Investigations With Rotary Cone Penetrometer

Recherches avec un pénétromètre conique rotatif

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Summary

Laboratory and field investigations with a rotary cone penetrometer for the development of a technique for prediction of the stability of Mississippi River banks with regard to liquefaction-type failure are reported. Tests to determine the change in density of sand during undisturbed sampling are also reported.

Sommaire

Dans ce rapport les auteurs rendent compte de recherches de laboratoire et de chantier avec un pénétromètre conique rotatif pour la mise au point d'une technique visant à la prédiction de la stabilité des rives du Mississippi contre la rupture du type « liquéfaction ». En outre, ils exposent des essais pour déterminer le changement de la densité de sable durant le prélèvement des échantillons non remaniés.

Introduction

Background—The natural meandering tendency of the Lower Mississippi River causes major bank failures in certain types of river deposits. These failures have threatened the levees at certain locations and have increased the problem of stabilizing the river's banks for navigation and development purposes. In 1947, extensive potamology investigations were started to study failure of revetted riverbanks and determine the causes and methods for prevention of bank failures, and to develop improved methods for riverbanks stabilization.

During the period 1947 to 1952, soils investigations established that all major bank failures investigated occurred in point bar deposits. Point bar deposits are formed in bends of the meandering river and are composed of a relatively thin stratum of more or less cohesive overburden materials underlain by a relatively thick stratum of fine sand. The failures, while of short duration, are progressive rather than entirely instantaneous. The failures are composed of a series of blocks which individually fail instantaneously, and are thought to be associated with partial to complete liquefaction of the fine sand stratum. It is believed that excess pore pressures develop in strata of the fine sand at subcritical densities, probably as a result of strain in the bank produced by an initial shear failure of the underwater toe caused by attack of river currents and subsequent scour ; this scour and initial shear failure create the conditions necessary for the development of liquefaction or flow-type failures.

The principal characteristics of the area after failure are : (1) relatively large compared to the area encompassed by ordinary bank caving and shear slides; (2) scallop-shaped with a narrow to quite narrow opening on the river side through which material flows; (3) trees on the bank fall with the tops pointed riverward, as opposed to tops pointed landward for ordinary shear slides; and (4) bank slope after failure is much flatter than that which could be predicted to be unstable by conventional analysis.

Test program—As a part of the 1947-1952 program, a rotary cone penetrometer was designed for rapid investigation of variations in the relative density of deep sand deposits along the riverbanks with a degree of detail greater than that obtainable by sampling and testing. Field tests with the cone penetrometer during the period 1951 to 1952 had shown promise; therefore, beginning in 1957, additional studies were initiated with the primary objective of developing a reliable relation between cone thrust and relative density of fine sand deposits in the field.

Since 1957, the investigations have included a series of laboratory penetration tests to determine the effects of surcharge pressure, relative density, and gradation of fine sand on cone thrust. Additional laboratory penetration tests were conducted to determine the minimum thickness of loose or dense strata which can be reasonably well detected by the cone penetrometer. Another series of tests was made to determine the change in density of sand occurring during undisturbed sampling. Also, a limited field investigation was conducted to develop a technique by which the cone could be used to predict the stability of point bar riverbank deposits with regard to liquefaction-type failures.

Cone Penetrometer

A sketch of the rotary cone penetrometer used in these investigations is shown in Fig. 1. Details of the device have been reported by Hvorslev (1953). The penetrometer is designed for use with a truck-mounted rotary drilling rig and consists of a sounding rod having a conical point with a base area of 10 cm^2 and a sleeve which fits over a downward extension of the hollow stem of a helical auger bit on the drill rod. The cone rod is tubular above the auger bit and extends up through the drill rod and a swivel to a proving frame attached by tie rods to the flange of the swivel. The proving frame has a maximum capacity of about 9 100 lb. During operation, drilling fluid flows down the inside of the cone rods and emerges from vents above the auger. The auger is rotated during the advance but the cone does not rotate. The force on the cone is transmitted by the cone rods to the proving frame. The distance between the bottom of the auger and the cone tip was 15-1/2 in. for these investigations.

