Published in Canadian Geotechnical Journal - June 1990

SM #136

New Equipment for Densification of Granular Soils at Depth

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ABSTRACT

An in-situ densification probe which employs the novel technique of simultaneous vibration and dewatering has been developed by Phoenix Engineering Ltd. to compact deep loose granular soils. It is believed that pumping water out of the soil during the densification process offers improved densification capability over systems operating with vibration alone. An independent study was undertaken by the In-Situ Testing Group at the University of British Columbia to evaluate the performance of the Phoenix system.

A field testing programme was conducted at a site in Vancouver where hydraulic sand fill overlies a natural silt and then medium Fraser River Sand. Characterization of the site and evaluation of the densification treatment process were achieved using in-situ tests. Changes to soil parameters due to densification treatment were examined, taking into account the modification of stresses brought about by the vibro-drainage process. The study investigated the degree of densification achieved; the value of concurrent drainage; the zone of influence of a single compaction probe; and group effects. The study also compares the performance of the Phoenix machine to other vibrocompaction equipment.

Key Words: In-Situ, Densification, Soils, Granular, Probe, Vibratory, Drainage, Compaction, R&D.

INTRODUCTION

The technique of densifying soil with a vibrating probe at depth was one of the earliest methods of deep compaction. Subsequent developments of this technique have led to the availability of a variety of equipment on the market today which make use of vibrating probes for the improvement of both cohesive and cohesionless soils. One of the most recently developed and novel of these techniques is the "Phoenix machine". This is the name given to the proprietary tool researched and developed by Phoenix Engineering Ltd. of Vancouver.

Hodge (1988) demonstrated the beneficial effect of pumping water from submerged sand fills during placement in model tests. Improvements were observed in the relative density of the fill. Also, improvements to the general engineering behaviour of the fill included increased resistance to scour erosion and increased side slope angles. These results constituted the basis for the proposal that a probe which could simultaneously vibrate and drain water from the soil would out-perform a probe which only developed vibration.

The equipment discussed in this paper consists of a vibrating and water pumping mechanism within a single probe. As with other vibrocompaction equipment, the vibratory action of the probe is believed to cause localized liquefaction of loose, saturated, granular soils. The soil particles are then able to compact under the prevailing conditions into a denser state of packing than existed previously. The Phoenix equipment has the advantage that the particles are allowed to compact not only under stress conditions which include self-weight and overburden stresses, but also under the influence of a seepage force. Under such conditions it is contended that the soil is able to achieve a denser state of packing than under purely vibrational treatment alone.

The theory was put into practice when the prototype vibro-drain or "Phoenix machine" was used to densify the periphery of the sand core of the mobile Arctic caisson, the Molikpaq (Stewart and Hodge, 1988). There the equipment was deployed at 3 meter centers to successfully densify a 6 meter wide strip immediately adjacent to the caisson walls which could not be densified by blasting, the technique used in the rest of the sand core. Despite the fact that the Phoenix method had been successfully applied to densify the submerged, hydraulically placed sand fill in the Molikpaq, little was known about the technique.

In order to evaluate the mechanism, performance and application of the Phoenix process a rigorous, independent assessment was carried out by the In-Situ Testing Group at UBC. The assessment was done using the following procedure. A site underlain by both a hydraulic sand fill and a natural sand deposit was selected. UBC set out an array of locations at which densification treatment was to be performed. UBC conducted a series of in-situ tests to establish the pre-treatment sand characteristics. Phoenix then operated the vibro-drain at the locations indicated. UBC supervised the field work and performed in-situ tests concurrently with, and subsequently to, the densification process. This work was carried out during the Autumn of 1988.

The results presented in this paper were mainly those collected from the UBC monitored field tests which have been supplemented with data from earlier, developmental tests performed by Phoenix Engineering at the same site.

VIBRO-DRAINAGE EQUIPMENT

The Phoenix machine consists of a torpedo shaped probe similar to other densification probes, but with the addition of a water pumping mechanism above the horizonally vibrating tip. Figure 1 shows the equipment details. The probe is built in two 190 mm (7.5 in.) dia. sections. The lower, or tip section, is 1.05 m (41 in.) long and houses the vibrating unit and air motor. The upper section is 1.67 m (65 in.) long and contains the drainage section.

Compressed air at 690 kPa (100 psi) is conveyed via the inner tube of the double walled connector pipes where it powers an air motor. The motor rotates an eccentric mass on the vertical axis to develop the horizontal vibrations. The unit rotates at 25 Hz and develops a centrifugal force of 23 kN (2.3 tons). This force is relatively small in comparison with the 250 kN (25 tons) which can be generated by similar vibroflotation equipment (Jebe and Bartels, 1983).

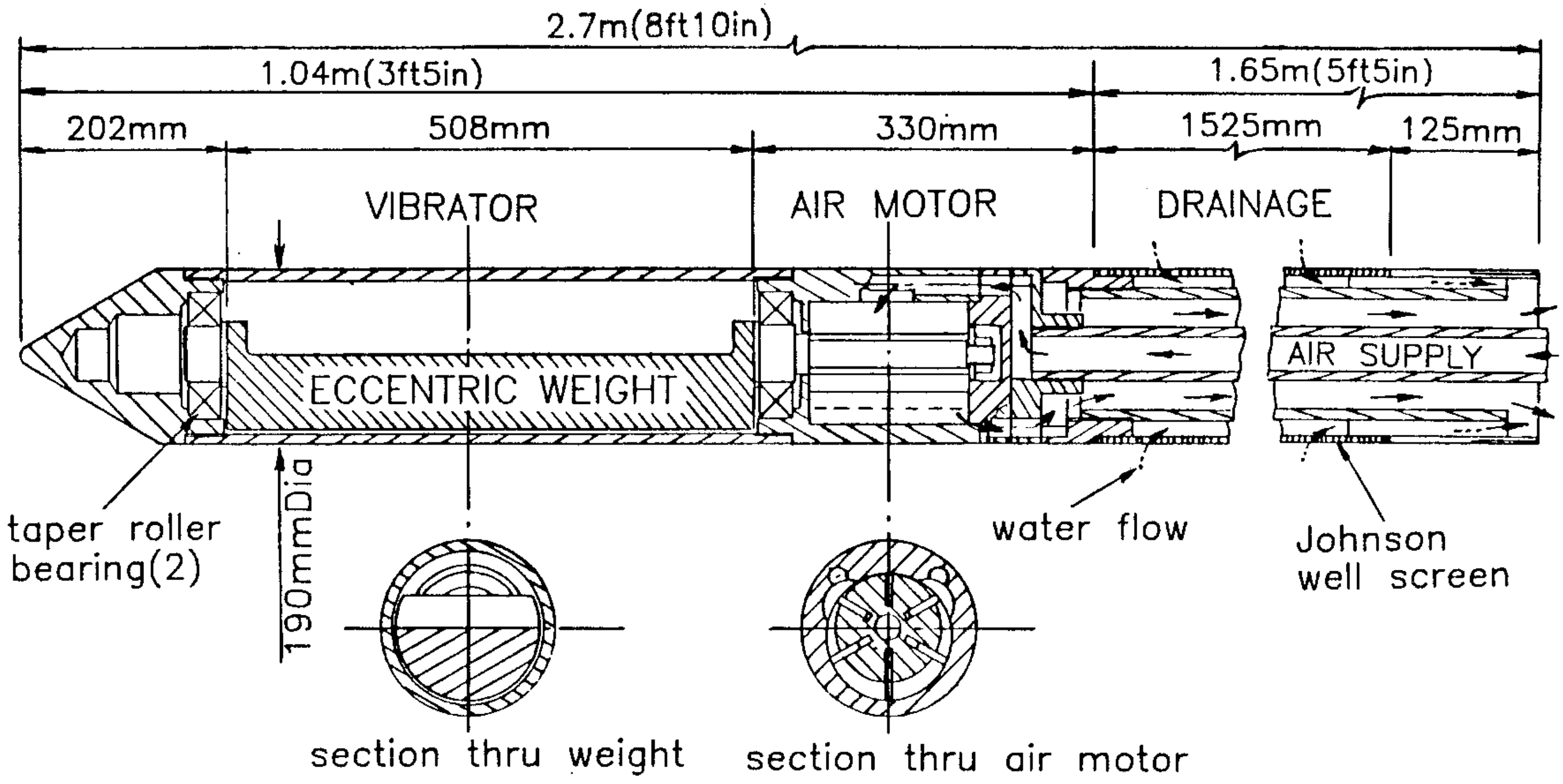

Fig. 1. Schematic of Phoenix Machine

The drainage section, located immediately above the air motor exhaust, consists of a supported Johnson well screen. As air exits the motor unit it passes upwards to develop an air lift pump which removes excess water and causes a pressure gradient towards the well screen. Water carried into the pumping unit is carried upwards in the air flow through the connector pipe annulus and discharged at the surface.

