Chapter 22

PENETRATION TESTING

Introduction

This chapter discusses the Standard Penetration Test (SPT), Becker Penetration Test (BPT), and Cone Penetration Test (CPT). Penetration tests are used to determine foundation strength and to evaluate the liquefaction potential of a material. SPTs for liquefaction evaluations are stressed in the discussion. The significant aspects of the tests and the potential problems that can occur are included.

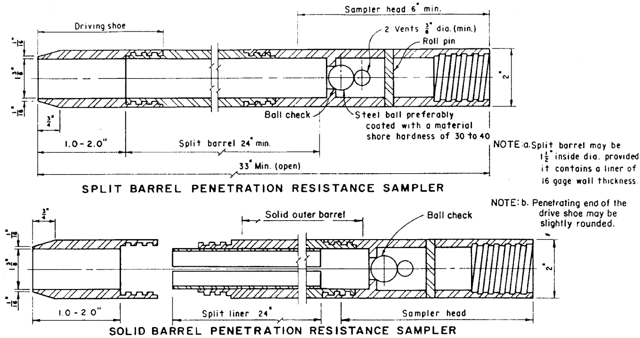
History

Penetration resistance testing and sampling with an open ended pipe was started in the early 1900s. The Raymond Concrete Pile Company developed the Standard Penetration Test with the split barrel sampler in 1927. Since then, the SPT has been performed worldwide. The SPT or variations of the test are the primary means of collecting geotechnical design data in the United States. An estimated 80-90 percent of geotechnical investigations consist of SPTs.

Standard Penetration Testing

Equipment and Procedures

The SPT consists of driving a 2-inch (5-cm) outside diameter (OD) "split barrel" sampler (figure 22-1) at the bottom of an open borehole with a 140-pound (63.6-kg) hammer dropped 30 inches (75 cm). The "N" value is the number of blows to drive the sampler the last 1 foot (30 cm), expressed in blows per foot. After the penetration



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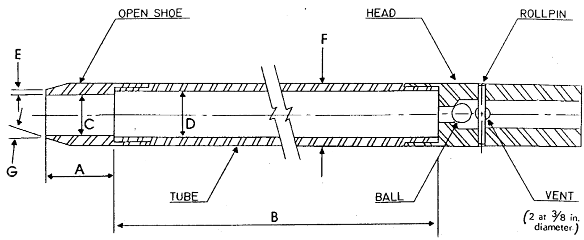


A = 1.0 to 2.0 in. (25 to 50 mm)
B = 18.0 to 30.0 in. (0.457 to 0.762 m)
C = 1.375 ± 0.005 in. (34.93 ± 0.13 mm)
D = 1.50 ± 0.05 − 0.00 in. (38.1 ± 1.3 − 0.0 mm)
E = 0.10 ± 0.02 in. (2.54 ± 0.25 mm)
F = 2.00 ± 0.05 − 0.00 in. (50.8 ± 1.3 − 0.0 mm)
G = 16.0° to 23.0°

The 1½ in. (38 mm) inside diameter split barrel may be used with a 16-gage wall thickness split liner. The penetrating end of the drive shoe may be slightly rounded. Metal or plastic retainers may be used to retain soil samples.

Split-Barrel Sampler

Figure 22-1.—ASTM and Reclamation SPT sampler requirements.

test is completed, the sampler is retrieved from the hole. The split barrel is opened, the soil is classified, and a moisture specimen is obtained. After the test, the borehole is extended to the next test depth and the process is repeated. SPT soil samples are disturbed during the driving process and cannot be used as undisturbed specimens for laboratory testing.

The American Society of Testing and Materials standardized the test in the 1950s. The procedure required a free falling hammer, but the shape and drop method were not standardized. Many hammer systems can be used to perform the test, and many do not really free fall. The predominant hammer system used in the United States is the safety hammer (figure 22-2) that is lifted and dropped with the a rope and cat head. Donut hammers (figure 22-3) are operated by rope and cat head or mechanical tripping. Donut hammers are not recommended because the hammers are more dangerous to operate and are less efficient than safety hammers. Automatic hammer systems are used frequently and are preferred because the hammers are safer and offer close to true free fall conditions, and the results are more repeatable.

The SPT should not be confused with other thick-wall drive sampling methods such as described in ASTM Standard D 3550 which covers larger ring-lined split barrel samplers with up to 3-inch (7.6-cm) OD. These samplers are also know as “California” or “Dames & Moore” samplers. These drive samplers do not meet SPT requirements because they use bigger barrels, different hammers, and different drop heights to advance the sampler.

