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Effect of Compaction Conditions on the Seismic Compression of Compacted Fill Soils

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ABSTRACT: Seismic compression is defined as the accrual of contractive volumetric strains in unsaturated compacted soil during earthquake shaking. Existing seismic compression analysis procedures are based on laboratory test results for clean uniform sands, and their applicability to compacted soils with fines is unclear. We evaluate seismic compression from cyclic simple shear laboratory testing of four compacted soils having fines contents that are sufficiently large that fines control the soil behavior, but possessing varying levels of fines plasticity. Each soil material is compacted to a range of formation dry densities and degrees-of-saturation. The test results show that seismic compression susceptibility decreases with increasing density and decreasing shear strain amplitude. Saturation is also found to be important for soils with moderately plastic fines (plasticity index, PI ≈ 15), but relatively unimportant for soils with low plasticity fines (PI ≈ 2) across the range of saturations tested ($\geq$54 %). The saturation effect appears to be linked to the presence or lack of presence of a clod structure in the soil, the clod structure being most pronounced in plastic soils compacted dry of the line-of-optimums or at low densities. Comparisons of test results for soils with and without low- to moderately-plastic fines suggest that fines can decrease the seismic compression potential relative to clean sands.

KEYWORDS: seismic compression, ground failure, simple shear, cyclic testing, volumetric strain, earthquakes

Introduction

Earthquake-induced ground deformations resulting from contractive volumetric strains in unsaturated soil, herein termed seismic compression, have been recognized as a major cause of seismically induced damage in hillside urban areas (Stewart et al. 2001). Previous laboratory investigations of seismic compression have focused primarily on clean uniform sands. The pioneering studies of Silver and Seed (1971), Youd (1972), and Pyke et al. (1975) involved laboratory testing of the volumetric strains induced in clean uniform sands by cyclic loading. They found that the seismic compression susceptibility of clean sands is influenced by the soil's relative density, the amplitude and number of applied shear strain cycles, and multidirectional shaking effects. More recent testing programs on clean sand have established relationships between volumetric strain and normalized accumulated energy (Shahnazari and Towhata 2001).

It has long been understood that the presence of fines (i.e., particles passing the #200 sieve) in soil significantly changes static soil properties such as shear strength relative to clean sands (e.g., Casagrande 1932). Dynamic soil behavior has also been found to be affected by the presence of fines. For example, the liquefaction resistance of sand-silt mixtures has been found to differ significantly from that of clean sands (e.g., Thevanayagam and Martin 2001; Yamamuro and Covert 2001; Polito and Martin 2001; Amini and Qi 2000; Verdugo and Ishihara 1996). With regard to seismic compression, however, few laboratory test results for soils containing fines have been published, and no previous studies have systematically evaluated the effect of fines through comparisons to clean sand behavior.

Previously published seismic compression test results for soils with fines include those by Pyke et al. (1975), Chu and Vucetic (1992), Hsu and Vucetic (2004), and Wang et al. (2000). The Pyke et al. (1975) work consisted of a limited number of cyclic simple shear tests on a well-graded clayey sand (SC) at two densities (modified Proctor relative compaction, $RC = 84.4$ and 92 %) and one water content ($w = 10$ %). The results indicated that volumetric strains in the clayey sand at $RC = 92$ % were less than approximately one-third of the expected settlement in a clean sand prepared to a comparable relative density ($D_R = 60$ %). Chu and Vucetic (1992) used cyclic simple shear testing to investigate seismic compression of a low plasticity index (PI = 10.5) clay. Specimens were compacted at three water contents to high modified Proctor relative compactions of $RC = 96$–100 %, and then were consolidated to a vertical stress of approximately 550 kPa, before horizontal cyclic loading was applied. Based on these test results, Chu and Vucetic concluded that the volumetric threshold strain for this clay, $\gamma_{tv} \approx 0.1$ %, and that volumetric strains from seismic compression are not significantly dependent on formation water content. Hsu and Vucetic (2004) found through simple shear testing that γ_{tv} is smaller for sands (0.01–0.02 %) than for PI = 30 clays (0.04–0.09 %) and that γ_{tv} does not depend significantly on saturation or vertical stress. Relative compaction levels for the tested specimens were not reported. Wang et al. (2000) investigated the effect of density on the seismic compression susceptibility of compacted loess (PI = 16) at one water content ($w = 16$ %) using a cyclic triaxial apparatus, and found volumetric strains to decrease significantly with density as expected. Neither Chu and Vucetic (1992), Hsu and Vucetic (2004), nor Wang et al. (2000) compared their results for soils with fines to results for comparable clean sand materials.

The prevailing analysis method for estimating seismic compression (Tokimatsu and Seed 1987) is based on the laboratory test

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results of Silver and Seed (1971) and Pyke et al. (1975) for clean uniform sands. Consequently, this procedure neglects the potentially important effects of fines. Moreover, the effects of formation degree-of-saturation (S) and PI on the seismic compression of compacted soil are not well understood, and therefore, are unaccounted for in this procedure.

The objectives of this paper are to present cyclic simple shear test results that provide insight into several key issues not explored in the limited previous seismic compression testing of soils with fines:

1. For soils with "large" fines contents (i.e., fines content is large enough that the fines control the soil behavior) but different fines plasticities, investigate the effect of formation RC and S on seismic compression.
2. Investigate the difference in seismic compression behavior of clean sands (zero fines) and sands with large fines contents.

As noted above, soil density is parameterized in this study in terms of modified Proctor RC. It is recognized that seismic compression susceptibility is likely to have a more fundamental association with the offset of the soil density/void ratio from a limiting state, e.g., as parameterized by the state index of Been and Jeffries (1985). However, modified Proctor RC was used because it is the most widely used parameterization of soil density for engineering applications involving compacted fill soils.