At the start of a treatment, the probe is set vibrating and penetrates without water jetting. If necessary, however, the equipment could be configured to accommodate a jetting procedure. Once at a depth slightly in excess of that to which improvement is sought, the probe is slowly retrieved to achieve the required densification. The probe is slowly moved up and down in the bore to make several densification "passes". An experienced operator can detect compaction by increased resistance to penetration on the downward plunge.

The Phoenix equipment configuration used for this study was a third generation prototype, custom designed for working inside the 3.3 m (10.7 ft) headroom constraint of the Molikpaq core. It was therefore built to be deployed from a regular top-drive rotary drill using 1.5 m (5 ft) long double wall extension pipes. This is an inefficient way to deploy the equipment in a normal situation and consequently a method of deploying the probe from a backhoe has subsequently been designed. Nevertheless, using a drill rig to deploy the probe made it convenient to pre-auger through the hard crust at the site, and to rotate or push the probe into the ground when resistance to penetration was high.

TEST SITE DESCRIPTION

The field tests were carried out at a site located at the north pier of the Alex Fraser Bridge, Annacis Island, Vancouver, B.C. The site is situated on land owned by the Ministry of Transportation and Highways of British Columbia, and constitutes an artificial promontory built adjacent to the north bank of the Fraser River to prevent ship collision damage to the bridge tower. The promontory was constructed by infilling with dredged sand behind a rockfill dike.

The sand fill had been dredged from the Fraser River and was placed through water. The fill rests directly on the original river channel deposits. Investigations performed for the bridge structure (Bazett and McCammon, 1986) suggest the thickness of sand fill increases from nil at the old river bank up to 11 m at the site of the bridge pier. Figure 2 is a section across the site. The fill sand was a grey, loose, silty sand, with occasional fine gravel. The river channel deposits consist of 2 m to 3 m of grey, soft silt, resting on the Fraser River Sand which is a grey, fine to medium sand, silty in part.

Figure 3 depicts the grain size characteristics of the fill sand and the Fraser River Sand. According to the classifications of Brown (1977), the soils are liable to improvement by vibrocompaction, but are too fine to be considered ideally suited to compaction by this method.

The groundwater level at the site varies between 1 m and 3 m below ground level, depending on tidal fluctuation and season. This was important in

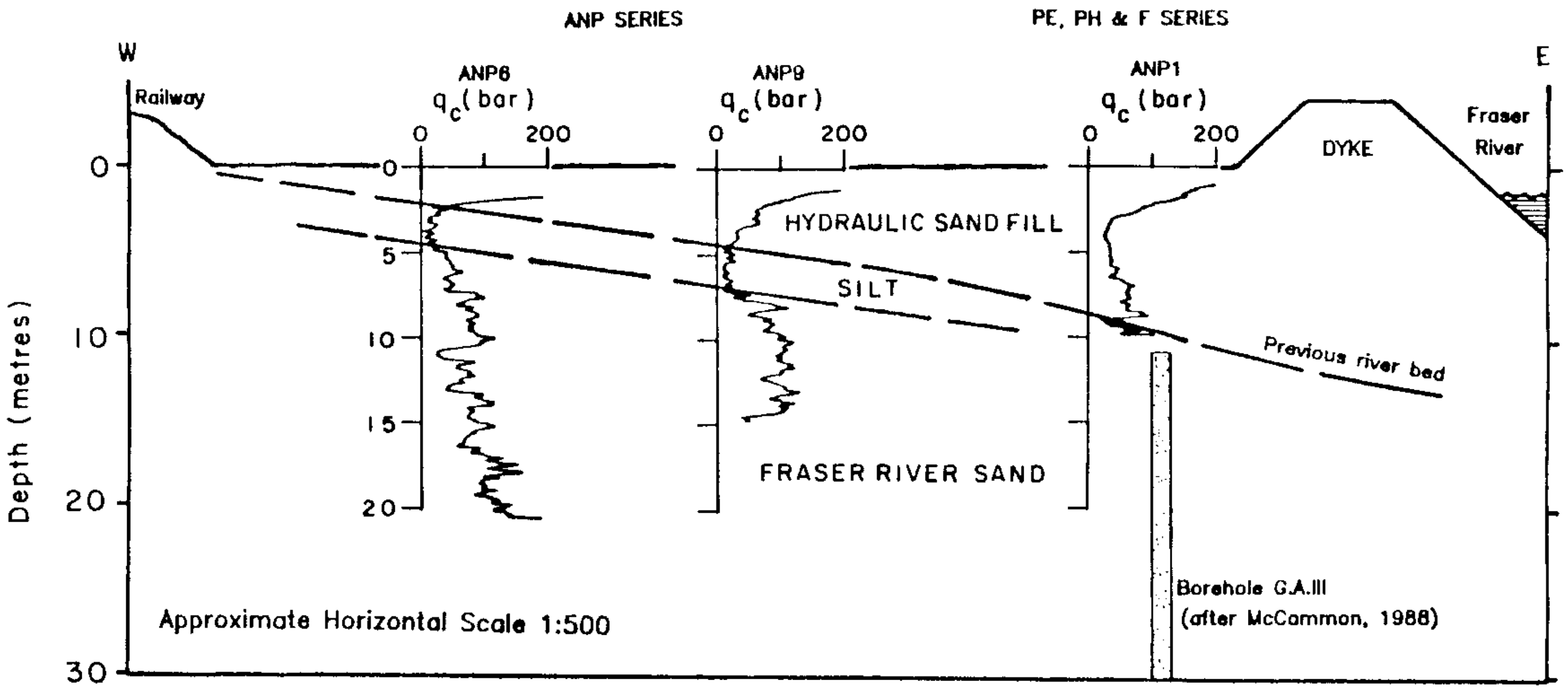

FIG. 2. Section Through Research Site Showing Soil Layers

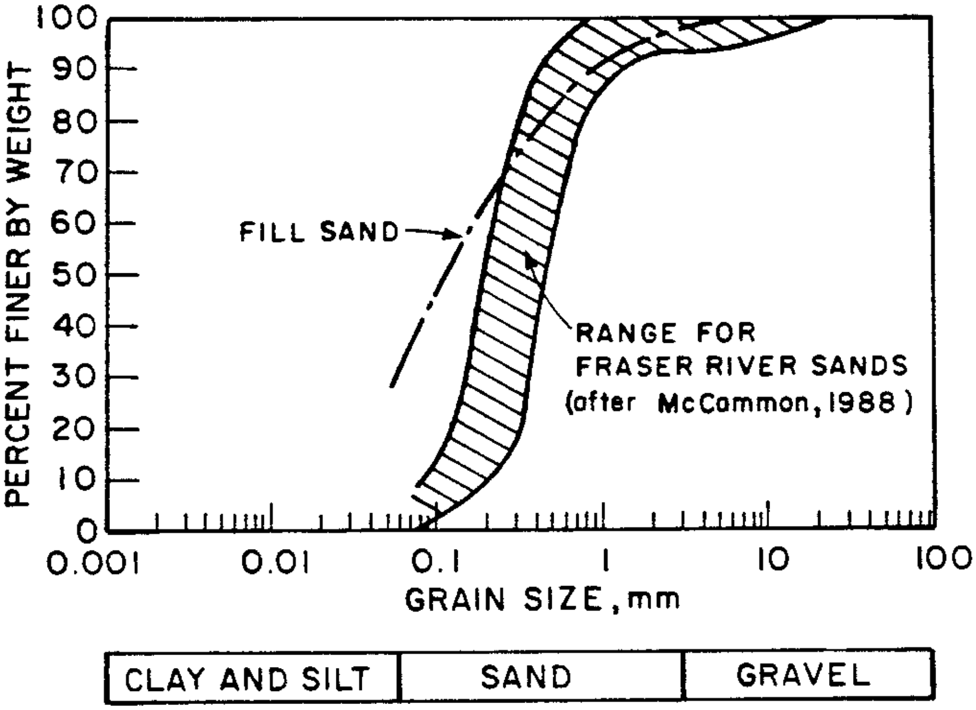

FIG. 3. Particle Size Distribution Curves For Hydraulic Fill Sand and Fraser River Sand

considering the site for field tests, since the Phoenix machine relies on submergence to activate the seepage forces.

Several years ago when the bridge was being constructed, the dredged sand fill was covered with a layer of silty crushed rock to facilitate trafficability. By the time of the Phoenix trials this had developed into a hard surface crust which extended to a depth of about 3 m. The presence of this crust influenced the trials inasmuch as it arched over the ground depressions which were developed at the probe locations.