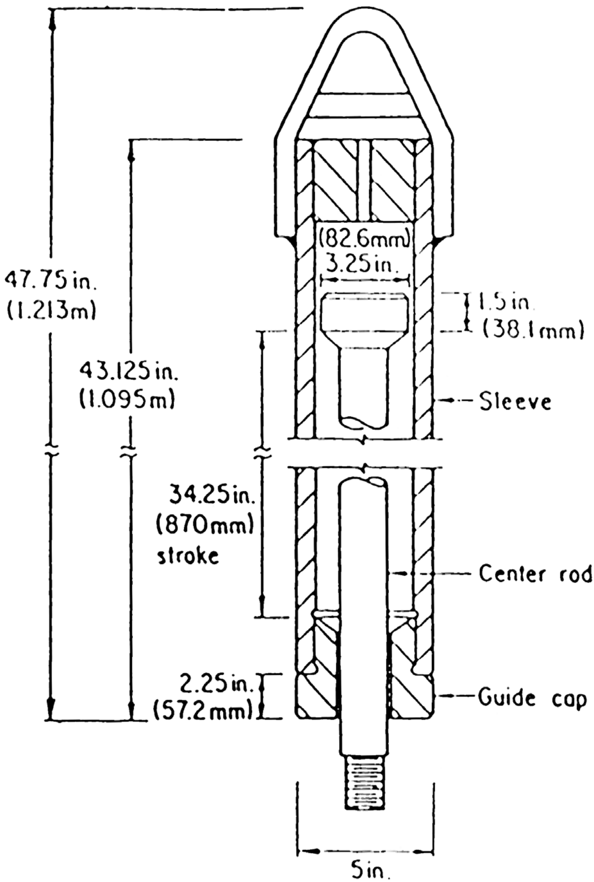


Figure 22-2.—Safety hammer.

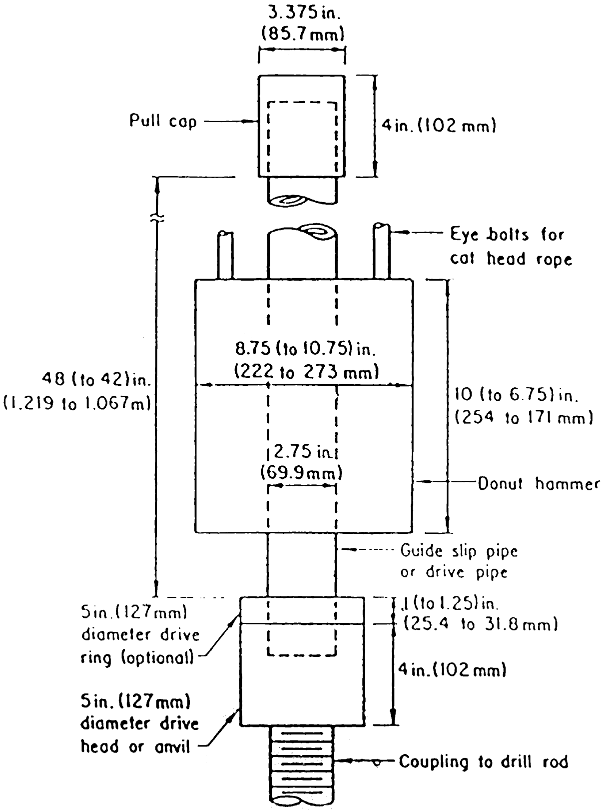


Figure 22-3.—Donut hammer.

The energy delivered to the sampler can vary widely because of the wide variety of acceptable hammer systems. Numerous studies of SPT driving systems indicate that the energy varies from 40 to 95 percent of the theoretical maximum energy. The "N" value is inversely proportional to the energy supplied to the sampler, and the energy delivered to the sampler is critical. Because of energy losses in the impact anvil, energy from the hammer should be measured on the drill rod below the impact surface. Drill rod energy ratio is determined by measuring the force-time history in the drill string. Both acceleration and force-time history can be measured and are important in determining the normalized penetration resistance of sands for liquefaction resistance evaluations (ASTM D 6066). Common practice is to normalize the SPT N value to a 60-percent drill rod energy ratio. Adjustment factors can be as large as 20 to 30 percent.

