THE SHEARING RESISTANCE OF SAND AT VARYING MOISTURE CONTENTS

by 45

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A MASTER'S REPORT

submitted in partial fulfillment of the

requirements for the degree

MASTER OF SCIENCE

Department of Civil Engineering

KANSAS STATE UNIVERSITY
Manhattan, Kansas

1969

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ACKNOWLEDGEMENTS

I wish to express my most sincere appreciation and thanks to Professor Wayne W. Williams for his advice and guidance.

I would also like to extend my sincere thanks to Dr. Jack B. Blackburn, Head of the Civil Engineering Department, for his suggestions and guidance.

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I INTRODUCTION

The stability and safety of a structure depends upon the performance of each of the structural members. The structural members are generally considered to be only the steel, masonry and wood involved in the structure. These materials are found to have a high degree of uniformity, exactly known physical properties, and a high degree of resistance to loss of strength under varying moisture content or other external conditions. The underlying soil acts as the fundamental support for these members and is the weakest link of all of the members. The "weakness" lies in a lack of general knowledge of the true fundamental properties of strength, the great variations that exist within short distances, and changes in strength which may occur with time. Hence, the strength characteristics of soil are difficult to analyse and predictions of performance are often inaccurate.

Statement of the Problem

In all soil stability problems, such as the design of foundations, retaining walls, and embankments knowledge is required concerning the strength parameters of the soil. The determination of the proper strength parameter to use in the solution of a problem can be the most difficult question which arises in soil mechanics and foundation engineering. A soil can be classed as cohesive or cohesionless depending on the source of its strength. Cohesive soils are soils with a very small grain size bound together by molecular attraction (Van Der Waal's forces) and are not considered in this report. Cohesionless soils are soils which have little cohesion or molecular attraction between individual particles. The resistance to shear of a cohesionless soil is derived from friction between grains and the interlocking of grains. The friction between grains results from rolling and sliding friction but normally no attempt is made to distinguish between them. The interlocking of the particles contributes a large portion of strength in dense sands and has a lesser effect in loose sands.

The shear strength of sand was first defined by Coulomb (1), whose classical equation ($\tau = \sigma \tan \phi$) has formed the basis for most of the work on this subject since it was originally proposed in 1773. The equation was based on some rather crude sliding friction tests of wood on wood. These tests showed that frictional resistance increased linearly with normal pressure and Coulomb assumed that the same law would be applicable for soils. This empirical equation has proved a valuable tool for many practical purposes. The strength of clean sand is conventionally determined by direct shear or triaxial compression tests performed on samples which have been formed in the laboratory to the desired conditions. Because of ease of forming and testing dry samples, as compared to moist or saturated samples, the laboratory tests are often performed on air dry soil.

Purpose of the Study

The strength of sand is affected by grain size distribution, grain shape, density, and grain surface characteristics. Many comprehensive investigations have been made to determine the effect of these factors on the strength of sands and gravels. Much more important but considered by only a few investigators is the influence of moisture on the strength characteristics of clean sand. The purpose of this study was to investigate the effects of varying moisture contents on the strength of clean fine sand.

Scope of the Study

This study consisted of an investigation of the effects of moisture on shear strength by a library search. During this library research, emphasis was placed on acquainting the investigator with previous studies on the strength of sand soils and the possible effect thereon of changes in moisture content. A limited laboratory investigation was pursued to augment the library search.

A preliminary search of the literature indicated that it was necessary to test a series of four sets of samples by the strain-controlled direct shear method. Methods were developed to insure equal density of all samples. The samples were tested at varying moisture contents and a comparison of the test results summarized.

II REVIEW OF LITERATURE

In 1773, the shear strength of sand appears to have been first defined by Coulomb (1) whose classical equation $\tau = \sigma \tan \phi$ has formed the basis for most of the work on this subject.

In 1857, Rankine (2) published a notable theory on earth pressure and equilibrium of earth masses, thus offering an analytical method of dimensioning retaining walls. The soil was assumed to be homogeneous, perfectly elastic, granular, cohesionless, and incompressible. The particles of the soil were assumed to be held in position by friction only, the magnitude of which is proportional to the normal pressure on the rupture surface. In other words, Rankine's theory was based on the principle of the internal stress condition in soil.

In 1936, Terzaghi (3) conducted numerous tests on sands, clay, and concrete, in which he found that a change of the neutral stress produced practically no volume change and has practically no influence on the stress conditions for failure. In addition, he concluded that the shearing resistance was exclusively due to changes in the effective stresses instead of the total stress as previously believed. He also defined the test results by an empirical equation $t_s = c_s + f_s(n)$, wherein c_s was a constant and $f_s(n)$ was a function of normal stress.

The strength of a soil can be affected by many factors. The soil moisture condition is one of these factors and is a more complicated factor than the others, especially in cohesive soils. However, capillary water in a form known as contact moisture which affects the shearing resistance will also be present in fine sand and gravel soils. At points where grains touch, or nearly touch, water percolating down through the soil has a chance to collect as contact moisture. A small amount of water surrounding a contact point forms a meniscus, and surface tension may hold this water in place indefinitely. This surface tension force which may affect strength of soils is sometimes called apparent cohesion. In large sand masses in nature, the hydrostatic excess pressure and the apparent cohesion may occur and greatly affect the strength of the sand. However, in most types of apparatus used for laboratory tests on small soil specimens, the high permeability of sands prevents the effects of these two factors to be an appreciable magnitude and they show a negligible effect on the testing results.

An attempt has been made by many investigators to determine whether the moisture content will cause a significant effect on the behavior of the fine granular soils. The search of the literature led to an understanding of the effects of changing water content on strength characteristics of cohesionless soils. Most of the previous investigators reported that water usually had little or no effect on the strength characteristics of cohesionless soil. However, a few scattered cases were reported where water was a significant detrimental influence on the strength of these materials. Many of the investigators presented the results of tests without an explanation of the observed differences in results. Lee, Seed, and Dunlop (11) performed a number of drained triaxial compression tests on the fine Antioch sand, and reported that strength of fine sand decreased with increasing moisture content. The decrease in strength with increasing moisture content was accompanied by a decrease in the dilatant volume change tendency. To explain the decreasing volume, a hypothesis was suggested that the decreasing volume might be due to the particle crushing of the sample during shearing. To check this hypothesis, sieve analyses were performed on the sand from the samples which had been tested, and the results of this study agreed with the hypothesis.

Some comprehensive investigations which have been made to determine the effect of moisture content on the strength of sands and gravels are summarized biographically as follows:

In 1948, Tschebotarioff and Welch (4) stated that the coefficient of sliding friction of the mineral grains in sands, excluding all interlocking effect, was significantly influenced by the water content, and stated that moisture eliminated the interlocking of the individual soil grains.

In 1953, Bishop and Eldin (5) performed drained triaxial compression tests on a fine to medium clean sand in both saturated and dry conditions using a confining pressure of 5.0 psi. The tests were performed on samples having a wide range of densities, and it was found that the angle of internal friction was consistently higher for the dry sand than it was for the saturated sand. The difference amounted to about 5 degrees for dense sand and about 2 degrees for loose sand.

In 1957, Zeller and Wullimann (6) presented the results of large-scale triaxial tests on coarse, well-graded, gravel with 4 in. maximum size at various initial densities. Their results showed that at all densities the strength of dry samples was 10% to 30% greater than the drained strength of samples at a water content of 5%.

In 1962, Horn and Deere (7) performed the direct shear test on powdered mica and found that the angle of internal friction of this material was reduced by the addition of water as shown in the following.

Oven dry	ϕ = 27 degrees	
Air dry	ϕ = 24 degrees	
Saturated	ϕ = 16 degrees	(drained)

ϕ = Internal frictional angle.

In addition to such direct studies of the effect of water on the shear strength of granular materials, investigation of the effect of sample volume change also provides information indirectly related to this subject. The earliest demonstration of volume changes accompanying shear deformation in sand was made by Reynolds (8) in 1885, who showed experimentally that dense sands dilate when sheared, however, no practical value seemed to have followed directly from his experiments.

In 1940, Casagrande (9) made an important study on the volume changes of sand and demonstrated the dependence of the angle of friction of sand on void ratio and the associated volume changes during shear. He showed that dense sands dilated during shear and exhibited a high angle of friction. Loose sands are compressed during shearing and develop a much lower angle of friction. He defined a critical void ratio to describe the particular state of density at which a sand may be sheared without volume change.

