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ABSTRACT In order to update existing regulations for the seismic design of tailings retention dikes, extensive investigations were undertaken for 15 existing tailings dams throughout Japan. Undisturbed samples procured from the tailings disposal ponds were tested in the laboratory to determine the cyclic strength of the in-situ tailings deposits. The results of cyclic triaxial tests on these materials are summarized by means of empirical formulae which are recommended for incorporation in the new seismic design code for the tailings dams.

INTRODUCTION

In a typical mining operation, minerals are recovered by crushing and grinding the ore until it is the size of sand and silt. Then, the crushed ore is subjected to a concentration process. Residues left after the mineral concentrates separated out are called tailings. Tailings are usually transported as a thin slurry through pipes or flumes to suitable disposal ponds retained by tailings dams. In the tailings ponds, the suspended fine grained tailings are sedimented very loosely. Unless adequate drainage is provided, the sedimented tailings remain under-consolidated for many years.

One of the major geotechnical engineering concerns posed by tailings disposal ponds is the possibility of earthquake-induced liquefaction, resulting in the failure of the pond containment dikes. The likelihood and seriousness of such liquefaction have been underscored by the failure of the Barahona tailings dam that occurred at El Teniente copper mine in Chile following the earthquake on October 1, 1928 (Dobry - Alvarez, 1967). During a more recent earthquake in Chile on March 28, 1965, the catastrophic failure of the tailings dike at El Cobre copper mine was also triggered by liquefaction that occurred in the tailings disposal pond. Another spectacular example of liquefaction-induced failure was the flow of tailings slime that took place at the Mochikoshi storage pond in Japan during the Near Izu-Oshima earthquake of January 14, 1978.

Primarily because of the recent failure of the Mochikoshi containment dam, the existing regulations for the design of tailings dams in Japan have come under critical scrutiny. In an effort to promulgate new, more stringent regulations, the Japanese government embarked on a nationwide investigation of the seismic safety of existing tailings retention dams. As part of this investigation, undisturbed samples of tailings from 15 dam sites were taken and tested in the laboratory. From the results of these tests, new design formulae were established to evaluate the in-situ strength of tailings deposits under seismic loading conditions. The following sections summarize the results of this investigation.

COMPARISON OF UNDISTURBED AND RECONSTITUTED SAMPLE BEHAVIOR

As previously discussed, the tailings slurry is spigotted through pipes or flumes into the pond near the dam and spreads over existing tailings deposits downward towards the center of the pond. During a single period of continuous slurry discharge, a thin homogeneous layer of tailings approximately 2 to 5 cm in thickness is formed over the zone near the spigot. When the spigot is moved to another location in the pond, another batch of slurry, probably with a different grain size, is carried over the zone surrounding the spigot, forming another homogeneous layer. Thus, during the ongoing process of slurry deposition, layered structures are laid down in the pond.

In order to obtain undisturbed samples, a thin-walled sampler was penetrated at the bottom of a vertical bore hole. About 70 cm long samples of tailings which have been deposited in the manner as described above, always contain many alternate horizontal stripes of coarse and fine tailings. Thus, specimens about 10 cm in length cut out of the long sample to fit the triaxial test apparatus, still contain several layers. The application of vertical cyclic load to such a highly stratified specimen in the triaxial test apparatus may not precisely recreate actual dynamic loading conditions during earthquakes, because during an earthquake, the shear stress is predominantly cycled in the horizontal plane, parallel to the direction of stratification. In view of this difficulty, testing of undisturbed specimens was not undertaken in the previous investigation (Ishihara et al., 1980) and instead, specimens reconstituted out of the materials from individual strata in the in-situ deposit were tested under the cyclic triaxial loading conditions. However, preliminary tests indicated that undisturbed specimens might be significantly

