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INFLUENCE OF SAMPLE DISTURBANCE AND TEST METHOD ON KEY ENGINEERING PROPERTIES OF MARINE SOILS

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ABSTRACT

Detailed measurements of bulk density and vane shear strength were made in situ and on gravity cores in the San Diego Trough, Wilkinson Basin, and Abyssal Plain and Mississippi Delta areas of the Gulf of Mexico. Comparisons of in situ and laboratory measurements were made to evaluate the influence of sample disturbance and test method on bulk density and vane shear strength. Location differences between in situ and gravity core locations and the associated areal variation of bulk density and vane shear strength were described in detail for all comparisons.

The influence of sample disturbance on vane strength was difficult to evaluate because of differences in vane rotation rate and vane size between in situ and laboratory vane measurements. Large strength differences resulted from the great differences in angular shear velocity at the vane blade edges between in situ and laboratory vane measurements. A direct linear relationship between vane strength and angular shear velocity was found to exist in the Wilkinson Basin and San Diego Trough Test Areas. Comparison of in situ and laboratory vane strengths at a standard shear velocity, rather than a standard rotation rate, is proposed to eliminate uncertainties associated with rotation rate and vane size differences. A vane test procedure for both in situ and laboratory vane tests based on angular shear velocity is outlined.

INTRODUCTION

The major problem associated with sampling in the marine environment is the unknown effect of physical and environmental disturbances on the engineering properties of fine-grained marine soils. Quantitative evaluations of disturbance effects on engineering properties have been hindered by the lack of accurate information on the undisturbed engineering properties of seafloor sediments. A number of investigations comparing laboratory vane shear measurements with in situ vane measurements have been made in recent years (Fenske, 1956; Inderbitzen and others, 1971; Demars and Taylor, 1971; Inderbitzen and Simpson, 1972; Richards and others, 1972). These investigations did not, however, attempt to quantitatively evaluate the effect of sample disturbance on vane shear strength. Emrich (1970) utilized comparisons of laboratory and in situ vane measurements to evaluate the performance of a deep-penetration soil sampler for marine borings. Inderbitzen and others (1970) determined the amount of disturbance associated with the Lockheed DEEP QUEST piston corer using in situ vane measurements. Lee (1973) evaluated the quality of samples obtained with the NCEL DOTIPOS fixed-piston corer using laboratory and in situ vane shear measurements.

Several important factors other than sample disturbance are not always appreciated by investigators and may greatly affect comparisons of in situ and laboratory measurements such as those described above. Vane test uncertainties are believed to be very important for measurements in fine-grained marine soils (Monney, 1971). Rotation rate differences, which sometime exist between laboratory and in situ vane measurements because of high ship costs and limited test station time (Richards and others, 1972), are known to affect shear strength measurements (Cadling and Odenstad, 1950; Osterberg, 1956; Wilson, 1963; Migliore and Lee, 1971; Halwachs, 1971; Monney, in press). The strength variation due to rotation rate differences is more pronounced for relatively undisturbed samples than remolded samples (Migliore and Lee, 1971). Confining stresses for laboratory vane measurements are generally much lower than in situ stress conditions (Fenske, 1956; Hansen and Gibson, 1949). Since confining stresses directly influence vane strength (Singler, 1971), differences between laboratory and in situ vane measurements may result from the confining stress differences. Comparisons of in situ and laboratory vane measurements may also be significantly affected by vane size differences. Since the shear velocity at the outer edges of the vane blades increases with increasing vane size, considerable differences in the rate at which the failure surface is sheared exists between in situ and laboratory vane measurements at identical rotation rates. Soil anisotropy also may cause differences between in situ and laboratory vane measurements (Aas, 1965). Another factor which may significantly affect comparisons of in situ and laboratory vane strengths is the unknown strength reduction resulting from vane penetration disturbance (LaRochelle and others, 1973). Comparison of vane shear measurements could be seriously misinterpreted if the contributions of rotation rate differences, vane size differences, soil anisotropy, and vane penetration disturbances are not considered.

Another factor, important in comparisons of in situ measurements with laboratory measurements made on samples raised by surface coring techniques, is location difference. In situ and core locations are almost never at identical locations on the seafloor because of positioning inaccuracies and location uncertainties associated with lowering a coring device or test platform to the seafloor with a long cable. This would not be the case for in situ measurements and cores obtained from the same location using a tethered test platform (Demars and Taylor, 1971) or a submersible (Inderbitzen and Simpson, 1972). If the variation of geotechnical properties over the distances believed to exist between core and in situ sites is not known, differences between laboratory and in situ measurements believed to result from sample disturbance may in reality reflect only areal property variability. Interpretation of comparisons of in situ and laboratory measurements should also consider possible location differences between core and in situ test sites and the areal property variability in the area as well as test method uncertainties.

To better understand the influence of sample disturbances and test method on the engineering properties of fine-grained marine sediments, comparisons of in situ and laboratory shear strength and bulk density measurements in four different sedimentary environments were made. This paper describes in detail results of these measurements from the San Diego Trough, Wilkinson Basin, and Abyssal Plain and Mississippi Delta regions of the Gulf of Mexico. The effect of sampling disturbances, test method uncertainties, and areal property variation associated with location differences on comparisons of in situ and laboratory measurements are evaluated. The effects of rotation rate differences, vane size differences, and vane penetration disturbances on vane shear strength are discussed in some detail.

SAMPLING, TESTING, AND ANALYTICAL PROCEDURES

Sampling

Cores from the four test areas were raised with similar type plastic-barrel gravity samplers designed to minimize disturbance (Richards and Parker, 1968). The samplers consisted of a 3 m long plastic core barrel, a large diameter check valve equal to the width of the core barrel, a simple friction clamp to attach the barrel to a weight stand, and a shroud for hydrodynamic stability. An external core retainer was used when necessary to prevent sample loss after collection.

One other gravity sampler was used on a coring investigation in the San Diego Trough. This borrowed sampler, designed primarily for the penetration of sand, consisted of Kastenlot weight stand and a 3 m long steel barrel with a plastic liner.

Measurement of Bulk Density

Bulk density of gravity core samples was measured nondestructively in the laboratory using gamma radiation (Preiss, 1968a; Chough and Richards, in press), and then destructively by the conventional weight-volume method.

In situ bulk density measurements were made using a nuclear transmission densitometer (Preiss, 1968b, 1969; Hirst and others, in preparation). The nuclear densitometer has been operated from the tethered Illinois Tower (Richards and others, 1972), tethered Lehigh or modified Illinois Tower (Hirst and others, in preparation), the small submersible ALVIN (Perlow and Richards, 1972; Richards, 1972), and the large submersible DEEP QUEST (Hirst and others, 1972; Richards, 1972; Terry and Richards, 1973). Deployment of the densitometer in each area is summarized in Table 1.

Measurement of Shear Strength

Laboratory measurements of shear strength on the gravity cores were made using a miniature vane. In situ shear strength measurements were made using a large field vane device operated from the tethered Illinois Tower (Richards and others, 1972) and submersible DEEP QUEST (Hirst and others, 1972; Richards, 1972). The vane sizes and rotation rates used in each area are also summarized in Table 1. Vane shear strength determined at the higher (23 m rad/s) rotation rate is the Marine Geotechnical Laboratory's (MGL) standard for in situ and laboratory vane strength comparisons in this study.

Comparisons

Laboratory bulk density and vane shear strength measurements on gravity cores are compared with in situ measurements made at or near the core locations. Position inaccuracies and location differences between core and in situ test sites are described for each comparison. The areal property variation believed to exist over the distances between core and in situ locations is assessed. Finally, the test method uncertainties, particularly those associated with the vane test which would contribute to differences between in situ and laboratory measurements are discussed.

The comparisons of in situ and laboratory vane strength results described in this study are limited to only those comparisons at core locations where in situ strength measurements using two vane sizes have been obtained.

SAN DIEGO TROUGH

Investigations

Detailed measurements of bulk density and shear strength were made in situ and on gravity core samples during a four-year cooperative program with Lockheed Ocean Laboratory to establish a small seafloor geotechnical test area in the San Diego Trough (Richards, 1970; Hirst, 1972). The Test Area is located approximately 24 km southwest of San Diego in a water depth of about 1.2 km. The surface sediments of the Test Area are primarily uniform clayey-silts according to the Shepard (1954) classification and slightly organic (OH) or micaceous (MH) clayey-silts of high plasticity according to the Unified Soil Classification. The geotechnical properties of the Test Area have been partly described by Inderbitzen and Simpson (1972), Hirst (1973), and in detail by Carius and Richards (in preparation).

A total of nineteen short (< 1.6 m) gravity cores were raised from the Test Area on two coring investigations during the four year program. In situ bulk density measurements were made at four of the gravity core locations. Although no in situ vane measurements were obtained directly at core locations, a number of vane tests were made within a distance of 0.5 km or less of six core locations. In situ vane measurements using two vane sizes were available only at a single core location in the east central portion of the Test Area.

Bulk Density

Core bulk density values, determined by both nuclear and volumetric methods, increased consistently with increasing sediment depth at the four core locations. In situ bulk density values, except for a small increase near the sediment surface, remained essentially constant with depth. Comparison of in situ and laboratory density results at the four gravity core locations showed that in situ values were lower than values determined from the cores. A typical comparison of in situ and laboratory bulk density results is presented in Figure 1.

In situ and gravity core locations were known to within ± 0.3 km, and the areal variability of in situ and core bulk density over the entire Test Area was only 0.05 Mg/m^3. Thus, the differences between in situ and laboratory bulk density measurements detected throughout the Test Area are believed to result from sample disturbances and not areal variability due to location differences. The relationship between the laboratory and in situ bulk density results appears to indicate that an alteration in the clayey-silt sediment structure occurred during sampling causing densification of the cores with depth (Perlow and Richards, 1974).

Shear Strength

Laboratory vane strengths at the six core locations increased with increasing sediment depth to 1.6 m, the maximum depth sampled. In situ vane strengths at these locations increased uniformly with increasing sediment depth to about 1.5 m, but at a greater rate than the laboratory vane strengths.

Comparison of in situ and laboratory vane strength measurements from the east-central core location in the Test Area showed that in situ vane strengths were noticeably higher than the laboratory vane strengths (Fig. 2).

In situ strengths obtained with a 10 by 20 cm vane at two sites near the core location were identical and averaged about 32 percent higher than the MGL standard 23 m rad/s laboratory vane strength based on linear regression analyses of the laboratory and in situ vane strengths with depth. In situ vane strengths measured with the smaller 7.5 by 15 cm vane averaged 27 percent higher than the 23 m rad/s laboratory strengths. Laboratory vane strengths determined at the 6 m rad/s rotation rate averaged about 5 percent lower than the 23 m rad/s laboratory vane strengths.