In a detailed analysis of factors contributing to the strength of granular soils, Rowe, Barden and Lee (10) recently proposed that the energy required to cause dilation could be subdivided into (a) energy absorbed in friction as the mass dilated and (b) energy required to do external work during volume changes.

The preceding search of the literature led to an understanding of the effect of water content on the strength characteristics of cohesionless soils. Since the soil supporting most structures is likely to become wet at some stage, it is very important to determine the effects of moisture on strength.

III Procedures and Apparatus

The soil used for this investigation was a fine uniform sand which had been dredged from the Blue River. As removed from the river, the particles of the sand were 75% coarser than the No. 50 sieve, and 4% finer than the No. 100 sieve. In order to obtain the necessary quantity of sand suitable for making test samples, the sand was thoroughly dried and that passing the No. 50 (0.197 mm) but retained on the No. 100 (0.149 mm) sieves was used to provide fine uniform material for testing.

Soil Testing Procedures

Specific Gravity: The specific gravity of the sand used for this study was 2.65 as determined by ASTM Standard Test Method D854-52.

Minimum Void Ratio: The minimum void ratio of the samples was 0.57. This void ratio was determined by vibrating the sand in a mold until no further densification was obtained.

Water Content: The air dry water content of the sand was 0.3% and the saturated water content was 21.5%.

Shear Strength: The strain-controlled direct shear tests were performed on 6.4 cm diameter by 2.4 cm samples of the clean sand which had been compacted by vibration to 100% relative density. The samples were axially loaded to the normal stress of 0.5 kg/cm^2 and 2.0 kg/cm^2 and then horizontally sheared to failure at a constant rate of strain of 2.5% per minute. The air dry soil was obtained by placing the soil in normal room air for three months prior to testing where it obtained an equilibrium water content of 0.3%. From the visual observations, it appears similar to the oven dry soil. The sand was saturated by mixing the soil with a small amount of distilled water and the soil was placed and tamped in the shear box. The sample was then completely saturated by adding the water by a burette.

For samples with a water content of 7.5% and 14.5%, the soil was oven dried and then mixed with the necessary amount of distilled water. All specimens were fitted with a coarse porous stone at the base and the top. Normal deformations were measured for all samples, and the volume changes were calculated from the normal deformation measurements.

Apparatus Used in Soil Testing

All apparatus required for the tests described above was available in the Soil Mechanics Laboratory. Where required the apparatus met necessary ASTM Standards for dimension, accuracy, or other specified characteristics necessary to assure conformance with prescribed test procedures and reproducibility of results.

IV DESIGN OF EXPERIMENT

The shear strength of a granular soil is usually determined experimentally by one of the following methods: (a) direct shear test; (b) triaxial compression shear test; or, (c) torsional shear test. The torsional shear test is now common in Europe but almost no use is made of it in this country. The other two tests are gaining in popularity in this country. The strain-control direct shear test was adopted for this study.

The design of the experiment to determine the effect of increasing moisture content on the shear strength of cohesionless clean fine sand, when subjected to two different levels of normal stress, is shown in Table 1. Three samples were tested at each of the eight combinations of moisture content and normal stress for a total of twenty-four samples. Moisture contents of 0.3% (air dry), 7.5%, 14.5% and 21.5% (saturated) were used in the experiments as shown in Table 1.

Table 1

Effect of Increasing Moisture Content on The Direct Shear Strength of Cohesionless Clean Fine Sand.

Normal Stress kg/cm^2	Test No.	Moisture Content, percent of dry wt. of sand			
		Air Dried w = 0.3%	w = 7.5%	w = 14.5%	Saturated w = 21.5%
0.5	1	x	x	x	x
	2	x	x	x	x
	3	x	x	x	x
2.0	1	x	x	x	x
	2	x	x	x	x
	3	x	x	x	x

V *PRESENTATION AND INTERPRETATION OF DATA*

As previously shown in Table 1, twenty-four direct shear tests were run for this study. Results from these tests are summarized in Figures 1 and 2. The curves represent plots of τ/σ (shear stress/normal stress) versus shear displacement. Detailed results are presented in Figures 3 to 10 and the peak values of τ/σ are presented in Table 2.

Table 2

Comparison of Peak Values τ/σ of The Samples Under Varying Water Content.

Normal Stress kg/cm^2	Test No.	Moisture Content, percent of dry wt. of sample Air Dried w = 0.3%	w = 7.5%	w = 14.5%	Saturated w = 21.5%
	1	0.89	0.84	0.81	0.75
0.5	2	0.88	0.842	0.82	0.76
	3	0.89	0.85	0.81	0.767
	1	0.870	0.835	0.80	0.735
2.0	2	0.884	0.833	0.794	0.73
	3	0.870	0.84	0.80	0.72

Results shown in Figure 1 indicate that the air dry samples are stronger than the saturated samples and the strength of the

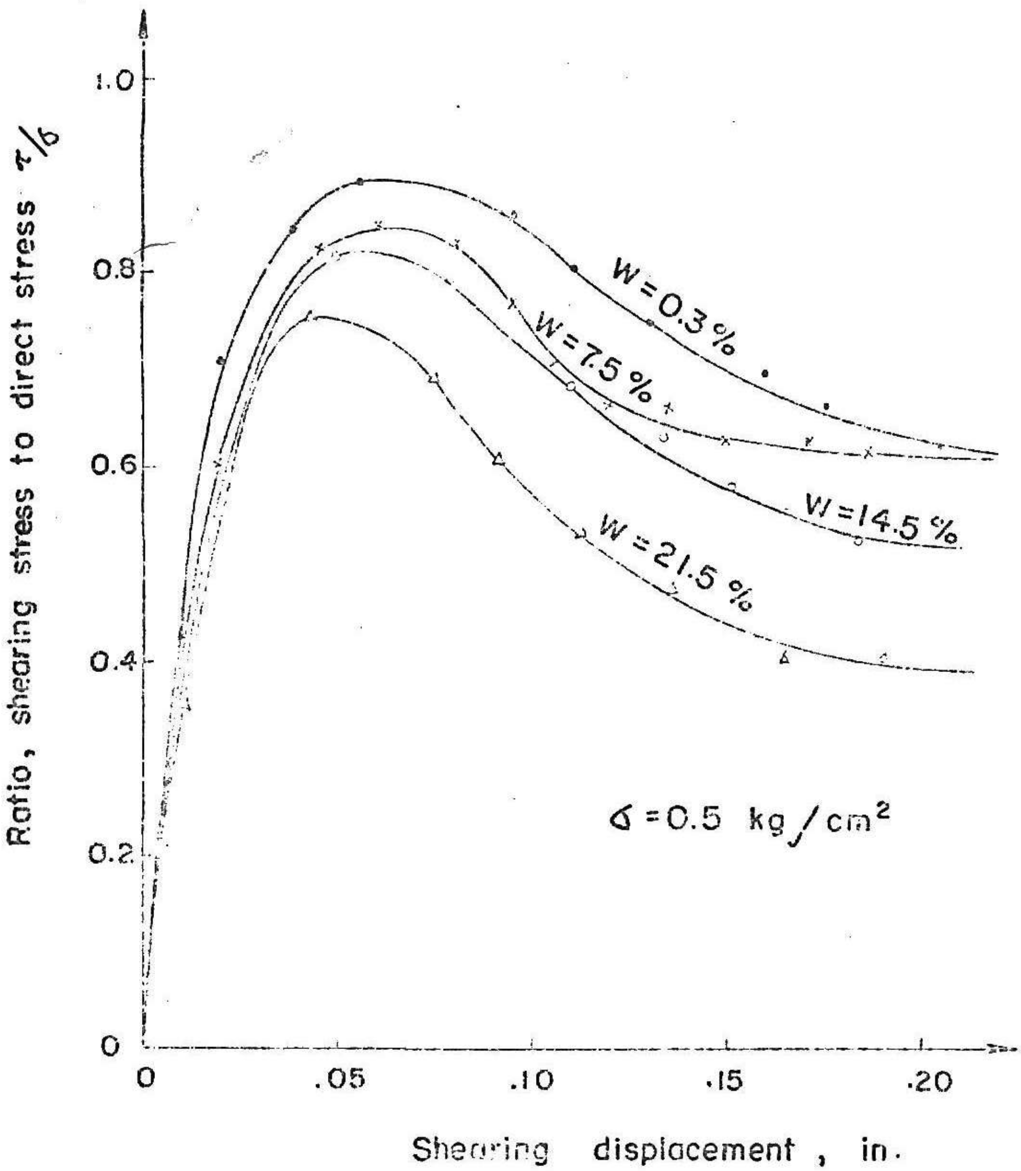

Fig. 1. Effect of water on the drained strength of dense clean fine sand.