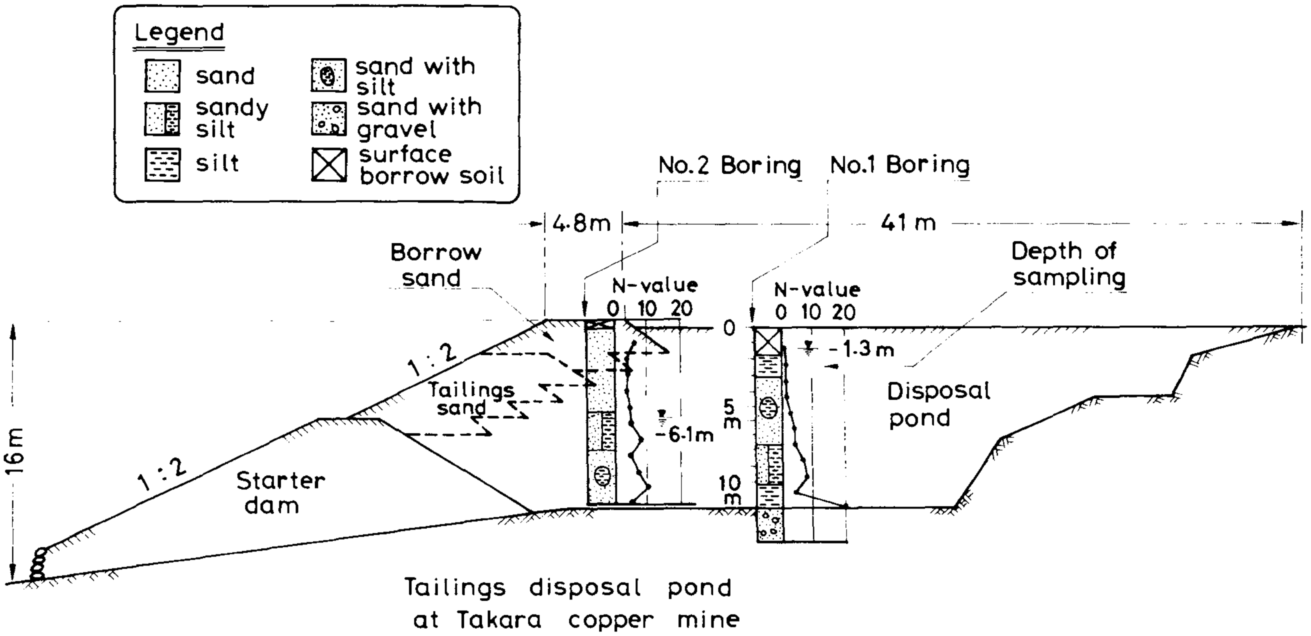

Fig. 1 A typical profile of tailings disposal pond in Japan

stronger than specimens reconstituted from individual strata. This tencency is clearly demonstrated by the results of cyclic triaxial tests performed both on reconstituted and undisturbed specimens obtained from the tailings pond at the Takara copper mine. This mine is located in the mountain area approximately 80 km west of Tokyo and the cross section of the tailings pond is shown in Fig. 1. This disposal pond was constructed by what is called the upstream method. In this method the crest of the dike is progressively moved in the upstream direction by depositing coarse grained tailings from the starter dam. Soil profiles were investigated at the two sections shown in Fig. 1. An undisturbed sample was obtained at a depth of 2 to 3 m in boring No. 1 using a thin-walled tube sampler. This sample was tested in the cyclic triaxial apparatus in the laboratory. The grain size distribution curve of blended material from the entire sample is shown in Fig. 2. Note that the material is predominantly of silt. The cyclic triaxial test results are shown in Fig. 3 (a) in terms of the cyclic stress ratio versus number of load cycles required to cause initial liquefaction, and 5 % and 10 % double-amplitude axial strain in the undisturbed specimens. After finishing the test, the materials were blended with water. This slurry was then poured into a forming mould to reconsitute the specimen. The specimens were reconstituted so as to have approximately the same void ratio as before and tested under the cyclic triaxial loading conditions. Results of the test on the reconstituted specimens are shown in Fig. 3 (b). A comparison of the test results presented in Figs. 3 (a) and 3 (b) clearly indicates that reconstitution of the sample in this manner decreases the number of load cycles necessary to cause initial liquefaction and specified strains as compared to the test results of the undisturbed samples.