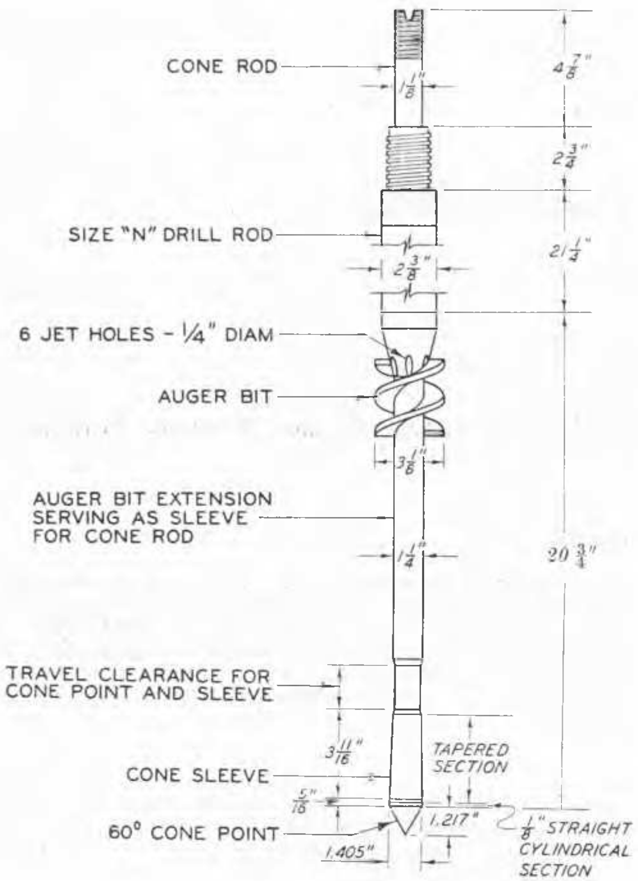


Fig. 1 Rotary cone penetrometer.
Pénétromètre conique rotatif.

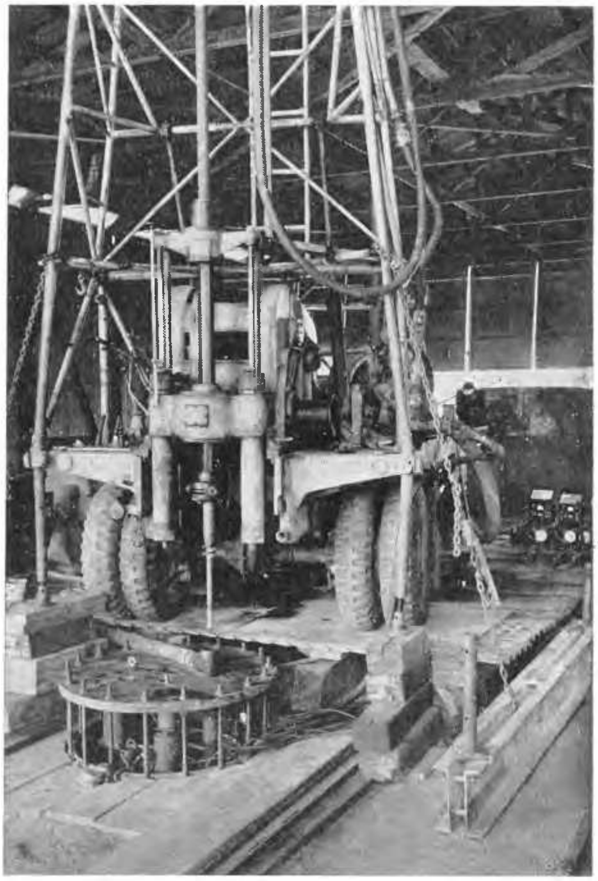


Fig. 2 View of cone penetration and assembled tank tests apparatus.
Vue de l'appareil de pénétration conique et de l'installation d'essai montée sur le réservoir.

