as reinforcements embedded within the finer grain matrix. This occurs until FC exceeds a limiting fines content FC_l. Beyond this, the behavior of sandy silt is primarily governed by the interfine void ratio e_f. This is categorized as case-iv-1 behavior. In the intermediate range ($FC_{th}<FC<FC_l$) both interfine void ratio and coarser grains influence the soil behavior. Neither the intergranular nor the interfine void ratio alone can be the sole index of the behavior of a silty sand and sandy silt in this range. This is categorized as case-iv-2 behavior. An equivalent interfine void ratio $(e_f)_{eq}$ may be used as an index. Obviously the zones of these behaviors (Fig.4) are not rigid, but rather consist of smooth transitions embedded between them.

With this framework, one may deduce the behavior of granular mixes at various finer grains contents and void ratios relative to the behavior of the host coarser grain soil or the finer grain soil. Based on this framework and reinterpretation of a limited amount of experimental data the following observations could be made about the liquefaction potential and fragility of granular mix prepared at the same initial confining stress. (a) When compared at the same e_c, an increase in finer grains content reduces the collapse potential, (b) When compared at the same e_f, an increase in finer grains content increases the collapse potential, (c) When compared at the same $(e_f)_{eq}$, an increase in finer grains content slightly increases the collapse potential, and (d) When compared at the same global void ratio e the collapse potential increases with an increase in finer grains content up to a certain threshold value FC_{th}. Beyond that the collapse potential decreases. FC_{th} depends on the host fines, size disparity ratio, and the global void ratio. The question remains on the possible differences on the nature of field deposits relevant for built environment versus what is studied in the laboratory.

These considerations need to be rationally incorporated in evaluating observed field performances at past earthquake sites and its extrapolations to predict the anticipated field performance at other sites. Correlations of SPT, CPT, and shear wave velocity data versus observed seismic response of ground need to be studied further beyond the traditional consideration for impeding drainage effects.

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