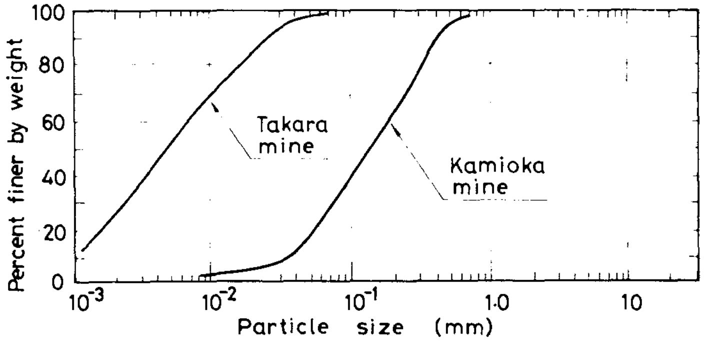

Fig. 2 Grain size distribution curves of typical fine grained and coarse grained tailings

Another example of difference in cyclic strength between undisturbed and reconstituted specimens is provided by the results of tests on coarse grained tailings obtained from a tailings dike at the Kamioka mine located about 140 km north of Nagoya. Sieve analysis results for this material are shown in Fig. 2. The results of cyclic triaxial tests, shown in Fig. 4, indicate that the liquefaction resistance of the undisturbed tailings sand is much greater than that of the sample reconstituted from the same sand.

The above observation of both silt sized and sand sized tailings test results indicate that cyclic strength of in-situ as-deposited tailings is better evaluated by testing undisturbed, rather than reconstituted specimens. The loss in accuracy inherent in testing reconstituted specimens seems to be more objectionable than the geometric dissimilarity between in-situ earthquake-induced stress and laboratory test-induced stress. This was a main incentive to initiate the test scheme as described in the following pages.

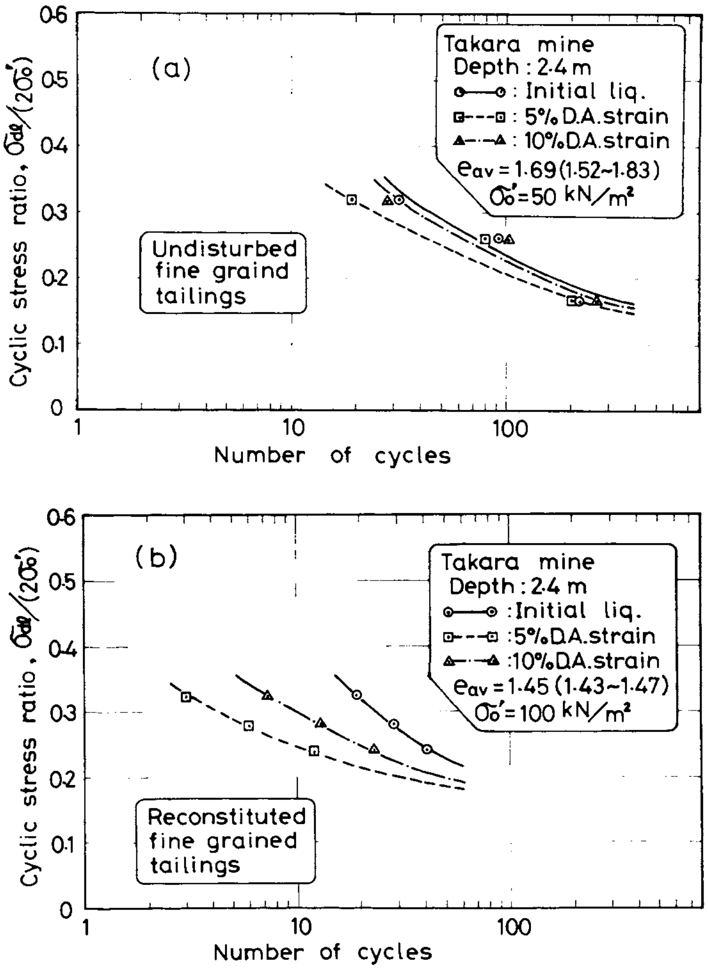

Fig. 3 Typical examples of cyclic strength for undisturbed and reconstituted specimens of fine grained tailings

