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Cyclic Strength Evaluation of Rockfill Dams

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SYNOPSIS: A method of modeling the cyclic behavior of gravelly soils containing particles too large to be tested in standard laboratory equipment has been described. This matrix model is based on the understanding that oversize particles floating in a matrix of smaller grains can be removed without significantly affecting the cyclic behavior of the total soil. Successful modeling of the total soil requires that the matrix be tested at the same relative density as that of the total material. Cyclic triaxial test results on two different gravelly soils are presented. Results of tests performed on the total soil with maximum grain size of 2 in. are accurately predicted by cyclic tests on smaller samples of matrix soil with 0.5 in. maximum grain size.

INTRODUCTION

The construction of large earth and rock fill dams requires large quantities of select materials which are becoming more difficult to obtain at reasonable cost in many parts of the world. Accordingly, increasing numbers of these structures are being constructed utilizing very coarse-grained fills, including gravel-boulder mixtures. The large size particles pose problems to the geotechnical engineer who must determine strength parameters for the fill material for use in design and stability analyses. Many particle sizes for coarse-grained materials are too large to be tested with conventional laboratory equipment and very few laboratories have large size testing apparatus. In order to determine the relevant properties of the prototype material (the actual material to be used), laboratory specimens of a model soil are prepared and tested. This model soil has a smaller maximum particle size than that of the prototype material. The successful determination of prototype material properties from tests on model soil depends on the appropriateness of the modeling criteria. Such criteria must be capable of selecting the composition and gradation of the model material and its density.

This paper briefly describes three modeling criteria which have been utilized for determining prototype strength parameters. A new modeling criterion for the determination of cyclic strength is then described. Test results using fill material from two California dams are presented which support the validity of the proposed (matrix) modeling criterion.

BACKGROUND

The diameter of the soil specimen controls the maximum grain size which can be tested with a given triaxial testing apparatus. Typically, a minimum ratio of specimen diameter to maximum grain size of six is considered necessary for meaningful test results. For the conventional triaxial specimen diameter of 2.8 inches, all particles larger than approximately 1/2 inch are "oversize" and must be removed before testing.

There are at least three procedures commonly used to overcome this problem of "oversize" particles. The oversize particles can simply be scalped and the laboratory samples prepared from the remaining material; the oversize particles can be scalped and replaced by an equal dry weight of the largest particle size fraction that can be satisfactorily incorporated in the laboratory specimens; or, the laboratory specimens can be entirely reconstructed with a particle size distribution parallel to that of the prototype material.

In addition to the selection of a suitable grain size distribution for the soil used in the laboratory tests, the correct choice of specimen density is also necessary for the accurate prediction of the strength properties of the prototype material. The laboratory specimen can be prepared either at the same dry density as that of the soil matrix of the prototype material, at a dry density corresponding to the same relative density as the prototype material, or at some other condition. The density selected for the laboratory specimen may be different for static vs. dynamic strength parameters.

Each of the modeling criteria described above have been used with limited success to determine static strength of fills containing oversize particles. For example, Marachi et al (1969) used the parallel gradation model originally proposed by Lowe (1964) for determining drained strength parameters for Oroville Dam located in Northern California. Donaghe et al. (1976) have performed numerous studies investigating the validity of the scalp and replace method for static strength predictions. Modeling studies for the prediction of cyclic strength parameters have been extremely limited. This is probably due to two reasons: (1) gravelly soils have generally performed much better than sands during past earthquakes; and (2) most soil laboratories are not equipped with large scale cyclic apparatus required for testing gravelly soils. Thus, the only available data for gravelly soils seem to be that presented by Lee and Fitton (1969), Wong et al. (1974) and Banerjee et al. (1979). Wong et al. (1974) reported that the cyclic stresses required to cause a given strain in gravelly soils are apparently somewhat higher than those needed to cause a similar strain in sandy soils. It was explained, however, that the difference could have been due entirely or in part to membrane penetration effects.