The structural alteration (densification) believed to occur during sampling would probably destroy many of the fragile interparticle bonds in the clayey-silt sediment and result in a significant reduction in laboratory vane strength. However, the low laboratory vane strengths may not be entirely the result of sample disturbance. Location differences between core and in situ sites were as great as

0.5 km. Areal variation of in situ vane shear strength over 0.5 km in the eastern and central portion of the Test Area is believed less than about 2 kPa. Since small scale areal variability has been shown to be independent of distance between test sites (Inderbitzen and Simpson, 1972), the magnitude of shear strength variation over the distances between core and in situ locations is unknown. Therefore, areal property variation may result in differences between in situ and laboratory vane strength measurements.

Differences between in situ and laboratory vane strengths due to the test uncertainties associated with the vane test may be even more important than the differences resulting from areal variability and will be discussed later.

WILKINSON BASIN, GULF OF MAINE

Investigations

In situ and laboratory measurements of bulk density and shear strength were made in the Wilkinson Basin Geotechnical Test Area, which is located in the Gulf of Maine approximately 120 km east of Boston in a water depth of about 260 m. The surface sediments of the Basin are clayey-silts in the upper 0.2 m and silty-clays at sediment depths below 0.2 m according to the Shepard (1954) classification. The sediments are inorganic clays of high plasticity (CH) according to the Unified Soil Classification. The geotechnical properties of the Basin Test Area have been partially described by Richards and Keller (1970), Dzwilewski (1972), Perlow and Richards

(1973), Parker (1973), Chough and Richards (in press), and in detail by Carius and Richards (in preparation).

Gravity cores were raised at the four sides and center of the NW-SE elongate Basin Test Area using a plastic-barrel gravity sampler. In situ bulk density and vane shear strength were made at the five core locations using the Illinois tethered tower (Preiss, 1968b, 1969; Richards and others, 1972). In situ vane measurements using a 7.5 by 15 cm vane and 5 by 10 cm vane were obtained at two of the five core locations; consequently, measurements at only the northwest and east-central sites will be discussed.

Bulk Density

In situ bulk density values increased slightly with increasing sediment depth to about 0.4 m and then remained almost constant with depth to 1.5 m, the maximum depth penetrated. Laboratory bulk density values from the three central Basin core locations increased with increasing sediment depth to about 0.3-0.5 m, depending on location within the basin, and then remained nearly constant with depth except for some small scale microvariations. Laboratory density values from the southeast core location were constant with depth to 0.5 m, then increased slightly with increasing sediment depth to 1.1 m, the maximum depth sampled. Laboratory bulk density values from the northwest core location increased slightly with depth to 0.3 m and then remained nearly constant with depth to the maximum depth sampled (Fig. 3).

Comparison of in situ and laboratory bulk density results at the three central Basin core locations showed that in situ values were equal to or slightly greater than laboratory nuclear and volumetric density values. In situ bulk density measurements at the northwest and southeast Basin locations were equal to or slightly lower than laboratory values. The maximum density difference between in situ and laboratory measurements at the five sites in the Basin was only 0.05 Mg/m^3, and this value was found at the northwest core location (Fig. 3).

The maximum location difference between in situ and core locations was about 1 km. Variability of in situ bulk density is known to be as much as 0.05 Mg/m^3 over a distance of 0.4 km in the northern portion of the Test Area and about 0.03 Mg/m^3 in the central portion (Perlow and Richards, 1973). Thus, areal variation of bulk density over the distances between core and in situ sites, may be responsible for all or part of the small density differences observed between in situ and laboratory measurements. The small density differences between in situ and laboratory bulk density results at each of the five locations indicate that the gravity cores were not appreciably disturbed during sampling and are probably of high quality.

Shear Strength

Laboratory vane strengths at the five core locations generally increased with increasing sediment depth to 0.2 - 0.3 m and then remained nearly constant with depth to 1 m, the maximum depth sampled. In situ vane strengths increased with increasing sediment depth to approximately 0.7 m; below this depth, values remained nearly constant with depth to 1.6 m and then exhibited a slight increase with increasing sediment depth to the maximum depth penetrated. At the northwest location, however, in situ vane strengths increased slightly with increasing sediment depth below 0.7 m to the maximum depth penetrated.

Comparison of in situ and laboratory vane measurements at the northwest and east-central locations showed that in situ vane strengths were approximately equal to the 6 m rad/s laboratory vane strengths in the upper 0.4 m. At the northwest core location, laboratory vane strengths for depths of 0.6 m to 1.6 m averaged about 2 kPa, in situ vane strengths obtained with the smaller 5 by 10 cm vane averaged about 4 kPa, and in situ vane strengths obtained with the larger 7.5 by 15 cm vane averaged nearly 5.5 kPa (Fig. 4). At the east central location for the same depth range (Fig. 5), laboratory vane strengths averaged 3.1 kPa, the smaller in situ vane strengths about 3.6 kPa, and larger in situ vane strengths approximately 4.1 kPa (Richards and others, 1972).

The maximum position difference between in situ sites and the northwest gravity core location was about 1 km. The maximum position difference between in situ sites and the east-central core location was nearly 2 km; the distance between in situ vane sites at this core location, varied by as much as 3.6 km. The accuracy of all core and in situ vane locations was known to ± 0.7 km of the stated position. Although areal variability of in situ vane strength in the upper 2.5 m between the five Basin test locations is only 1 kPa, information on small scale variability over the distances known to exist between test sites is not available. Therefore, the magnitude of strength differences between in situ and laboratory vane measurements resulting from location differences, particularly at the east-central core location, although believed small, are unknown.

The gravity core samples raised from the Test Area are believed to be of high quality, so that the significant difference between in situ and laboratory vane strengths is not easily reconciled. The effect of rotation rate differences between in situ (23 m rad/s) and laboratory vane measurements (6 m rad/s) is believed to account for a portion of the strength differences detected. The unknown effects of differences in shearing velocity between different radii laboratory and in situ vanes, soil anisotropy, and vane penetration disturbances are believed significant and will be discussed later.

ABYSSAL PLAIN, GULF OF MEXICO

Investigations

In situ and laboratory measurements of bulk density and vane shear strength were made at two locations in the Sigsbee Abyssal Plain of the Gulf of Mexico in water depths of about 3.7 km. The surface sediments at the two test locations are clays according to the Shepard (1954) classification and light brown organic clays of medium to high plasticity (OH) according to the Unified Soil Classification. The geology and geotechnical properties of this area have been described by Bryant and others (1967), Bryant and Delflache

(1971), and Richards and others (1969), and Richards and others (1972).

Four vane profiles, three using a 10 by 20 cm vane and one using a 7.5 by 15 cm vane, were obtained at one of the two Abyssal Plain test locations (Richards and others, 1972). In situ bulk density measurements were obtained at the other test location (Hirst and others, in preparation). A single gravity core was raised at both locations.

Bulk Density

Results of the in situ and laboratory bulk density measurements are presented in Figure 6. In situ bulk density values increased with depth to 0.1 m. Between 0.1 m and 0.3 m, values exhibited noticeable microvariation with depth. Below 0.3 m, values remained nearly constant with depth to 0.5 m, the maximum depth penetrated. Laboratory bulk density values increased with increasing sediment depth to the maximum depth sampled.

Comparison of in situ and laboratory volumetric measurements (Fig. 6) showed that at a depth of 0.1 m in situ and laboratory density values were nearly equal. At a depth of 0.5 m, in situ bulk density values were about 0.1 Mg/m^3 lower than laboratory values. The observed density differences, similar to those detected in the San Diego Trough, are possibly the result of core densification which may have occurred during sampling.

The gravity core was raised shortly after the in situ test was completed, thus little location difference in the surface ship position between the core and in situ sites is believed to exist. However, due to the considerable water depth and great outlay of cable required, an unknown amount of location difference between the core and in situ test sites probably exists. As there is no information on the areal variation of bulk density for the Abyssal Plain area of the Gulf of Mexico, the density differences observed between core and in situ measurements may be partially the result of location differences and not entirely the result of sample disturbances.

Shear Strength

Results of the laboratory and four in situ measurements are presented in Figure 7. In situ vane strengths measured with the larger 10 by 20 cm vane increased with depth to 0.7 m, except for the in situ profile which begins at 0.2 m. Strength values then decreased appreciably with depth to approximately 1.0 m. Below 1.0 m, in situ vane strengths increased uniformly with increasing sediment depth. In situ vane strength obtained with the 7.5 by 15 cm vane increased to a depth of 0.26 m then decreased appreciably with increasing depth to 1 m. Laboratory vane strengths exhibited a marked strength increase in the upper 0.2 m due to the presence of an iron-rich sediment layer. Below 0.2 m, laboratory strengths exhibited considerable variation with increasing sediment depth to about 1 m, below which depth laboratory strength values increased uniformly with depth.

In situ vane strengths in the upper 1 m were 1 to 2 kPa greater than the 23 m rad/s laboratory values, except at the iron-rich sediment layer. Below 1 m, in situ and laboratory vane strengths were about equal. In situ vane strengths in the upper 1 m exhibited noticeable areal variability (3 kPa). Laboratory vane strengths determined at the lower 6 m rad/s rotation rate were generally greater than the 23 m rad/s laboratory vane strengths except at the iron-rich sediment layer and between 1.0 and 1.4 m.

Vane strengths obtained with a 7.5 by 15 cm vane were about the same or slightly greater than vane strengths obtained with a larger 10 by 20 cm vane. This is contrary to results obtained from the Wilkinson Basin and San Diego Trough where higher vane strengths were consistently measured with larger vane sizes. The difference may be partly explained by the use of two different torque sensors for the two vane sizes. A C-ring torque sensor was used for the 7.5 by 15 cm vane measurement while a load cell torque sensor was used for the three 10 by 20 cm vane measurements.

The maximum location difference between the in situ vane and gravity core locations was about 3.7 km. Location differences between the four in situ test locations was approximately 1.7 km. Even if the ship positions for the in situ and core locations were identical, the true locations of the core and in situ test sites would not be known due to the uncertainties associated with operating at such a water depth of 3.7 km. Little is known of the areal variability of shear strength in this area of the Gulf of Mexico. Therefore, comparison of in situ and laboratory vane measurements is complicated by the unknown variation of strength between test locations. The difference observed between vane strengths obtained with the two vane sizes may be the result of areal property variation as well as systematic error between the two torque sensors used. The uncertainties due to rotation rate differences, vane size differences, and penetration disturbances associated with the vane test are believed to be important also in the comparison of in situ and laboratory vane measurements and will be discussed in a later section.

MISSISSIPPI DELTA, GULF OF MEXICO

Investigations

In situ and laboratory vane shear strength measurements were made at a single test location east of the South Pass of the Mississippi River in a water depth of about 95 m. The surface sediments for the area investigated are silty-clays according to the Shepard (1954) classification, and brown organic clays of high plasticity (OH) according to the Unified Soil Classification. The geology and geotechnical properties for the Mississippi Delta sediments have been described by Kolb and Kaufman (1967), McClelland (1967), Bryant and others (1969), and Richards and others (1972).

Two in situ vane profiles were obtained from the Delta site. In situ vane strength measurements were made using a 7.5 by 15 cm vane and a 10 by 20 cm vane. A single gravity core was also raised from the same location (Richards and others, 1972). In situ bulk density measurements were not made at this location.