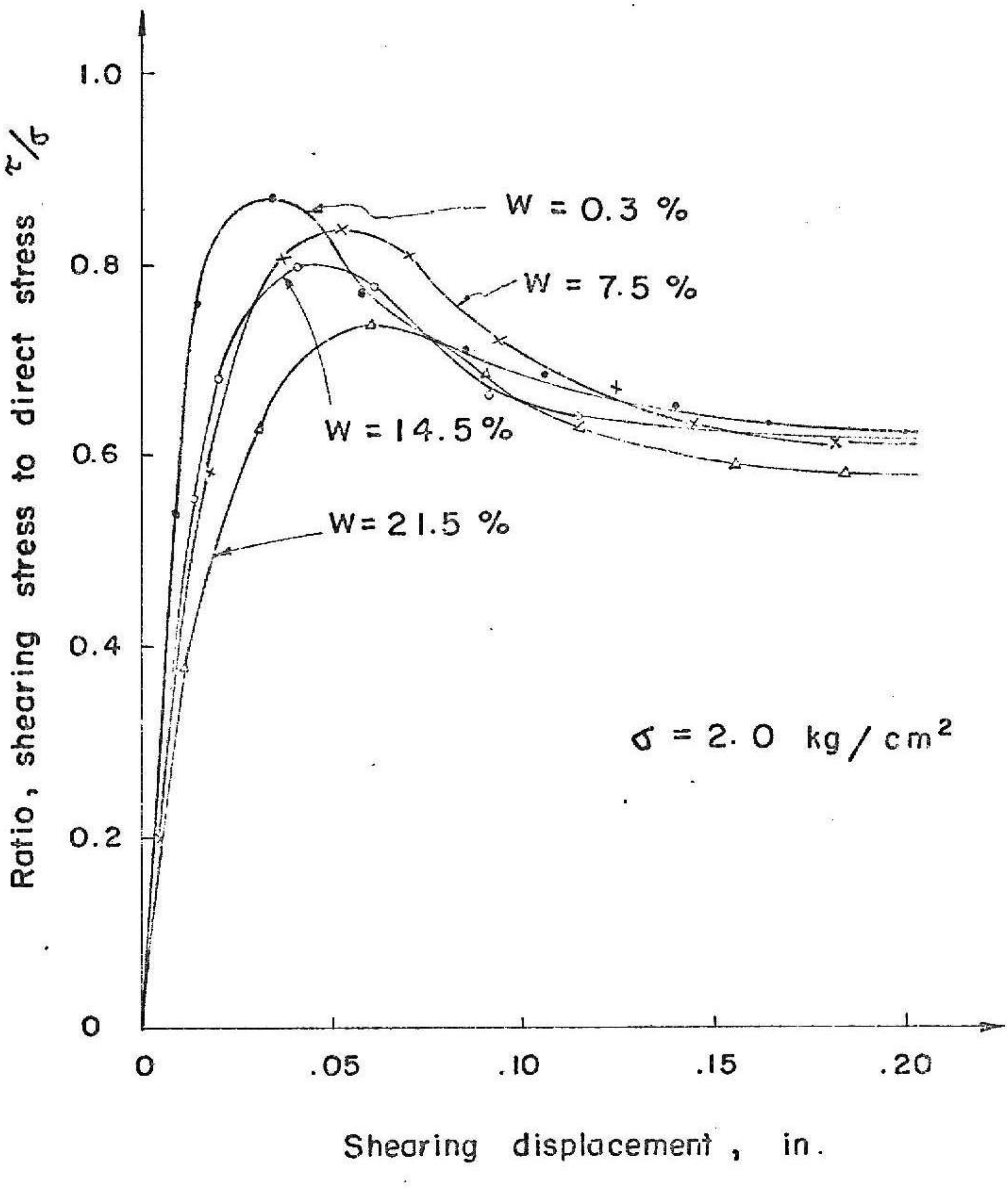

Fig. 2. Effect of water on the drained strength of dense clean fine sand.

samples decreases as the water content of the samples increases. In Figure 2 this relationship is not nearly as pronounced with the tests conducted under the increased normal stress of 2.0 kg/cm^2.

Table 3

The Axial Strain of the Samples at Varying Moisture Contents (the thickness of the samples = 0.945 in.)

Normal Stress kg/cm^2	Test No.	Moisture Content, percent of dry wt. of sand: Air Dried w = 0.3%	w = 7.5%	w = 14.5%	Saturated w = 21.5%
0.5	1	0.0190	0.0175	0.0154	0.0135
	2	0.0187	0.0173	0.0151	0.0133
	3	0.0194	0.0175	0.0150	0.0134
	Ave.	0.0190	0.0174	0.0152	0.0134
2.0	1	0.0182	0.0163	0.0143	0.0119
	2	0.0180	0.0162	0.0142	0.0120
	3	0.0180	0.0165	0.0149	0.0118
	Ave.	0.0181	0.0163	0.0145	0.0119

Reference to the axial strain measurements shown graphically in Figures 3 - 10 (Appendix), and summarized in Table 3, indicates that the axial strain was greatest in the samples with the lowest moisture content when tested at both low and high normal stress. Since the section area ($32.17\ cm^2$) and the thickness of the samples (2.4 cm) were constant, the change of axial strain was directly related to the volume changes of the samples.

It was reported that the tendency for sand to dilate is strongest at low normal stress, and is completely eliminated in tests at sufficiently high confining pressures. This trend is also exhibited by the samples in this study in both air dry and saturated conditions. Each test at the higher normal stress of $2.0\ kg/cm^2$ showed less tendency to dilate than the test at a lower normal stress of $0.5\ kg/cm^2$ as shown in Table 3.

The search of the literature indicated that the dense sand which has less tendency to dilate or which may even decrease in volume when sheared must do so as a result of particles crushing. In sands subjected to drained tests at higher confining pressure a volume decrease occurs by further densification even if the tests are conducted on the sand at 100% relative density. The only mechanism whereby a dense sand can be further densified in this way is by particle crushing so that the fragments can occupy the void spaces between the larger particles. Semiquantative data has been presented by Lee, Seed, and Dunlop, (11) and by others, to verify this hypothesis. All of the available data show that the amount of particle crushing increases progressively with an increase in the confining pressure of the test. The same explanation relating strength to volume change, and particle crushing also apply to tests at the same confining pressure but performed under different moisture conditions.

Reference to the axial strain data in Table 3 shows that the air dry samples dilate more than the wet samples, and indicates that dry samples should evidence less particle crushing than wet samples. To check this hypothesis, seive analyses were performed on the sand from all the samples which had been tested for this study. These tests did not show any obvious differences in grain size distributions on the samples before and after testing at a normal stress of 0.5 kg/cm^2. However, a few wet samples which were run by the direct shear tests at a normal stress of 2.0 kg/cm^2 showed a small amount of particle crushing. Obviously, the sample will show a significant amount of particle crushing at still higher normal stress. This was confirmed by Seed, Lee, and Dunlop (11) stating that this additional crushing at higher moisture contents partly explained the different volume changes which were observed for dry and wet sand. They concluded that the moisture may lubricate the fine particles making it easier to occupy the void space of the sample. Thus, the wet samples have less dilatancy and have smaller void ratio than of dry samples. The decrease in dilatancy would appear to explain the difference in the strength of this sand when tested dry as compared to the strength when tested wet.

The laboratory data suggests the importance of considering that the strength of clean sand may be affected by moisture content. In tests at high confining pressures, the influence of particle crushing on the strength of sand must be considered. The influence of this factor will be similar to that of remolding or rearranging grains in loose sands. Crushing of grains in tests at high confining pressures will absorb energy and in addition, since the failure strain becomes large in tests at high confining pressures, there will be an increase in the energy required for remolding and rearranging the grains.