The tested materials were retrieved from two field sites in Santa Clarita, California that experienced seismic compression induced ground settlements during the 1994 Northridge earthquake. The testing of soils from these sites was part of a broader effort to examine the extent to which seismic compression can explain observed levels of ground deformation; detailed documentation and analyses of the case histories are provided elsewhere (Stewart et al. 2004). It should be noted that the testing program in this study does not cover a comprehensive range of soil compositional factors, such as fines content and fines plasticity. Nonetheless, the present test results provide valuable new insights into the mechanics governing seismic compression susceptibility of soil with fines, and the lessons learned from this work have significant implications for how compaction specifications should be developed for compacted fills in seismically active areas.

Laboratory Testing Equipment

Two cyclic simple shear devices were used in this research to perform the laboratory testing. The UCB-2D bidirectional cyclic simple shear device developed by Boulanger et al. (1993) was used to perform the preliminary phase of testing. A *d*igitally *c*ontrolled *s*imple *s*hear device recently developed at UCLA (UCLA-DCSS) was used to perform the majority of the testing program. Results from the two devices were compared by compacting the same soil to similar densities (at comparable saturation levels), and then applying similar cyclic shear strain amplitudes to samples using each device. Measured vertical strains were found to be within 5 % of each other, indicating good compatibility of test results between the two devices.

The UCLA-DCSS device was designed using the UCB-2D device (Boulanger et al. 1993) as a prototype. UCLA-DCSS retains all of the main features of the UCB-2D device, such as inclusion of cell pressure for purposes of backpressure saturation, limited mechanical compliance with respect to simple shear boundary conditions (e.g., top and base platen "rocking"), and bidirectional loading capability. In addition to these features, UCLA-DCSS incorporates several design improvements, including:

1. The use of a tri-post frame with high performance track bearings to further reduce rocking;
2. A digitally controlled hydraulic control system to allow for high frequency loading and high-precision control;
3. A dual axis load cell to obtain postfriction shear stress measurements.

Further details on the UCLA-DCSS device are provided by Whang (2001).

Testing Procedures

Cyclic simple shear tests were performed under partially drained conditions to evaluate vertical strain accumulation when uniform-amplitude cycles of shear strain are applied to the soil specimen. Commercially available wire-reinforced membranes were used to laterally confine the cylindrical soil specimens, which were prepared to a diameter of 102 mm and a height of 23 mm. These membranes minimized lateral expansion of the test specimens, while providing negligible shear stiffness. Since the effect of overburden pressure on vertical strain has previously been found to be minor (e.g., Silver and Seed 1971; Youd 1972; Pyke et al. 1975), all tests were performed under the same vertical stress of 101.3 kPa. A sinusoidal loading frequency of 1 Hz and three nominal cyclic shear strain amplitudes ($\gamma_c = 0.1$, 0.4, and 1.0 %) were used. A relatively small number of tests were performed at $\gamma_c = 0.1$ % because this strain level is near the threshold strain, and hence, the seismic compression effects that are the subject of this paper are not as clearly manifest as at larger strains.

Specimen Preparation

Specimens were prepared by air-drying the soils and passing them through a No. 4 Sieve in order to control the size of clods in the soil prior to compaction. Specimens were compacted in two lifts into a mold using a Harvard Miniature-Compactor. This compactor has been shown to replicate accurately the fabric of field-compacted soils compacted wet of the optimum moisture content, although differences in fabric may exist dry of the optimum moisture content (Prapaharan et al. 1991). The pressure applied by the Harvard Mini-Compactor was varied through a pressure regulator to achieve the desired density. Pressures of 70–480 kPa were applied using 30 tamps per layer. Tops of specimens were leveled using a straight edge to a tolerance of ±0.1 mm, and holes were filled using the same soil and gentle taps from a rubber hammer.

Test Results

Materials Tested and Representative Test Results

Strain-controlled cyclic simple shear tests were performed on four different reconstituted soils from the two field sites. The formation water contents and dry densities were selected to represent the range of in situ conditions at the field sites immediately before the earthquake, which were inferred from pre-earthquake field construction logs and post-earthquake subsurface exploration. Additional tests were performed to investigate the effect of formation