Shear Strength

Comparison of in situ and laboratory vane shear strength results are presented in Figure 8. In situ vane strengths increased uniformly with depth to 0.7 m. Below 0.7 m, in situ strengths obtained with the 10 by 20 cm vane remained nearly constant with depth to 1.6 m; strengths obtained with the smaller 7.5 by 15 cm vane were higher, and they continued to increase slightly with depth to 2.5 m, the greatest depth penetrated. Laboratory vane strengths increased uniformly with depth to about 0.7 m, then exhibited small scale strength microvariations to a depth of 1.2 m. Below 1.2 m, laboratory values again increased uniformly with depth to 1.8 m, the maximum depth sampled.

In situ vane strengths were about equal to laboratory strengths in the upper 0.7 m. In situ strengths measured with the larger vane equaled laboratory values to 1.8 m, the maximum depth of the core. In situ vane strengths obtained with the smaller vane below 0.7 m were about 2 kPa greater than both the laboratory and the 10 by 20 cm in situ vane values. Laboratory strength values determined at the lower 6 m rad/s rotation rate were very slightly lower than the MGL standard 23 m rad/s rate.

Two different torque sensors were again used for the two in situ vane tests. A C-ring torque sensor was used for the vane measurements with the smaller (7.5 by 15 cm) vane while a load-cell sensor was used for measurements with the larger (10 by 20 cm) vane. The higher vane strengths obtained with the smaller vane size, also detected in the Abyssal Plain results, may again partly be the result of a systematic error associated with the C-ring torque sensor. However, since the vane tests were made near the mouth of the Mississippi Delta, considerable shear strength variability may also exist over small distances as a result of the changing sedimentary environment. Although the ship positions for the in situ and core sites are nearly the same, location differences between bottom core and in situ test locations may exist due to ship drift and cable outlay. Therefore, the appreciable difference between the two in situ vane profiles may be the result of areal property variation as well as systematic differences between the two torque sensing arrangements. The good agreement of the 10 by 20 cm vane strengths and laboratory values may be fortuitous because of possibly areal property variation. The unknown effects of the vane test uncertainties on the laboratory and in situ vane measurements may also be important and are discussed later.

BULK DENSITY DISCUSSION

Methods of in situ and laboratory density measurements are directly comparable (Preiss, 1968b, 1969) and are not affected by test method uncertainties such as those associated with the vane shear test. Bulk density usually exhibits little areal variability, so comparisons of in situ and laboratory density measurements are not affected by location differences to the extent that in situ and laboratory vane shear strength comparisons are.

Results of comparisons of in situ and laboratory bulk density measurements from the San Diego Trough, Wilkinson Basin, and Gulf of Mexico Abyssal Plain were very useful in evaluating the changes in sediment structure that occur as a result of sampling disturbances. Comparison of in situ and laboratory bulk density results from the San Diego Trough Test Area and the Gulf of Mexico Abyssal Plain enabled the detection of core densification. Comparison of in situ and laboratory density results from the Wilkinson Basin Test Area substantiated the belief that the gravity cores raised from the Basin were not significantly altered by sampling disturbances and were of high quality.

SHEAR STRENGTH DISCUSSION

Comparisons of in situ and laboratory vane shear strength measurements are difficult to evaluate because of the many uncertainties associated with the vane test. The important effects of vane rotation rate, vane size, and vane penetration disturbance on measurements of in situ and laboratory vane shear strength are not well understood.

The vane test measures the torsional force required to shear a cylindrical failure surface described by the vane blade edges. Undrained shear strength is obtained by converting the torsional force to a unit shearing resistance of the cylindrical failure surface (American Society for Testing and Materials, 1974). However, the shearing resistance at the failure surface is greatly influenced by the rate at which shear occurs. The angular velocity at the outer edges of the vane blades determines the rate of shear and therefore significantly influences vane strength measurements. Angular shear velocity at the vane blade edges is a function of vane rotation rate and also vane size as shown by the expression presented below:

$$v = r\omega$$

where v = angular velocity, r = vane radius, and ω = vane rotation rate. The effects of vane rotation rate and vane size differences on measurements of vane shear strength are important and must be considered when evaluating comparisons of in situ and laboratory vane measurements.

Another vane test uncertainty, which is believed to appreciably affect comparisons of in situ and laboratory vane measurements, is vane penetration disturbance. Significant strength reductions in sensitive clays are known to result from disturbance caused by vane penetration. The effects of vane penetration disturbances, however, have only been investigated for one sediment type and are unknown for fine-grained marine sediments.

<u>Rotation Rate Differences</u>

The effect of vane rotation rate on vane strength measurements has long been recognized as an important consideration in vane shear testing. Cadling and Odenstad (1950) showed that in situ vane strength measured at a rotation rate of 17 m rad/s was 20 percent higher than strengths determined at a rotation rate of 1.7 m rad/s. Monney (in press) found that laboratory vane strengths obtained at a rotation rate of 26 m rad/s were nearly 30 percent higher than strengths measured at 0.3 m rad/s on relatively undisturbed marine clayey-silts. Migliore and Lee (1971) showed that laboratory strength differences resulting from vane rotation rate differences increased with increasing core quality. The effect of vane rotation rate on vane shear measurements is highly dependent upon sediment type (Wilson, 1963) and has only been investigated in the laboratory for several types of fine-grained marine sediments.

Laboratory vane strengths for all the gravity cores considered in this study, except the five samples raised in the Wilkinson Basin Test Area, were measured at two rotation rates (Table 1) to evaluate vane strength differences due to differences in vane rotation rate. Results showed that vane strengths measured at the faster 23 m rad/s rotation rate consistently yielded slightly higher values than strengths determined at the slower 6 m rad/s rotation rate. The strength differences resulting from differences in the laboratory rotation rate, however, were small compared to those observed between in situ and laboratory measurements. It is believed that the small strength differences between the laboratory vane measurements at the fast and slow rotation rates are the result of the small angular shear velocity difference of 0.11 mm/s between the laboratory measurements at the two rotation rates. The angular shear velocity difference between the laboratory and in situ measurements is 1.1 mm/s, an entire order of magnitude greater than the difference between the laboratory measurements.

In the Wilkinson Basin, a difference of 17 m rad/s existed between in situ and laboratory vane rotation rates (Table 1). An unpublished study of laboratory strength differences due to a 17 m rad/s rotation rate difference for a series of ten gravity cores raised from the Basin Test Area indicated that strengths determined at the faster 23 m rad/s rotation rate averaged about 11 percent higher than vane strengths determined at the slower 6 m rad/s rotation rate (Smith and Richards, in preparation). However, the 11 percent laboratory strength difference associated with the 17 m rad/s rotation rate difference is again only a small portion of the 100 percent strength difference observed between in situ and laboratory vane measurements in the Basin Test Area. The angular shear velocity differences between the laboratory vane measurements (0.11 mm/s) and in situ and laboratory vane measurements (1.10 mm/s) were almost identical to the corresponding observed strength differences of 11 and 100 percent.

The close correlation of observed strength differences with corresponding angular shear velocity differences from the Wilkinson Basin indicated that vane strength may be directly related to angular shear velocity.

Vane Size Effects

Little attention has been paid to strength differences that may result from the large angular shear velocity differences which exist between in situ and laboratory vane measurements. The large size difference between laboratory and in situ vanes results in a significant difference in the angular shear velocity at the failure surface, even at the same rotation rate (Fig. 9). The angular shear velocity differences at the standard MGL rotation rate of 23 m rad/s associated with the laboratory and in situ vanes used in this study are illustrated in Figure 9. At the 23 m rad/s rotation rate the angular shear velocity is about 0.15 mm/s for the laboratory vane, 0.60 mm/s for the 5 by 10 cm vane, 0.90 mm/s for the 7.5 by 15 cm vane, and 1.20 mm/s for the 10 by 20 cm vane. The angular shear velocity for a 10 by 20 cm vane rotated at a rate of 23 m rad/s is 8 times greater than that of the laboratory vane. When laboratory vane rotation rates are smaller than those used for in situ vane measurements, the angular shear velocity difference between in situ and laboratory vane measurements becomes even greater. This was the case in the Wilkinson Basin where in situ angular shear velocity was an order of magnitude greater (10 times) than the angular shear velocity associated with the laboratory measurements.

The close correlation of observed strength differences with differences in angular shear velocity for the in situ and laboratory measurements from the Wilkinson Basin indicated that vane strength may be a direct function of the angular shear velocity at the vane blade edges. To evaluate this possible relationship, comparisons of vane shear strengths from both in situ and laboratory vane measurements with the angular shear velocity at which these strengths were determined were made for test locations in the Wilkinson Basin and San Diego Trough.

Figure 10 presents results of vane strength and angular shear velocity comparisons at four sediment depths from the northwest

Wilkinson Basin test location. A nearly linear relationship between vane shear strength and angular shear velocity existed for three of the four sediment depths compared. A linear relationship was not indicated at a sediment depth of 0.4 m possibly because of small scale areal or vertical variability of shear strength at this depth. A similar comparison of vane strength and angular shear velocity at the east-central Wilkinson Basin test location did not exhibit the linear relationship detected at the northwest test location. It is believed that areal and vertical property variability over the large distances (3.7 km) between in situ vane test sites masked the expected linear relationship of vane strength and angular shear velocity.

A comparison of in situ and laboratory vane strength with angular shearing velocity was made for the east-central test location results from the San Diego Trough (Fig. 11). Again, a nearly linear relationship between vane shear strength and angular shear velocity was observed at two of the four sediment depths. Laboratory vane strengths at the 1.0 and 1.4 m sediment depths appear to be higher than would be expected at the two shearing velocities. The gravity core considered in this comparison was significantly shortened during sampling, having a recovery ratio of only 0.45. Also, the core was sectioned at 0.5 and 1.1 m and transported to the laboratory. Leakage occurred in each of the three sections causing the core to dry somewhat at the top and bottom of each section. The net effect of these disturbances on laboratory vane shear strength is unknown. The lack of a linear relationship between vane strength and angular shear velocity at the two lower sediment depths is probably the result of shortening and drying disturbances. A significant location difference (0.5 km) existed between the core and in situ test locations. Therefore areal property variability could also obscure any linear relationship which may exist at the two lower sediment depths.

Similar comparisons of vane strength and angular shear velocity for the Abyssal Plain and Mississippi Delta test locations in the Gulf of Mexico were not attempted due to the possible test uncertainties associated with the C-ring and load-cell torque sensors and appreciable location differences known to exist between in situ and gravity core sites.

The observed relationships between vane shear strength and angular shear velocity from the Wilkinson Basin (Fig. 10) and San Diego Trough (Fig. 11) appear to indicate that vane shear strength is a direct function of the velocity at which the vane failure surface is sheared. The large strength differences (100 percent) observed between in situ and laboratory vane strength measurements from the Wilkinson Basin, originally believed the result of sampling disturbances (Richards and others, 1972), may be entirely explained by angular shear velocity differences.