VI CONCLUSION

Fully drained direct shear tests on samples of a clean river sand indicated that soil had greater shear strength in the air dry state than in the saturated state. At lower normal stress increasing moisture causes only a small strength reduction. However, at higher normal stress increasing moisture was found to cause a significant reduction in shear strength.

VII RECOMMENDATION FOR FUTURE WORK

It was found in this study that the particles were crushed during the shear test in direct proportion to the normal stress and the moisture content. Lee, Seed, and Dunlop (11) confirmed this and attributed it to a weakening of the mineral particles by the action of the water. In the present study it was concluded that mineralogical composition of particles played a more important role than the presence of moisture on the decrease in strength which accompanied increasing moisture content. It is therefore recommended that the causes of this particle crushing be studied further.

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APPENDIX

PLOTS OF THE RESULTS OF DIRECT SHEAR TEST ON CLEAN FINE SAND.

THE FOLLOWING PAGES CONTAIN CROOKED TYPING AND IS THE BEST POSSIBLE IMAGE AVAILABLE

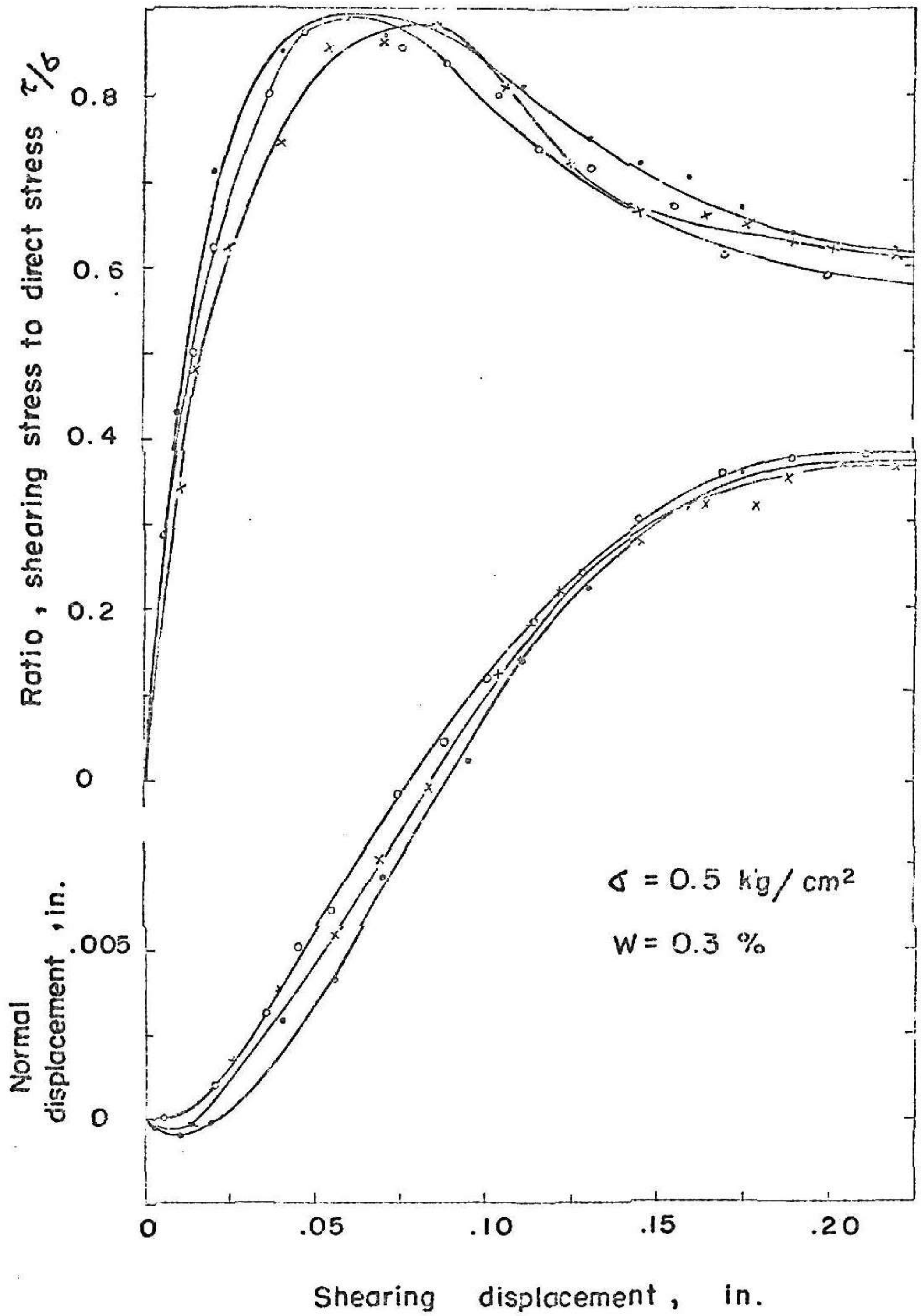

Fig. 3. Plots of the results of direct shear test on clean fine sand.

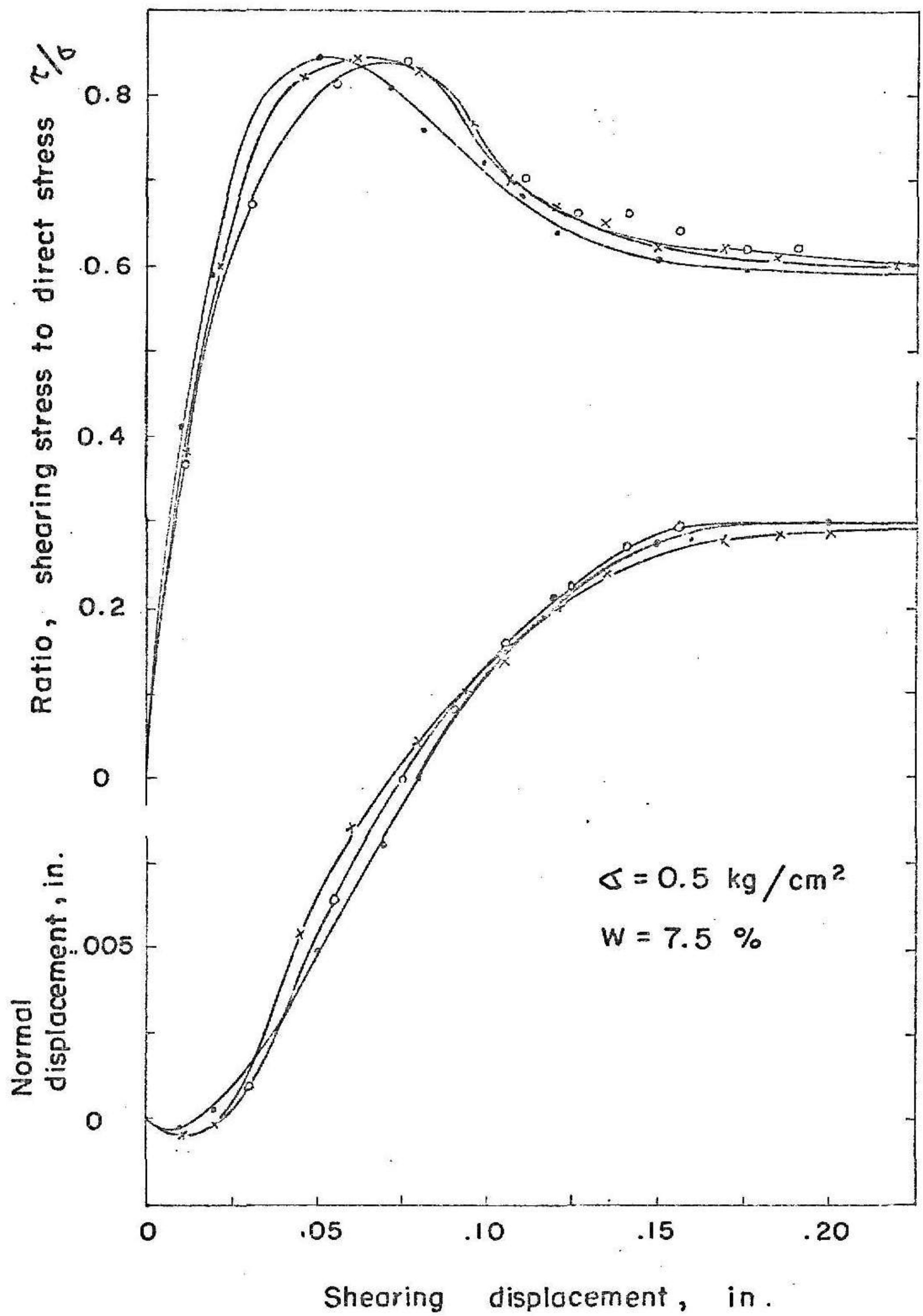

Fig. 4. Plots of the results of direct shear test on clean fine sand.