Investigations Conducted and Results

Laboratory tank tests—To determine the relation between cone thrust and surcharge pressure, relative density, and gradation, penetration tests were performed on three different fine sands subsequently referred to as sand 1, sand 2, and sand 3. The D_{90}, D_{50}, and D_{10} grain sizes and the coefficients of uniformity of these sands are as follows :

Material	*Grain Size, mm*			*Coefficient of Uniformity* D_{60}/D_{10}
	D_{90}	D_{50}	D_{10}	
Sand 1	0·32	0·24	0·16	1·6
Sand 2	0·55	0·33	0·19	2·0
Sand 3	0·18	0·13	0·06	2·3

These sands are uniformly graded and cover the range of gradation associated with liquefaction-type failure of point bar deposits on the Mississippi River. The angle of shearing resistance of the sands as determined by drained direct shear tests for the densities tested ranged from about 30° to 37°.

Eight penetration test specimens were prepared, four of sand 1 placed at relative densities of 20, 40, 65, and 90 per cent, one of sand 2 placed at a relative density of 40 per cent, and three of sand 3 placed at relative densities of 20, 40, and 65 per cent. The tests were conducted in a steel tank 6-1/2 ft high by 3-1/2 ft. in diameter. The specimens were built in 3-in. lifts using oven-dried material placed and tamped as necessary to produce specimens of uniform density. Surcharge loads up to 100 psi were applied to the top of the specimens by three hydraulic jacks. A view of the cone penetrometer and assembled tank test apparatus is shown in Fig. 2.

Since friction at the walls of the tank reduce the normal pressure inside, WES-type pressure cells were placed in each of the penetration test specimens for measurement of vertical pressure at various depths within the tank. All specimens were saturated under a surcharge load of 30 psi and penetration tests were made at three different locations in the specimens, once each with surcharge pressures of 30, 60, and 100 psi. Drilling mud was used and the hole made during the penetration test was backfilled with sand before a subsequent penetration was made in the same specimen. The rate of penetration was controlled to a nominal rate of 1 ft./min.

From pressure-cell and cone-thrust data, the relation between cone thrust and vertical pressure was obtained for each test specimen. Measurements of placement density, pressures, and cone thrust for sand 1 placed at a nominal relative density of 40 per cent, for which the data are somewhat more consistent than those from other tests, are shown in Fig. 3. For this particular specimen, cone thrust ranged from about 900 lb. to 2 900 lb. for vertical pressures of 20 to 80 psi.

A summary plot of cone thrust versus vertical pressure for each of the eight penetration specimens is shown in Fig. 4. This plot indicates that cone thrust increases with increasing vertical pressure, increasing relative density, and increasing grain size. However, it is also noted that the cone thrust for medium fine sand 2 at 40 per cent relative density is greater than that for the very fine sand 3 at 65 per cent relative density. Therefore, it is apparent that cone thrust in