FIELD WORK

Piezocone (CPTU) and flat dilatometer tests (DMT) were performed to investigate the geotechnical conditions at the site and to monitor compaction performance. Tests were performed from the research vehicle of the In-Situ Testing Group of the University of British Columbia. This is a purpose designed, self contained truck from which a variety of field tests are performed (Campanella and Robertson, 1981). The CPTU and DMT tests were performed using recognized procedures (ASTM, 1986; Schmertmann, 1986).

A number of separate treatment locations were laid out in an area within the pier protection promontory at the Annacis site. The UBC test area was chosen to avoid areas which had previously been used for Phoenix prototype trials and situated far enough from the bridge so as not to cause the owners concern. Treatment areas larger than single equilateral triangles were not attempted because of space limitations and cost constraints.

Phoenix holes were pre-augured to 4.5 m with an 0.2 m (8 in.) diameter auger to penetrate the surface crust. In the sand fill, treatment was attempted from 2 m to 6 m depth, while in the underlying Fraser River Sands treatment was attempted from 4.5 m to 10 m. No densification treatment was attempted in the soils above these depths. The level at which treatment was considered to be active was arbitrarily taken to be the base level of the well screen or about 1.0 m above the tip of the vibrator.

Densification treatment was carried out by withdrawing the Phoenix machine from the hole at an average rate of 1 meter in 6 minutes while it was vibrating and exhausting seepage water. It was decided that no backfill or water would be added to the bore during the course of densification. It was known from previous experience with this equipment that pumping a sand slurry into the hole during vibration significantly improved the situation, however, in the interests of obtaining a straightforward assessment of the vibro-drainage system it was decided not to do so in this trial series. In hindsight, after witnessing how much the presence of the hard surface crust hindered natural backfilling of the bore, and how much the ground arched over the treated areas because of this crust, it would have been better to add sand to the holes while the probe was being withdrawn. Due to local ground collapse and some surface caving, it was necessary to backfill the open holes and level the ground surface after densification and before in-situ testing.

Mechanical difficulties were experienced on several occasions with this prototype equipment. These were caused by unreliable functioning of the air discharge valve above the air motor which led to occasional loss of vibrational activity. Also, it was apparent that the water discharge system requires more refined hydraulic design to allow a more efficient discharge of seepage water.

MEASURED SOIL CHANGES AND EVALUATION OF VIBRO-DRAINAGE PROCESS

Penetration Resistance

The comparison of cone resistance or cone bearing stress, Qc profiles before and after treatment with the Phoenix equipment are shown in Fig. 4 for the fill sand and Fig. 5 for the Fraser River Sand. The penetration profiles used for post-densification interpretation were those performed down the centreline of Phoenix probe holes, since those demonstrated the most significant increases in compaction. A five-fold increase in cone bearing was observed over the depth of treatment for the loose sand fill, while a two-fold increase was measured in the Fraser River Sand. The uniformity of the sand after treatment was considerably greater in the sand fill than in the Fraser River Sand. The lack of uniformity of cone bearing in the densified

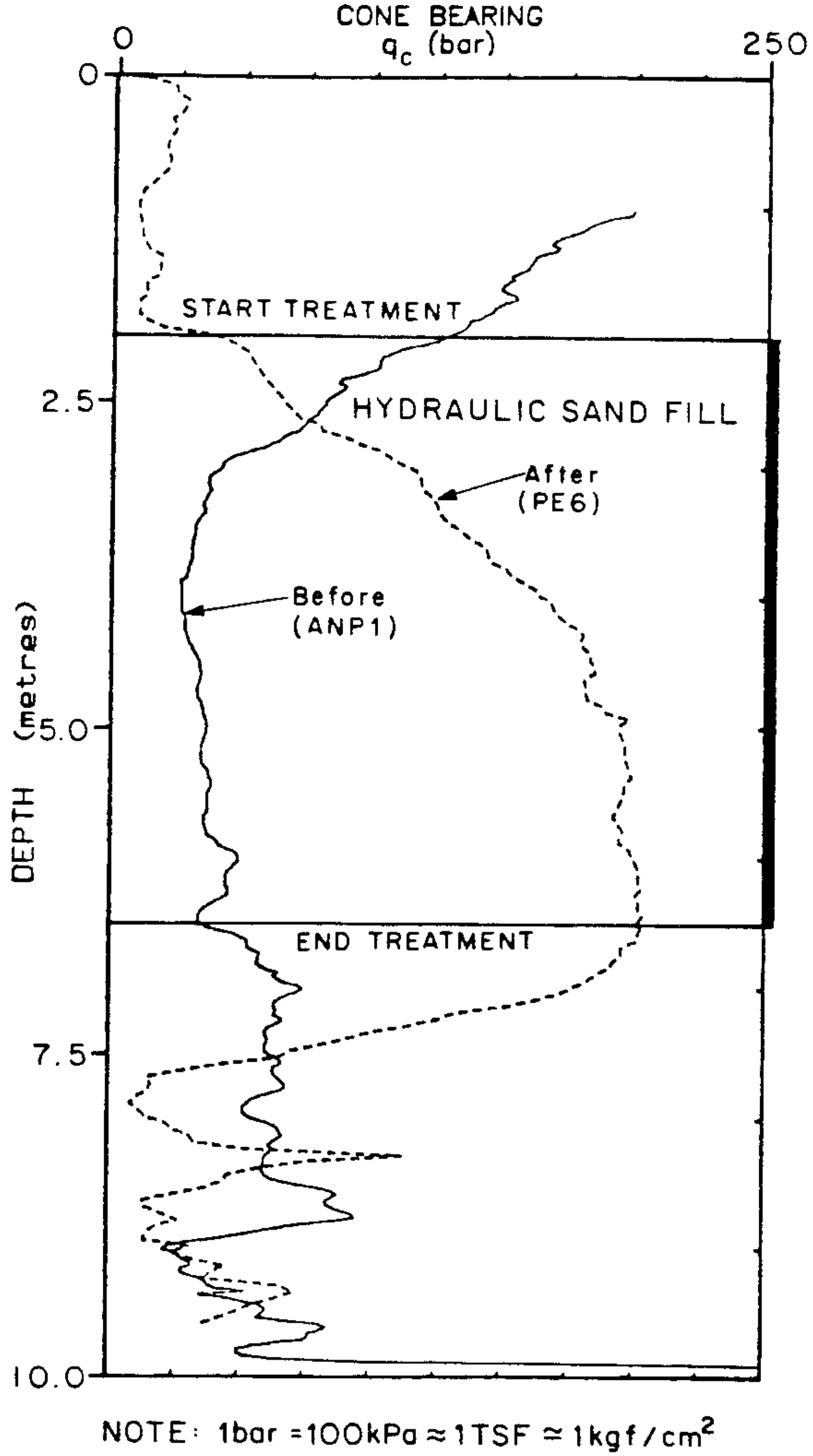

FIG. 4. Comparison of CPT Soundings Performed in Hydraulically Placed Sand Fill Before and After Treatment with Phoenix Machine

Fraser River Sand is believed to be due both to the inhomogeneity of the original Fraser River Sand deposits and to occasional starvation of backfill at the tip in this deeper deposit.

The lower extent of range of treatment coincides with the depth reached by the base of the water pumping mechanism or about one meter above the tip of the probe.

The cone resistance is low in the upper sections of the post-treatment profiles. This is because no attempt was made to densify the upper section of bore, which generally remained open immediately after treatment, later collapsing and requiring the filling with uncompacted backfill. Also, in the intermediate depth, between the base of the hard crust and the water table, the pumping mechanism was ineffective because of the absence of groundwater.