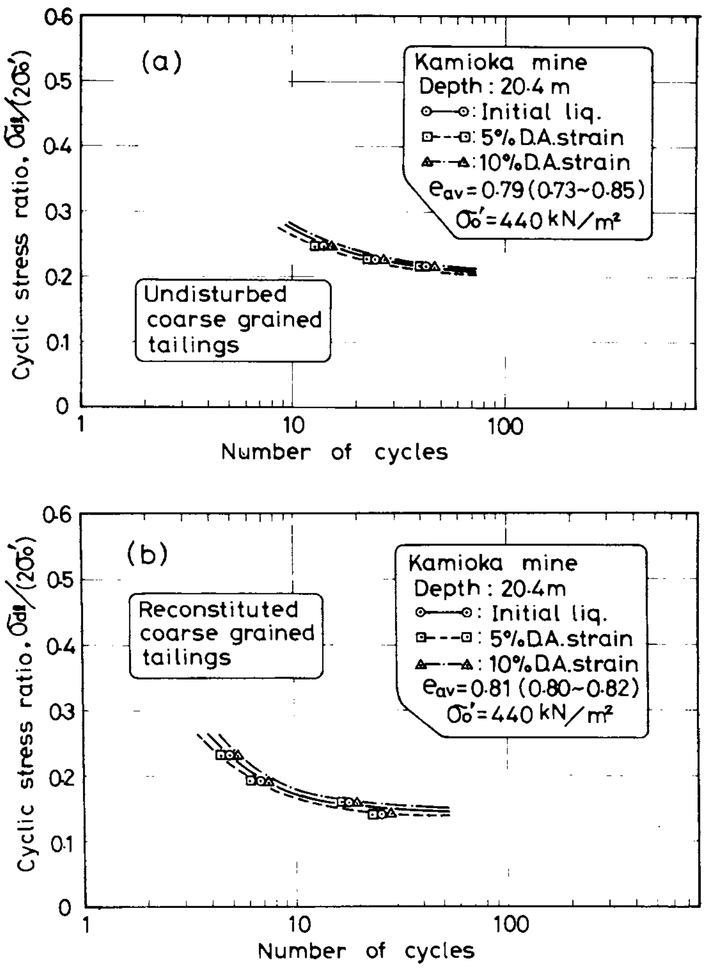

Fig. 4 Typical examples of cyclic strength for undisturbed and reconstituted specimens of coarse grained tailings

TEST MATERIALS

The undisturbed samples used in the present test scheme came from 15 disposal ponds all over Japan. Out of 15 dispcsal ponds, 5 were from old abondoned ponds. The sites investigated were disposal ponds of a wide variety of mines including gold and silver mines, lead and zinc mines, copper mines, Kuroko mines and so forth.

The undisturbed samples were obtained by penetrating a 3 inch in diameter thin-walled tube sampler, having an area ratio of 8.2 %, into the bottom of drilled holes. Sample recovery was satisfactory. The standard penetration test was performed between the sampling depths to establish approximate soil profiles and to obtain blow count values at each depth of sampling.

Fig. 1 shows a typical soil profile where borings have been performed. In this particular pond, which is the Takara copper mine, two holes were drilled to obtain a total of 10 thin-walled tube samples. The standard panetration test results in Fig. 1 show that at mid-depth between the original bedrock and the surface crust there exist layers of silt and sand grained tailings having blow count values on the order of 5.

LABORATORY TRIAXIAL TESTING

Undisturbed tailings samples, approximately 70 cm in length, were removed from the thin-walled tubes using a piston extruder. Samples were then cut into smaller specimens about 10 cm long. And the side surfaces were slightly trimmed to have a finished diameter of 5 cm so as to fit exactly into the triaxial test equipment. Generally, the specimens were strong enough to maintain their geometry without confinement. After circulating deaired water through the specimen for about 3 hours, the specimen was consolidated with an ambient pressure about 20 % greater than the overburden pressure corresponding to the depth at which the specimen had been procured. Then, a back pressure of 300 kN/m^2 was applied to ensure a state of near-saturation with a B-value exceeding 0.95. Once the specimen was consolidated, the drainage valves were closed and a 1 Hz sine wave cyclic axial load was applied until the specimen deformed to a peak-to-peak axial strain of 10 %.

Following the cyclic testing, the specimen was removed from the triaxial cell and the void ratio of the specimen was determined. The tests were also performed on the specimen at this time to determine the liquid limit and plastic limit.