The largest cause of error in the SPT is drilling disturbance of the material to be tested. This is especially true when testing loose sands below the water table. Field studies have shown that "sanding in" can be prevented by using rotary drilling with drill mud and upward-deflected-discharge bits and by maintaining the fluid level in the drill hole at all times. Hollow-stem augers are especially popular for drilling in the impervious zones in dams but can cause problems when loose sand is encountered below the water table. Many other drilling methods are available for performing SPTs, and each should be evaluated relative to potential problems and how the data will be used.

Information Obtainable by SPT

The SPT does provide a soil sample. Sampling is not continuous because the closest recommended test interval is 2.5 feet (75 cm). Typical sampling is at 5-foot (1.5-m) intervals or at changes in materials. The test recovers a disturbed soil sample that can be classified on site, or the sample can be sent to the laboratory for physical properties tests.

SPT N values have been correlated to numerous soil properties. In cohesionless soils (sands), the SPT can be used to predict the relative density of sands (i.e., very loose, loose, medium, etc.) (table 22-1).

Table 22-1.—Penetration resistance and soil properties based on the SPT (Peck, et al.)

Sands (Fairly reliable)		Clays (Rather reliable)	
Number of blows per foot (30 m), N	Relative density	Number of blows per foot (30 cm), N	Consistency
		Below 2	Very soft
0-4	Very loose	2-4	Soft
4-10	Loose	4-8	Medium
10-30	Medium	8-15	Stiff
30-50	Dense	15-30	Very stiff
Over 50	Very dense	Over 30	Hard

The SPT has been widely used to predict the allowable bearing capacity of footings on sand. There are several empirical methods that are based either on case histories or on drained modulus of deformation predictions. The application of these predictions should be tempered by local experience. There are many proposed methods for estimating bearing capacity. The methods are probably slightly conservative and should be applied carefully.

SPT N values must be corrected for overburden pressures and the location of the water table.

For clays, the SPT is less reliable for predicting strength and compressibility, especially for weaker clays. The SPT is commonly used to assess the consistency of clays by grouping clays as very soft, soft, medium, etc. Predictions of undrained strengths should be used with extreme caution, especially in weak clays, because the SPT barrel remolds the clay, and the penetration resistance is more a measure of remolded strength. For evaluating undrained strength in clays, vane shear, unconfined compression, or CPTs are better than SPTs. SPT data should not be used to estimate the compressibility of clays. To evaluate compression behavior of clays, use either empirical factors based on water content and atterberg limits or obtain undisturbed samples for laboratory consolidation testing.

SPT data routinely have been used for predicting liquefaction triggered by earthquake loading. If liquefaction is predicted, the SPT data can be used to estimate the post-earthquake shear strengths. Extensive case history data have been collected to evaluate liquefaction; however, the data are subject to drilling disturbance errors and the energy delivered by the hammer system must be known. If drilling disturbance is evident or suspected, the CPT is an alternative because the soil can be tested in place. Procedures for evaluating liquefaction from SPTs are given in Reclamation's *Design Standards No. 13, Embankment Dams*, "Chapter 13, Seismic Design and Analysis." SPT N data can be used to estimate the shear modulus of clean sands, but the method is approximate. If the shear modulus is needed, directly measuring the shear wave velocity is preferred.

Liquefaction occurs when water pressure builds up in granular soils during an earthquake. Soils mostly susceptible to liquefaction are "cohesionless" soils, primarily clean sands and gravels (GP, SP, GW, SW, GP-GM, SP-SM) and silty sands and gravels (SM, GM). The term, "sands," in the following discussion refers to all these soils. The water pressure buildup results in strength loss and possibly deformation, slippage, and failure. Data collected at liquefaction sites have been used to assess whether a deposit is liquefiable.

Testing Cohesionless Soils

Earthquake induced liquefaction is commonly associated with sands below the water table. Good drilling technique is critical to ensuring that the sands are undisturbed prior to the SPT. Unfortunately, loose sand is one of the most difficult materials to drill.

If disturbed sands are present, take measures to avoid continued disturbance. Perform depth checks to assess the sand depth at the bottom of the drill hole. These depth checks are made by seeing exactly where the sampler rests before testing. Depth checks that can be made during drilling will be discussed below. Do not drill at excessive rates. Signs of disturbance are excessive slough in the SPT barrel, drill fluid in the sample, and failure of the sampler to rest at the proper cleanout depth. Slough is the disturbed material in the drill hole that caves from the sidewalls but can include disturbed sand that heaves or flows upward into the drill hole. Slough can also consist of cuttings which settle from the drill fluid before testing.