The cone traces in Fig. 5 could be interpreted as indicating an improvement in the silt layer between 5 m and 7 m depth. This is unlikely to be the case and the measured increase in penetration resistance is

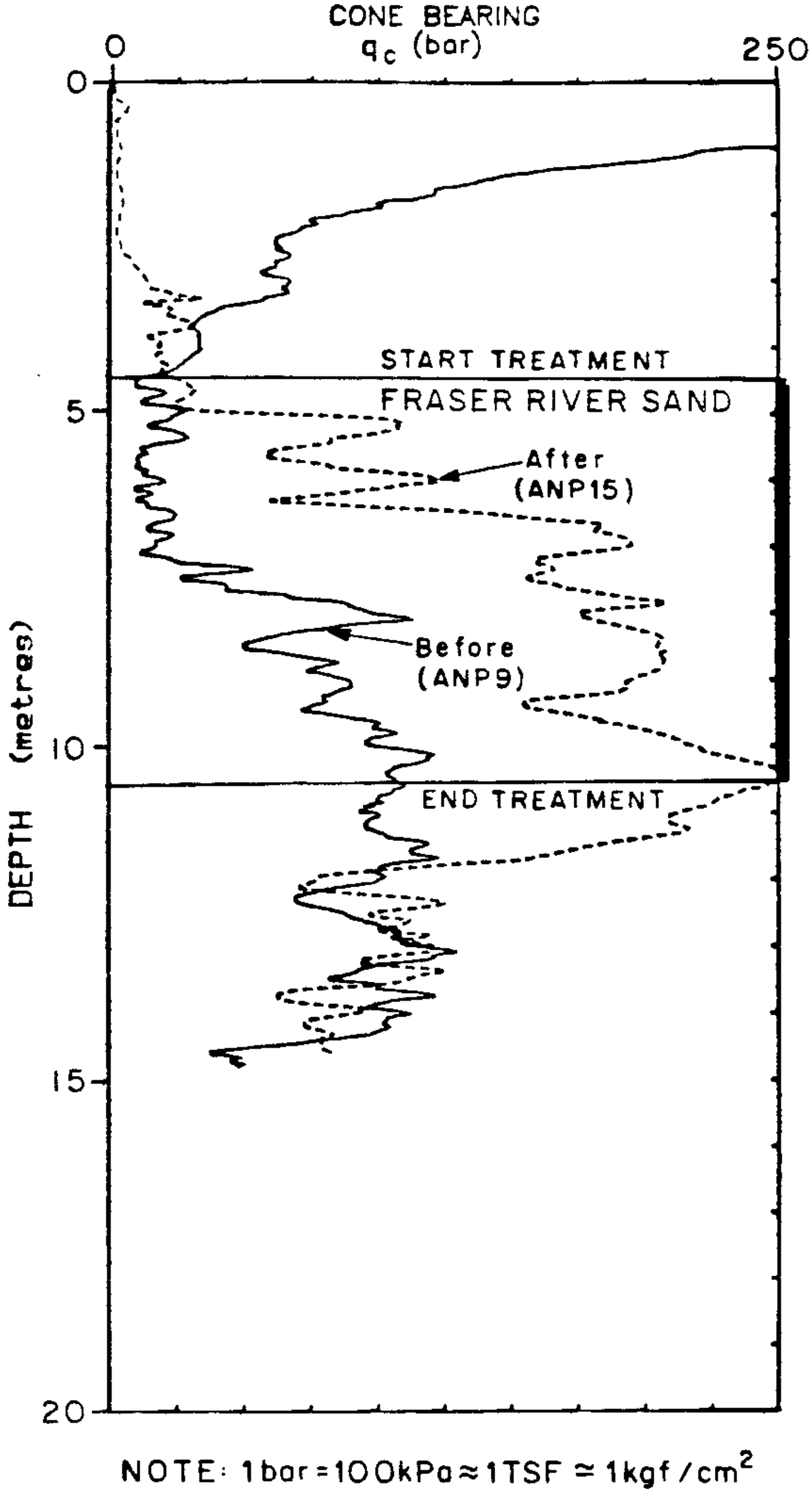

FIG. 5. Comparison of CPT Soundings Performed in Natural Fraser River Sands Before and After Treatment with Phoenix Machine

believed to be due to intermixing of sands and silts within the bore as the probe was worked up and down.

Effect of Time after Densification

The results shown in Fig. 6 suggest that for the Fraser River Sand over the depth interval from 6 m to 10.5 m the increase in cone bearing on the centreline of the Phoenix probe was on the average almost instantaneous and reached a working maximum about 1 day after densification. These findings are in sharp contrast to those presented by Mitchell and Solymar (1984) where it was reported that the cone bearing initially decreased immediately after compaction followed by a relatively long period (2 weeks and more) of continuous increases in cone penetration resistance. In a recent project also on Annacis Island, B.C., Brown (1989) reports that cone bearings did not reach a maximum until almost 10 weeks after densification by the Franki Tristar probe. In that project there were initial decreases followed by increases in cone resistance after compaction in saturated fine to silty sands. That behaviour was believed to be related in part to initial increases in pore pressure followed by time dependent decay resulting in effective stress increases,

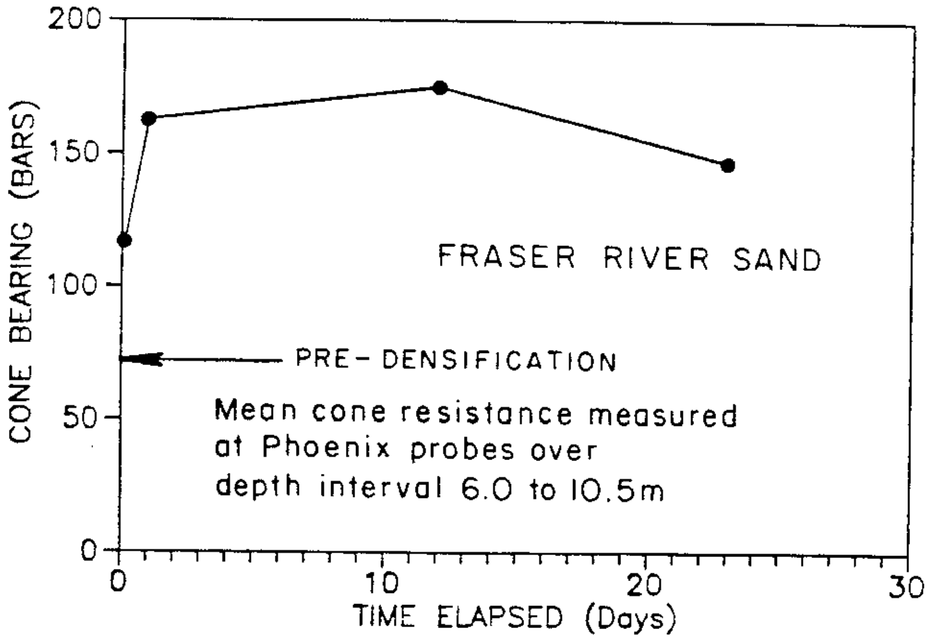

FIG. 6. Influence of Time following Densification with Phoenix Machine on Cone Resistance for Fraser River Sand

consolidation, and secondary compression with time.

It is therefore significant that the Phoenix machine showed a very rapid increase in strength or cone resistance which is likely attributable to the drainage aspects of the probe in combination with the vibration. Unfortunately, similar data for the shallow hydraulic sand fill was not conclusive because of its proximity to the water table and the effect of arching of the thick dense gravel crust. Hence, additional studies are required to verify this very important response of rapid strength gain associated with a vibro-draining probe.

Relative Density

Figure 7 shows the change in relative density interpreted from CPT (Robertson and Campanella, 1983) of the fill sand due to Phoenix treatment. Before treatment the sand fill relative density was estimated at 45-55% relative density, and after treatment was increased to 85-90%.

Figure 8 shows the change in relative density caused

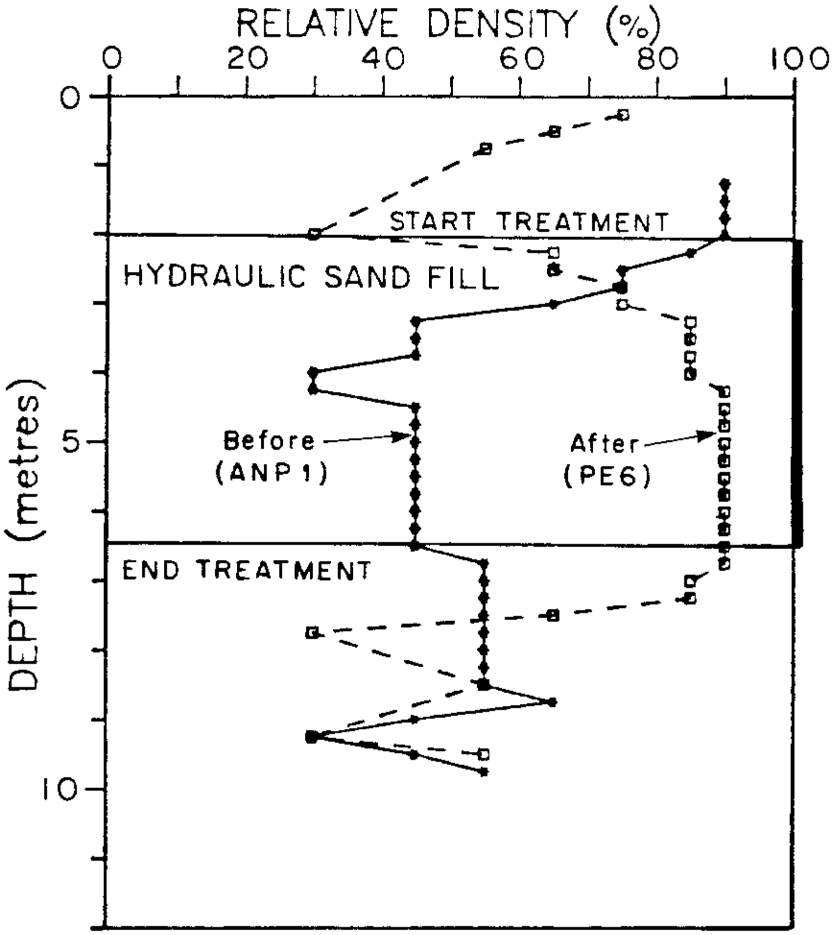

FIG. 7 Comparison of Relative Density from CPT before and after Treatment with Phoenix Machine for Hydraulically Placed Sand Fill

