The Behaviour of a Compacted Tertiary Siltstone Under Seismic Loading

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SUMMARY: A comprehensive laboratory testing programme including both monotonic loading triaxial tests and stress controlled dynamic triaxial tests has been carried out to assess the suitability of fine sandy siltstone as fill material in the construction of a 72m high earth dam. The grading suggests that the compacted siltstone can provide high frictional resistance as well as low permeability. The monotonic triaxial tests indicated that the material tends to compact under load and this may lead to build up in pore pressure under cyclic earthquake loading. However, the dynamic triaxial tests subsequently showed that the compacted siltstone will provide a high resistance to liquefaction. It was concluded that the compacted siltstone will provide a satisfactory fill material for the proposed dam.

1 INTRODUCTION

This paper summarises the work carried out during the feasibility study for the Patea Hydro Electric Scheme for the Egmont Electric Power Board. The construction of a large (1 million cubic metre volume) earthfill dam was proposed on the Patea River (and is now in the detailed design stage). The selected dam site is situated in a deep sided valley. The meanders are deeply incised in near horizontal layers of sedimentary Tertiary Sandstone. The materials considered for use in the dam were the Tertiary Sandstone (which underlies the whole area) or silts and gravels deposited by various means on the river terraces.

The silts (volcanic ash) deposited on the old elevated river terraces were considered not suitable due to the high in-situ moisture content. The old terrace gravels found beneath the volcanic ash were variable in degree of weathering and were a long distance from the dam site. The river gravel would require costly dredging and hauling due to the difficult terrain. Comparative studies indicated that the most economical source of fill material would be the Tertiary Sandstone obtained from the high ground adjacent to the dam site.

Preliminary work indicated that the Tertiary Sandstone deposit consists of thick layers of mudstone, siltstone and sandstone interbedded with thinner layers of limestone. The mudstone layer was found to be suitable as core material but could not be readily quarried due to excessive depth of overlying material. Grading tests showed the sandstone layer to be an almost uniform fine sand which is not suitable due to its likely high permeability.

The siltstone layer is evenly graded and was observed to be readily available in large quantities adjacent to the dam site.

The Patea dam site is situated in a seismic zone. Doubt has been previously expressed regarding the competence of the sands and silts derived from these Tertiary deposits as an earth dam material. The near uniform particle size suggested that saturated compacted siltstone in the dam shoulders may liquefy or become mobile if subjected to severe earthquake shaking.

A laboratory testing programme consisting of both monotonic loading triaxial testing and dynamic triaxial testing was carried out to assess the behaviour of the saturated compacted siltstone under earthquake shaking.

2 LABORATORY STUDY

2.1 Volumetric Strain Behaviour

A simple approach to the study of liquefaction potential of a granular material is to postulate that for a certain effective confining pressure there exists a critical density above which the material will tend to dilate under loading and below this critical density the material will tend to compact. A saturated sand compacted to a density below its critical density will develop positive pore pressures under undrained conditions when loaded to failure, while above this critical density the pore pressure developed will be negative. The development of positive pore pressures may lead to liquefaction if the pore pressure accumulates as a result of repeated loading and approaches the level of the confining pressure.

In order to study the variation of volumetric strain behaviour of the Tertiary siltstone proposed to be used in the dam with different degrees of compactive effort the siltstone was compacted as follows:-

(i) standard effort : 2.5 kg hammer falling 300mm 25 blows/50mm layer

(ii) heavy effort : 4.5 kg hammer falling 458mm, 25 blows/50mm layer

(iii) extra heavy effort : 3 times the heavy effort.

The maximum dry densities achieved are shown in Table 1.

TABLE 1

RESULTS OF MONOTONIC TRIAXIAL (CD) TESTS

Compaction Effort	Optimum Moisture Content %	Maximum Dry Density t/m^3	Effective Cohesion C' = kPa	Effective Friction Angle ϕ' = degrees
"Standard"	16	1.76	55	29
"Heavy"	13	1.91	186	32
"Extra Heavy"	11	2.01	210	38

100mm diameter samples compacted at optimum moisture content were loaded monotonically in a conventional triaxial cell. Consolidated drained triaxial tests were carried out with continuous volume monitoring. These were carried out as staged triaxial tests in order to study the volumetric behaviour of the material over a wide range of effective confining pressures.