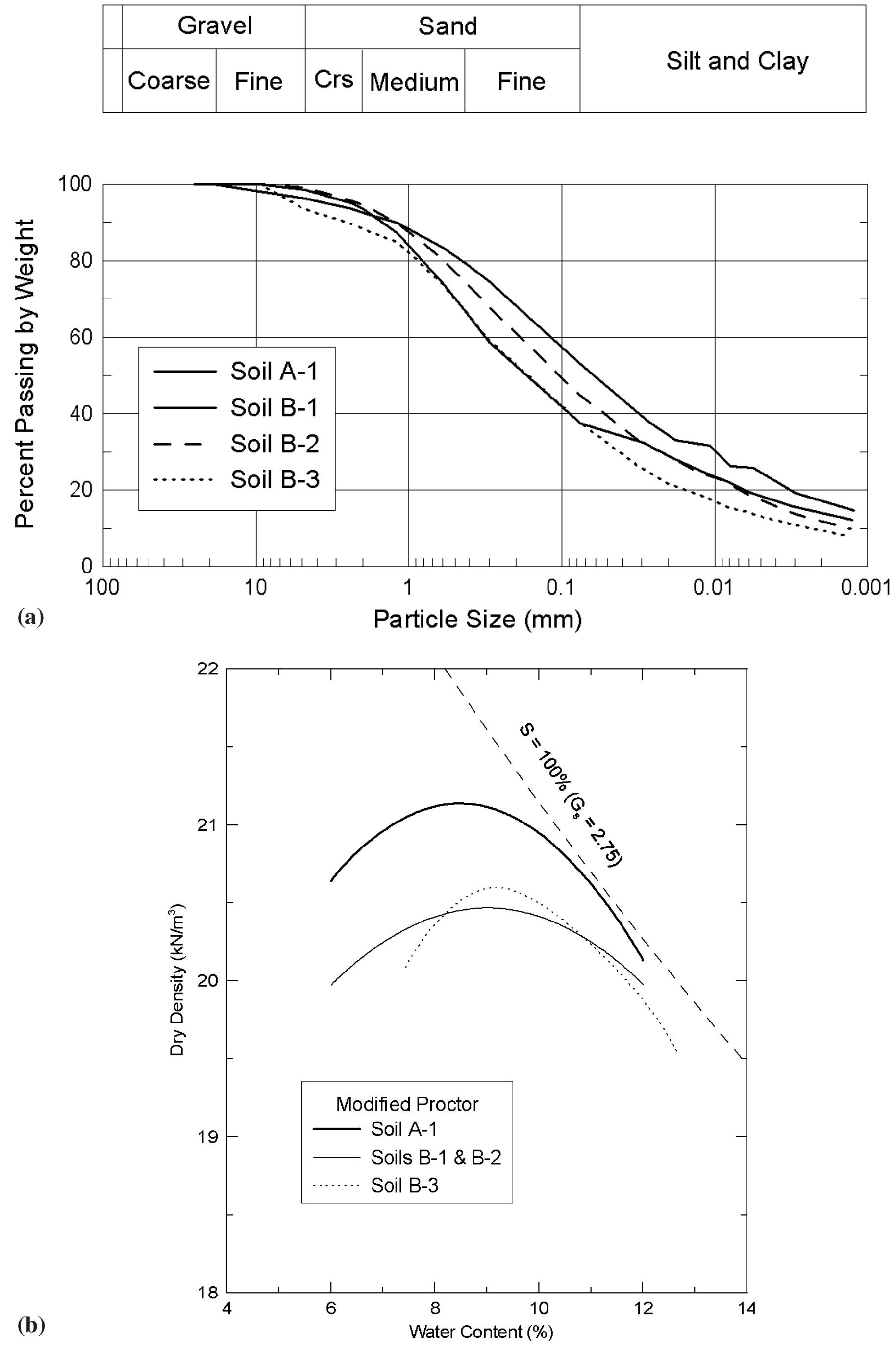


FIG. 1—*Grain size distributions and compaction curves of tested fill soils.*

relative compaction and degree-of-saturation on the seismic compression behavior.

Index testing (Atterburg Limit, hydrometer/sieve analyses, and standard and modified Proctor Compaction) was performed to characterize each of the tested soils, and the results are summarized in Table 1. The fill specimens are generally classified as silty or clayey sand by the Unified Soil Classification System (either SM or SC), but one soil is a low plasticity clay (CL). The tested soils have fines contents ranging from 40 to 54 % and plasticity indices ranging from 2 to 15. Grain size distributions and modified Proctor compaction curves for all tested soils are shown in Fig. 1.

TABLE 1—*Summary of index properties for tested soils.*

Soil	Classification	PI	LL	$\gamma_{d,\max}$	W_{opt} (%)	% fines
A-1	CL	15	33	21.2	8.5	54
B-1	SC	14	35	20.6	8.0	40
B-2	SC	9	20	20.4	8.0	48
B-3	SM	2	27	20.6	8.0	44

The results from a representative cyclic simple shear test are shown in Fig. 2 (Soil A-1, modified Proctor $RC = 88$ % and $w = 14.8$ %). Essentially uniform cyclic shear strain amplitudes

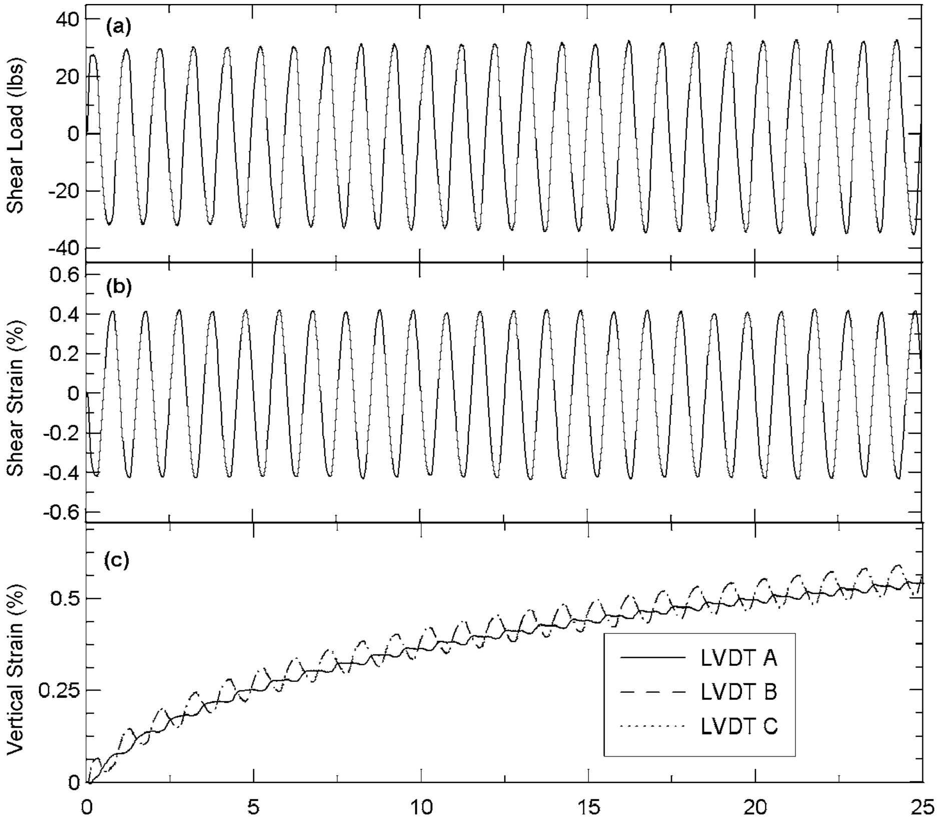


FIG. 2—*Representative cyclic simple shear test (Soil A-1, RC = 88 % and w = 14.8 %).*

are achieved through a slight increase in the applied shear load during the first few cycles until the soil's shear modulus has stabilized. The soil's equivalent shear modulus is essentially constant after 10 cycles of loading. As shown in Fig. 2*c*, the majority of vertical strain accumulation occurs within the first few cycles of loading.