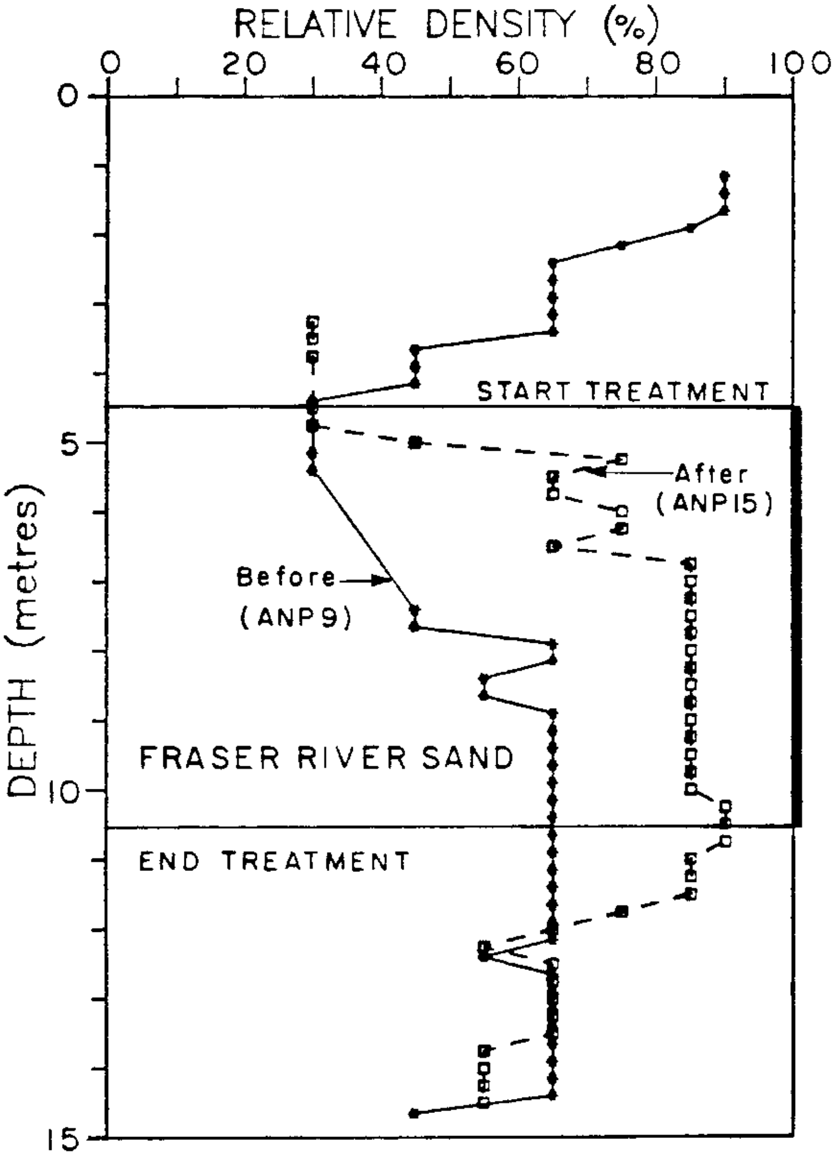

FIG. 8. Comparison of Relative Density from CPT before and after Treatment with Phoenix Machine for Fraser River Sands

by the Phoenix machine in treating the Fraser River Sand. Prior to treatment the sand was consistently estimated at 65% relative density, whereas subsequent to treatment the relative density was increased to 85-90%.

For both sand types in which densification was performed, the highest relative density achieved by the Phoenix compaction system was the same and about 85-90%. Such a state of compaction appears to be achievable independent of the depth and also independent of the initial or pre-compaction sand density.

Horizontal Stress

Calibration chamber research has demonstrated that penetration resistance in sands is a function of in-situ horizontal stress, as well as relative density (Baldi et al, 1981, Houlsby and Hitchman, 1988); consequently, an increase in horizontal stress would, if not taken into consideration lead to an overestimation of the improvements in relative density.

The mechanism of this vibrating equipment is such that large horizontal forces are imparted to the soil at depth. Also, the seepage forces generated by the pumping system within the Phoenix probe could produce an alteration in the horizontal stress regime. It seems reasonable therefore to expect that these influences might lead to some permanent increase of in-situ horizontal stresses in the vicinity of vibro-drainage treatment.

Marchetti (1985) developed a method to determine Ko in sands from flat dilatometer test data such as were obtained during this test programme.
As anticipated, prior to compaction treatment, the Ko values in the sands average about 0.5. Subsequent to treatment with the Phoenix equipment there was an increase in the horizontal stress and Ko increased to around 0.7. By combining the estimation of Ko and the vertical effective stress, the profile of in-situ horizontal stress shown in Fig. 9 was generated. Below 5 m the profiles show a marked increase in horizontal stress. In part this can be attributed to silt replacement by sand, but an increase is clearly shown for the sands also. According to the relationship

proposed by Baldi et al (1981) the increased horizontal effective stress indicated in Fig. 9 could only lead to an overestimation of relative density of the order of 5%.

Radius of Influence of a Single Probe Treatment

The extent of the range of influence of a single compaction probe has been explored by performing cone penetration tests at various distances from the center of treatment.

Figure 10 shows the variation of cone bearing around a number of single Phoenix densification probe for both soil types. Data points refer to calculated mean cone bearings over the depth ranges of improved soil. To evaluate the effect of treatment at the different vertical stresses at the various depths the cone bearings have been normalized by dividing the post-compaction value by the cone bearing before treatment.

The results in Fig. 10 show that the improvement is greatest at the probe and decreases with increasing distance from the probe. These findings are in general agreement with a similar study of a vibroflot by

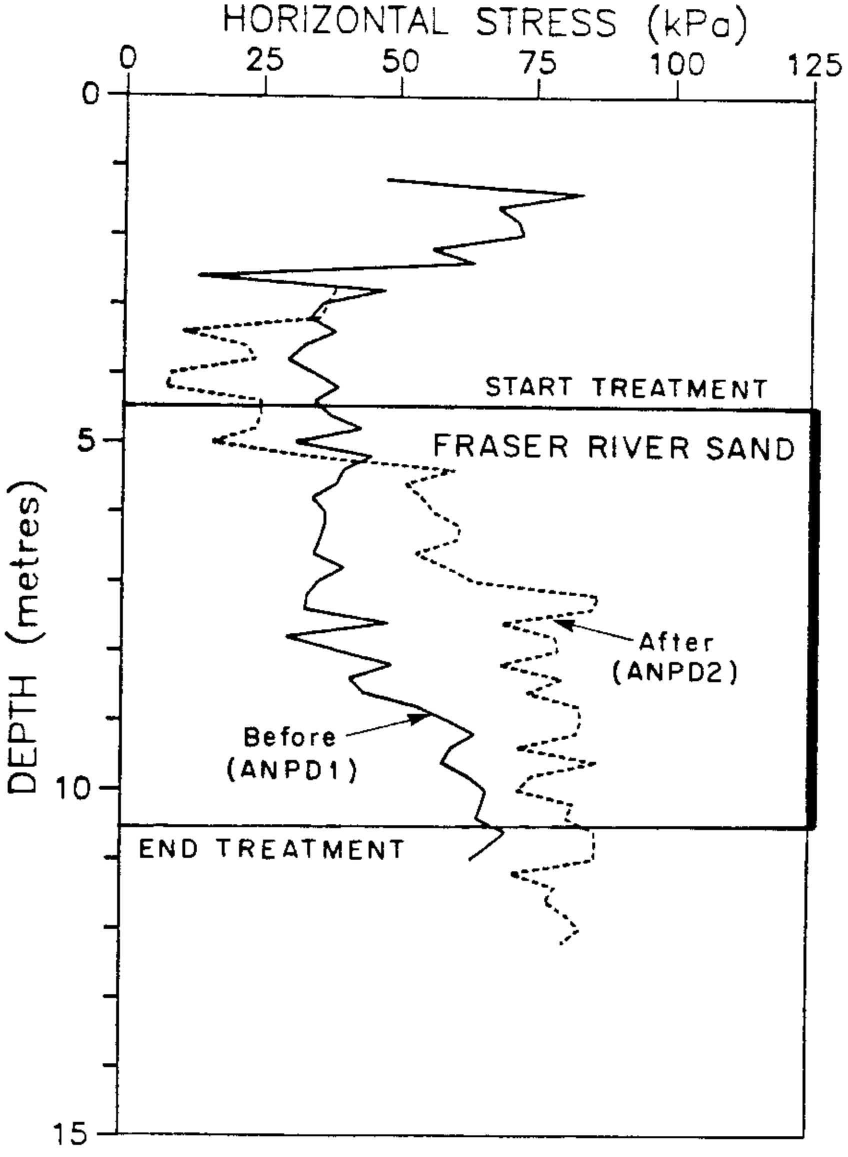

FIG. 9. Comparison of In-Situ Horizontal Stress from DMT before and after Treatment with Phoenix Machine for Fraser River Sand