THE MATRIX METHOD

To properly model the engineering behavior of a granular soil with oversize particles, it is necessary to understand the interaction of oversize grains with the remaining "matrix" soil. Depending upon the quantity of oversize grains present in the prototype material, these oversize particles may exist either in a "floating" or "non-floating" state (Siddiqi, 1984). In the floating state the oversize particles are not in contact with each other and are "floating" in a matrix of smaller grains. In the non-floating state there is a continuous grain-to-grain contact between oversize particles, and the matrix soil merely fills the voids created by the structure of these oversize grains. It has been found (Siddiqi et al, 1987) that for most gravelly soils, the floating state exists when the oversize particles make up approximately 40% or less by weight of the total material. The non-floating state occurs when the percentage by weight of the oversize particles exceeds approximately 60%. In the range between 40 and 60% there is grain-to-grain contact between some of the oversize particles, but not all oversize grains are in continuous contact with each other.

The soil matrix around oversize particles has been shown by Siddiqi (1984) and Fragaszy et al (1990) to exist in two distinct zones called the near-field and the far-field. The near-field soil matrix is relatively loosely packed due to geometric surface effects. A few grain diameters away from the oversize particle in the zone of far-field, the soil matrix is less influenced by the oversize particle and therefore more densely packed. Su (1989) has shown that the drained strength of the total material is primarily dependent on the far-field matrix density when the oversize particles are in the floating state.

Cyclic strength behavior (and the tendency for the material to decrease in volume under cyclic loading) is related to the difference between the dry density of the material and its minimum and maximum densities. This difference is expressed by relative density. Therefore, the relative density (or the degree of compaction) can be expected to control the cyclic strength behavior of granular soils. For a given material, the relative density of the prototype (total) material and of the soil matrix contained within the total material are the same. If the oversize particles exist in the floating state the resistance to external cyclic loading is primarily derived from the soil matrix of smaller particles. The oversize particles are merely a part of the mechanism which allows the transfer of external loading to the soil matrix without contributing any significant resistance to the loading. In other words it is the soil matrix which controls the cyclic behavior of the prototype material. Consequently, the test results obtained for the soil matrix alone (with no oversize grains) will predict the cyclic behavior of the prototype material regardless of the percent of oversize particles as long as they exist in the floating state. It is therefore hypothesized that in order to predict the cyclic behavior of a prototype (total) material with "floating" oversized grains, tests should be performed on the soil matrix alone in the laboratory at the same relative density, not the same absolute density, as that of the prototype (total) material. Since it is the overall volume change involved in cyclic behavior, it is further hypothesized that the computations for the relative density of the soil matrix in the presence of the oversized grains should be based on the computed "average" soil matrix density. To test these hypotheses, a cyclic triaxial testing program as described below was undertaken.

MATERIALS AND TESTING PROGRAM

Two distinctly different types of gravelly soils were selected to test the matrix modeling hypothesis described above. One material was obtained from Lake Valley Dam, a rock-fill dam located in the Sierra Nevada mountains of Northern California, approximately 50 miles northwest of Lake Tahoe. The other material came from Oroville dam, also in California.

The Lake Valley dam material consisted of cobbles, gravel, sand and a small amount of silt. Due to the size constraints of the testing equipment available, only the minus 2 inch material was used. The gravel particles are rounded to sub-rounded with specific gravities ranging between 2.70 and 2.76. The minus number 4 sieve material has an unusually high specific gravity of 2.92.

The Oroville dam material consisted of cobbles, gravel and sand. Again, only minus 2 in. material was utilized. The gravel size particles are rounded to sub-rounded and the specific gravity ranged from 2.78 to 2.92.

For both soils, the oversize material was defined to be particles larger than 0.5 in. so that the matrix material could be tested with a 2.8 in. diameter triaxial sample. Grain size distribution curves for model and prototype Lake Valley and Oroville Dam materials are presented in Fig. 1. Additional information on the physical properties of these materials are contained in Tables 1 and 2.