In the following discussion, test results are summarized by the vertical strain associated with 15 cycles of uniform shear strain, $(\varepsilon_v)_{N=15}$. Results are organized into two subsections, one presenting results for materials with moderate plasticity (A-1, B-1, and B-2) and another presenting results for a low plasticity silty sand (B-3).

Results for Moderate-Plasticity Soils (Soil A-1, B-1, and B-2)

Observations—For brevity, we present detailed results for only Soil A-1; results for B-1 and B-2 have similar trends to those for A-1, as shown subsequently. A large number of tests were performed on Soil A-1 to identify the effect of modified Proctor relative compaction (RC) for a given degree-of-saturation (S), and the effect of S for a given RC. The effect of RC on the seismic compression of Soil A-1 is illustrated in Fig. 3, which shows $(\varepsilon_v)_{N=15}$ for a series of specimens compacted to a common $S = 74$ %, but at different relative compaction levels ($RC = 84$, 88, and 92 %). Parameter $(\varepsilon_v)_{N=15}$ decreases with increasing RC for all ranges of tested shear strains. This observation is consistent with previous research, and highlights the importance of RC (or dry density) on the magnitude of seismic compression strains.

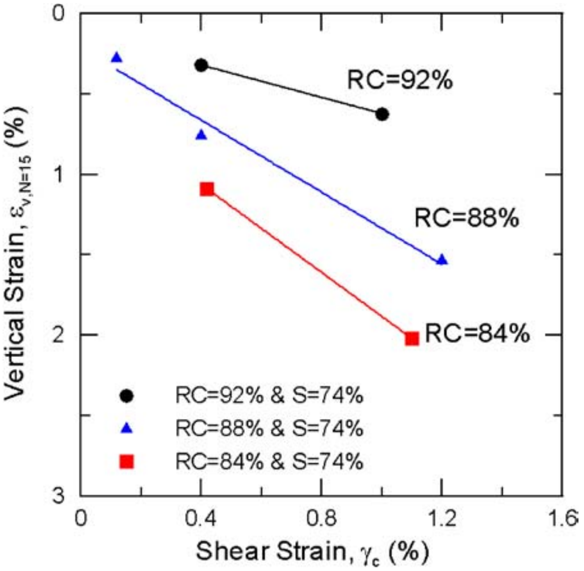


FIG. 3—*Effect of formation relative compaction (relative to modified Proctor standard) on the seismic compression of Soil A-1.*

Figure 4 illustrates the effect of S on $(\varepsilon_v)_{N=15}$ for Soil A-1. Each shaded band in Fig. 4 corresponds to a given relative compaction ($RC = 84$, 88, and 92 %), and variability within the bands is a result of variations in S. The results indicate that S can significantly influence seismic compression at moderate dry densities ($RC =$ 88–92 %) when the induced shear strains are large (i.e., $\gamma_c > 0.1$ %). For this RC range, $(\varepsilon_v)_{N=15}$ varies by as much as a factor of two due to variations in S. Interestingly, at lower densities ($RC = 84$ %), specimens at $S = 53$, 74, and 87 % experienced similar amounts of vertical strain.

The aforementioned effects of RC and S are illustrated by contours of $(\varepsilon_v)_{N=15}$ associated with induced cyclic shear strain level

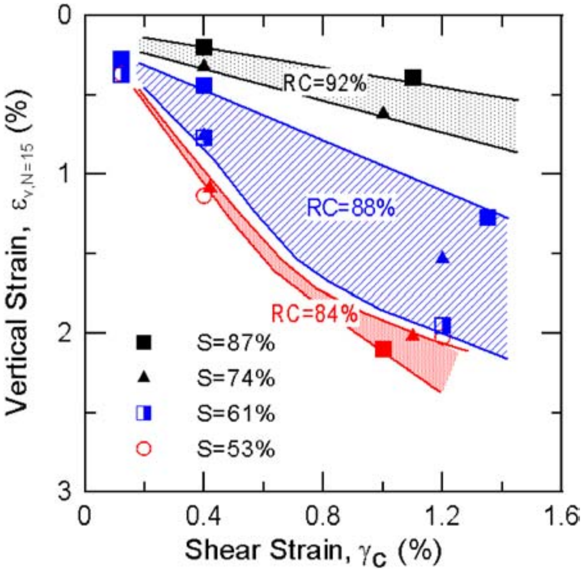


FIG. 4—*Effect of formation degree-of-saturation on the seismic compression of Soil A-1 for various fixed values of RC.*

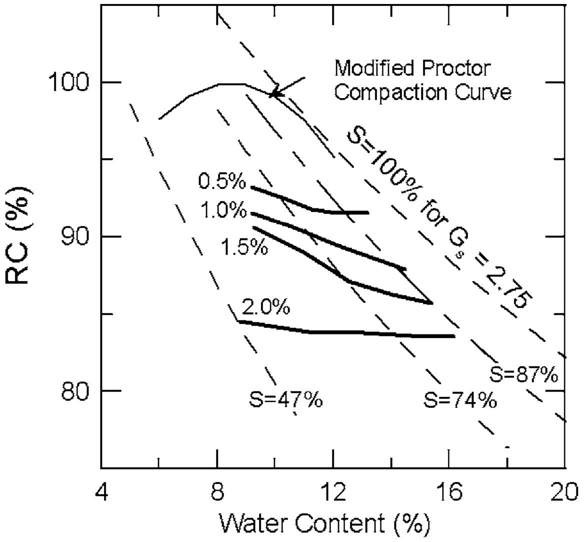


FIG. 5—*Contours of* $(\varepsilon_v)_{N=15}$ *for Soil A-1 at* $\gamma_c = 0.4$ *%.*