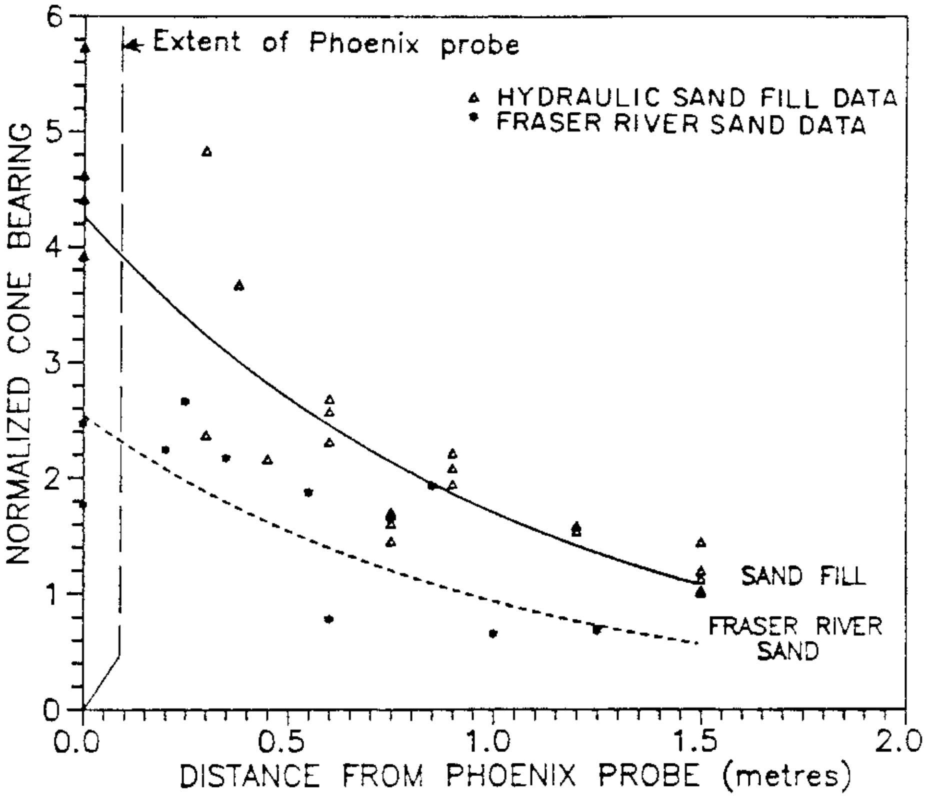

FIG. 10. Ratio of Cone Bearing Stresses,after and before Treatment,with Distance from Phoenix Probe

D'Appolonia (1953). The rate of decrease of cone bearing was fitted approximately by the exponential curves shown. The higher values of normalized cone bearing in the sand fill reflect the lower sand densities prior to compaction. For both soil types, there was no influence of a single compaction probe outside a radius of 1.5 m from the probe center or 8 diameters. In fact, the results for the Fraser River Sand suggest that the compaction treatment may actually reduce the cone resistance at distances in excess of 1 m from the probe in this material. However, as discussed earlier this may be due to either inadequate backfilling of the bore under gravity alone, or the result of arching in the surficial crust.

Effect of Spacing and Pattern

To investigate the effect of probe spacing and pattern on the Phoenix process, a series of triangular probe configurations were performed. In the Fraser River Sand, densification was conducted on triangular spacings of 1.5 m and 2.5 m. Cone tests were performed at the centroids of these two triangles and the results are presented in Fig. 11. In the case of the 1.5 m pattern a very significant improvement, in excess of

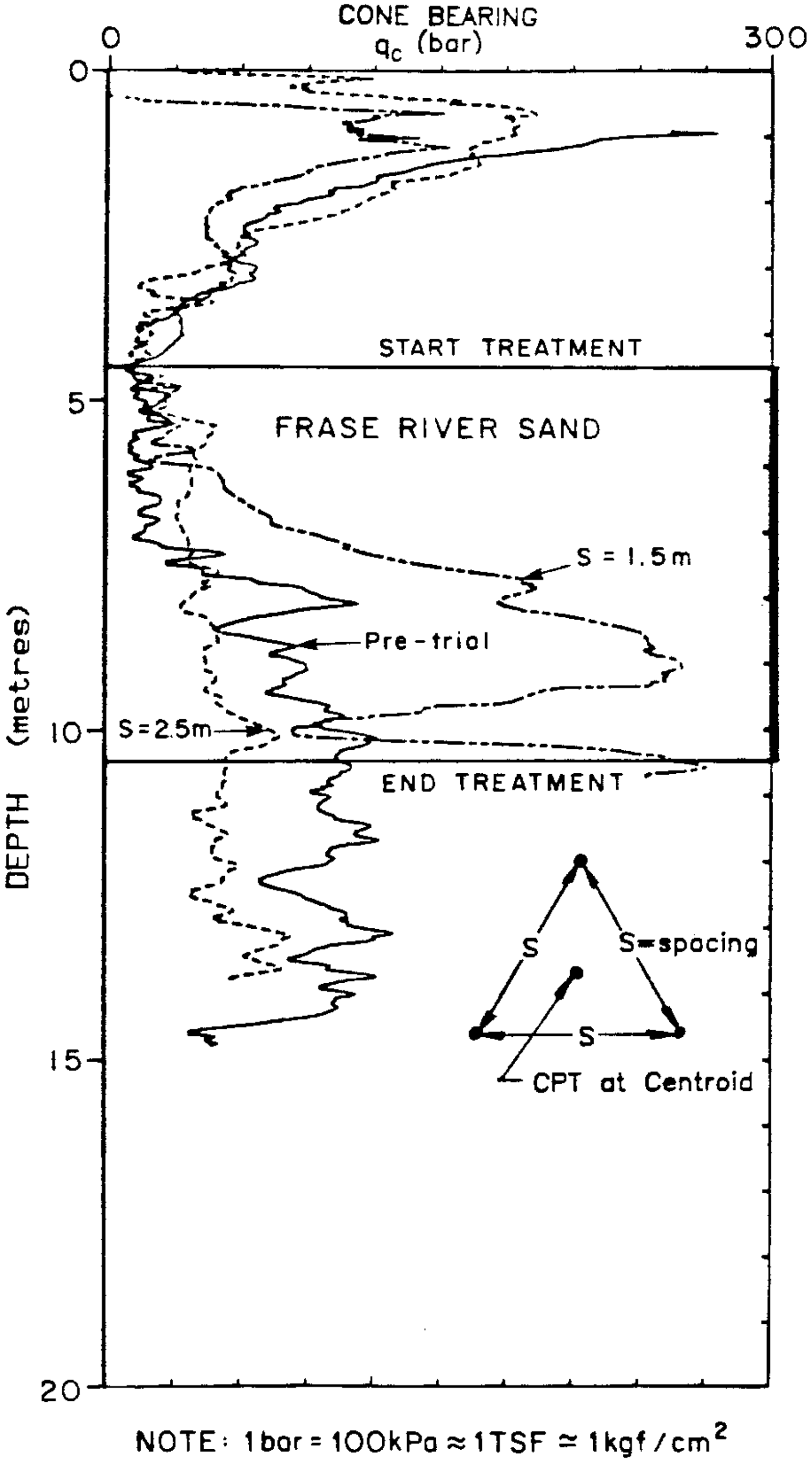

FIG. 11. Influence of Triangular Spacing of Phoenix Probes on Cone Bearing at Centroid for Fraser River Sand

120% of the initial cone resistance, was demonstrated. The improvement was considerably in excess of what would be expected at an equivalent distance from a single probe, showing there was interaction or overlapping among probes, at this spacing. At the larger spacing of 2.5 m, it was found that the cone resistance at the centroid of the probes was significantly lower following Phoenix treatment than before treatment. The development of a zone of loose sand at the center of the 2.5 m triangle may be due to a shortage of backfill soil available at the tip to make up for the loss in volume caused by compacting soil (Brown, 1977). It may also be attributable to the seepage forces developed around the vibro-drain pulling soil in towards the probe and away from the centroid. However, finding a loose zone at the center of a triangular compaction configuration is consistent with the investigations of a single probe where it was found that soil may be loosened in a zone approximately 1.0 m to 1.5 m from a single compaction probe.