Results of the stress and strain and volume change curves as shown in Fig. 1, 2 and 3 indicate that the siltstone tends to contract initially under the range of confining pressures used for all three levels of compacted densities. The level of volume reduction is greatest in the "standard" sample and decreases for the samples compacted with greater effort. No dilation was noted at failure in the "standard" sample, however some dilation occurs at failure in the "heavy" and "extra heavy" samples (following initial contraction).

It was noted that for small levels of strain, the siltstone will tend to contract, even if it was compacted to 114% of standard compaction ("extra heavy"). Castio and Poulos (1977) state that liquefaction only occurs in materials that are highly contractive, i.e. their effective confining stresses and density must lie above the steady state line (point A in figure 4). The material would then reduce in volume under drained test conditions or develop positive pore pressure under undrained conditions.

A material whose density and stress state lie below the critical line, (point C in figure 4) may tend to contract slightly at first but then it will move horizontally towards the steady state line as load is applied. This denser material would tend to dilate at failure under drained test conditions and develop negative pore pressure under undrained conditions.

However, even for a dense material (as defined by Lee and Seed, 1967), the material tested as described above will tend to contract under a confining pressure higher than the critical confining pressure (point E, figure 4).

The volume change records shown in Fig 1 indicate the critical effective confining pressure to be about 150 kPa. According to the critical void ratio theory, the siltstone compacted using the "standard" compaction effort may liquefy when sheared under an effective confining pressure in excess of 150 kPa.

Figs 2 and 3 indicate that for the siltstone compacted using the "heavy" compactive effort, the critical confining pressure would be about 250 kPa and for the "extra heavy" compactive effort in excess of 500 kPa.

The practical level of compaction achievable in dam construction using sandy material is in the order of 95% to 100% of the "standard" compactive effort and hence the "heavy" and "extra heavy" compactive efforts would not be economically achievable in the field.

The effective confining pressure under a 72m high dam would be in excess of 700 kPa. Therefore it is concluded from the test results obtained that the compacted siltstone will develop positive pore pressures under earthquake loading. However, this may not necessarily mean that liquefaction will occur under earthquake as liquefaction will depend on the magnitude of the pore pressure rise during an earthquake load cycle, its rate of dissipation and the eventual build up due to the accumulation of the residual pore pressure at the end of each load cycle.

The next step was to study the pre pressure behaviour under cyclic loading which simulates earthquake loading.

2.2 Pore Pressure Build up Under Cyclic Loading

Stress controlled dynamic triaxial tests were carried out in the Civil Engineering Department of the University of Auckland. The samples were 100mm diameter and compacted to a range of densities, similar to those used for the monotonic load tests described above. The cell pressure was kept constant, the pore pressure was continuously monitored and the cyclic loading was applied axially. Full details of the dynamic triaxial apparatus have been published (Taylor, 1967).