The SPT sampler must rest at the intended depth. This depth is to the end of the cleanout bit or the end of the pilot bit in hollow-stem augers. If the sampler rests at an elevation that is 0.4 foot (12 cm) different from the cleanout depth, disturbance of the soil may be occurring, and the hole must be recleaned.

There are a number of advantages to the SPT:

(1) The test is widely used, and often local experience is well developed.

(2) The test is simple, and many drillers can perform the test.

(3) The SPT equipment is rugged, and the test can be performed in a wide range of soil conditions.

(4) There are numerous correlations for predicting engineering properties with a good degree of confidence.

(5) The SPT is the only in place test that collects a soil sample.

Although the SPT is commonly used and is a flexible in place test, there are significant disadvantages. The test does not provide continuous samples. Different soils in the SPT interval tend to be logged as one soil, especially if the soil core is combined into one laboratory test specimen and laboratory data are used in the logs. Hollow-stem augers can give disturbed samples between test intervals, and the intervals between tests can be logged. The greatest disadvantage to SPTs is the lack of reproducibility of the test results. Drilling disturbance, mechanical variability, and operator variability all can cause a significant variation in test results. The SPT should not be used unless the testing is observed and logged in detail. Old data where drilling and test procedures are not documented should be used with extreme caution. Another disadvantage to SPTs is that progress is slower than other in place tests because of incremental drilling, testing, and sample retrieval, and SPTs may be more expensive than other in place tests. The SPT is influenced by more than just overburden stress and soil density. The soil type, particle size, soil age, and stress history of the soil deposit all influence SPT results.

Drilling Methods

Fluid Rotary Drilling

Rotary drilling with clear water results in N values that are much lower than N values that are obtained when drilling mud is used. Two factors are involved: (1) the water from drilling can jet into the test interval disturbing the sand, and (2) the water level in the borehole can drop and the sand can heave up the borehole when the cleanout string is removed. These two factors must be minimized as much as is practical.

The best way to drill loose, saturated sands is to use bentonite or polymer-enhanced drill fluid and drill bits that minimize jetting disturbance. Also when drilling with fluid, use a **pump bypass line** to keep the hole full of fluid as the cleanout string is removed from the drill hole. **The lack of fluid in the hole is one of the most frequent causes of disturbed sands**. If the soils are fine-grained, use a fishtail-type drag bit with baffles that deflect the fluid upwards. A tricone rockbit is acceptable if gravels or harder materials are present, but adjust the flow rates to minimize jetting.

Casing can help keep the borehole stable, but keep the casing back from the test interval a minimum of 2.5 feet

(75 cm) or more if the hole remains stable. Using a bypass line to keep the hole full of fluid is even more important with casing because the chance of sand heave up into the casing is increased if the water in the casing drops below natural groundwater level. The imbalance is focused at the bottom, open end of the casing. In extreme cases, the casing will need to be kept close to the test interval. Under these conditions, set the casing at the base of the previously tested interval before drilling to the next test interval. Intervals of 2.5 feet (75 cm) are recommended as the closest spacing for SPTs.

Use drilling mud when the SPT is performed for liquefaction evaluation when rotary drilling. A bentonite-based drilling mud has the maximum stabilizing benefit of mud. Bentonite provides the maximum weight, density, and wall caking properties needed to keep the drill hole stable. When mixing mud, use enough bentonite for the mud to be effective. There are two ways to test drill mud density or viscosity—a Marsh Funnel or a mud balance. A mud sample is poured through a Marsh Funnel, and the time needed to pass through the funnel is a function of the viscosity. Water has a Marsh Funnel time of 26 seconds. Fine-grained soils require mud with Marsh Funnel times of 35 to 50 seconds. Coarser materials such as gravels may require funnel times of 65 to 85 seconds to carry the cuttings to the surface. If using a mud balance, typical drill mud should weigh 10-11 pounds per gallon (lbs/gal) (1-1.1 kilograms per liter [kg/L]). Water weighs about 8 pounds per gallon (0.8 kg/L).