The testing program described in this paper consisted of two sets of undrained cyclic triaxial tests on Lake Valley gravel and one set of tests on Oroville gravel. The first set of tests on Lake Valley gravel was conducted on the total material and incorporated 12 inch diameter samples. The second set was conducted on the

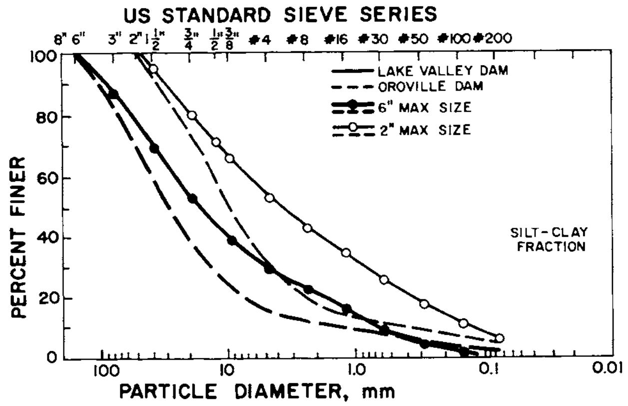

Fig. 1 Gradation Curves for Test Soils

TABLE 1. Physical Characteristics of Lake Valley Gravel

	Total Material	Matrix Material
Type of material	River Gravel	
Classification	GW-GM	SW-SM
Mean Grain Diameter	3.8mm	1.4mm
Uniformity Coeff. (C_u)	62.5	29.3
Coeff. of Curvature (C_c)	1.0	1.07
Specific Gravity		
Minus No. 4:	2.92	2.92
No. 4 to 0.5"	2.76	2.76
0.5" to 2"	2.74	-
Average	2.81	2.84
Plasticity	NP	NP
Max. dry density (Mg/m^3)	2.23	2.12
Min. dry density (Mg/m^3)	1.83	1.68
Maximum void ratio	0.538	0.688
Minimum void ratio	0.261	0.343
Amount of oversize particles (0.5" to 2.0")	29%	-

TABLE 2. Physical Characteristics of Oroville Gravel

	Total Material	Matrix Material
Type of material	River Gravel	
Classification	GW-GM	GW-GM
Mean Grain Diameter	9.5mm	4.0mm
Uniformity Coeff. (C_u)	47.0	38.7
Coeff. of Curvature (C_c)	3.85	4.83
Specific Gravity		
Minus 3/16"	2.78	2.78
3/16" to 2"	2.92	-
3/16"to 0.5"	-	2.92
Average	2.85	2.85
Plasticity	NP	NP
Max. dry density (Mg/m^3)	2.46	2.24
Min. dry density (Mg/m^3)	2.00	1.72
Maximum void ratio	0.440	0.617
Minimum void ratio	0.165	0.240
Amount of oversize particles (0.5" to 2.0")	41%	-

model material and incorporated 2.8 inch diameter samples. For each triaxial test, the number of cycles required to cause a residual pore pressure of 100% (initial liquefaction) was determined, as well as the number of cycles required to cause 2.5%, 5%, 10% and 20% double amplitude axial strain. The cyclic stress ratio was varied across tests so that a relationship between cyclic stress ratio and number of cycles could be developed. All tests were conducted at a relative density of 40% with an effective confining pressure of 2 kg/cm^2. Both system compliance and membrane strength corrections were applied to all test results (Siddiqi, 1984)

Testing of Oroville gravel consisted of 2.8 in. diameter cyclic triaxial tests on the matrix material in which the number of cycles to cause initial liquefaction was determined as a function of cyclic stress ratio. These data are compared with the results of tests performed on 12 in. diameter specimens of the prototype material by Banerjee (1979). The specimens of the matrix and the prototype material from Oroville Dam were prepared at 84% relative density. All other aspects of these tests were the same as that for Lake Valley Dam material.