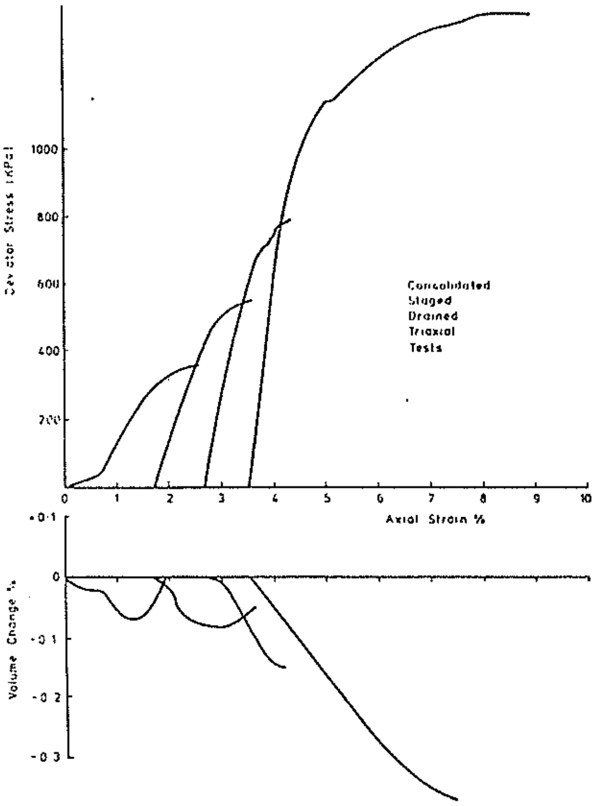

Fig. 1 Compacted Siltstone - "Standard" Effort

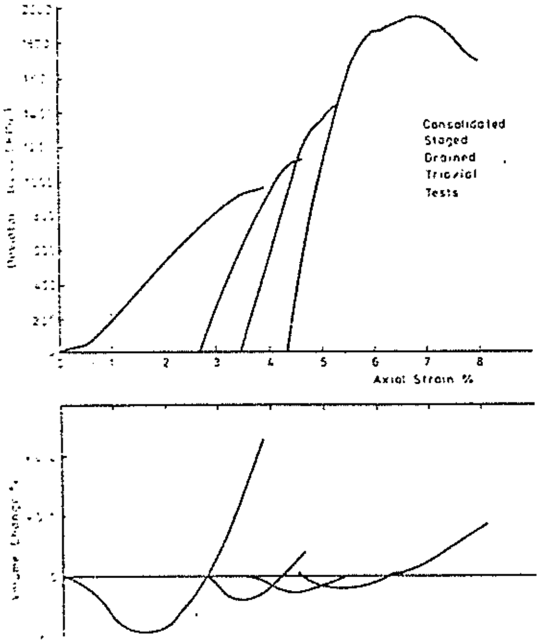

Fig. 2 Compacted Siltstone - "Heavy" Effort

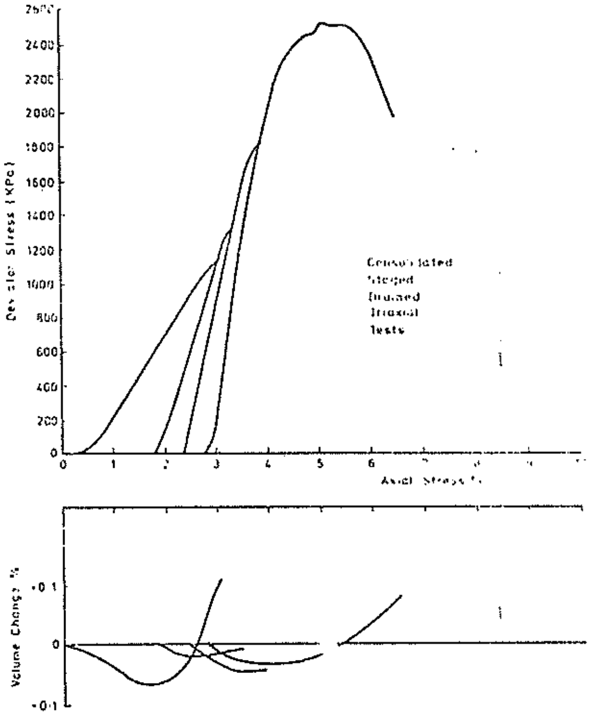

Fig. 3 Compacted Siltstone - "Extra Heavy" Effort

Each of the samples was subjected to varying levels of cyclic shear stress ratio for up to 500 cycles or 5% strain. Once 5% strain is reached, the sample was then failed under monotonic loading and the final pore pressure recorded. Table 2 summarises the data obtained from the series of dynamic triaxial tests and Table 3 shows some typical relationships between earthquake magnitude and expected cyclic stress ratios.

Cyclic stress ratio is defined as the ratio between the cyclic deviator stress and two times the initial effective confining stress ($\sigma_{dc}/2\sigma_{3i}$).

Fig. 5 shows the grading of the siltstone material compared to the grading envelope of material which are generally regarded as being susceptible to liquefaction. Also shown on Fig. 5 is the grading of a fine sandstone (also available at the dam site but judged to be unsuitable). The grading curve for the siltstone shows it has basically a granular nature so that when compacted the material has a high frictional shearing strength. Table 1 indicates an effective angle of internal friction of 29° is readily achievable. In addition it has sufficient clay content to give it the desirable low permeability (in the order of 10^{-5} cm/sec) and the effective cohesion of a clayey soil (about 55 kPa). The clay and silt content in the compacted siltstone will also provide high resistance to liquefaction when subjected to earthquake shaking.