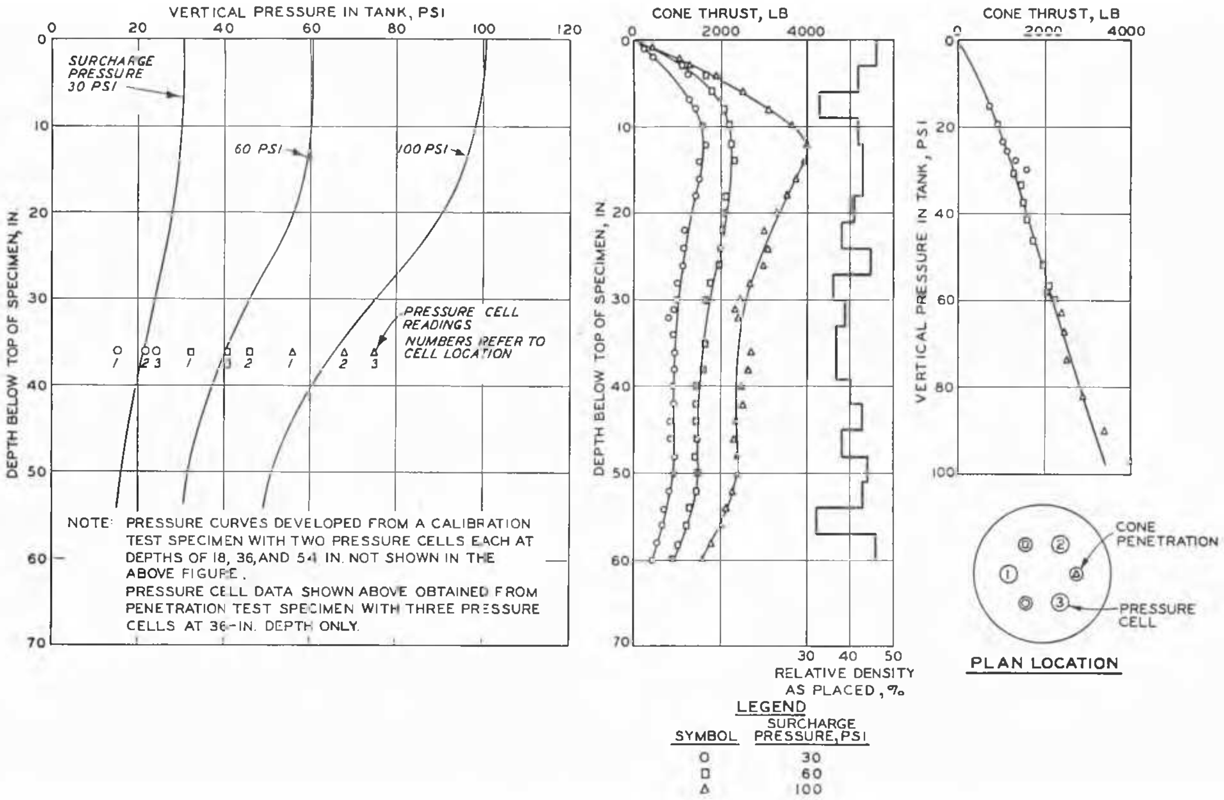


Fig. 3 Pressure-measurement and cone thrust data for sand 1 placed at 40 % relative density.
Données de mesure de pression et de la poussée du cône pour sable 1 mis en place à 40 % de densité relative.

these tests was not uniquely a function of relative density but was also dependent on gradation, which suggests that the lower permeabilities of the finer sands permit the development of greater pore pressures and reduced penetration resistance in the vicinity of the advancing cone tip, even at the moderately slow rates of penetration used for these tests.

The cone thrust data have also been compared with theoretical penetration resistance computed from equations developed by Skempton (1953). The measured cone thrust was always significantly less than the computed. It is believed that the difference between the measured and computed penetration resistance may be attributed to a combination of factors, the most important of which perhaps are the influence of (1) pressure gradient in the tank test specimens, 2) pressure relief afforded by the augered hole 15-1/2 in. above the cone tip, 3) pore pressure resulting from non-uniform drainage of the fine sands in the tank even at the moderately slow rate of penetration used for these tests, and 4) lateral pressures in the tank possibly smaller than those assumed in the theoretical expression.

Laboratory penetration tests were also conducted on loose sand specimens with 12-, 6-, and 3-in.-thick built-in strata of dense sand, and on dense specimens with 12-, 6-, and 3-in.-thick built-in strata of loose sand. In these tests, the loose and dense materials were placed at 40 and 90 per cent relative density, respectively. The penetration tests showed that the presence of 12-, 6-, and 3-in. strata could be detected, although a 6-in. stratum probably is the minimum thickness for which the cone thrust value is not significantly influenced by adjacent material of different relative density.

To determine the change in density that occurs during undisturbed sampling of sand, undisturbed samples of sand 1 and sand 2, confined in the same tank used for the penetration tests, were obtained in another series of tests. Four specimens were prepared, two of sand 1 placed at relative densities of 40 and 90 per cent, and two of sand 2 placed at relative densities of 24 and 90 per cent. The relative densities were chosen to simulate the extremes of natural densities suspected to exist in the field. The specimens were subjected to surcharge pressures of 30, 60, and 100 psi. Three 30-in.-long undisturbed samples, one at each of the three surcharge pressures, were obtained from each specimen with a 3-in.-diameter, Hvorslev fixed-piston, thin-walled, steel tube sampler. The samples were cut into 3-in. increments and the variation of change in density was determined with respect to surcharge pressure and position of increment in the sample tube.