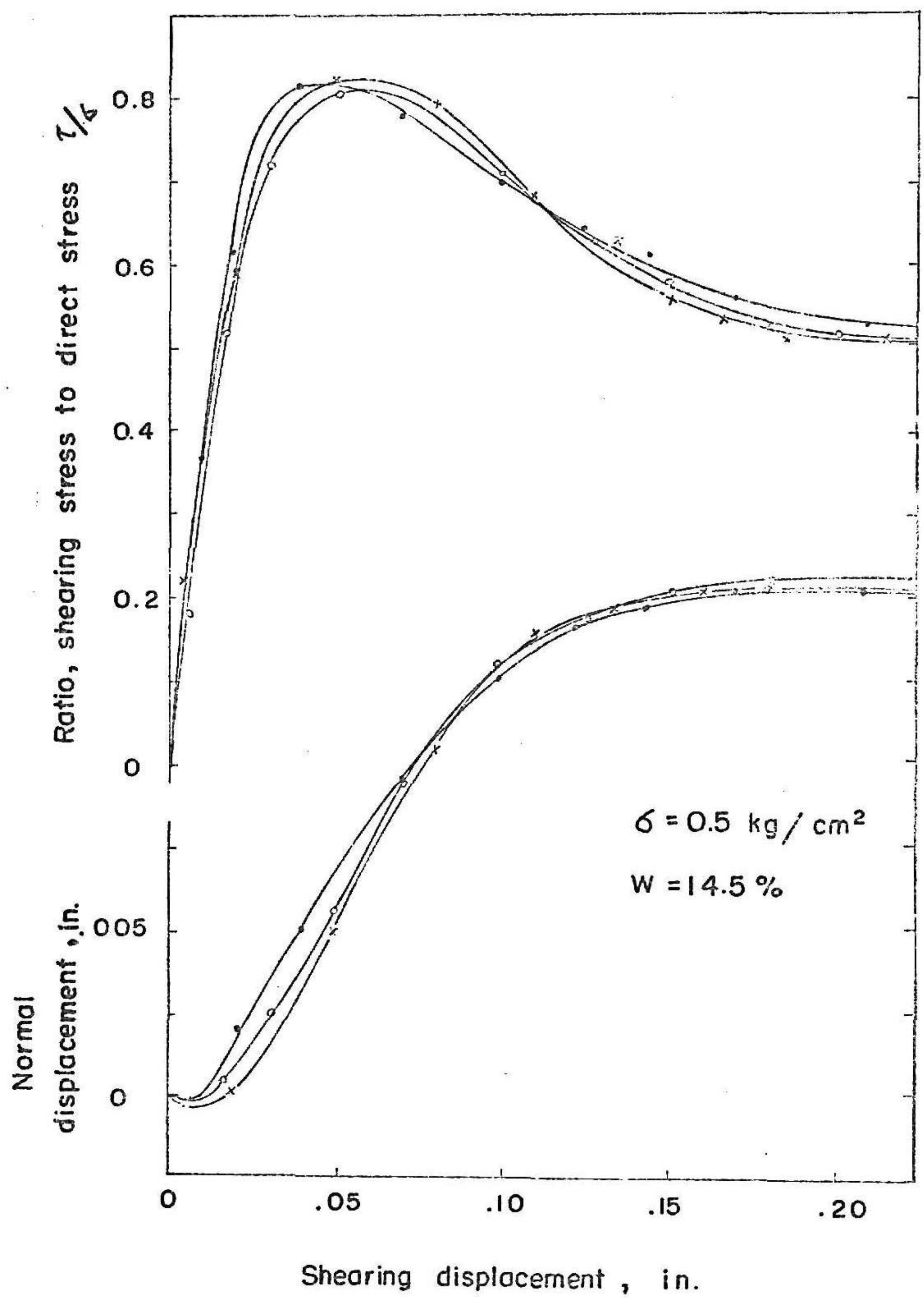

Fig. 5. Plots of the results of direct shear test on clean fine sand.

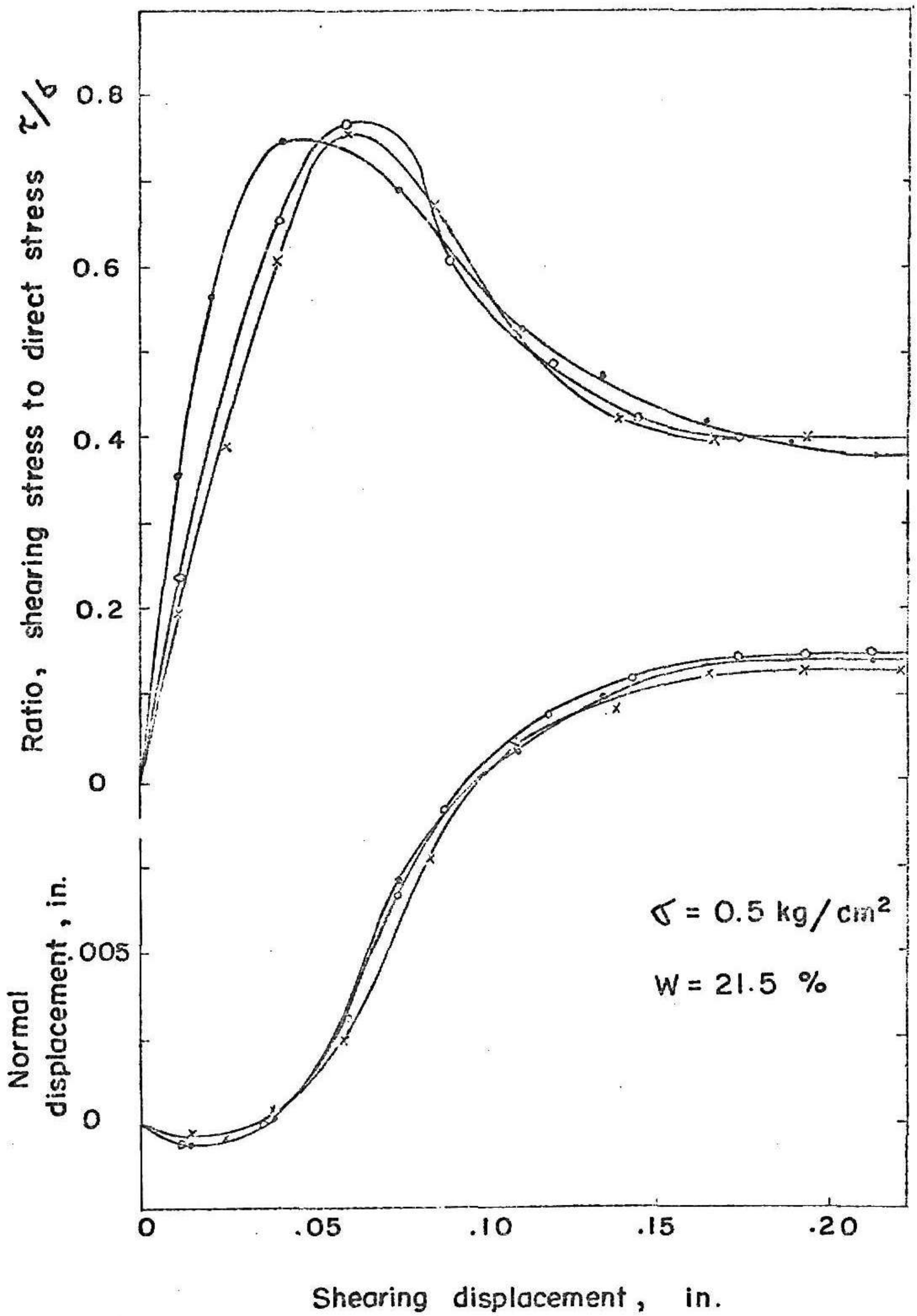

Fig. 6. Plots of the results of direct shear test on clean fine sand.