In the Wilkinson Basin, little strength difference was detected between in situ and laboratory vane measurements in the upper 0.4 m despite the large angular shear velocity difference (1.1 mm/s). It is believed that the very low shear strength of 2 to 3 kPa causes the sediment to act as a viscoelastic material (Sherif and others, 1971), thus diminishing the influence of shearing rate along the failure surface. The close correlation of in situ and laboratory vane measurements at strengths of 3 kPa or lower was also observed at both the Abyssal Plain and Mississippi Delta test locations.

The establishment of a standardized vane rotation rate for in situ and laboratory vane measurements has been the subject of much controversy. The vane rotation rate currently considered the standard for field vane tests is 1.7 m rad/s (American Society for Testing and Materials, 1974). No standard rotation rate exists for the laboratory, although 1.7 m rad/s has been commonly used by convention throughout the world. However, experience with laboratory vane measurements at this slow rotation rate indicate that possible drainage may occur because of the slow rate of shear at the failure surface. Thus, higher vane rotation rates are being used to ensure drainage does not occur and also to save test time. The standard rotation rate at the Marine Geotechnical Laboratory was arbitrarily adopted at 23 m rad/s in 1967. More recently the Naval Civil Engineering Laboratory adopted 26 m rad/s as their standard vane rotation rate. This rate has also been adopted as a standard by the JOIDES Committee on Sedimentary Petrology and Mass Properties for the Deep Sea Drilling Project (Richards, in press). Monney (in press) recommends that 26 m rad/s be the standard rotation rate for the laboratory vane test because (1) this rate will probably always result in an undrained test, (2) the change in strength with small changes in rotation rate near 26 m rad/s is smaller than at 1.7 m rad/s, and

(3) the tests at 26 m rad/s are fast and save time.

The establishment of a single standard rotation rate for laboratory and in situ vane tests does not, however, take into account the large angular shear velocity differences which can exist between large and small size vanes. All the uncertainties associated with rotation rate and vane size would be eliminated if vane shear strengths were compared at similar angular shear velocities. It is proposed that an angular shear velocity of 0.15 mm/s be considered as a possible standard. An angular shear velocity of 0.15 mm/s would correspond to a vane rotation rate of 23.6 m rad/s for the standard 2.5 cm diameter laboratory vane (Fig. 9). The difference in vane strengths between 23 and 26 m rad/s appears to be minimal (Richards, in press), so that any vane laboratory rotation rate within this range would be acceptable. To maintain an angular shear velocity of 0.15 mm/s for in situ vane measurements, the vane rotation rate would have to be 6 m rad/s for a 5 by 10 cm vane, 4 m rad/s for a 7.5 by 15 cm vane, and 3 m rad/s for a 10 by 20 cm vane (Fig. 9). The in situ strength differences between 3 and 6 m rad/s are probably not significant, so that any rotation rate within this range would again be acceptable. The in situ vane rotation rates corresponding to the 0.15 mm/s angular shear velocity are slightly higher than the standard rotation rate of 1.7 m rad/s for the field vane test (American Society for Testing and Materials, 1974). The strength differences between 1.7 and 6 m rad/s rotation rates may be small enough to retain the 1.7 m rad/s rotation rate as standard.

The advantage of comparing vane shear strengths at a standard angular shear velocity (0.15 mm/s) is that the uncertainties associated with different rotation rates and vane sizes would be eliminated. Laboratory vane strengths based on an angular shear velocity of 0.15 mm/s would be determined at a fast rotation rate (23 to 26 m rad/s) that is recommended to insure drainage does not occur (Monney, in press). In situ field vane measurements at an angular shear velocity of 0.15 mm/s would be determined at rates (3 to 6 m rad/s) very near the accepted standard ASTM rate of 1.7 m rad/s.

A single standardized vane shear test method for both laboratory and in situ vane may be possible based on comparisons of vane strength at a standard angular shear velocity. An additional advantage to comparing vane strengths at a common angular shear velocity would be that if the relationship between vane strength and angular shear velocity could accurately be established for a given area, then vane measurements obtained at different angular shearing velocities could still be compared. This would be particularly important for in situ marine vane testing where ship or submersible time is expensive and station time may be very limited.

Vane Penetration Disturbances

Studies by LaRochelle and others (1973) on the effects of vane penetration disturbance indicated that significant strength reductions result from intrusion of the vane in very sensitive Champlain (Leda) clays. Strains generated by intrusion of the vane were large enough to destroy many of the inter-particle bonds thereby causing a significant reduction in vane strength. In their study, a perimeter ratio (α) was defined by

$$\alpha = \frac{4e}{\pi D}$$

where α = perimeter ratio, e = vane blade thickness, and D = vane diameter. This ratio relates the disturbed vane perimeter to the total perimeter of the cylindrical failure surface. In situ vane measurements with four vanes of differing blade thicknesses (perimeter ratios) were made at rotation rate of 1.7 m rad/s and angular shear velocity of 0.04 mm/s. Results showed that greater strength reductions occur with vanes having higher perimeter ratios. The range of perimeter ratio considered by LaRochelle and others (1973) was about 4 to 12 percent.

An evaluation of the perimeter ratios for the vanes used in this study (Table 1) showed that perimeter ratios were lowest (1.6 percent) for the largest vane size (10 by 20 cm) and highest (4.9 percent) for the laboratory vane (1.2 by 2.5 cm). Thus, strength reductions due to vane penetration disturbances may be more important for laboratory vane strength measurements than in situ vane measurements. However, the effect of vane penetration on laboratory and in situ vane strength measurements have not been investigated for fine-grained marine sediments.

SUMMARY AND CONCLUSIONS

Comparisons of in situ and laboratory vane shear strength and bulk density measurements from the San Diego Trough, Wilkinson Basin, and Abyssal Plain and Mississippi Delta regions of the Gulf of Mexico were made to evaluate the influence of sample disturbance and test method differences on shear strength and bulk density.

Significant differences between in situ and laboratory bulk density measurements were observed in the San Diego Trough and to a lesser extent in the Abyssal Plain of the Gulf of Mexico. These differences are believed the result of core densification that occurs during sampling. In situ bulk density values agreed closely with laboratory values in the Wilkinson Basin indicating that little or no densification occurred.

In situ vane strengths were significantly higher than laboratory vane strengths in the San Diego Trough. In situ vane strengths from the Wilkinson Basin were approximately equal to laboratory vane strengths in the upper 0.4 m. Below this depth, in situ vane strengths were nearly 100 percent greater than the laboratory strength values. In situ vane strengths from the Abyssal Plain were somewhat higher than laboratory vane strengths in the upper 1.0 m, below which depth they were about equal. At the Mississippi Delta location, in situ vane strengths were about equal to a depth of 0.7 m. Below this depth in situ vane measurements obtained with a 7.5 by 15 cm vane were nearly double the laboratory vane measurements. In situ vane strengths obtained with a 10 by 20 cm vane were nearly identical to laboratory vane strengths.

In the Wilkinson Basin and San Diego Trough Test Areas, in situ vane strengths obtained with large vane sizes were consistently higher than strength values obtained with smaller vane sizes. This was not exhibited in the two Gulf of Mexico test locations where vane strengths obtained with a smaller vane were equal to or greater than vane strengths measured with a larger size vane. This discrepancy is believed the result of location differences between in situ test sites and possible test uncertainties associated with the two torque sensors used with the two vane sizes.

The influence of sample disturbance on vane strength and bulk density was difficult to establish because of areal property variation over the distances known to exist between in situ and gravity core locations. Information on areal property variability from locations other than core locations was usually available. In most cases, the known areal property variability was of sufficient magnitude to be important in the comparison of in situ and laboratory measurements.

The influence of sample disturbance on vane shear strength was very difficult to evaluate because of vane rotation rate and vane size differences between in situ and laboratory vane measurements. Also, strength reductions resulting from vane penetration disturbances complicated the comparisons of in situ and laboratory vane measurements. Laboratory vane strength differences resulting from vane rotation rate differences were found to be small compared to the strength differences observed between in situ and laboratory measurements. Strength differences were noticed to be directly proportional to angular shear velocity differences. Large strength differences resulted from the great difference in angular shear velocity between in situ and laboratory vane measurements, while only small strength differences were observed for the small difference in angular shear velocity between laboratory vane measurements at the two rotation rates.

Comparison of in situ and laboratory vane strengths with angular shear velocity at the vane blade edges in the Wilkinson Basin and San Diego Trough Test Areas indicate the existence of a direct linear relationship between vane strength and angular shear velocity. Thus, the large strength differences observed between in situ and laboratory vane measurements may be partially or entirely the result of angular shear velocity differences.

Comparison of in situ and laboratory vane shear strength measurements at a standard angular shear velocity would eliminate many of the uncertainties associated with differences in vane rotation rate and vane size. An angular shear velocity of 0.15 mm/s is proposed as the standard for in situ and laboratory vane measurements. Laboratory vane measurements with a standard 2.5 cm diameter vane would be determined at a rotation rate of 24 m rad/s to maintain an angular shear velocity of 0.15 mm/s. In situ vane measurements, depending upon vane size, would be determined at rotation rates ranging from 3 to 6 m rad/s. The advantage of comparing in situ and laboratory vane measurements at an angular shear velocity of 0.15 mm/s is that: (1) laboratory vane measurements are made at a rotation rate high enough to insure that drainage does not occur, (2) the laboratory rotation rate is very near the rotation rate of 26 m rad/s that has been adopted as a standard laboratory rate by a number of organizations, and (3) the in situ vane rotation rate is near the standard field vane rotation rate of 1.7 m rad/s that has been used since the development of the vane test.

Table 1.