TRIAXIAL TEST RESULTS

The grain size of typical tailings materials ranges from that of clay to coarse sands and the standard concept of relative density does not apply. In view of this, void ratio is used to indicate the density of tailings materials tested in this investigation. Strength of the tailings under cyclic loading conditions will be represented by the cyclic stress ratios causing failure in 20 load cycles. The cyclic stress ratio is defined as the amplitude of the cyclic axial stress devided by twice the initial confining pressure. Five percent double-amplitude axial strain is adopted as the failure criterion because it provides the most meaningful comparison among many tailings materials having different physical properties.

Cyclic test results on undisturbed tailings specimens from 5 lead and zinc mines are summarized in Fig. 5. Here the cyclic stress ratio causing 5 % double-amplitude strain in 20 load cycles is plotted versus the void ratio of the specimen after the consolidation. Each data point plotted as a circle was obtained from specimens containing less than 50 % fines passing #200 mesh. The cyclic stress ratio values obtained from specimens containing more than 50 % fines are indicated by solid circles. Cyclic stress ratio values tend to decrease slightly with increasing void ratio, but not as significantly as anticipated. This may be because samples having higher void ratios also contain greater percentage of fines and thus benefit from increased cohesion and thus increased resistance to shearing. It is also of interest to note that these tests indicate virtually no difference in cyclic strength between fine grained and coarse grained tailings taken from the lead and zinc mines.

Fig. 6 shows a summary of the cyclic triaxial test results on the tailings specimens from gold and silver mines. Because the concentration process for gold and silver ore generally involves grinding the ore into clay or silt sized particles, all of the tailings tested were materials having fines exceeding 50 %. Fig. 6 shows that in this case the cyclic stress ratio is practically independent of the void ratio and approximately equal to 0.25.

Cyclic stress ratio for tailings specimens from copper mines are shown in Fig. 7. These specimens were coarse grained and the test results showed an average cyclic stress ratio of 0.25, independent of the void ratio.

Fig. 8 shows the result of the cyclic triaxial tests on the specimens from the Kuroko mine. The Kuroko mine is a kind of copper mine, but