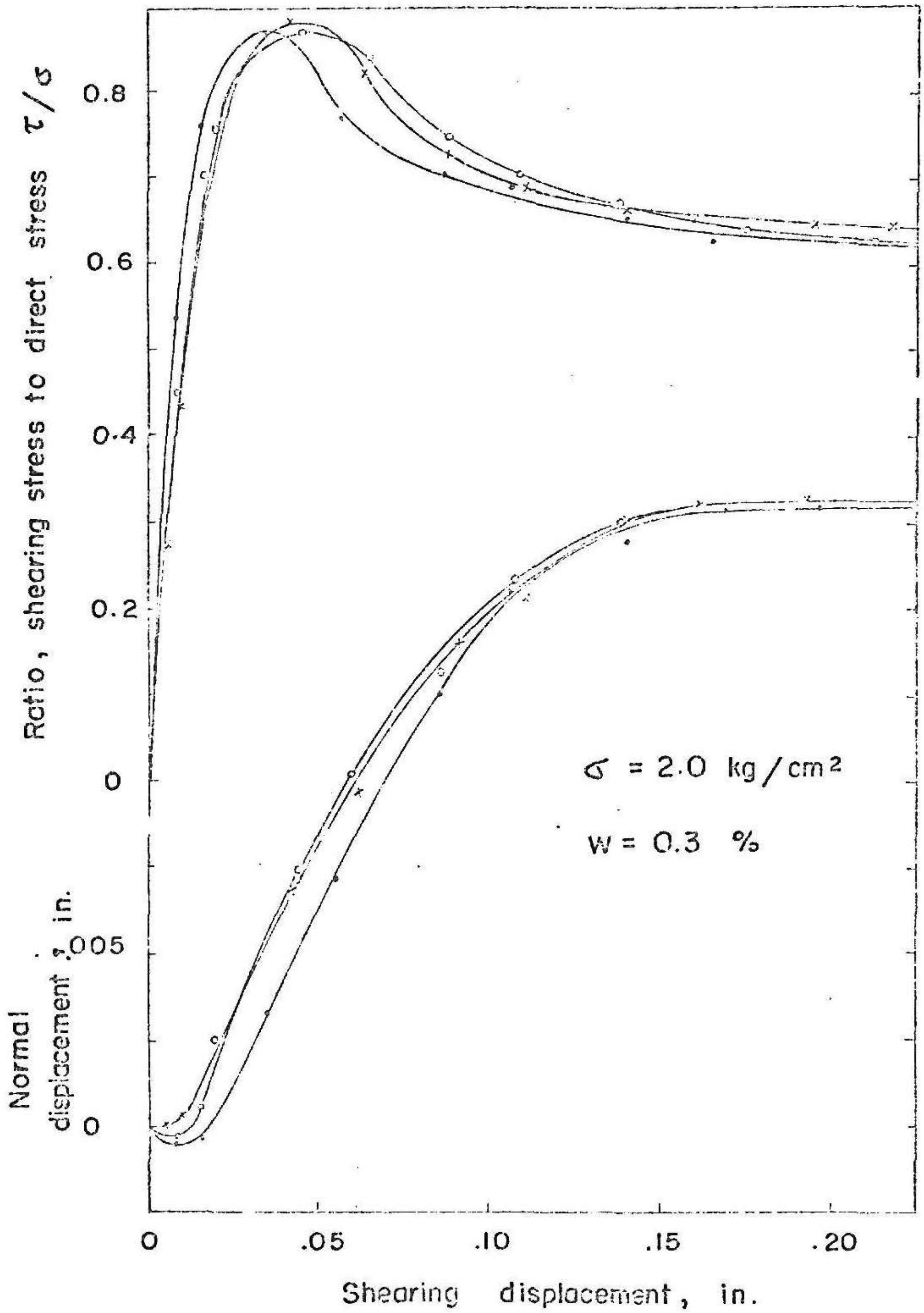

Fig. 7. Plots of the results of direct shear test on clean fine sand.

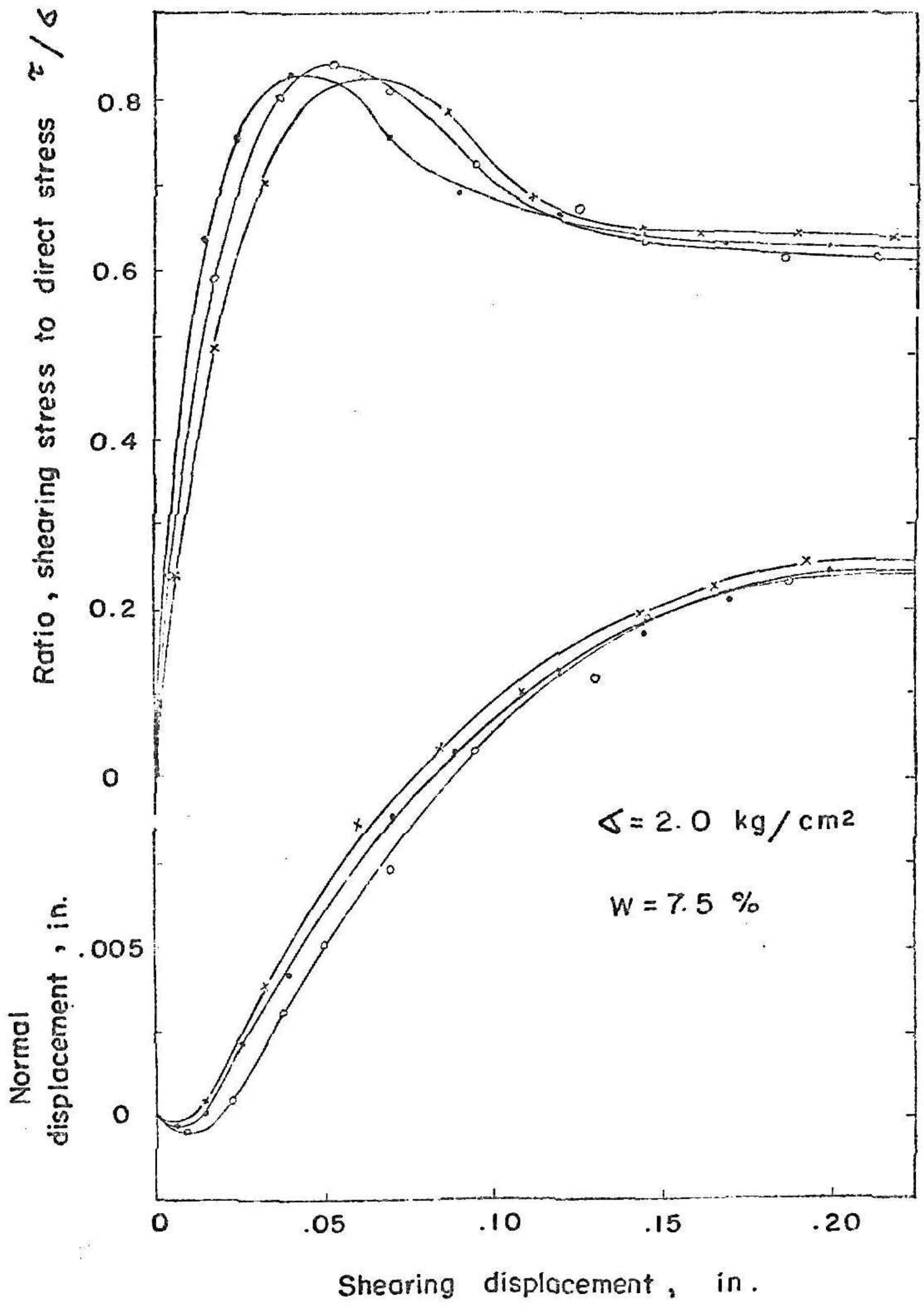

Fig. 8. Plots of the results of direct shear test on clean fine sand.