Analysis of data indicated that the change in density during undisturbed sampling of sand is dependent on overburden pressure and the position of the sample increment within the sample tube. In general, loose material increased in density and dense material decreased in density during sampling. Correction factors, based on a comparison of the measured density of sampled increments with placement density, were developed for both overburden pressure and position of the increment in the sample tube. The combined correction factor generally amounted to less than 1 pcf., or about 5 to 6 per cent in relative density for the middle 18 in. of the 30-in. sample for conditions commonly encountered in the field. It is concluded that the change in density which occurs during undisturbed sampling of sand does not appear to be a serious problem for the current studies of riverbank deposits.

Field tests—A field investigation was conducted on a Mississippi River bank to develop a technique for predicting those areas believed to be susceptible to liquefaction-type failure. Two undisturbed sample borings and two cone penetrations were made in an area where the fine sand was known to be at least 35 ft. thick. One undisturbed sample boring was located 5 ft. from each cone penetration, and 30-in.-long undisturbed samples were obtained at 3-1/2-ft. intervals of depth, using the sampler described previously.

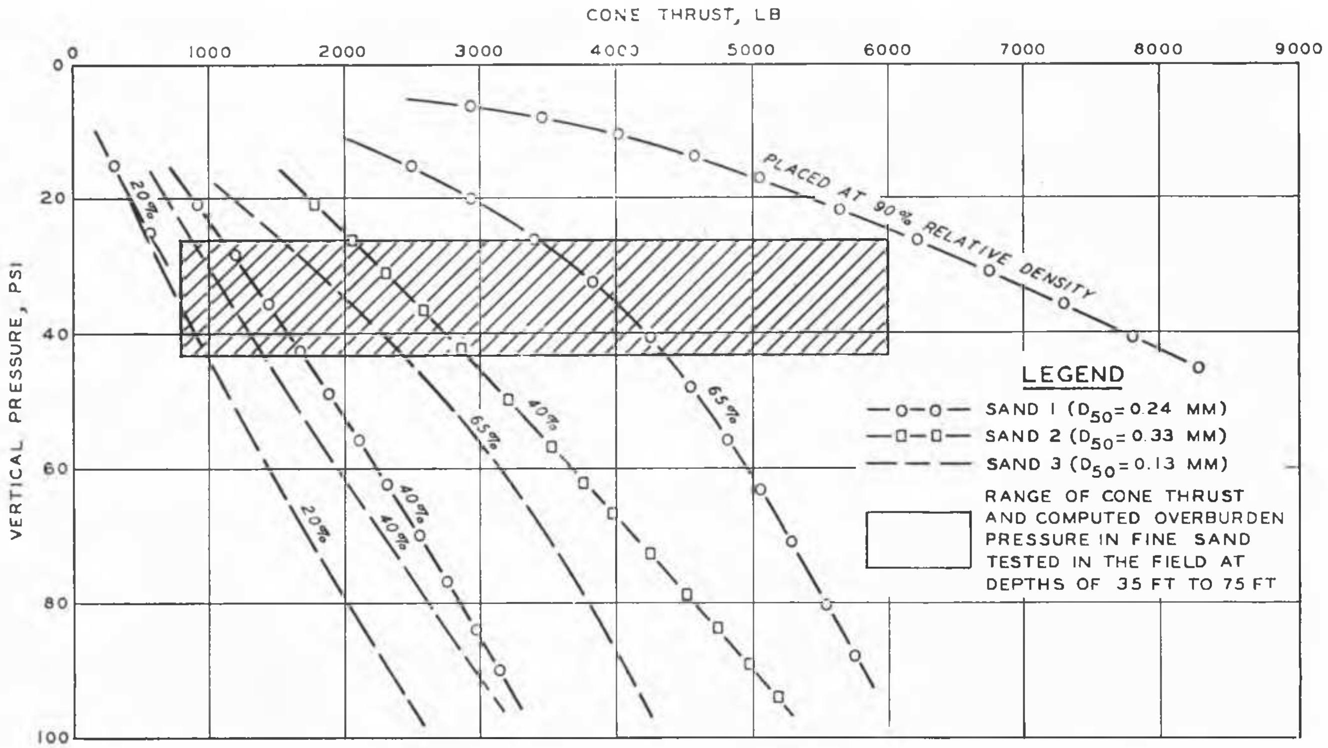
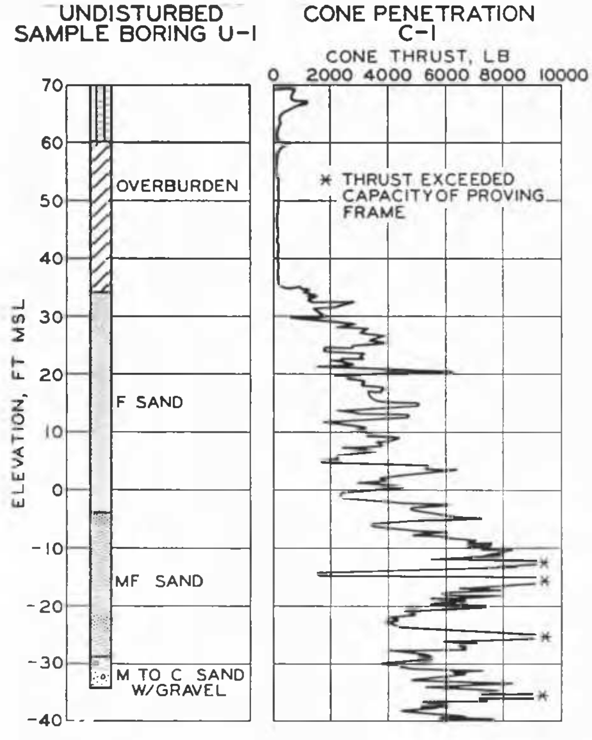