The results in Fig. 12 show the effect of changing the spacing between densification probes in the sand fill. The cone soundings were performed at the centroids of

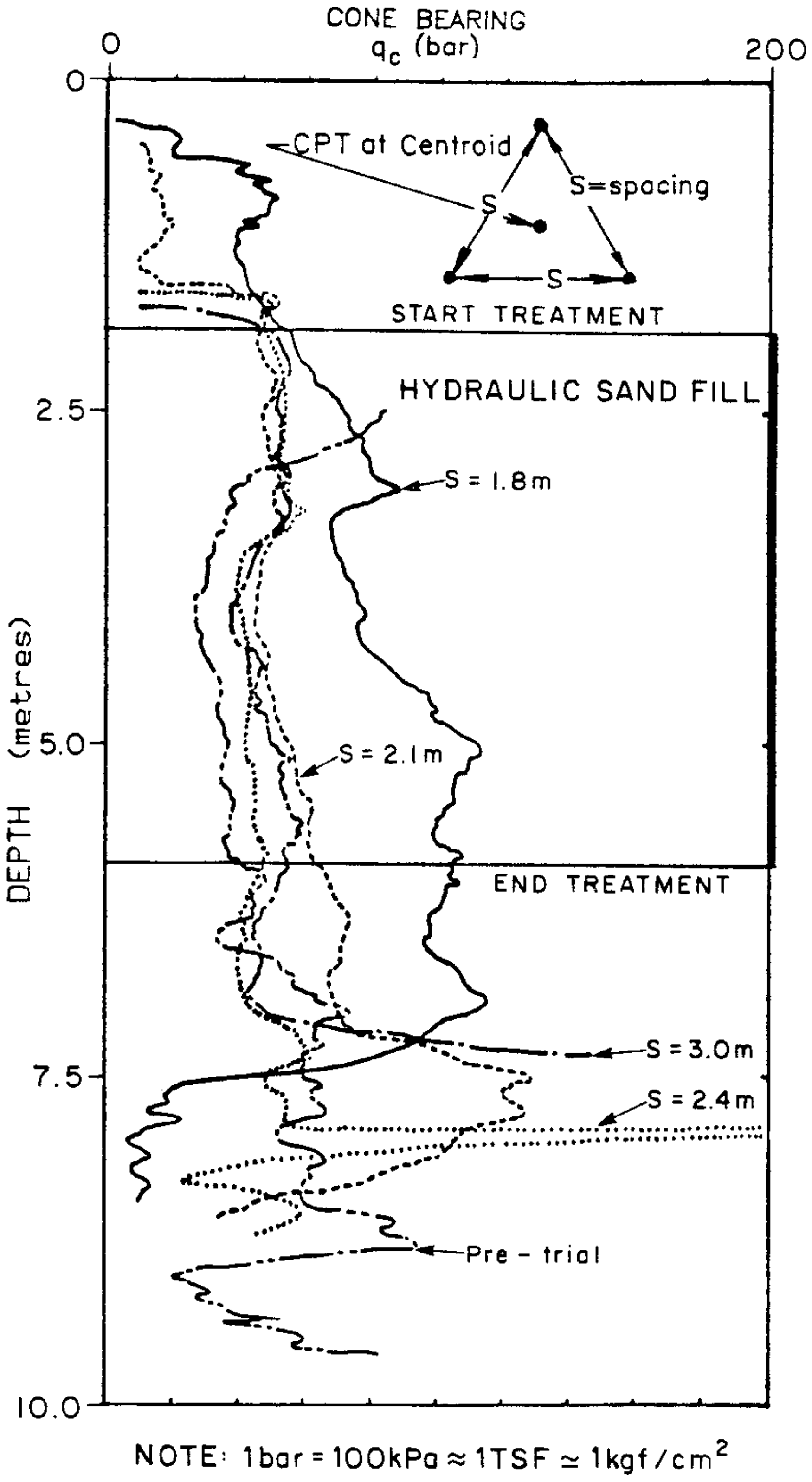

FIG. 12. Influence of Triangular Spacing of Phoenix Probes on Cone Bearing at Centroid for Hydraulic Sand Fill

triangles of compaction probes spaced at 1.8 m, 2.1 m, 2.4 m, and 3.0 m. The 1.8 m spacing demonstrates an increase in excess of 100% over the initial cone bearing. For probe spacings of 2.1 m and greater, only slight or no improvement could be detected. There was no reduction in cone bearing at larger probe spacings as was observed for the Fraser River Sands. It is postulated that in the case of the looser sand fill it was possible for sand to migrate downward in the bore. Therefore, since an adequate unaided supply of backfill was maintained, a high state of compaction was achieved.

Influence of Simultaneous Drainage

In order to isolate the significance of the drainage effect on compaction, comparative field trials were conducted with and without the water pumping unit. The Phoenix equipment can be run in a vibration only mode by simply leaving out the drainage element.

The results are shown in Fig. 13, where the mean cone bearings calculated for the depth interval 6.0 m to 10.5 m are plotted against distance from the center of a single probe hole. Here, it may be seen that there

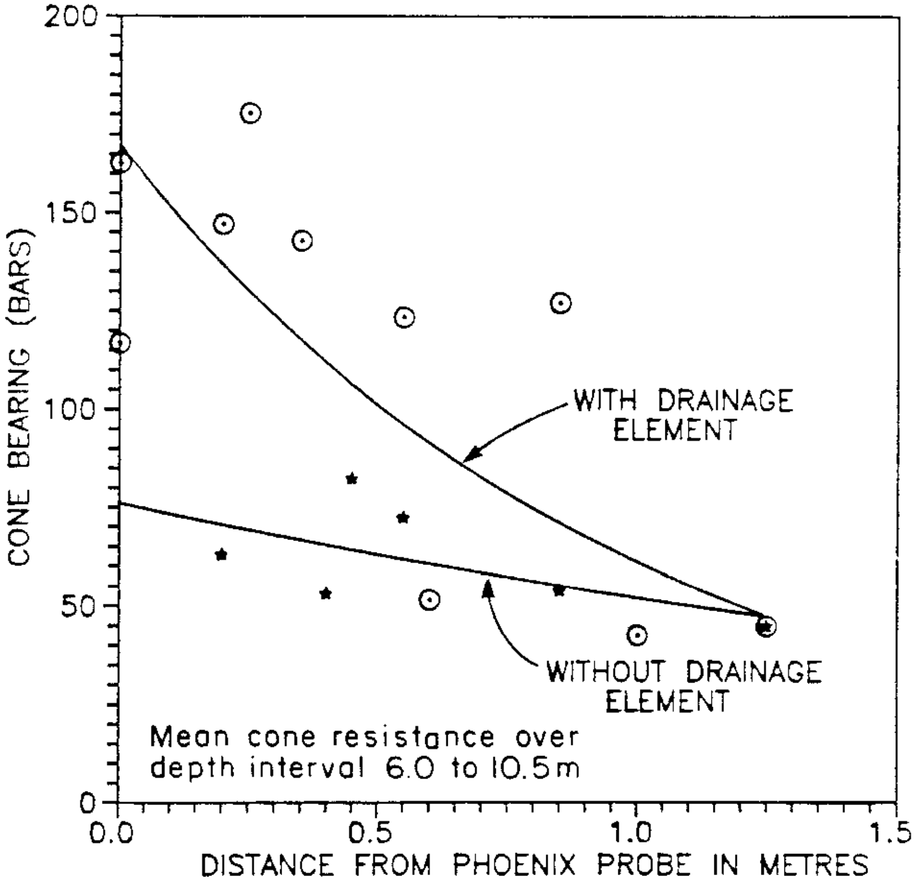

FIG. 13. Influence of Drainage on Cone Bearing for Fraser River Sand

was a strong trend towards significantly higher cone bearing values around the probe hole performed with pumping than for the probe hole performed without pumping. The cone bearing with the drainage section active was up to double the value for the case without drainage, in the close vicinity of the probe hole. The effect decreases with increasing distance from the probe hole as both the compaction influence and the seepage forces are reduced.