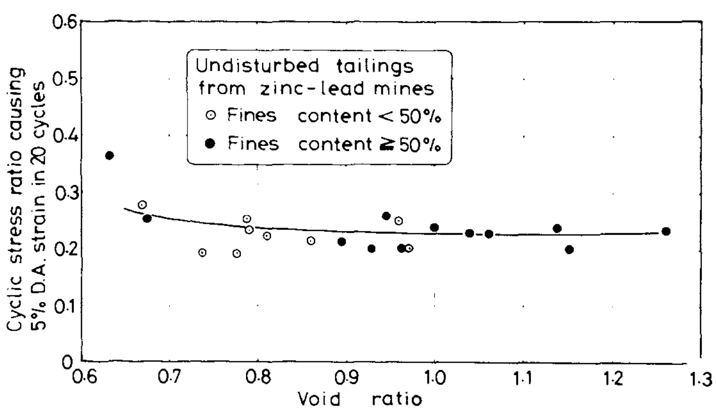

Fig. 5 Cyclic strength versus void ratio

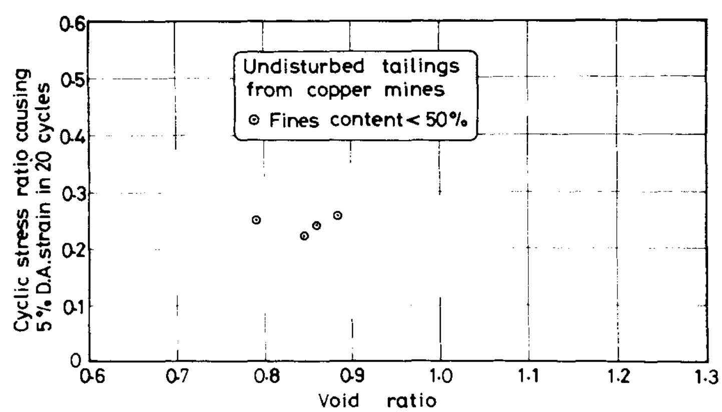

Fig. 7 Cyclic strength versus void ratio

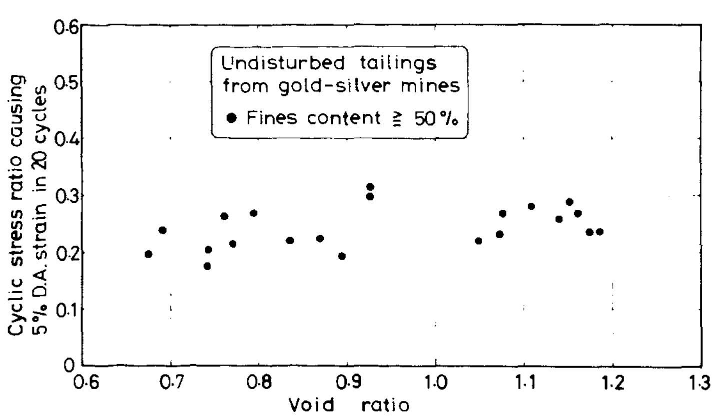

Fig. 6 Cyclic strength versus void ratio

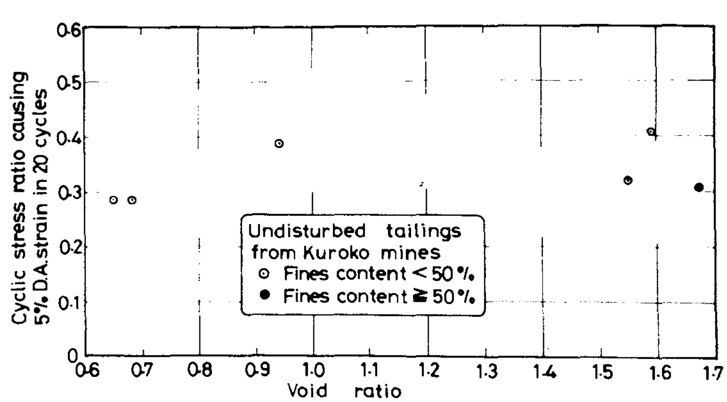

Fig. 8 Cyclic strength versus void ratio

the mill wastes it produces are more plastic and cohesive than any other kinds of tailings. Therefore, the cyclic stress ratios presented in Fig. 8 show values well over 0.3 as distinguished from the low values of the cylic stress ratios that were obtained for other tailings materials.

DISCUSSIONS OF THE TEST RESULTS

The results of cyclic triaxial tests on undisturbed specimens of the tailings obtained from different kinds of mines have been presented. It was found that the cyclic strength of the tailings specimens was not closely related to variation in void ratio or grain size. The cyclic strength of specimens from many kinds of mines was very similar. One other factor that could be conceived to influence the cyclic strength of specimens is the degree of cohesiveness of the fine grained particles present in the tailings. This characteristics is indicated by the plasticity index. Most of the coarse grained tailings tested were identified as non-plastic, but the fine grained tailings showed plasticity index values ranging between 10 and 40. For the fine grained tailings, cyclic stress ratio values were plotted versus the plasticity index. It may be seen in Fig. 9 that these cyclic strength values tend to increase as the plasticity index of the tailings becomes large.

The relationship between cyclic strength and blow count value from the standard penetration test is of interest for practical purposes. It has been shown by Tatsuoka et al. (1978) that the cyclic stress ratio causing 5 % double-amplitude strain in reconstituted specimens of clean sands in 20 load cycles, Rc, is given on the average by

$$Rc = 0.088 \sqrt{\frac{N}{\sigma_v' + 0.7}} \qquad \text{....... (1)}$$

where N is the blow count value and σ_v' is the overburden pressure in terms of kg/cm^2. The cyclic stress ratio as calculated by the above formula represents a typipal value of the cyclic strength that can be used only for clean sands. For the tailings materials containing fines, the above formula needs to be modified. Using the parameter, D_{50}, which is defined as the grain size of 50 % passage in the sieve analysis, a corrective term was determined, for the cylic stress ratio of Eq. (1) for ordinary tailings and Kuroko tailings materials. First of all, with known values of the blow count, N, and also the effective overburden pressure, σ_v' the cyclic stress ratio which would be predicted to occur without the fines is computed through the formula of Eq. (1). This value is then subtracted from the measured test value of cyclic stress ratio causing 5 % double-amplitude strain in 20 load cycles, R_ℓ. The difference in cyclic stress ratio between that measured and that computed by Eq. (1) was plotted versus the mean diameter, D_{50}. These plots, in Fig. 10, show that the data points for the Kuroko tailings fall in the upper portion of the figure as compared to the data point group for