Fig. 6 shows the comparison of results of dynamic triaxial test on the compacted siltstone with results of similar tests obtained from construction materials for dams (Selig et al, 1978) with known performance during strong earthquake shaking and other laboratory compacted materials (Seed, 1979).

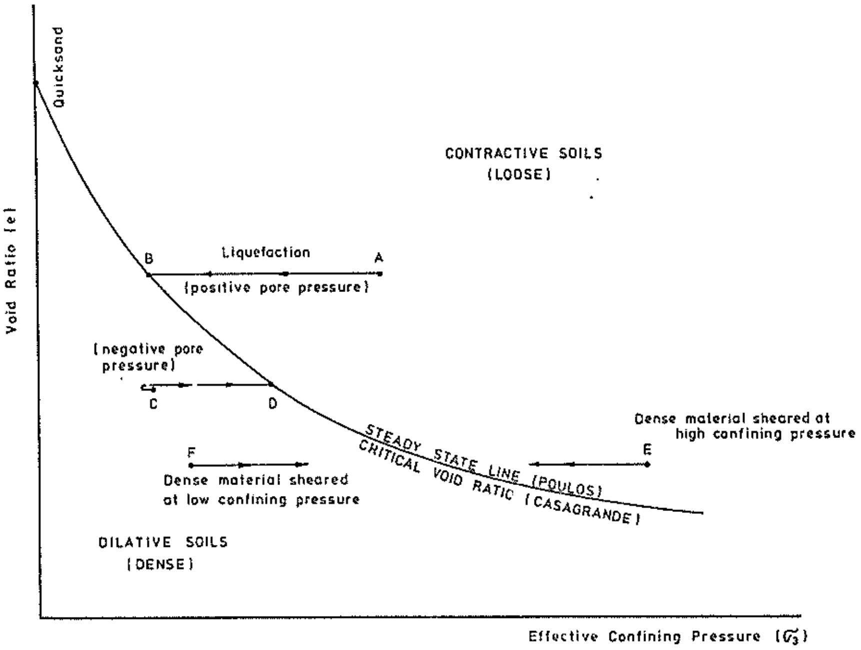

Fig. 4 Steady State Line Concept (After Castro & Poulos, 1977)

TABLE II

RESULTS OF DYNAMIC TRIAXIAL TESTS

Compaction Effort	Dry Density (t/m^3)	Test No.	Shear Stress Ratio	No. of Cycles	Cycles to 5% Strain	Initial Confining Pressure (kPa)	Increase in Pore Pressure (kPa)	Monotonic Failure	
								Effective Confining Stress (kPa)	Effective Vertical Stress (kPa)
Heavy	2.02	1	.125	500	>500	500	28		
		2	.206	500	>500	462	35		
		3	.332	500	>500	423	79	702	3955
Heavy	2.04	4	.122	500	>500	500	20		
		5	.215	500	>500	480	40		
		6	.277	500	>500	440	35	795	2545
Standard	1.82	7	.118	500	>500	500	48		
		8	.184	500	>500	452	32		
		9	.258	500	>500	420	165		
		10	.529	100	68	255	200	420	1380
Standard	1.80	11	.125	500	>500	500	70		
		12	.176	500	>500	430	27		
		13	.241	500	>500	403	50		
		14	.338	500	385	353	303	360	1220
Standard	1.78	15	.530	8	7	300	275	265	1067
Standard	1.76	16	.300	600	525	300	275	255	1135

The concept of equivalent number of shear stress reversals has been generally used (Seed, 1979) to represent earthquakes of varying magnitude. Table 3 shows relationships between earthquake magnitude, number of equivalent cycles at 65% of the peak stress and typical range of cyclic stress ratios. The numbers of equivalent shear stress cycles shown in Table 3 are the result of statistical study of the representative number of cycles for a number of different earthquake motions and the effects of typical irregular stress history of earthquake vibrations.

This concept of equivalent number of uniform stress cycles allows simple cyclic shear tests to be performed and the results compared with records of past performance. Due to the inherent inaccuracies contained in this simplified approach, considerable judgement is required in the assessment of the liquefaction potential.

Fig. 6 includes cyclic load test data on relatively loose sand with a relative density of 54% (Dr = 54%) and also dense sand with a relative density of 82% (Seed, 1979). Sands compacted under different methods were studied by Mori, et al (1977).