In Situ and Laboratory Test Information

MEASUREMENT	San Diego Trough	Wilkinson Basin	Gulf of Mexico	
			Abyssal Plain	Mississippi Delta
In Situ Bulk Density				
Deployment	DEEP QUEST	Illinois Tower and ALVIN	Lehigh Tower	---
In Situ Vane Shear				
Deployment	DEEP QUEST	Illinois Tower	Illinois Tower	Illinois Tower
Vane size, cm (Perimeter ratio, %)	10 by 20(1.6) 7.5 by 15(2.6)	7.5 by 15(2.5) 5 by 10(3.8)	10 by 20(1.9) 7.5 by 15(2.5)	10 by 20(1.9) 7.5 by 15(2.5)
Rotation rate, m rad/s deg/min	21 72	23 79	23 79	23 79
Laboratory Vane Shear				
Vane size, cm (Perimeter ratio, %)	1.2 by 2.5(4.9)	1.2 by 2.5(4.9)	1.2 by 2.5(4.9)	1.2 by 2.5(4.9)
Rotation rate, m rad/s deg/min	6 and 23 21 and 79	6 21	6 and 23 21 and 79	6 and 23 21 and 79

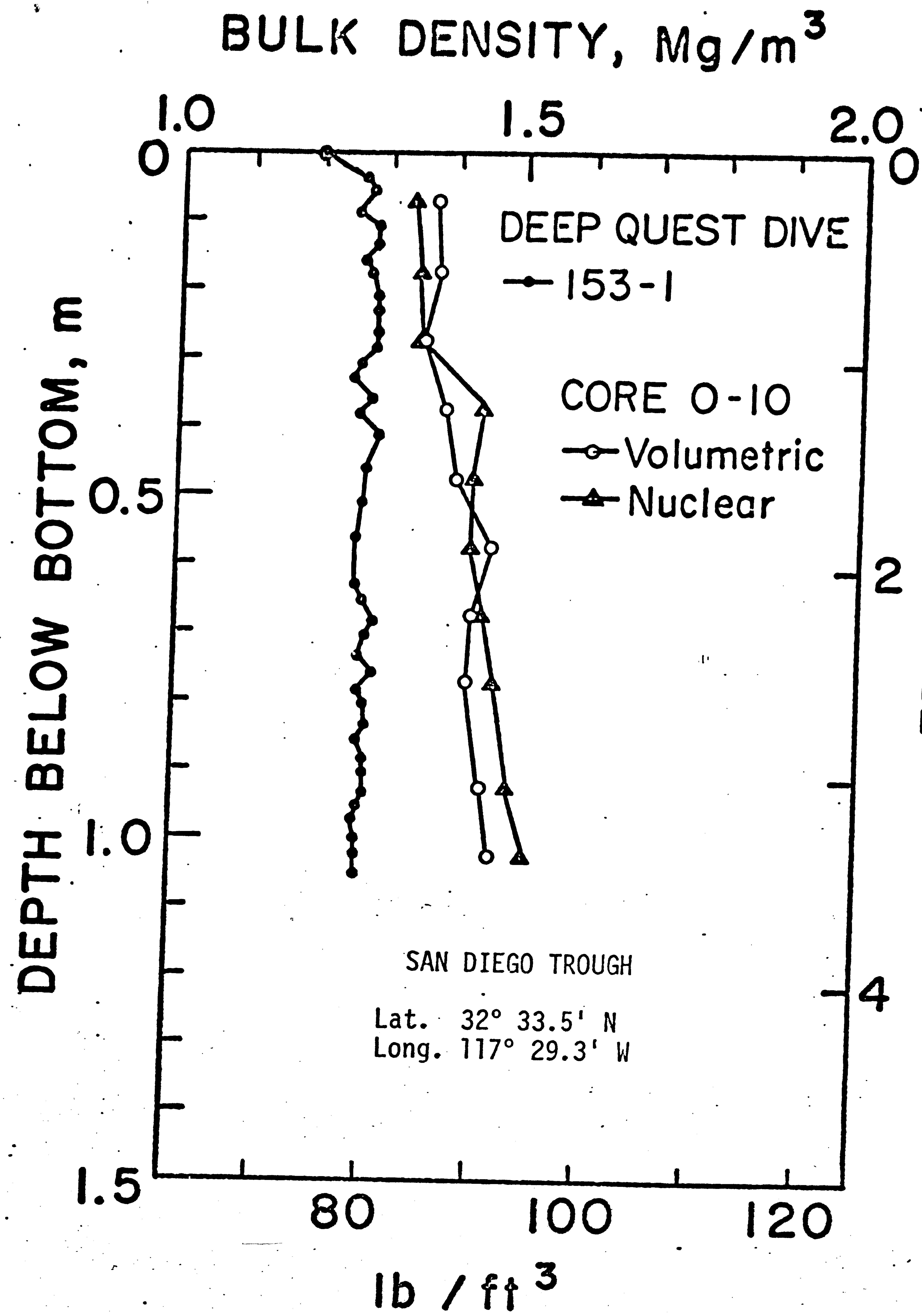

Figure 1. Comparison of in situ and laboratory bulk density measurements from the San Diego Trough.

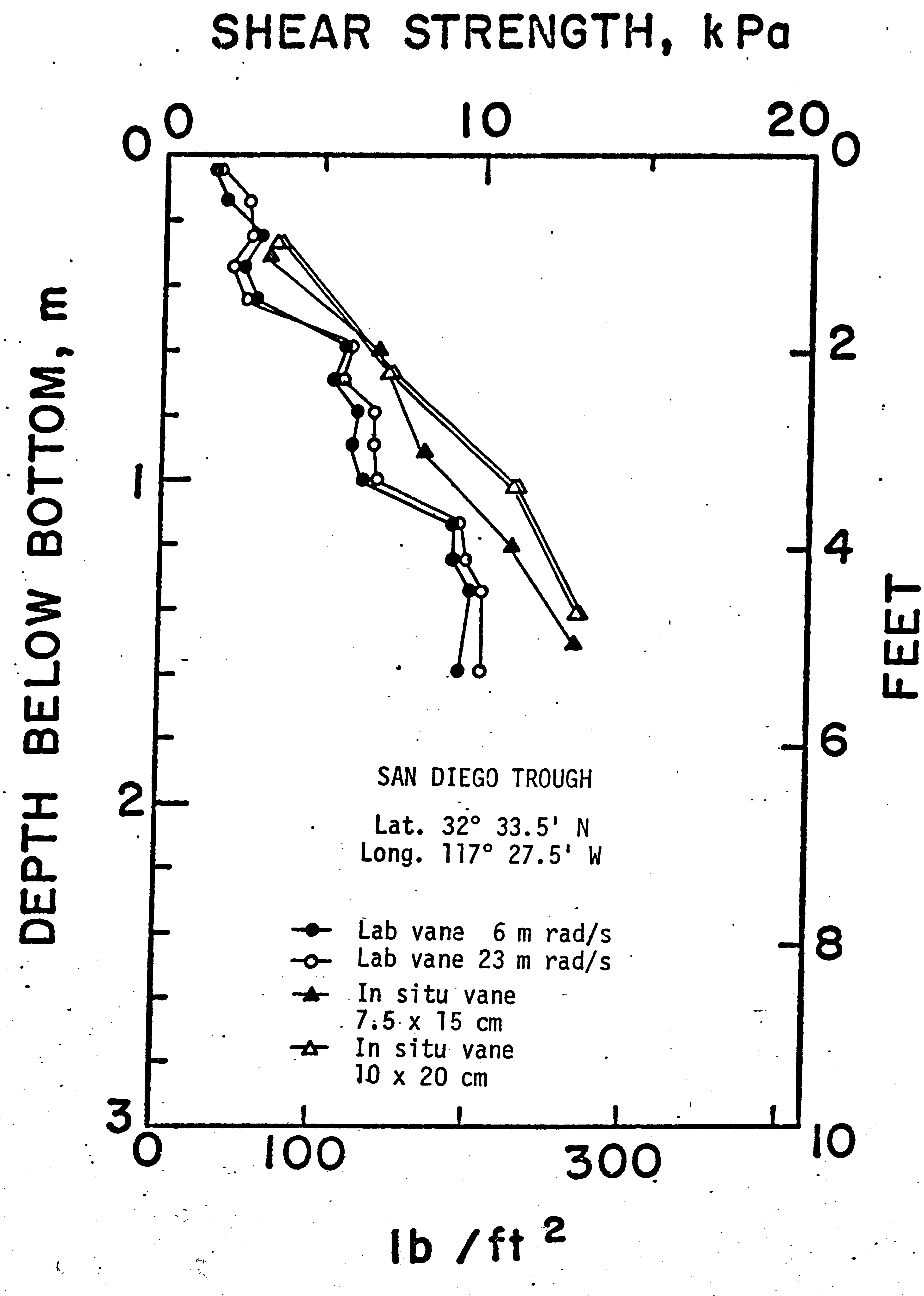

Figure 2. Comparison of in situ and laboratory vane shear strength results from the east-central San Diego test location.

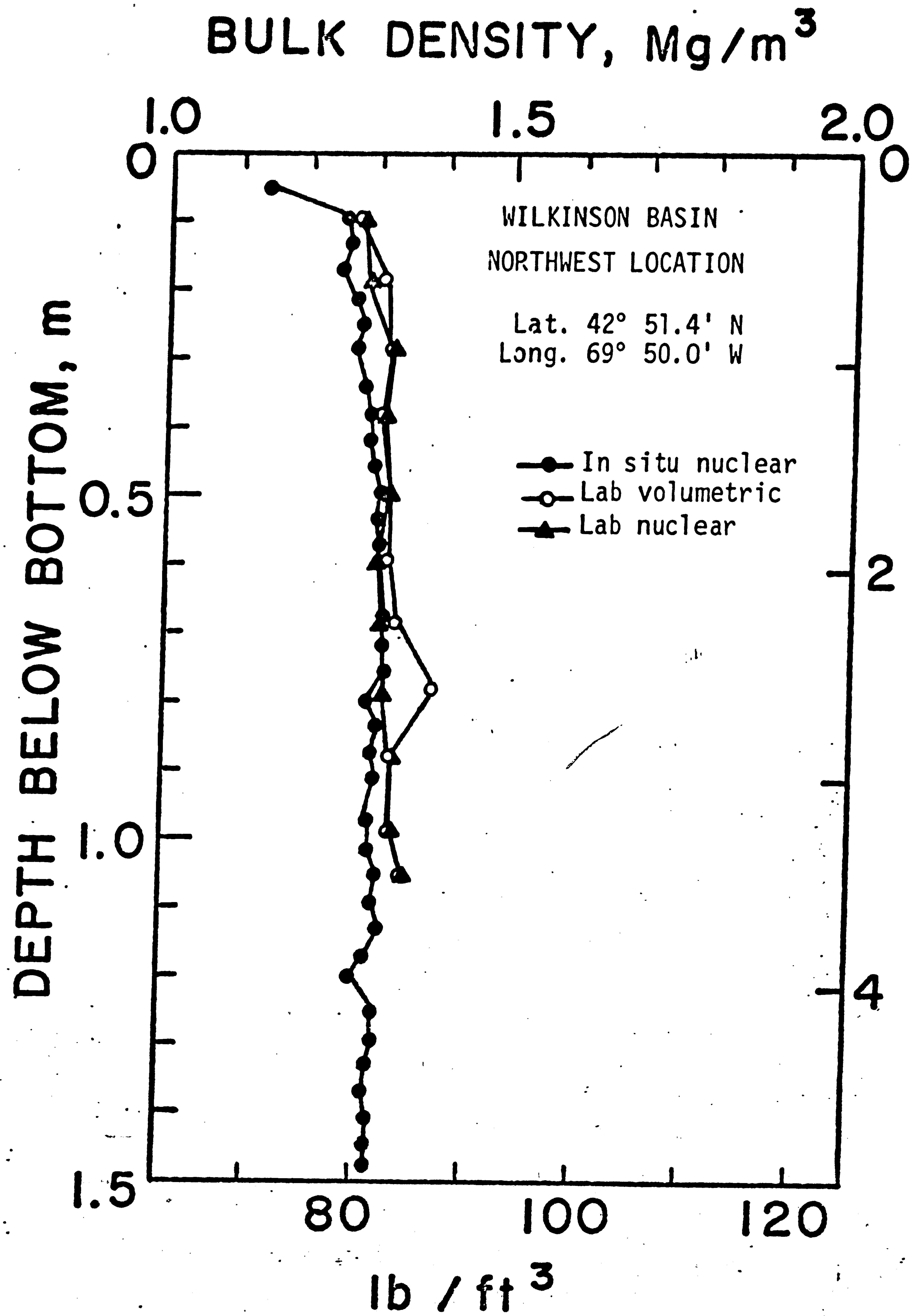

Figure 3. Comparison of in situ and laboratory bulk density measurements from the northwest Wilkinson Basin test location.