$\gamma_c = 0.4$ % in Fig. 5. The contours show $(\varepsilon_v)_{N=15}$ decreasing with increasing RC, decreasing with increasing S for moderate RC, and being relatively insensitive to S for low RC. Similar trends were found for test results obtained at shear strain level $\gamma_c = 1.0$ % (not shown).

Trends similar to those identified for Soil A-1 were observed for the other low-plasticity materials tested in this research (i.e., Soils B-1 and B-2 that have PI = 14 and 9, respectively). As shown in Fig. 6, $(\varepsilon_v)_{N=15}$ increases with increasing γ_c and decreases with increasing RC and S. The tendency of $(\varepsilon_v)_{N=15}$ to decrease with S can be seen, for example, by comparing B-1 soil specimens prepared to $S = 61$ and 81 % for $RC \approx 90$–91 %, and $S = 74$ and 97 % for $RC = 95.5$ %. For both RC levels, increasing S decreases $(\varepsilon_v)_{N=15}$ by up to 30 %.

Interpretation—A critical consideration in the interpretation of test results for moderately plastic fine-grained compacted soils is the presence or absence of a clod macro-structure. Work on the macro-structure of compacted clayey soils by Barden and Sides (1970) found that the behavior of compacted clays can be explained by a deformable aggregate (or "clod") soil model. According to this model, prior to compaction, soil particles are grouped into agglomerations or "clods" whose size and strength are affected by formation water content. The clods are strong at low water contents and resist breakdown during compaction, giving rise to significant inter-clod voids. At higher water contents, the clods are broken down during the compaction process. Bengochea et al. (1979) compiled evidence in support of this hypothesis in their analyses of pore size distributions of compacted silty clays. They found that the pore size distributions of plastic soils were bimodal, in which the larger pore modes (1.0–10 μm) were influenced by water content and compaction effort, while the smaller pore modes (0.1 μm) remained relatively constant. Variations in the larger pore size distributions were explained by clod breakdown at high water contents during the compaction process. The larger pore modes were less apparent at low soil plasticities, indicating decreasing clod formation for these soils, which was later confirmed by Leroueil et al. (2002). Studies by Benson and Daniel (1990), Watabe et al. (2000), and Leroueil et al. (2002) further investigated and confirmed the compaction conditions that give rise to a clod soil macro-structure. They found that compacted fine-grained soils can have a clod structure when compacted at moderate energy levels (i.e., standard Proctor) and at water contents dry of optimum. The clod structure is lost when fine-grained soils are compacted at moisture contents wet of optimum or at high compactive energies (i.e., modified Proctor).

In this study, specimens were examined upon the completion of testing to evaluate the level of clod breakdown during compaction. Figure 7 shows photographs of two specimens both compacted to $RC = 88$ %, but one compacted at $S = 66$ % (dry of the line-of-optimums) and another at $S = 87$ % (wet of the line-of-optimums). The specimen compacted at $S = 66$ % is seen to have remnant clods while the $S = 87$ % specimen shows a relatively homogeneous soil macrostructure. In general, specimens compacted at high S with at least a moderate compactive effort were found to have relatively homogeneous structures with little to no clods, whereas specimens compacted at relatively low S with moderate compactive effort had more of a clod structure. Specimens compacted at $RC \approx 84$ % maintained a clod structure across the range of S employed during our testing.

These apparent variations in soil structure with formation RC and S can help explain a number of key trends in the test results. For moderate compactive efforts (i.e., $RC \sim 88$ and 92 %), the decrease of vertical strain with increasing S is likely associated with S serving as a proxy for interclod void space. At very low compactive efforts (i.e., $RC \sim 84$ %), the apparent inability of the compaction process to break down clods results in no significant variation in vertical strain with S. We did not prepare specimens of these plastic soils to very high RC levels. However, the aforementioned test results by Chu and Vucetic (1992) on a similar material at high modified Proctor relative compaction ($RC \approx 96$–100) indicated no significant variation in vertical strain with water content. This may be due to the breakdown of clod structure at very high compactive efforts.

Results for Low Plasticity Silty Sand (Soil B-3)

A series of tests was performed on the low plasticity Soil B-3 that was similar in scope to those performed on the moderately plastic soil specimens, the objective being to identify the effects of Formation RC and S on seismic compression. Figure 8 shows that $(\varepsilon_v)_{N=15}$ for Soil B-3 decreases as RC increases from ~90–92 %