RESULTS

The cyclic load test data for 12 inch and 2.8 inch diameter specimens of Lake Valley gravel prepared at a relative density of 40% are presented in Figs. 2 and 3. In Fig. 2 the cyclic stress ratio required to cause initial liquefaction is plotted against number of cycles. The number of cycles to initial liquefaction varied from 4 at a stress ratio of 0.272 to 180 at a stress ratio of 0.158. Data from both 12 and 2.8 in. diameter specimens fall on virtually the same curve.

In Fig. 3 the cyclic stress ratio required to cause 10% double amplitude axial strain is plotted against number of cycles. Again, the data for the model and prototype soils match very well with the number of cycles ranging from 5 to 184 at stress ratios of 0.272 and 0.158, respectively. Tables 3 and 4 present results of all cyclic tests performed on Lake Valley gravel.

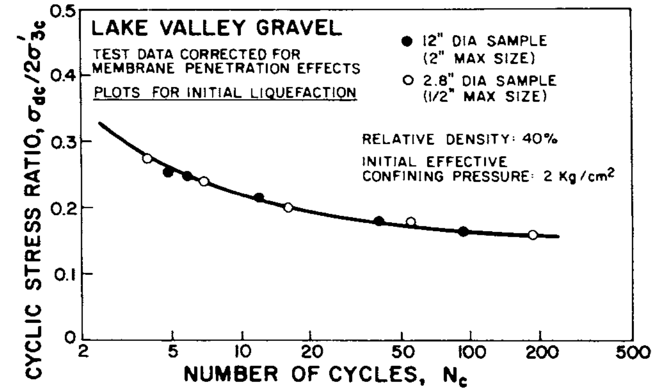

Fig. 2 Cyclic Stress Ratio vs. Cycles to Cause Initial Liquefaction-Lake Valley Gravel

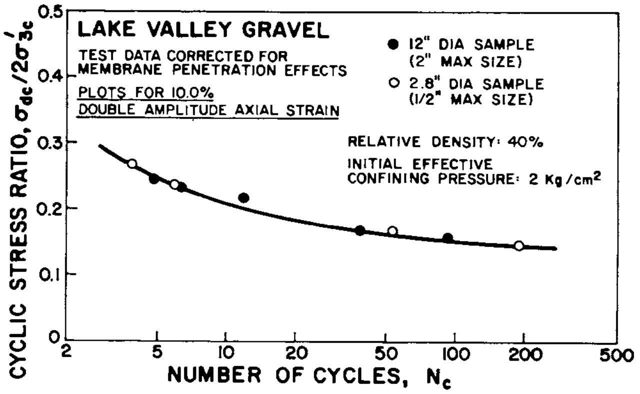

Fig. 3 Cyclic Stress Ratio vs. Cycles to Cause 10% Double Amplitude Axial Strain - Lake Valley Gravel

TABLE 3. Summary of Tests on Lake Valley Gravel (Total Material) Corrected for System Compliance

Ave. Cyclic Stress Ratio	Number of Cycles to Develop Initial Liquefaction	Strain[1] of 2.5%	5%	10%	20%
0.252	5	4	5	6	7
0.248	6	5	6	7	8
0.237	4	3	4	5	6
0.225	12	11	12	13	14
0.180	39	38	39	40	42
0.168	90	89	90	91	92

[1] Double Amplitude Axial Strain

TABLE 4. Summary of Tests on Lake Valley Gravel (Matrix Material) Corrected for System Compliance

Ave. Cyclic Stress Ratio	Number of Cycles to Develop Initial Liquefaction	Strain[1] of 2.5%	5%	10%	20%
0.272	4	3	4	5	6
0.238	7	4	6	8	10
0.187	16	13	15	17	21
0.173	52	49	52	54	58
0.158	180	176	179	184	190

[1] Double Amplitude Axial Strain

Fig. 4 presents the comparison between results of Banerjee's liquefaction tests on prototype material and the results of tests on the modeled soil matrix performed during this study. The number of cycles to cause initial liquefaction ranged from 21 to 540 at average cyclic stress ratios between 0.43 and 0.27, respectively. As with the Lake Valley gravel, there is an excellent agreement between prototype and model test results.