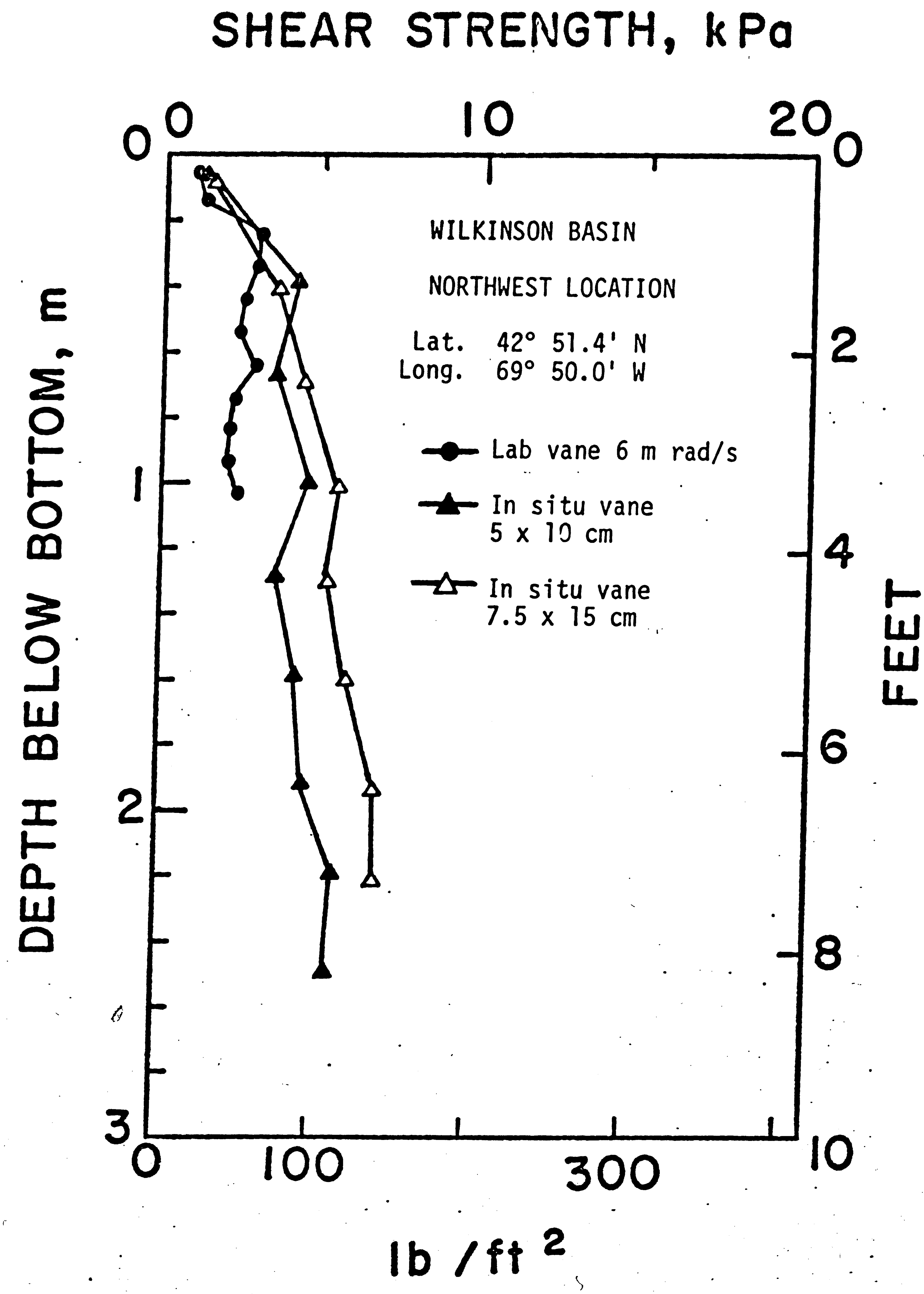

Figure 4. Comparison of in situ and laboratory vane shear strength measurements from the northwest Wilkinson Basin test location.

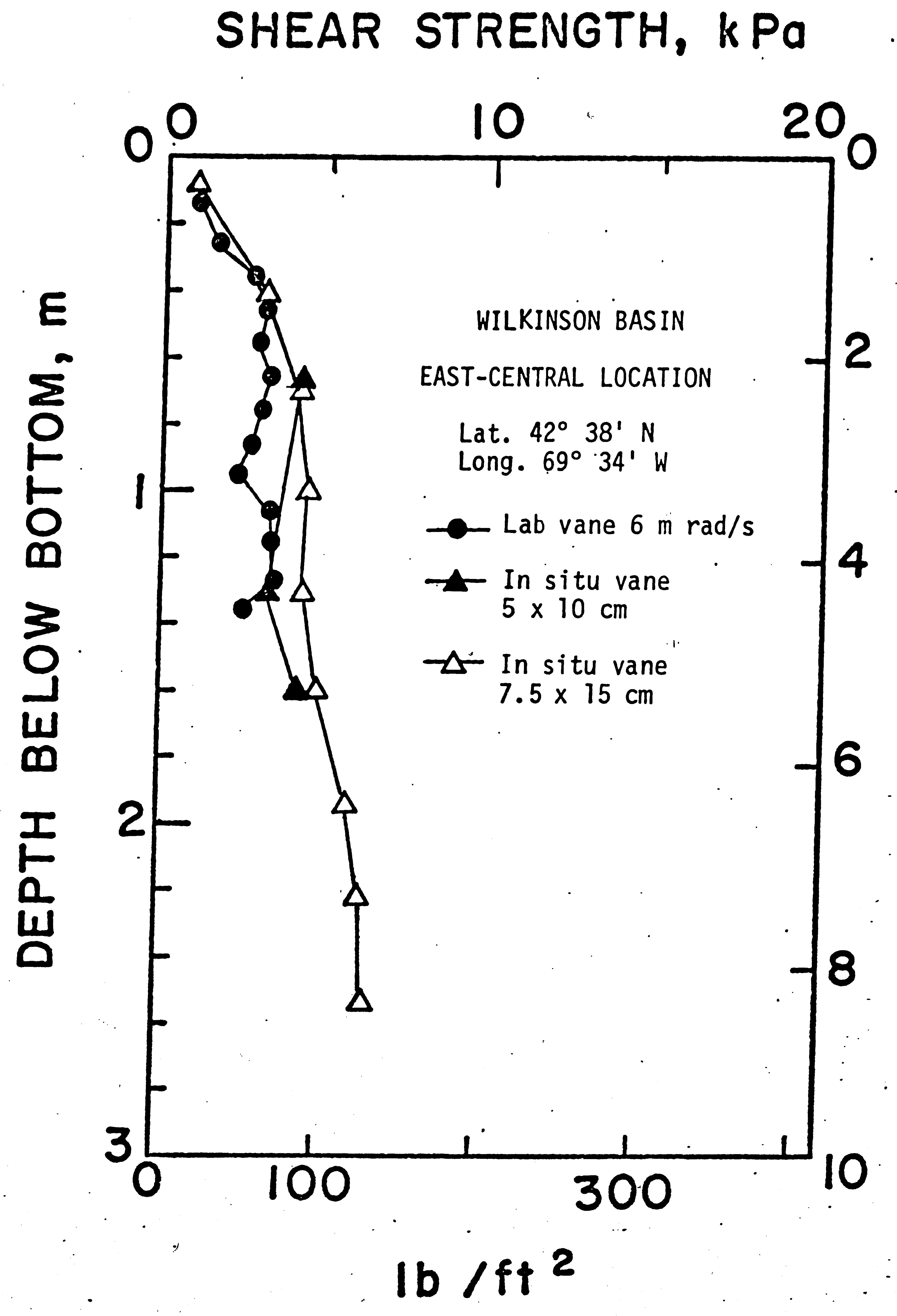

Figure 5. Comparison of in situ and laboratory vane shear measurements from the east-central Wilkinson Basin test location.

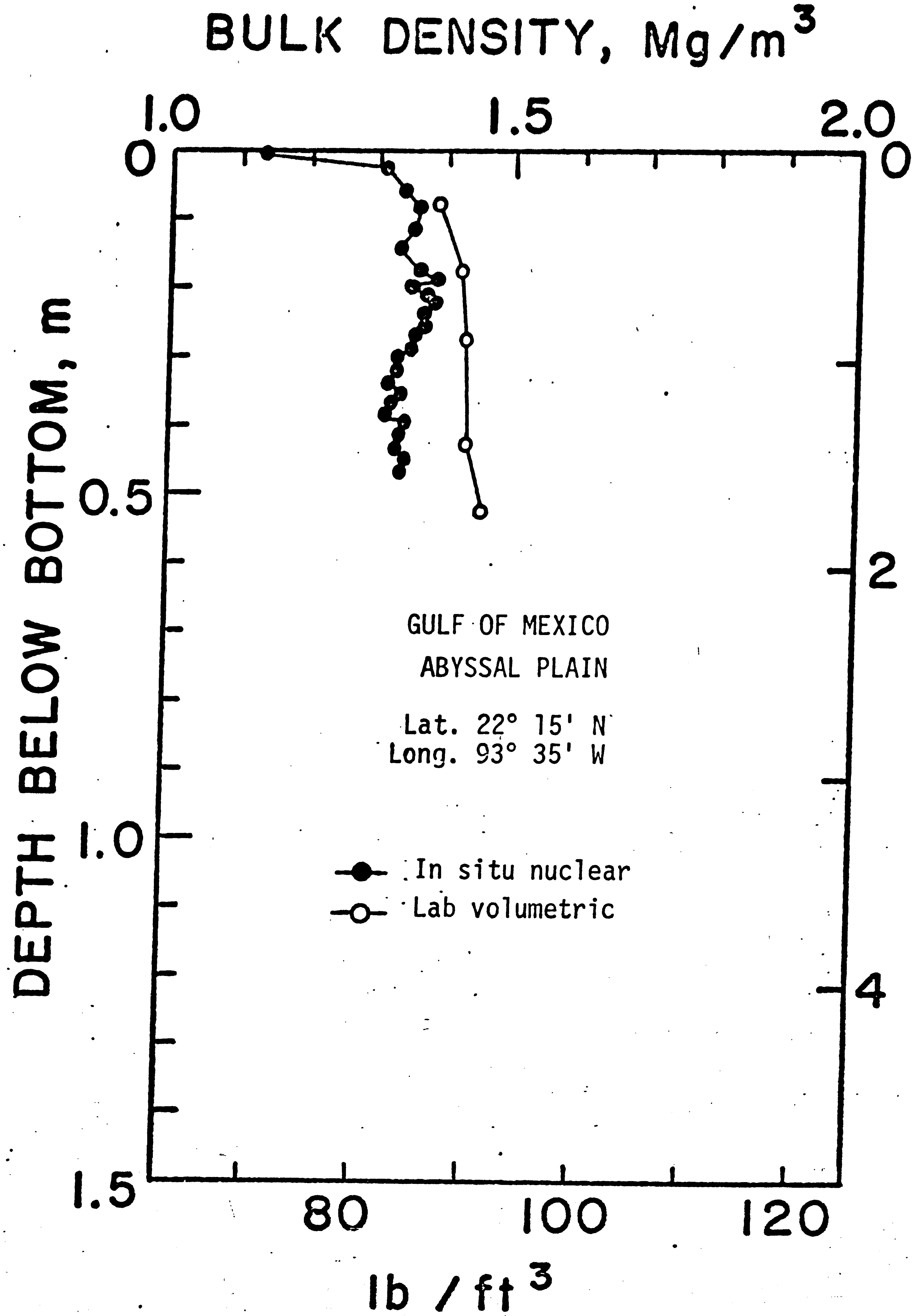

Figure 6. Comparison of in situ and laboratory bulk density measurements from the Gulf of Mexico Abyssal Plain.