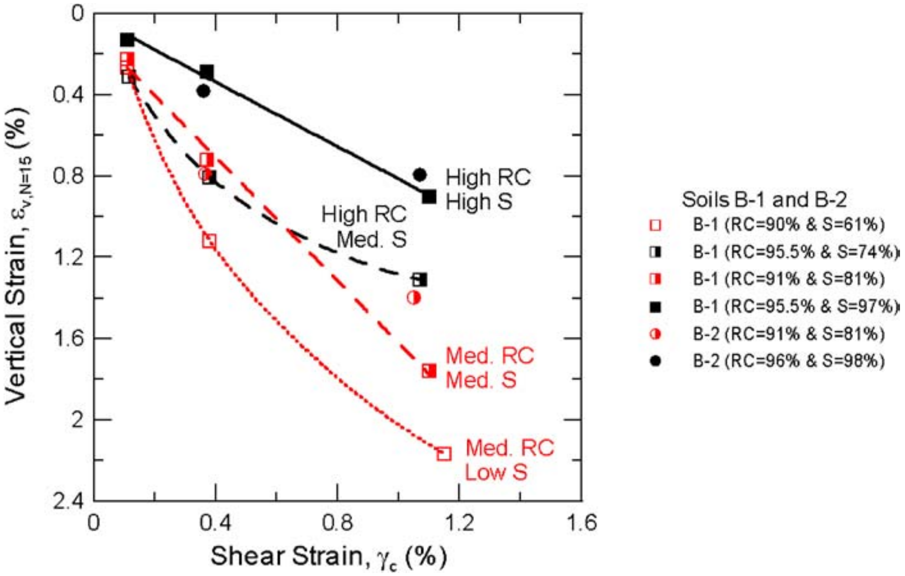
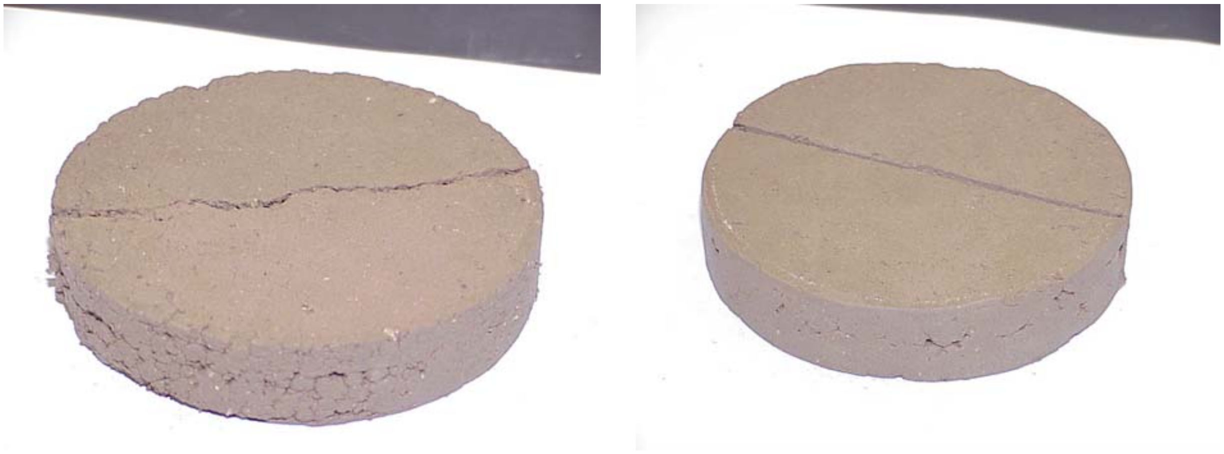


FIG. 6—*Seismic compression of Soils B-1 and B-2*.



RC=**88% &** *S*=**66%**

RC=**88% &** *S*=**87%**

FIG. 7—*Photographs showing macrostructure of Soil A-1*.

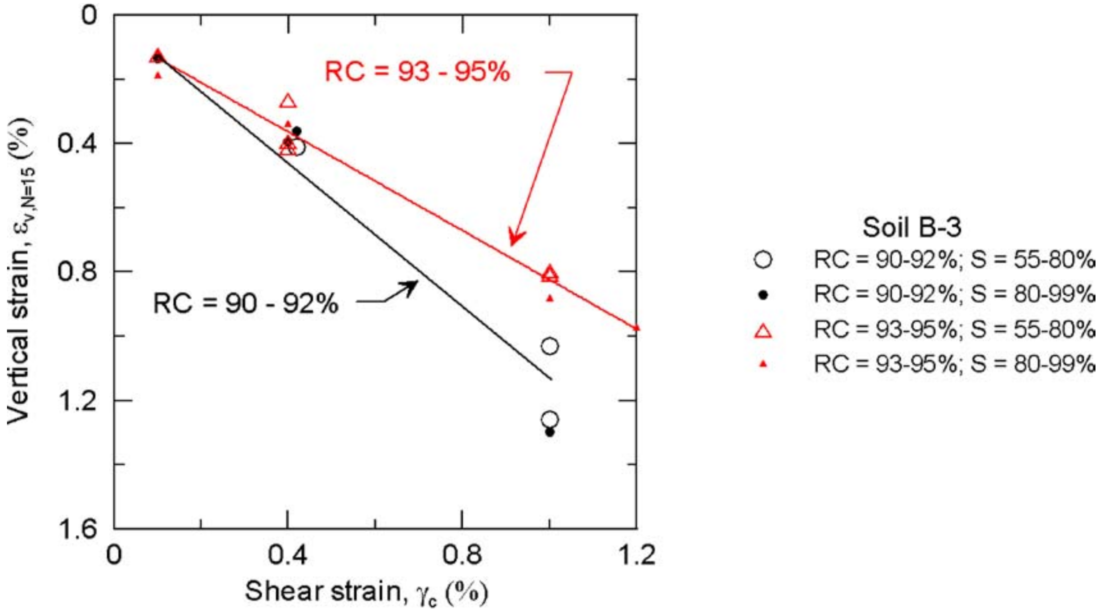


FIG. 8—*Seismic compression of Soil B-3*.