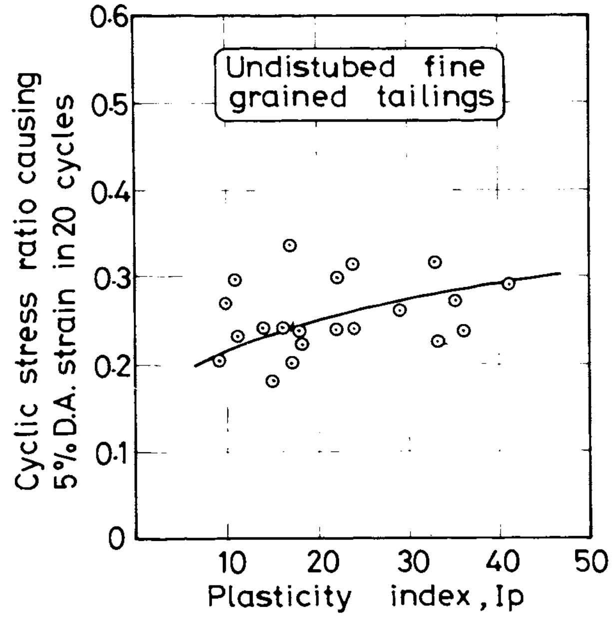

Fig. 9 Relationship between cyclic strength and plasticity index of tailings

the ordinary tailings. Average curves are drawn in Fig. 10 for these two kinds of tailings. Based on the two average straight lines depicted in the figure, empirical formulae as follows can be derived.

For the ordinary tailings;

$$R_\ell = 0.088\sqrt{\frac{N}{\sigma_v' + 0.7}} + 0.085 \log_{10}\left(\frac{0.50}{D_{50}}\right) \qquad \text{....... (2)}$$

For the Kuroko tailings;

$$R_\ell = 0.088\sqrt{\frac{N}{\sigma_v' + 0.7}} + 0.20 \qquad \text{....... (3)}$$

The above formulae were incorporated in the Japanese code for the tailings dam design which was put into effect in March 1980.

In Fig. 10 an average line derived by Tatsuoka et al. (1978) from a number of similarly arranged cyclic triaxial test results on alluvial and reclaimed soils in Japan is also indicated for comparison with the results of the present investigation. It is worthy of note that most of the data points for the tailings materials fall below the Tatsuoka's line. This tendency indicates that the increase in cyclic strength of the tailings materials with the decrease in the mean particle size is less pronounced compared to the average alluvial soils.

CONCLUSIONS

Cyclic triaxial tests were performed on undisturbed samples of in-situ tailings obtained from 15 tailings disposal ponds throughout Japan.