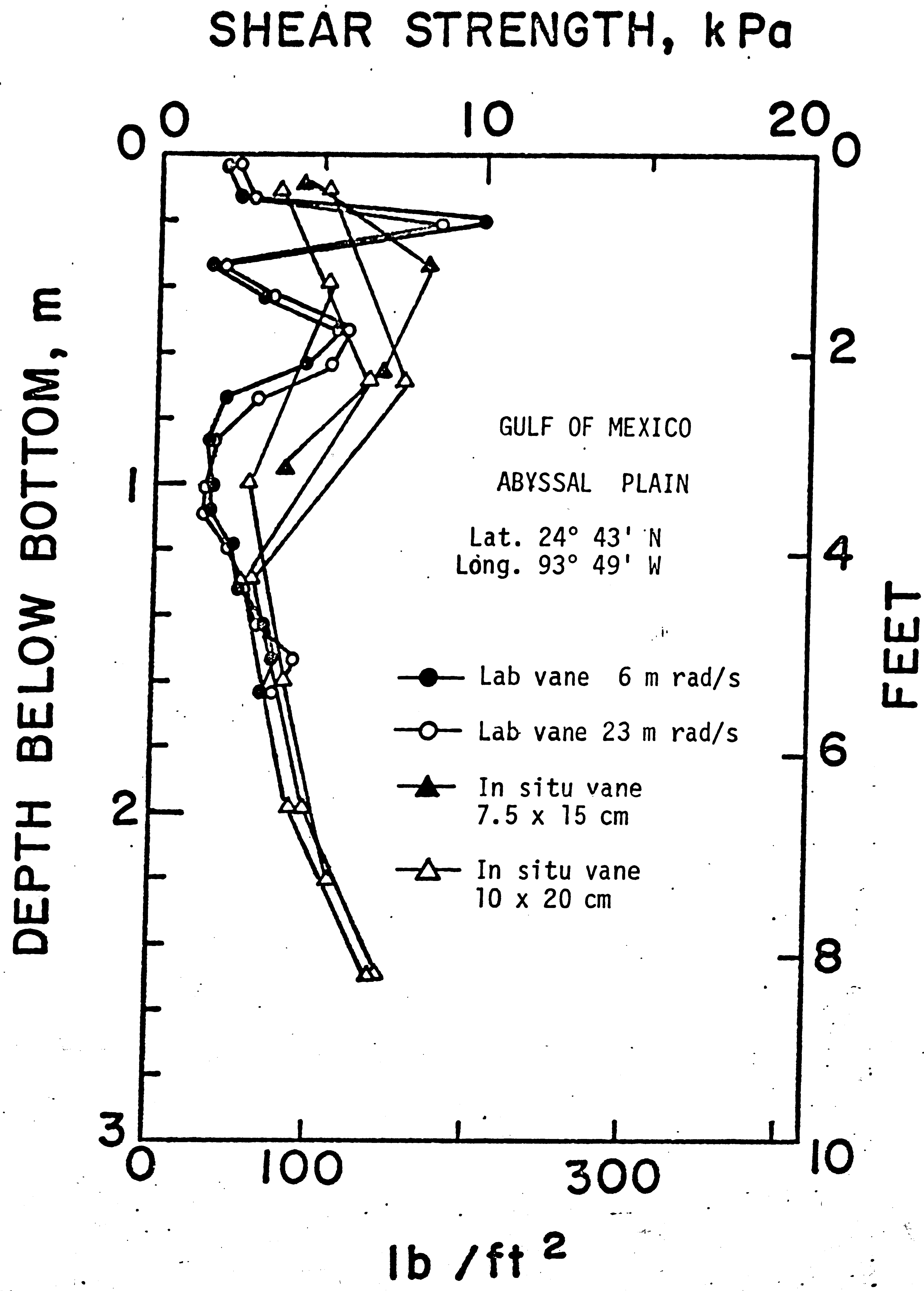

Figure 7. Comparison of in situ and laboratory vane shear strength measurements from the Gulf of Mexico Abyssal Plain.

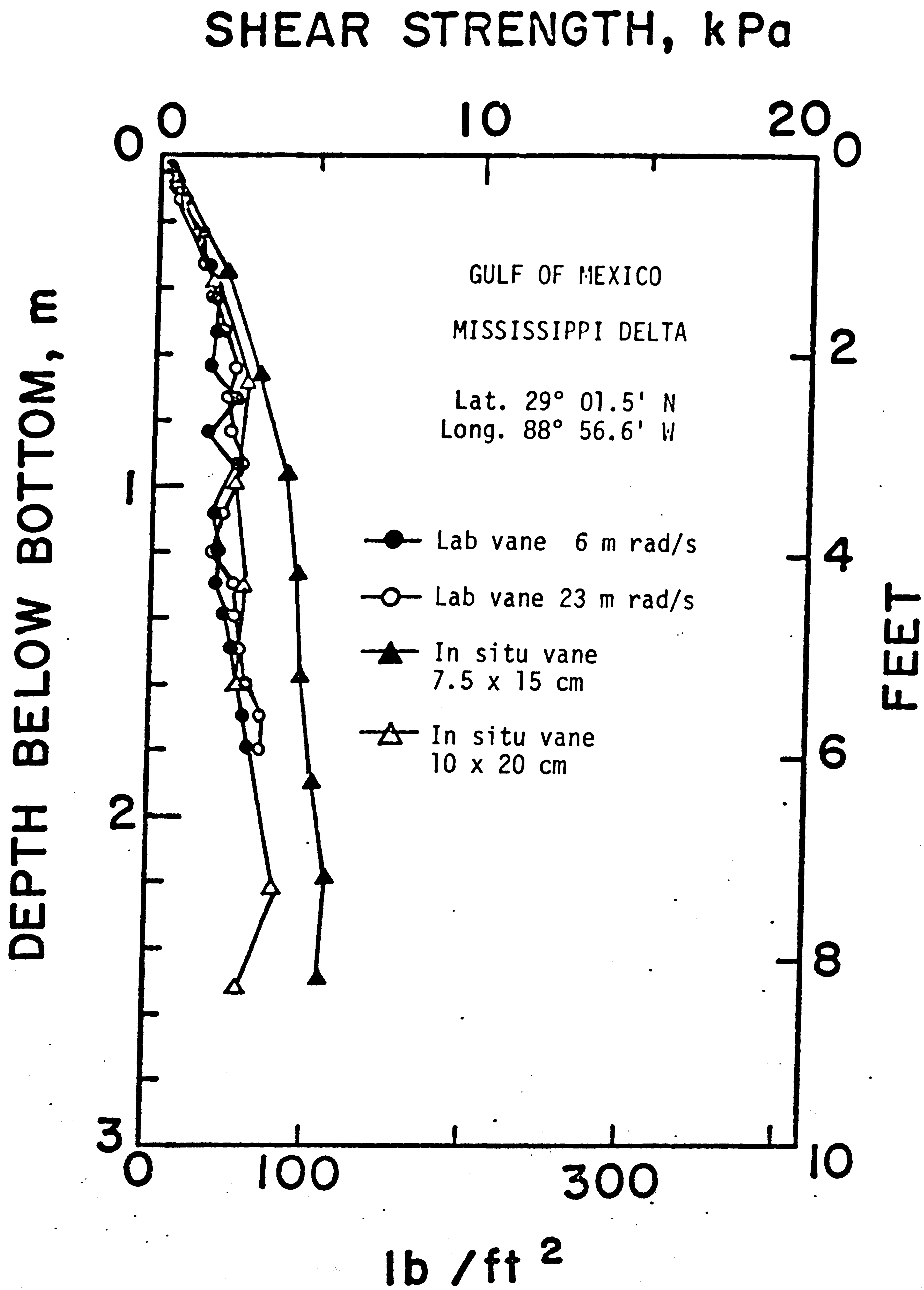

Figure 8. Comparison of in situ and laboratory vane shear strength measurements from the Mississippi Delta.