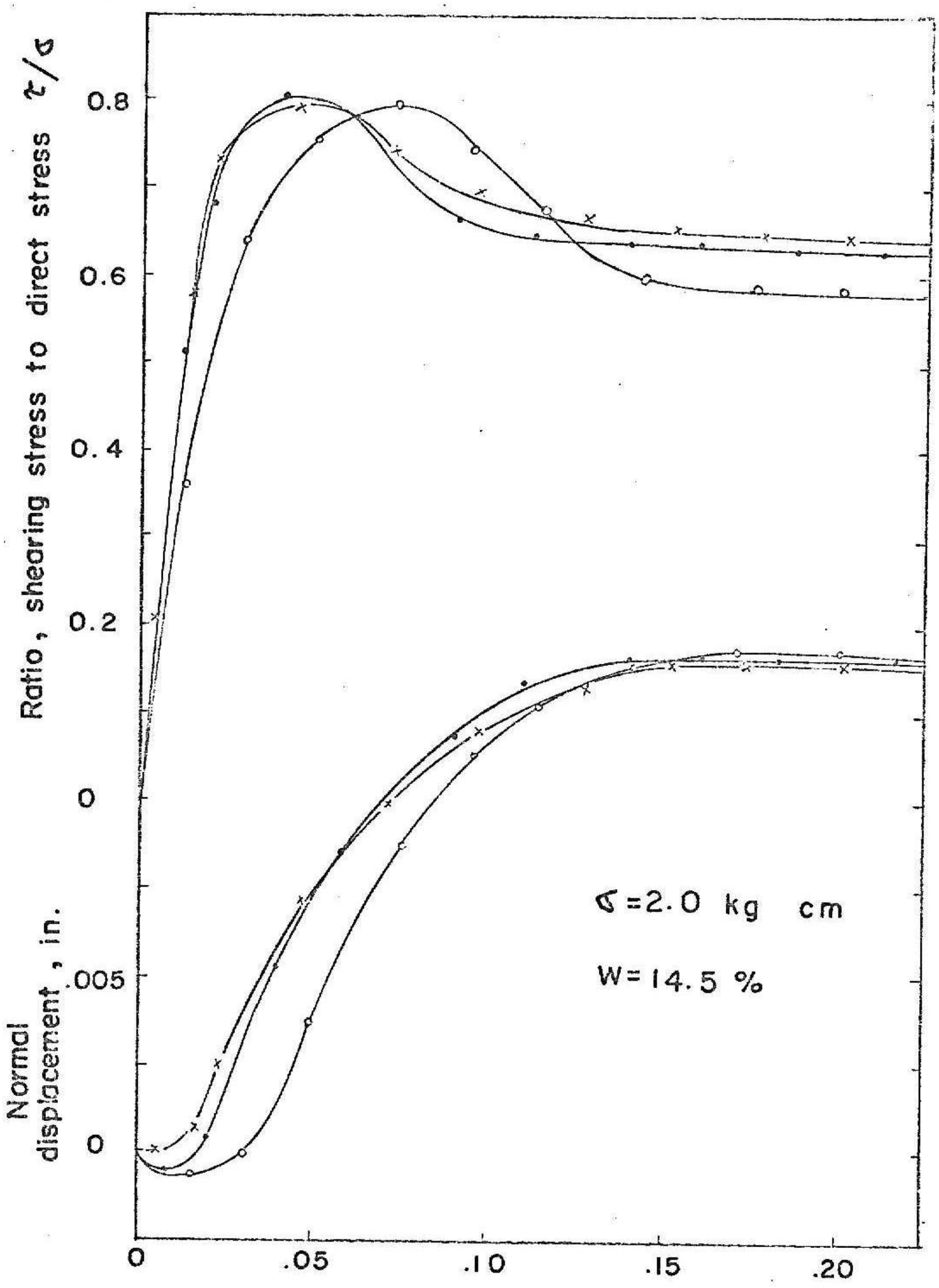

Fig. 9. Plots of the results of direct shear test on clean fine sand.

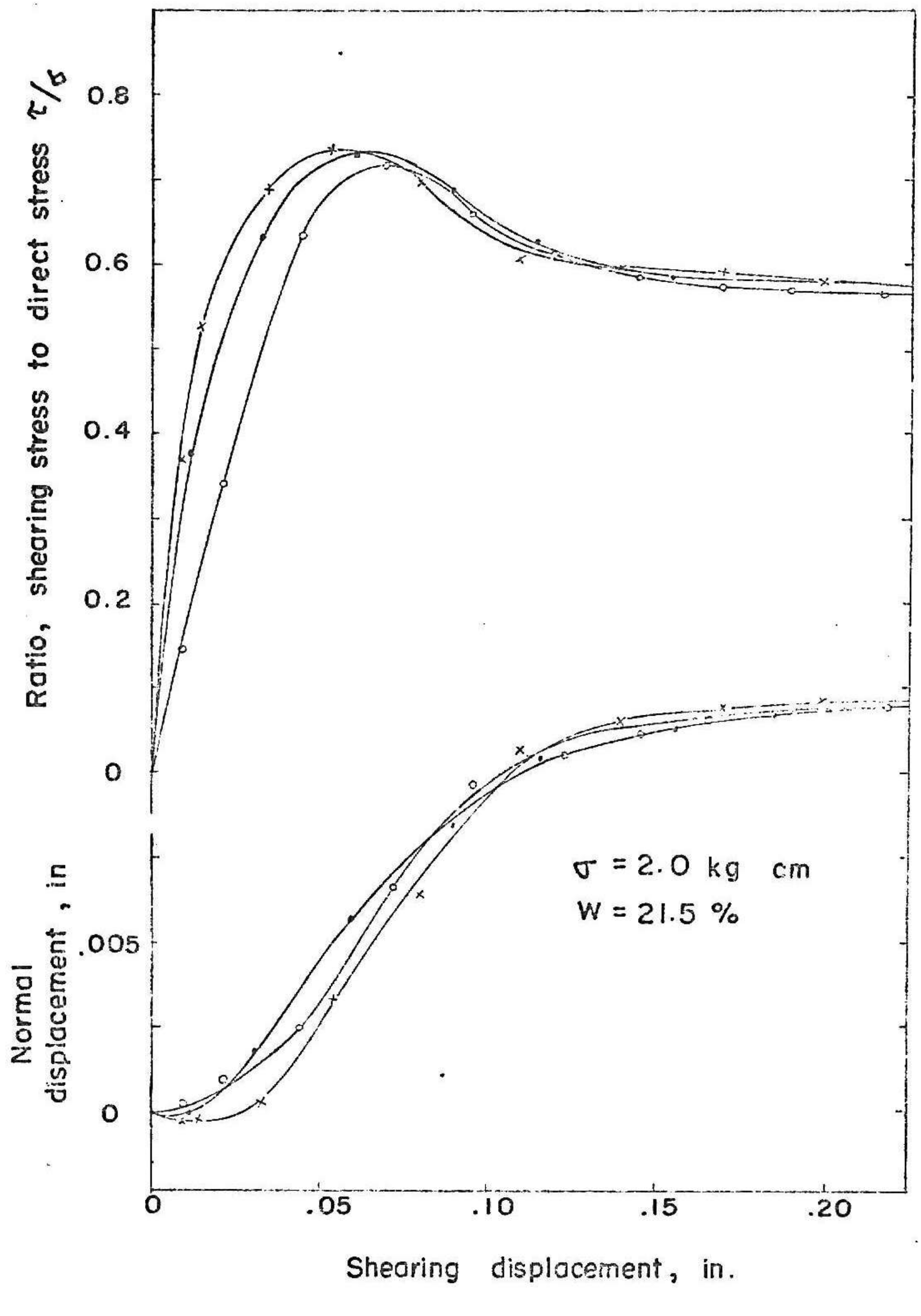

Fig. 10. Plots of the results of direct shear test on clean fine sand.

Table 3

Comparison of the Values of Shearing Stress of the Samples Under Varying Water Content.