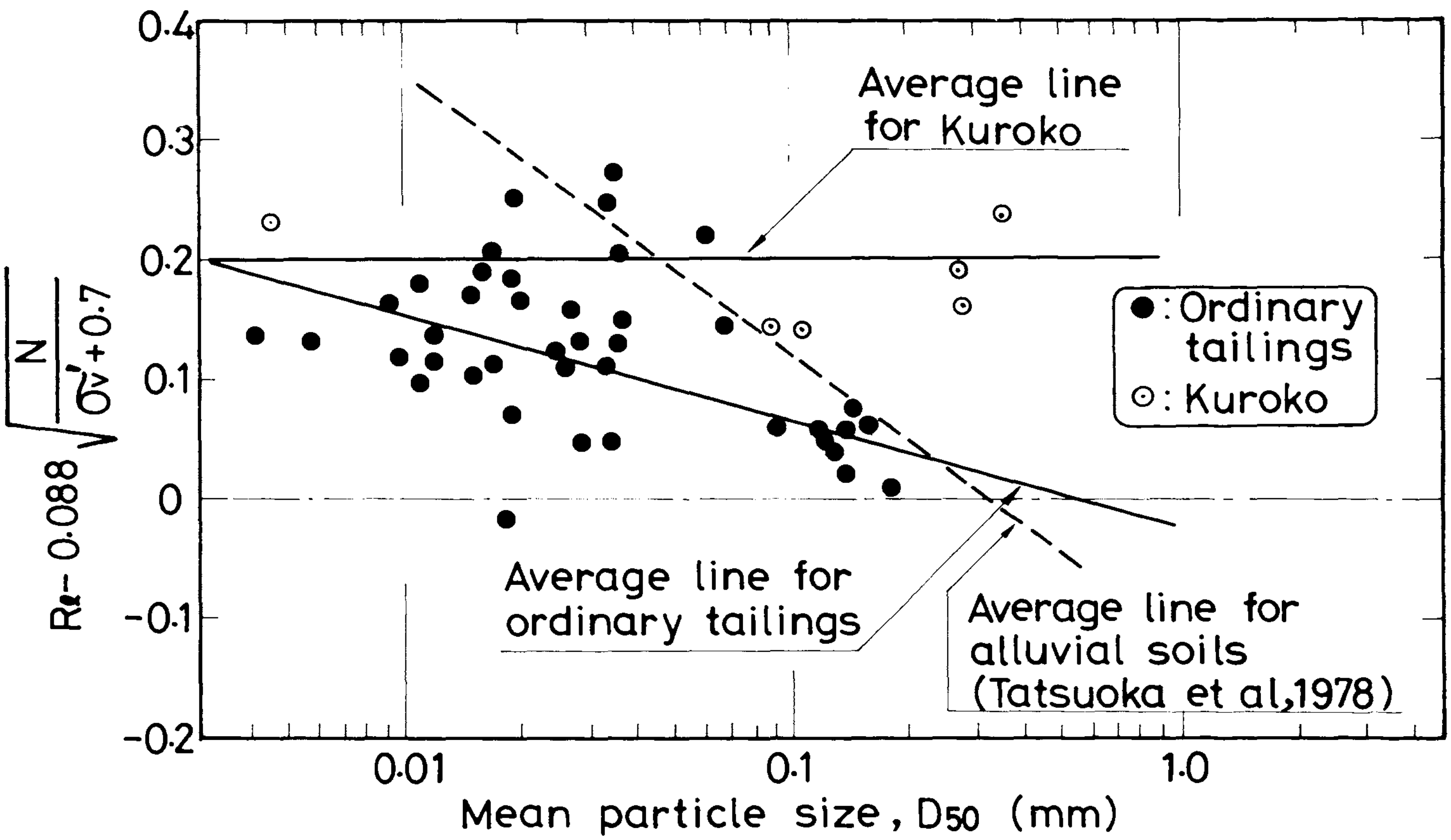

Fig. 10 Plots of test data to establish formulae

The test results showed that the cyclic stress ratio causing 5 % double-amplitude axial strain in 20 load cycles was on the order of 0.25 for ordinary tailings materials and on the order of 0.30 for a particular kind of tailings called Kuroko. It was also found that these values of cyclic strength are nearly independent of the void ratios and grain size characteristics of the undisturbed specimens, but they increase slightly with an increase in plasticity index of the tailings materials. Finally, the test results were expressed in the form of empirical formulae which are funcitons of the blow count value and the mean particle diameter of the materials.

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REFERENCES

Dobry, R. and Alvarez, L. (1967), "Seismic Failures of Chileam Tailings Dams," Proc. ASCE, Vol. 93, No. SM6, pp. 237-260.

Ishihara, K., Troncoso, J., Kawase, Y. and Takahashi, Y. (1980), "Cyclic Strength of Tailings Materials," Soils and Foundations, Vol. 20, No. 4, pp. 433-449.

Tatsuoka, F., Iwasaki, T., Tokida, K., Yasuda, S., Hirose, M., Imai, T. and Konno, M. (1978), "A Method for Estimating Undrained Cyclic Strength of Sandy Soils Using Standard Penetration Resistances," Soils and Foundations, Vol. 18, No. 3, pp. 43-58.