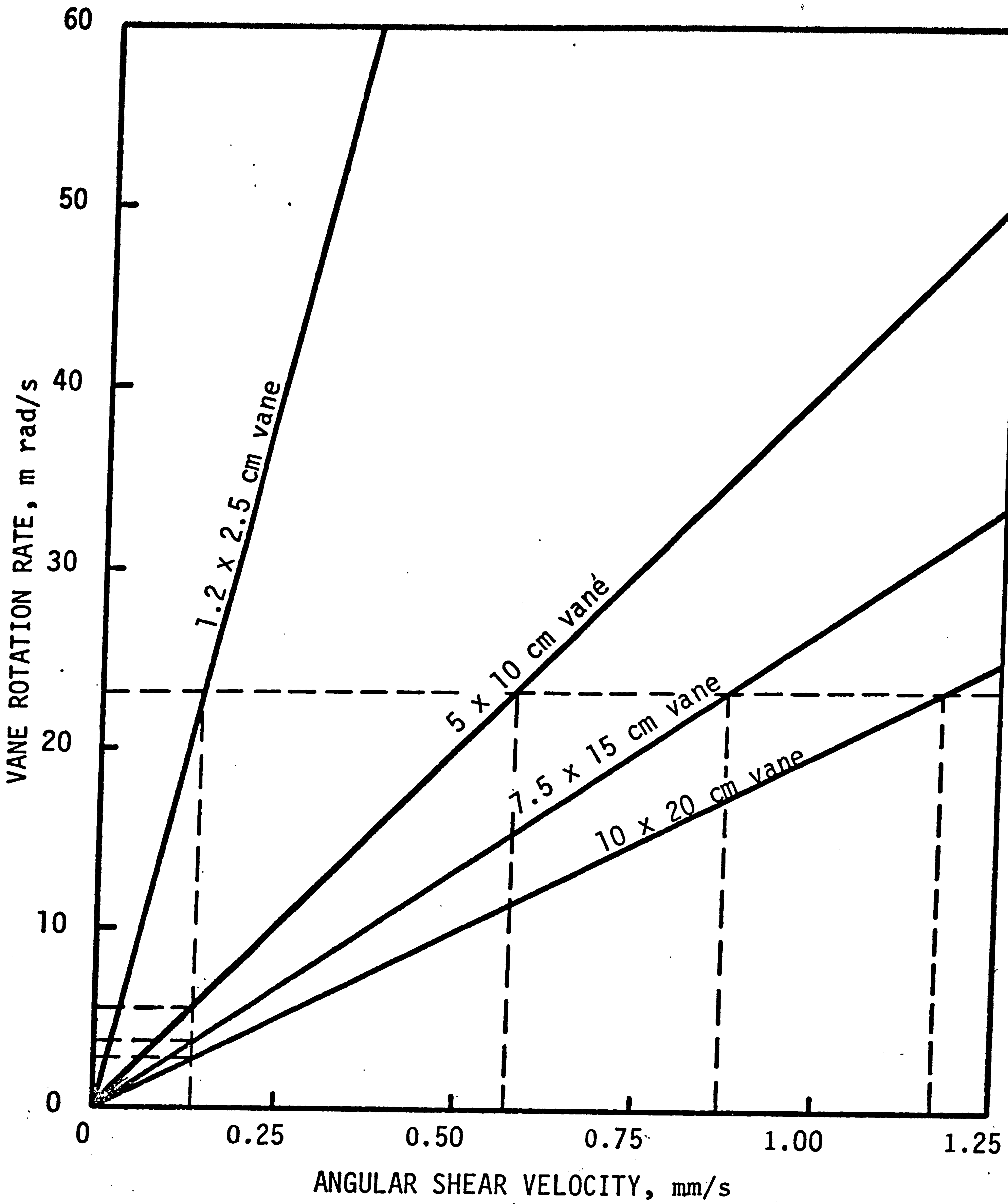

Figure 9. Relationship of angular shearing velocity, vane size, and vane rotation rate.

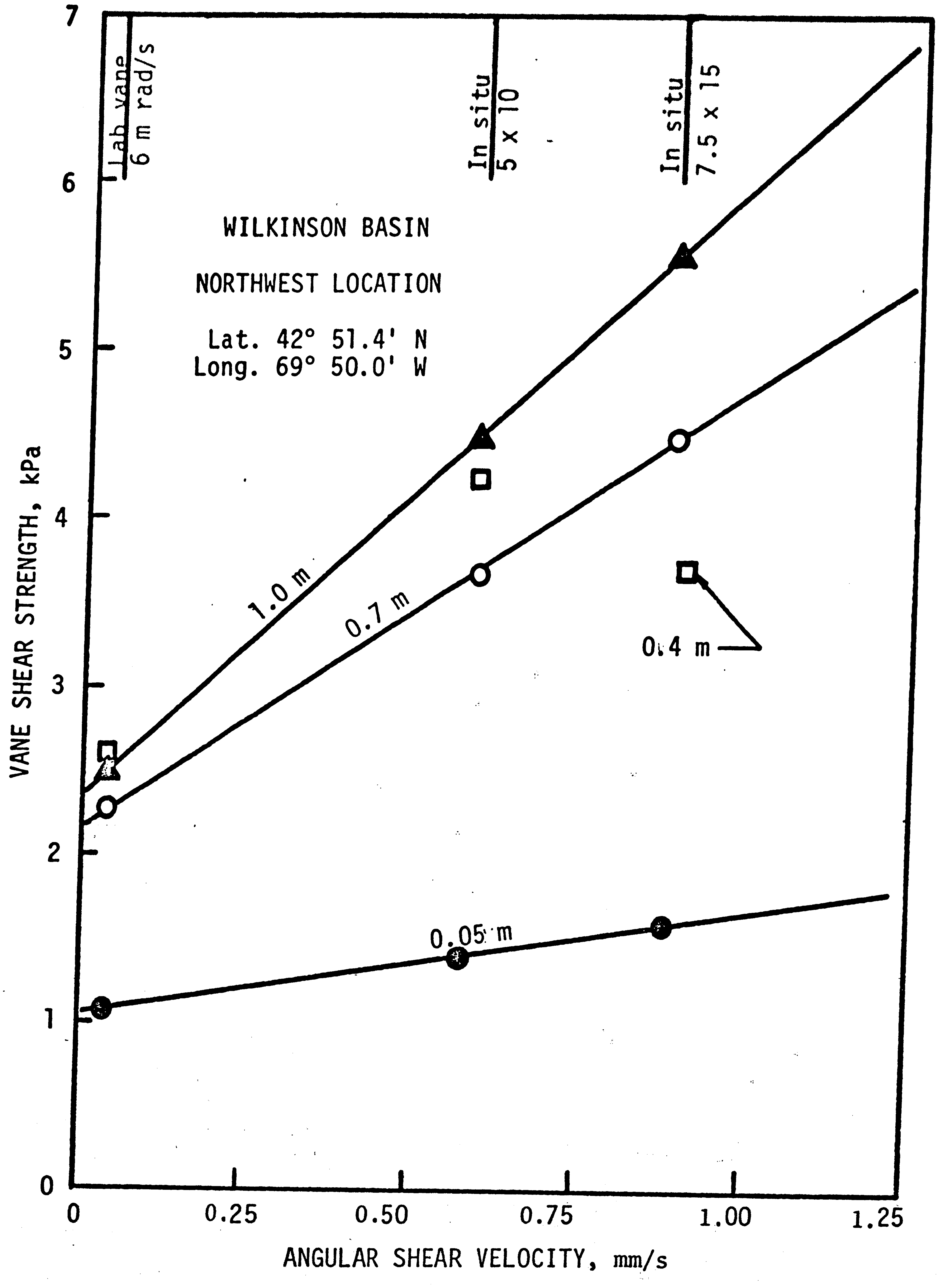

Figure 10. Comparison of in situ and laboratory vane strengths and shearing velocity for the northwest Wilkinson Basin test location.

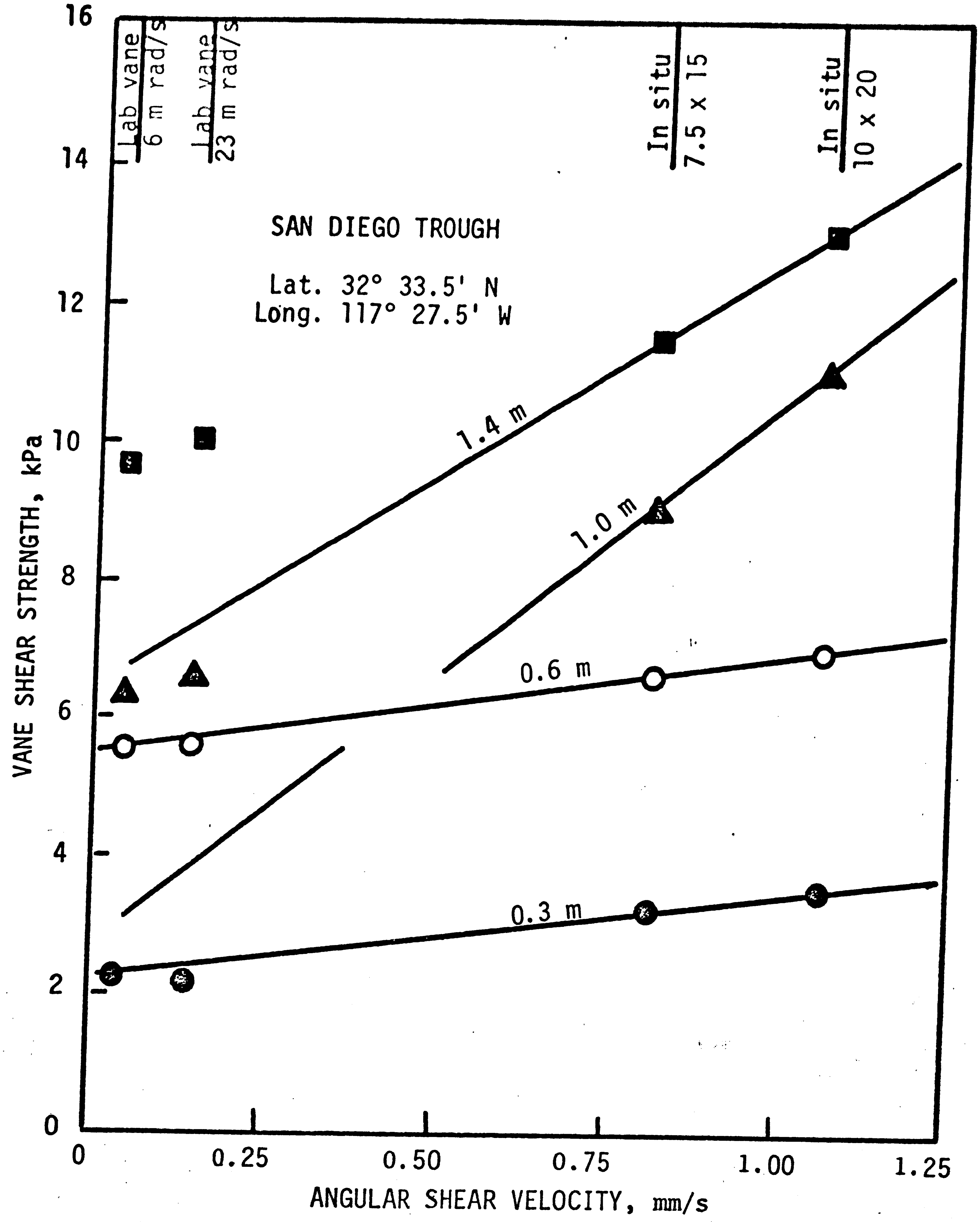

Figure 11. Comparison of in situ and laboratory vane strengths and angular shearing velocity for the east-central San Diego Trough test location.

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APPENDIX II.-NOTATION

D = vane diameter;

e = vane blade thickness;

r = vane radius;

v = angular shear velocity;

α = vane perimeter ratio;

ω = vane rotation rate.

VITA

Michael Perlow, Jr. was born on March 11, 1950 in Bethlehem, Pennsylvania. He was raised and schooled in Bethlehem where he lived with his parents, Michael, Sr. and Jacqueline. He attended Lehigh University and received a Bachelor of Science degree in Civil Engineering in 1972. Since graduation he has been working at the Marine Geotechnical Laboratory, Lehigh University towards a Master of Science degree in Civil Engineering.

Mr. Perlow was the recipient of a National Science Foundation Undergraduate Research Grant for ocean engineering research in the summer of 1971. He also served as a Technical Associate to the Ocean Affairs Board of the National Academy of Sciences and Marine Board of the National Academy of Engineering during the summer of 1972. He has authored four publications on the studies of the geotechnical properties of marine sediments.