Normal Stress kg/cm^2	Test No.	Moisture Content, percent of dry wt. of sample			
		Air Dried w = 0.3%	w = 7.5%	w = 14.5%	Saturated w = 21.5%
0.5	1	0.445	0.42	0.405	0.375
	2	0.44	0.421	0.41	0.38
	3	0.445	0.425	0.405	0.383
2.0	1	1.74	1.67	1.60	1.47
	2	1.768	1.66	1.588	1.46
	3	1.74	1.68	1.60	1.44

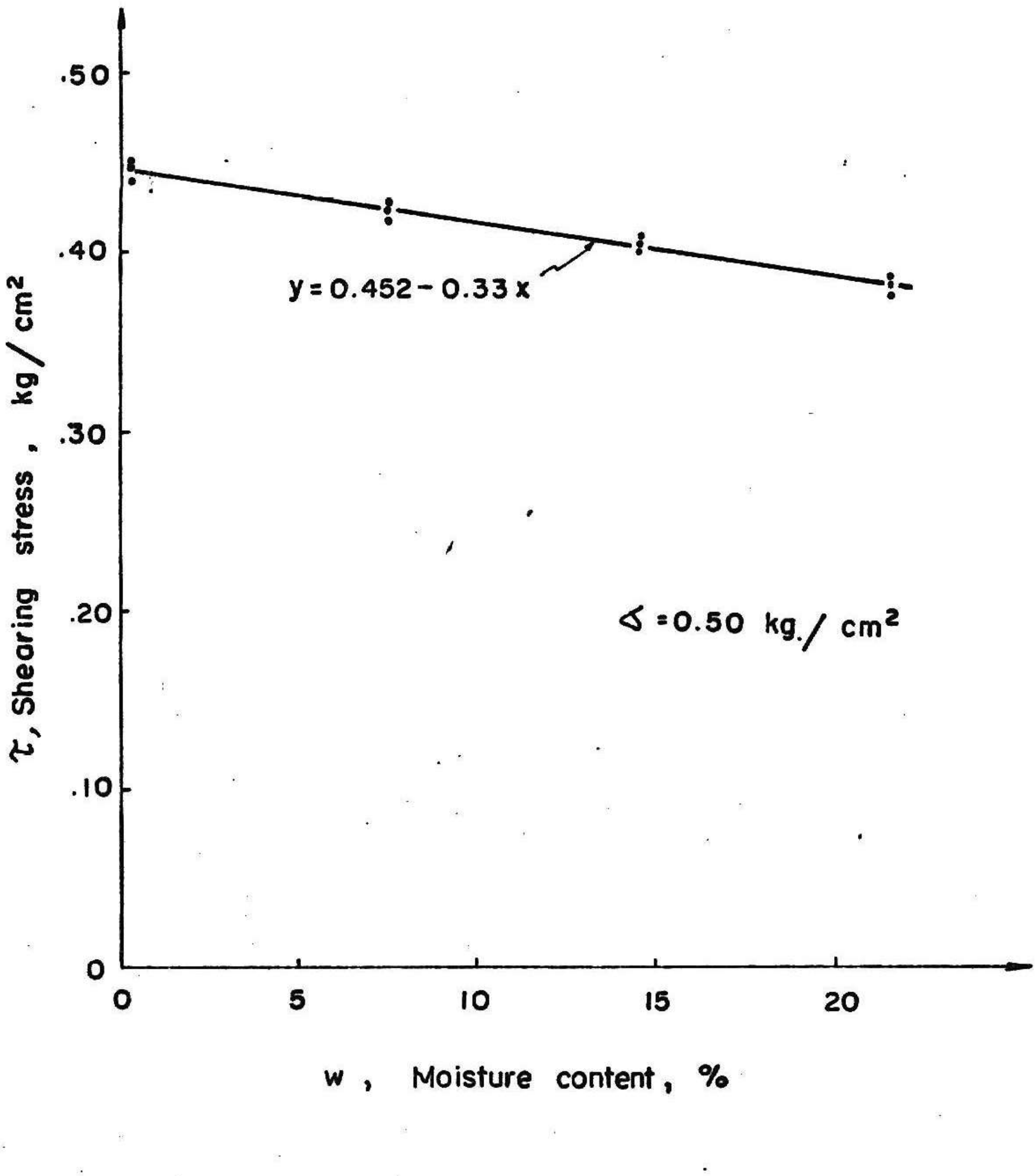

Fig. 11. Effect of moisture content on the drained shear strength of dense clean fine sand.

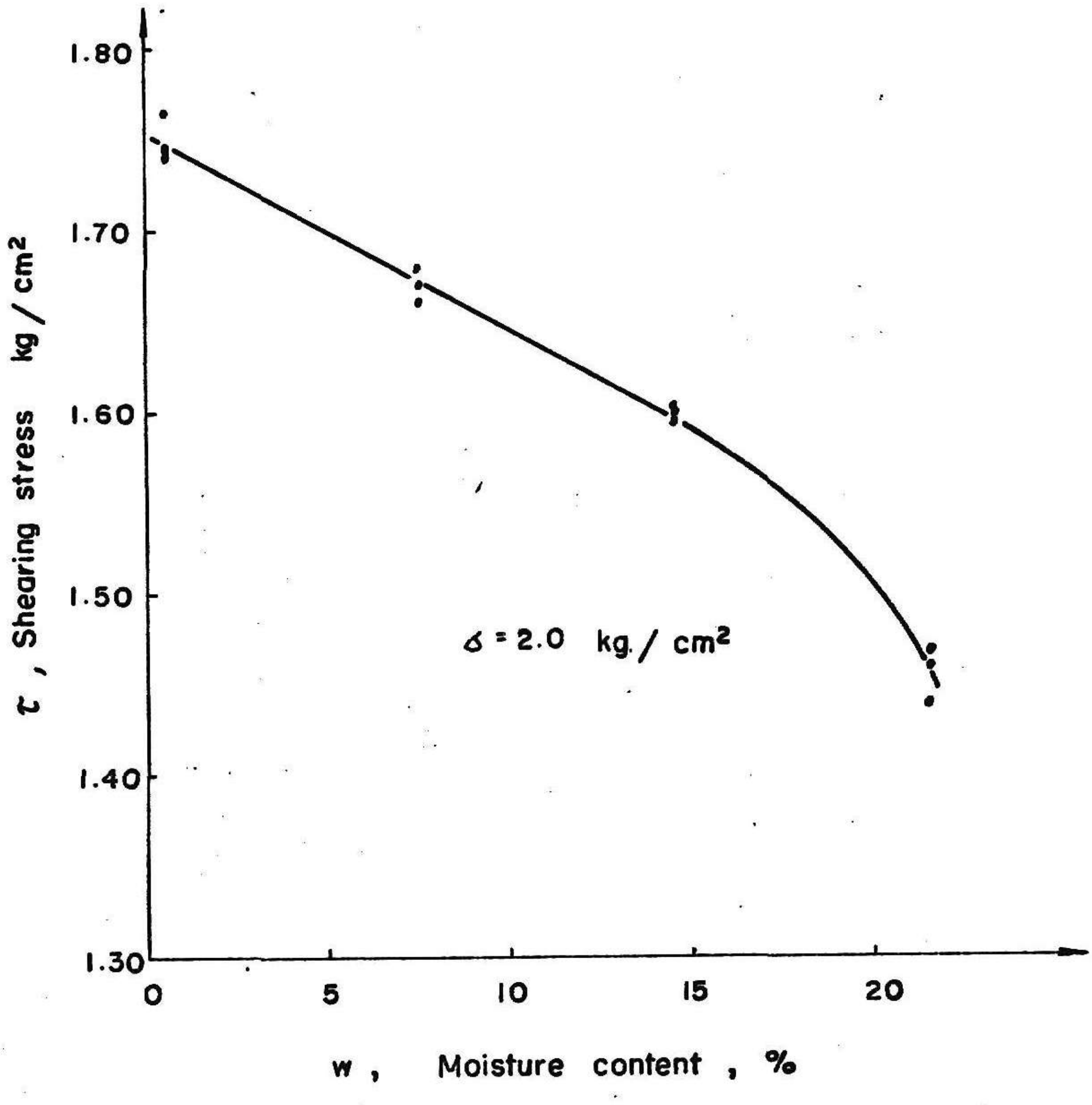

Fig.12. Effect of moisture content on the drained shear strength of dense clean fine sand.

THE SHEARING RESISTANCE OF SAND AT VARYING MOISTURE CONTENTS

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Diploma in Civil Engineering,
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Taiwan, China, 1960

AN ABSTRACT OF A MASTER'S REPORT

submitted in partial fulfillment of the

requirements for the degree

MASTER OF SCIENCE

Department of Civil Engineering

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1969

ABSTRACT

The shearing resistance of sand is affected by changing moisture contents. To study the effects and magnitude of these changes a clean fine sand was tested by controlled strain direct shear testing. Equally spaced moisture contents at four levels from air dry to saturated were studied and compared. Two normal stresses of 0.5 kg/cm^2 and 2.0 kg/cm^2 were used.

Results from these tests indicate that increasing moisture content causes a decrease in the shearing resistance of this material. This was attributed to lower axial strains with increasing moisture. This was further confirmed by the greater reduction in shear strength with increasing moisture at higher normal stress.