Pouring sand through water (hydraulic fill) achieved rather low degree of compaction.

Tamping produced a much higher degree of compaction giving densities closer to Dr = 80%. High frequency vibration compaction was effective in producing a very dense material with high resistance to liquefaction. The test data points shown in Fig. 6 indicated that the compacted siltstone (using "standard" compaction effort) achieved a relatively high resistance to cyclic loading. Referring to Tables 2 and 3, it can be seen that the compacted siltstone may resist a magnitude 8 earthquake at a distance of the order of 30 km or an earthquake of magnitude 6.5 at a distance of about 5 km.

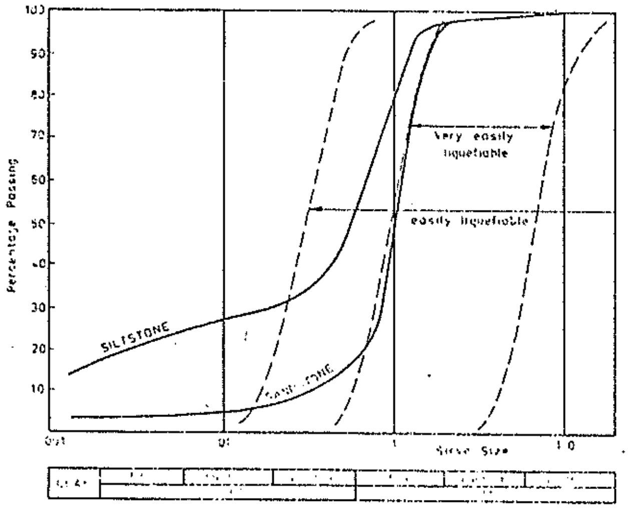

Fig. 5 Material Grading Curves

The data points obtained from the dynamic triaxial tests carried out on the compacted siltstone showed (Fig. 6) that this material performs in a manner representative of typical compacted soils used in dams with proven good performance during known strong earthquake shaking. For example, the Chabot Dam survived a magnitude 8½ earthquake at a distance of 20 miles (0.4g max horizontal acceleration) with no apparent damage and would probably survive a magnitude 7 earthquake at a distance of 2 miles (0.6g max. horizontal acceleration). The Lower Franklin and Fairmont dams survived a magnitude 6½ earthquake at a distance of 20 miles (0.2g max. horizontal acceleration) with no apparent damage.

Fig. 7 showed the results of monotonic loading carried out on the dynamic triaxial sample after the conclusion of the cyclic shear test. In the cases of tests 10, 14, 15 and 16, the monotonic loading was carried out after 5% strain was achieved. It was also noted that the compacted siltstone sample retained its cylindrical shape, even though the pore pressure had reached up to 92% of the initial confining pressure. The effective shear strength recorded was still equivalent to that measured in conventional triaxial tests. This suggested that the compacted siltstone material did not become "liquefied" (and hence with no residual resistance) but conditions of cyclic mobility had occurred and that the soil would stabilise under the applied loads once the pore pressure dropped.