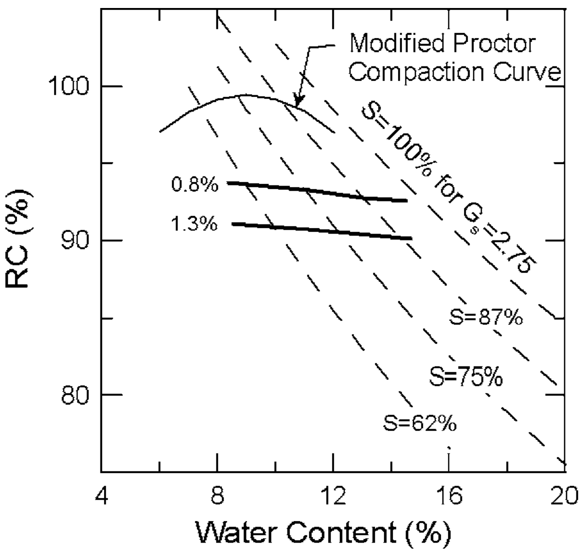


FIG. 9—*Contours of* $(\varepsilon_v)_{N=15}$ *for Soil B-3 at* $\gamma_c = 0.4$ *%.*

to ~93–95 % as expected. The variation of $(\varepsilon_v)_{N=15}$ with RC is most apparent at $\gamma_c = 1.0$ %; at $\gamma_c = 0.4$ % the variation with RC is relatively small and within the inherent scatter of the test data. Unlike the moderately plastic soils, saturation level does not appear to have a detectable effect on the seismic compression of Soil B-3 across the tested range of $S = 54$–91 %. This is well illustrated in Fig. 8 by the $RC = 90$–91 % data, which show that $(\varepsilon_v)_{N=15}$ values were consistent for two widely different saturation levels that place the specimens on opposite sides of the line-of-optimums, i.e., $S = 54$ and 91 %. The effects of RC and S are illustrated by contours of $(\varepsilon_v)_{N=15}$ associated with shear strain level $\gamma_c = 0.4$ % in Fig. 9. The contours show $(\varepsilon_v)_{N=15}$ decreasing with increasing RC and being insensitive to S. Similar trends were found for test results at shear strain level $\gamma_c = 1.0$ % (not shown).

Inspections of specimens upon the completion of testing consistently revealed no obvious clod formation. We interpret the lack of influence of S on $(\varepsilon_v)_{N=15}$ to be associated with a minimal presence of clod-like structure in these materials, which in turn is likely related to their low fines plasticity. The observed reduction of clod formation with decreasing soil plasticity is consistent with the previous findings of Bengochea et al. (1979) and Leroueil et al. (2002).

Comparison to Clean Sands

In this section, we compare the vertical strains measured during cyclic simple shear testing of two soils containing significant fines (i.e., Soils A-1 and B-3) to vertical strains measured from tests on clean sands to gain preliminary insight into the effects of fines content on seismic compression. The sand materials that were tested were as follows:

- Sand A was manufactured from Soil A-1 by washing out the portion of the soil passing the No. 200 sieve. The resulting sand has uniformity coefficient, $C_u = 5.0$ and median grain size, $D_{50} = 0.34$ mm.
- Sand B was similarly manufactured from Soil B-3 by washing out the fines. The resulting sand has $C_u = 4.9$ and $D_{50} = 0.25$ mm.
- Crystal Silica No. 30, a commercially available, clean uniform sand similar to that tested by Silver and Seed (1971) ($C_u = 1.5$ and $D_{50} = 0.52$ mm).

As modified Proctor relative compaction (RC) is used to characterize soils containing fines while relative density (D_R) is used to characterize clean sands, a comparison between the two can only be made with the use of a soil-specific relationship between D_R and RC for the sands. The general relationship between relative compaction and relative density has been expressed as (Lee and Singh 1971):

$$D_R\ (\%) = 5[RC\ (\%) - 80]; \quad 80 \le RC\ (\%) \le 100 \tag{1}$$

Material-specific relationships were evaluated from testing and were found to be:

$$\text{Sand A}: \quad D_R\ (\%) = 665 - 56530/RC\ (\%); \quad 84.9 \le RC\ (\%) \le 100 \tag{2}$$

$$\text{Sand B}: \quad D_R\ (\%) = 487 - 38710/RC\ (\%); \quad 79.5 \le RC\ (\%) \le 100 \tag{3}$$

$$\text{C.S. No.30}: \quad D_R\ (\%) = 546 - 44590/RC\ (\%); \quad 81.6 \le RC\ (\%) \le 100 \tag{4}$$

At an equivalent modified Proctor RC of 92 %, Sands A, B, and Crystal Silica No. 30 have $D_R = 51$, 66, and 60 %, respectively.

Using the above relations for sand, $(\varepsilon_v)_{N=15}$ for the clean sands and compacted fills are compared for $RC = 90$–92 %. In Fig. 10, test results for Soil A-1 (moderately plastic clay) are compared to those for Crystal Silica No. 30 and Sand A. Whereas the range of results for sands is narrowly banded, the range of $(\varepsilon_v)_{N=15}$ for Soil A-1 is much broader, and has systematic increases in $(\varepsilon_v)_{N=15}$ with decreasing S. Fill specimens compacted at $S \ge 74$ % (wet of the line of optimums) experienced levels of seismic compression that were 3–5 times smaller than those for clean sands. However, specimens compacted at $S = 66$ % (dry of the line of optimums) experienced vertical strains within the range for clean sands. A similar comparison is made in Fig. 11 between Soil B-3 (low plasticity silty sand) and Crystal Silica No. 30 and Sand B. Vertical strains in B-3 specimens are consistently less than those from the clean sands. In particular, Soil B-3 specimens experienced vertical strains 2–3 times less than Sand B specimens prepared to similar RC for all tested degrees-of-saturation.

Conclusions

Cyclic simple shear testing was performed on four reconstituted fill specimens for a wide range of formation modified Proctor relative compaction levels (RC) and degrees-of-saturation (S) to evaluate the effects of these parameters on seismic compression susceptibility. One specimen had low plasticity silty fines; the others had moderately plastic silty clayey fines. The test results were also compared to those for sands to gain insight into the effects of fines content on seismic compression.