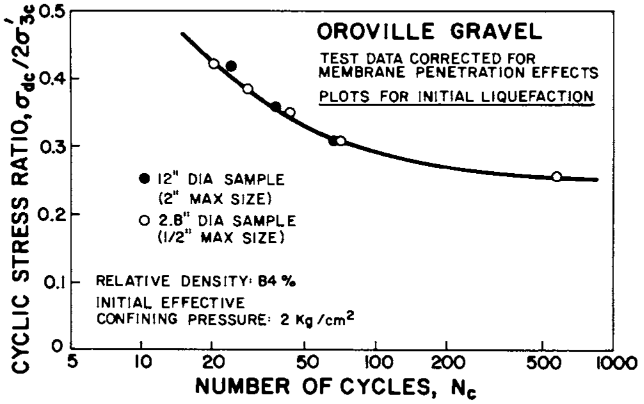

Fig. 4 Cyclic Stress Ratio vs. Cycles to Cause Initial Liquefaction - Oroville Gravel

DISCUSSION

The test data presented above provide very convincing evidence that the cyclic strength behavior of gravelly soils is not significantly influenced by the coarsest grains if they exist in the floating state. Consequently, the cyclic strength parameters for these gravelly soils can be predicted by simply removing the "floating" coarse fraction and testing the soil matrix of smaller particles in the laboratory with standard triaxial testing equipment. The density of the triaxial specimens of the soil matrix should correspond to the same relative density as that of the total or prototype gravelly soil in accordance with the matrix method as presented above.

In the tests described above, the cyclic stress ratios required to cause initial liquefaction in specimens of the total material and the soil matrix without coarse fraction prepared at the same relative density are virtually identical. Additional test data for other cyclic strains as shown in Tables 3 and 4, further confirm the close similarity between the behavior of the total and matrix soils. The results of tests on Oroville gravel which were conducted at a much higher relative density than those performed on the Lake Valley gravel, as well as additional test data for Lake Valley gravel presented by Siddiqi (1984) show that the match between the prototype and model test data extends over a large range of relative densities.

The maximum percentage of oversize material which can be removed without significantly affecting the cyclic strength behavior of the soil matrix of finer particles can not be exactly determined at this time. Since 41% of the Oroville gravel was oversize, the upper limit is at least this high. Recent work by the authors on modeling static strength (Fragaszy et al., 1990; Fragaszy et al., in review) suggests that the upper limit may be in the range of 40-50% with the grain geometry and surface texture influencing the exact value within this range.

Additional work is required to expand the data base to include silty and clayey soils, and a wider range of grain shapes, textures and gradation. However, the authors believe that the basic assumptions of the matrix method will prove valid over a wide range of soil types.

SUMMARY AND CONCLUSIONS

A matrix modeling method for predicting the cyclic strength behavior of gravelly soils containing particles too large to be tested in standard triaxial equipment has been described. Cyclic triaxial tests on two different gravelly soils with maximum grain size of 2 in. were conducted utilizing 12 in. diameter specimens. The results of these tests were successfully duplicated by cyclic tests performed on 2.8 in. diameter specimens of the same soils created by scalping the oversize particles (all particles larger than 0.5 in.) and compacting the remaining matrix soil to the same relative density as that of the total material. The results of this testing program lead to the following conclusions:

1) The very coarse fraction in gravelly soils does not significantly influence cyclic strength behavior of these soils provided the very coarse fraction exists in a "floating" state.

2) The cyclic strength behavior of gravelly soils containing particles too large to be incorporated in a triaxial specimen may be modeled by scalping the oversize particles and testing the remaining matrix material, provided the oversize particles are "floating" in the soil matrix.

3) The matrix material used to model the cyclic strength behavior of the total soil must be tested at the same relative density as that of the total soil.

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