Comparison with Other Vibrocompaction Systems

In Fig. 14 the improvement in cone resistance in relatively clean sands with three other compaction probes which only vibrate has been compared with the Phoenix machine in order to assess the effect of adding a pumping unit to a vibrator. For the purpose of comparison, the quantity plotted along the ordinate is the final cone bearing which has been normalized to the initial cone bearing and then multiplied by the initial relative density. In this way differences in overburden stress and initial densities may be taken into consideration. On the abscissa is plotted the distance from the probe, normalized by the diameter of the probe. This is important since the effective sizes of probes differ by nearly an order of magnitude. No

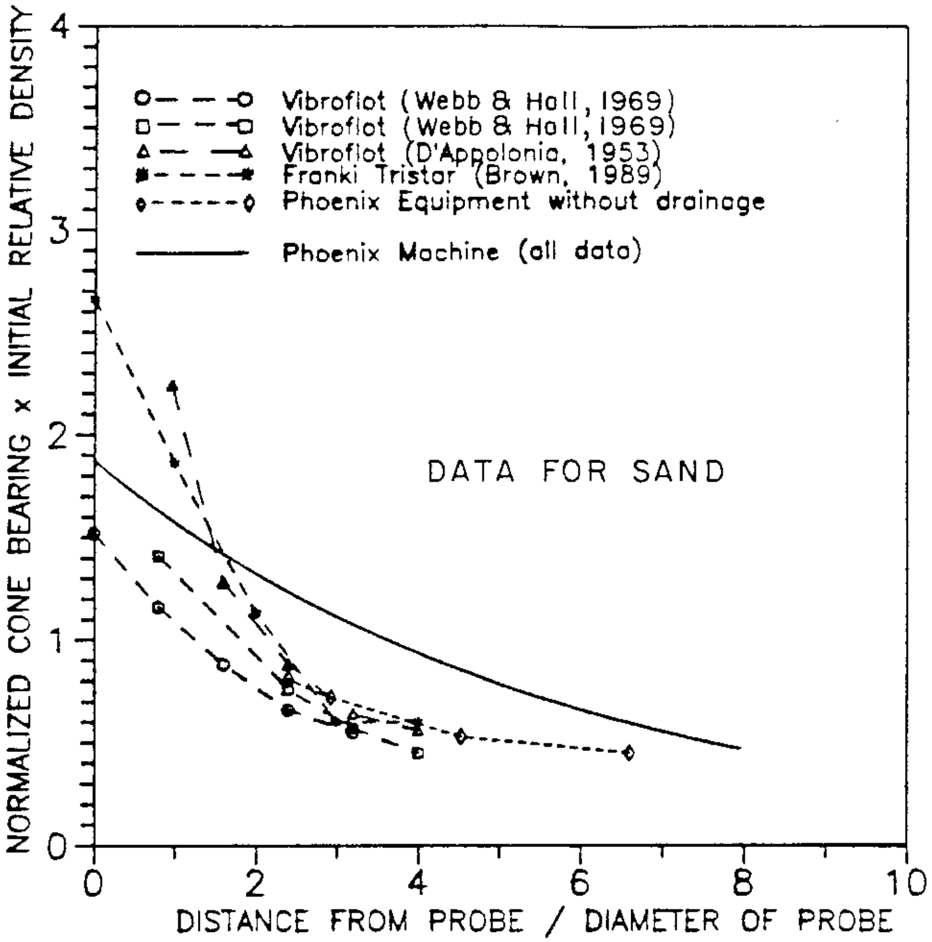

FIG. 14. Ability of Phoenix Machine to Densify Sand Around a Single Compaction Probe Compared to Other Equipment

allowance has been made for differences of machine power demand or output. For instance, the vibroflot reported by D'Appolonia (1953) developed a centrifugal force of 100 kN (10 tons) compared to only 23 kN (2.3 tons) for the Phoenix machine.

For the performance criteria proposed the results in Fig. 14 show that the improvement achievable with the Phoenix machine was of a different character to that achievable with systems which do not have simultaneous water pumping. The latter systems were able to cause soil improvement at up to distances equal to about 3 probe diameters, whereas the Phoenix machine was capable of improving soil at distances of up to 6 or more probe diameters. In the region close to the probe itself, the degree of improvement of the Phoenix equipment falls in the middle of the range displayed by the conventional systems. The Phoenix equipment without drainage follows the trend of the conventional systems. The advantage of the Phoenix vibro-drainage system over the conventional equipment was most marked in the region from 2 to 8 probe diameters, and shows that if the sizes of the probes are taken into consideration, the Phoenix equipment constitutes a very efficient densification system.

Table 1
Details of Various Vibrocompaction Systems

Machine	Dia. D (m)	Frequency (Hz)	Spacing S (m)	S/D ratio	Ref.
GKN Vibroflot	0.45	30	2.7-3.7	6-8	Brown 1977
Foster Terraprobe	0.76	15	0.9-2.4	1-3	Anderson 1974
Vibrorod	0.5	-	1.7	3	Saito 1977
Mytilus	2.1	25	6.5	3	Davis et al, 1981
Vibro-wing	1.6	20	2.5	1.6	Massarsch & Broms 1983
Franki Tristar	1.0	20	2.0	2	Massarsch & Vanneste 1988
Phoenix Machine	0.19	25	1.8	9	Present study

Table 1 shows details of the major systems available for deep compaction of relatively clean sandy soils in-situ. The ratio of typical probe spacing to probe diameter, or S/D, has been used to compare approximately the effectiveness of the various machines. Typical values of S/D for the vertically vibrating systems are in the range of 1 to 3, while the horizontally vibrating vibroflot attains values from 6 to 8, reflecting the widely held belief that the horizontally vibrating devices are far more effective than the vertically vibrating probes. If the optimum spacing of 1.8 m is adopted for the Phoenix machine, then it achieves the highest spacing to diameter ratio of 9. This indicates that for its size, the Phoenix machine was particularly efficient in comparison to the systems considered in Table 1. It is not yet clear, however, if this high value of 9 would stay the same if the size of the Phoenix machine were increased to be comparable to the larger probes considered in Table 1.

SUMMARY AND CONCLUSIONS

The Phoenix machine is an efficient mechanical means of densifying granular, saturated sands at depth using simultaneous drainage and vibration. In terms of relative density, improvements to a value of 85-90% were consistently achieved at the study site, independently of the initial starting density and overburden stress. The process appears to improve the engineering characteristics of the sand primarily by increasing the relative density of the granular soil, and secondly by increasing the effective horizontal stress. The maximum computed value of relative densities achievable should be reduced by 5% to account for increases in horizontal stress caused by the densification process.

The results suggest that after densification the cone penetration bearing strength increases to its maximum value within a day in the natural Fraser River medium sand. These results are in contrast to those published for other densification methods where strength increases were delayed for periods of several weeks and more. This important aspect may be due to simultaneous drainage during vibration and requires further verification.

The degree of compaction achievable diminishes with increasing distance from the center of a single treatment probe, and in an approximately exponential form. The outer limit of improvement appeared to be a radius of 1.0 m in the natural Fraser River Sand and 1.5 m in the looser hydraulic sand fill for this lightweight probe of only 190 mm (7.5 in.) in diameter.

Reduced cone resistances at points outside the effective radius of compaction were measured for both single and triangular patterns. Such reductions may be attributable to inadequate make-up sand at the probe tip. Experience suggests that sand may be drawn into the compaction area by the seepage forces generated by the drainage at the probe. However, it also appears that the hard surface crust at the Annacis test site complicated the situation. Backfill starvation could have been overcome by adding sand, preferably as a sand slurry, at the surface, or simply by allowing the water from the drainage exhaust to discharge down the hole again.

For the soil conditions encountered at this research site a triangular probe spacing of 1.8 m appears appropriate for efficient treatment. At such a spacing the sand confined within the triangular area gains an additional degree of compaction by virtue of interaction between the individual probes.

The addition of the drainage function seems to play a significant role within the overall densification process. Drainage of water during compaction treatment can increase the cone resistance to almost double that attainable by vibration treatment alone. This is an important finding since it is this aspect which sets the Phoenix process apart from other processes of vibrocompaction.

The Phoenix machine compares favorably with other equipment available in the marketplace, if spacing requirements and probe size are taken into consideration. In fact, the small size of the equipment has enabled its deployment in special situations where larger equipment could not be utilized.

The prototype equipment used in this field trial requires design modifications to make it mechanically more functionally reliable and hydraulically more effective and efficient. Also, the use of a drill rig to deploy the probe, while advantageous in some particular circumstances, is not cost effective in open ground. These problems have been addressed in a later prototype design.

ACKNOWLEDGEMENTS

The authors are indebted to Phoenix Engineering for making their probe available for this study and providing the support equipment and personnel to deploy it.

The financial support of the Natural Sciences and Engineering Research Council, Canada, in the form of a Research Assistantship, Technicians and equipment is gratefully acknowledged.

The cooperation and assistance of the University of British Columbia graduate students and technicians in Civil Engineering are much appreciated.

The authors would also like to thank the Ministry of Transportation and Highways of B.C. for making the area adjacent to the Alex Fraser Bridge accessible for this research.

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