The test results confirmed previous findings that the seismic compression susceptibility of soils containing significant fines increases with decreasing formation relative compaction (Pyke et al. 1975) and increasing shear strain amplitude. However, the test results provide significant new insights into the influence of degree-of-saturation and plasticity. Saturation was found to be important for soils with moderately plastic fines, but relatively unimportant for soils with low-plasticity fines, and these trends appear to be associated with variations in soil macro-structure. For a given soil material, the seismic compression susceptibility was found to increase with increasing clod formation, which is most pronounced

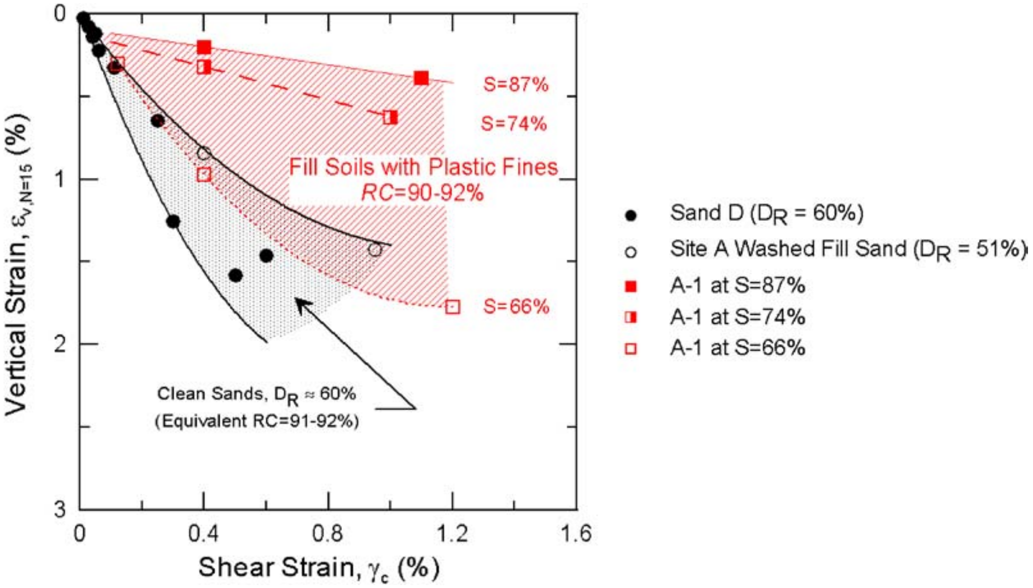


FIG. 10—*Comparison of vertical strains for Soil A-1 and clean sands at* $RC = 90$–92 %.

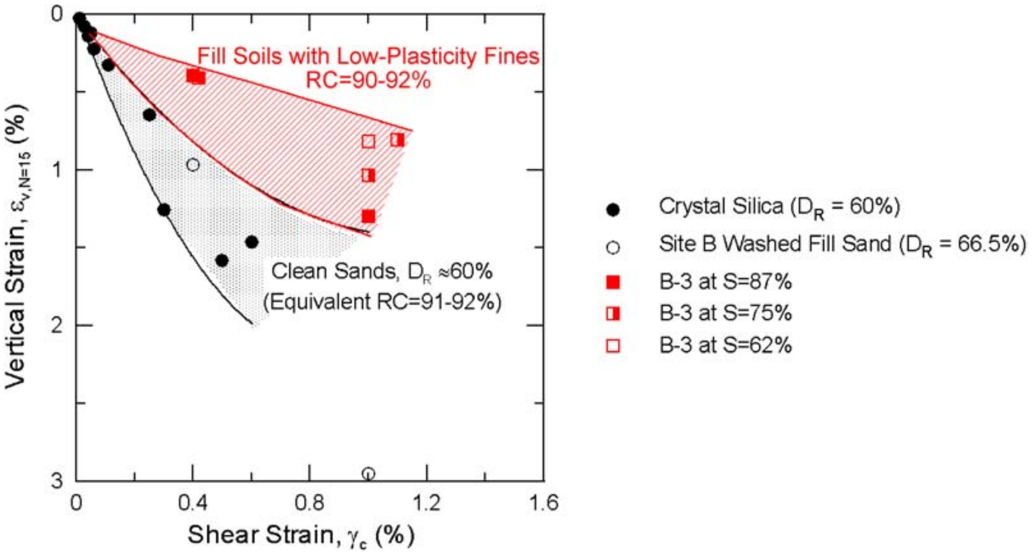


FIG. 11—*Comparison of vertical strains for Soil B-3 and clean sands at* $RC = 90$–92 %.

in plastic soils at low RC, and at moderate RC if the formation S is dry of the line-of-optimums.

Comparisons of test results between fill materials containing fines of low to moderate plasticity and clean sands suggest that soils with significant fines generally undergo systematically lower volumetric strain at similar loadings and relative compactions than clean sands. For soils with plastic fines, the effect of fines is strongly dependent on S, whereas the effect of nonplastic silty fines is relatively insensitive to S. It should be noted that these findings apply for materials having fines contents large enough that the fines would be expected to control the soils' mechanical properties. Further research is needed to investigate the effect of fines content on seismic compression across a wide range of fines contents and fines plasticities.

Based on these results, existing analysis procedures for seismic compression (i.e., Tokimatsu and Seed 1987), which were developed based on testing of clean, uniform sands, should be modified for soils that contain fines. Based on the findings presented herein, for design of new fills, we recommend compaction specifications be developed to minimize clod formation by controlling the initial clod size before compaction, as well as compacting to moderately high densities ($RC > \sim 90$ %) at water contents higher than the line-of-optimums. Caution should be exercised in extrapolating the test results presented in this paper to estimate the seismic compression susceptibility of existing fills, since the influence of factors such as aging and post-construction wetting are presently unknown.

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