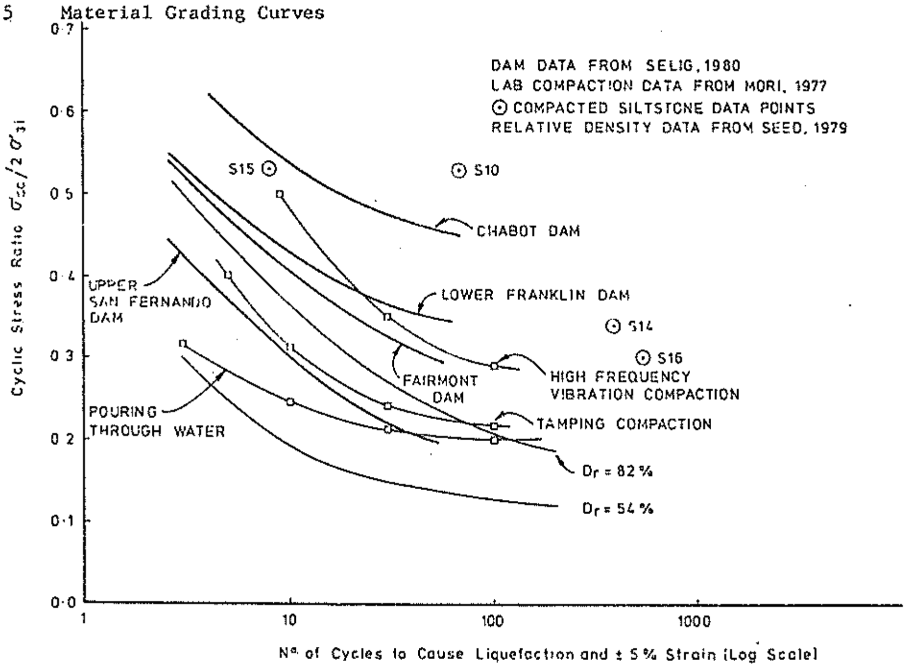

Fig 6 Comparison of Compacted Siltstone with Existing Liquefaction Data

TABLE III

EARTHQUAKE INDUCED LIQUEFACTION DATA

EQ Magnitude	No. of Equivalent Cyclics (*)	Typical Cyclic Stress Ratio (+)	Duration of Strong Shaking (*) (secs)	Typical Acceleration at 20 km (⁑) (%g)	Typical Acceleration at 5 km (⁑) (%g)
5½-6	5	0.1 - 0.25	8	0.12	0.35
6½	8	0.12- 0.35	14	0.18	0.46
7	12	0.15- 0.40	20	0.25	0.56
7½	20	0.20- 0.45	40	0.35	0.68
8	30	0.35- 0.50	60	0.45	0.80

Note: (*) Seed et al, 1976
(+) deduced from Mori et al, 1977
(⁑) Donovan et al, 1978

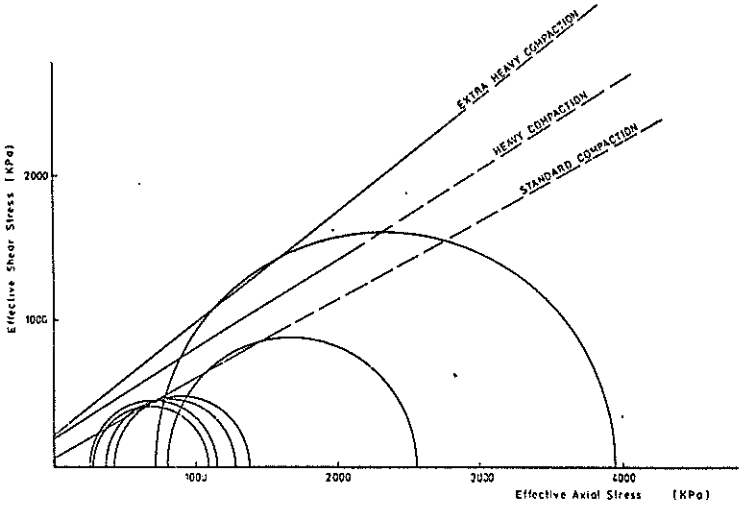

Fig 7 Compacted Siltstone Strength After Dynamic Triaxial Testing

3 CONCLUSIONS

The laboratory testing programme described in this paper has established that:-

(i) the tertiary siltstone material selected for use in the construction of the earth dam after quarrying and compaction into place is a fine sand/silt mixture with high frictional strength. The siltstone also contains silt and clay content to give the compacted material effective cohesion and good potential resistance to liquefaction.

(ii) Drained triaxial tests indicated that the compacted siltstone tend to contract under monotonic loading at low strains even at very high level of compactive effort which is not readily achievable in field conditions. Hence it is expected that pore pressure may build up during earthquake loading.

(iii) Stress controlled dynamic triaxial tests have shown that the compacted siltstone performs well under repeated cyclic shear even at high cyclic stress ratios in a manner representative of typical compacted soils used in dams with proven good performance. The pore pressure was found to increase under repeated cyclic shear loadings but the test sample retained its cylindrical shape and still retained unaltered effective shear strength under monotonic loading following the dynamic tests.

It was concluded that the compacted siltstone will provide a competent material for the construction of an earth dam despite the observed fact that this material contracts under monotonic loading at compactive efforts which are readily achievable under field conditions.

4 ACKNOWLEDGEMENTS

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