Fig. 4 Summary plot of cone-thrust data for three sands tested in the laboratory and fine sand tests in the field.
Diagramme sommaire de données de la poussée du cône pour trois sables essayés dans le laboratoire et sable fin essayé sur chantier.

Cone penetration resistance was measured for each 0·1 ft. of penetration with a rate of advance of 1 ft./min.

Logs from one undisturbed sample boring and one cone penetration are shown in Fig. 5. The undisturbed field samples were cut into 3-in. increments and the gradation and densities determined. The D_{50} size of the sand ranged from 0·13 mm to 0.25 mm. Measured relative densities of selected 3-in. increments ranged from 30 to 97 per cent. Estimated relative densities, based on cone thrust and correlations for sands 1 and 3 shown in fig. 4, ranged from 25 to 100 per cent and averaged about 8 per cent greater than those obtained from measurements on sample increments.

Because of wide variations in material, even within a lateral distance of 5 ft, individual comparisons of measured and estimated relative densities at about the same elevation generally were considered only fair. However, cone thrust measured in the field was generally of the same magnitude as that measured in the laboratory tank tests. The range of cone thrust data obtained from the field investigation is shown as a shaded area in Fig. 4. Since liquefaction-type failures are believed to be caused by development of excess pore pressure in relatively loose sands, data in Fig. 4 suggest that an area may be susceptible to liquefaction-type failure when the cone thrust for vertical pressures of 25 to 42 psi ranges from less than about 2 000 to 3 000 lb. When cone thrust ranges from greater than 3 500 to 4 500 lb. for similar respective pressures, the fine sands may be stable. When cone thrust is greater than the 2 000 to 3 000 lb. range, but less than the 3 500 to 4 500 range, stability may be uncertain. Field studies for verification of these criteria are now being planned.



NOTE: CONE PENETRATION C-1 LOCATED 5 FT FROM UNDISTURBED SAMPLE BORING U-1.

Fig. 5 Field data from boring U-1 and cone penetration C-1.
Données de chantier du sondage U-1 et de la pénétration conique C-1.

References

[1] SKEMPTON, A. W., A. A. YASSIN and R. E. GIBSON (1953). Theory de la force portante des pieux dans le sable. *Annales de l'Institut technique du Bâtiment et des Travaux Publics*, vol. 6, 1953, pp. 285-290.

[2] HVORSLEV, M. JUUL (1953). Cone Penetrometer Operated by Rotary Drilling Rig. *Proceedings of the Third International Conference on Soil Mechanics and Foundation Engineering*, Switzerland, vol. 1. pp. 236-240.