Exploration holes are often completed as piezometers. Revertible drilling fluids have been improved, and there are synthetic polymers that break down more reliably. If necessary, specific “breaker” compounds can be used to break down the mud and clean the borehole. If the borehole cannot be kept stable with polymer fluid, bentonite mud should be used and a second hole drilled for the piezometer installation. Do not combine drill hole purposes if the data from SPTs or piezometers are compromised.

Drilling sands with clear water is possible, but only if the driller is very experienced. As long as drilling is carefully performed, drilling with water can result in SPT N values close to those obtained using mud. Disturbance can be avoided; but without drill mud, jetting disturbance, cave, and sand heave caused by fluid imbalance are likely.

If the water level in the sand layer is higher than the ground surface, sand heave is really going to be a problem. Under these conditions, heavy bentonite mud (80 to100 sec on the Marsh Funnel) is required. A fluid bypass to keep the hole full of mud is required, and an elevated casing or drill pad to hold down the sand can be used. Some successful mud improvement is possible with Barite or Ilmenite additives. Mud can be weighted to about 15 lb/gal with these additives. Sodium or calcium chloride can be used to give polymer fluid better gel strength. In artesian conditions, it may not be possible to keep the sand stable. In these cases, other tests such as the CPT can be used to evaluate the sand.

When using fluid rotary drilling, circulate the drill fluid to remove the cuttings. Pull back the cutting bit several feet, cut fluid circulation, and then slowly and gently lower the bit to rest on the bottom of the hole. Check to see if the depth is within 0.4 foot (10 cm) of the cleanout depth. This check determines if there is cuttings settlement, wall cave, or jetting disturbance.

The bottom of the borehole normally heaves when the cleanout drill string is pulled back creating suction. Fluid should be added to the drill hole as the cleanout string is removed to help avoid problems. Once the sampler is placed, check the sampler depth and compare it to the cleanout depth. A difference of 0.4 foot (10 cm) is unsatisfactory. If sands or silty sands heave up into the borehole, the SPT sampler will often sink through most of the slough. The only way to check for this situation is to carefully inspect the top of the sampler and the ball check housing for slough or cuttings. If the ball check area is plugged with cuttings, the SPT N value may have been affected. A thin plastic cover is sometimes used to keep the slough out of the sampler. The cover is either sheared off at the first blow or it is shoved up into the sampler.

The fluid rotary method is probably the best method for determining SPT N values in saturated sands. In the following sections, two other acceptable drilling methods are discussed. If these methods do not work, use the fluid rotary method.

Hollow-Stem Augers

Hollow-stem augers (HSA) have been used successfully to do SPTs in loose saturated sands. With the proper precautions, hollow-stems can be used reliably in sands, but there are some problems with HSAs. The primary problem with the HSA in loose sands is sand heaving into the augers. This occurs when the pilot bit or the HSA sampler barrel is removed in preparation for the SPT. Sometimes, sand can heave 5 to 10 feet (1.5 to 3 m) up inside the augers. SPT N values taken with this amount of disturbance are unacceptable. These problems can be overcome in most cases by using water-filled augers and removing the pilot bit or HSA sampler **slowly** to avoid the suction. Drilling mud is not usually required and can cause sealing problems.

There are two types of HSA systems shown in figure 22-4—wireline and rod type. With either type of system, removal of the pilot bit or HSA sampler barrel can result in sand heaving into the augers. The rod type system is best at preventing sample barrel rotation during soil sampling. In sanding conditions, the wireline system is sometimes harder to operate because the withdrawal rate of the bit or HSA sampler is harder to control. Sanding-in also prevents re-latching of the wireline barrel. Rod type systems are recommended when drilling in heaving sands. If sand heaves a considerable height into the augers, the auger will need to be cleaned or retracted in order to continue drilling using either system. If the augers have to be pulled up 3 feet (1 m) to re-latch a pilot bit or sampler barrel, tremendous suction occurs at the base of the boring, which can disturb the next SPT test interval.

When using HSAs below the water table, the hole must be kept full of fluid, just like it must when using fluid rotary methods. **A water or mud source and a bypass line are required**. Some successful techniques for hollow-stem drilling in flowing sands are:

- When approaching the test interval, slow the auger rotation to just enough to cut the soil; do not continue to rotate without advancement near the test interval. In flowing sands, continued rotation near the test interval will create a large void around the hole annulus and increase the chance of caving and disturbance of the test interval. If high down pressure is used with wireline systems, the pressure should be relaxed; and the augers should be slightly

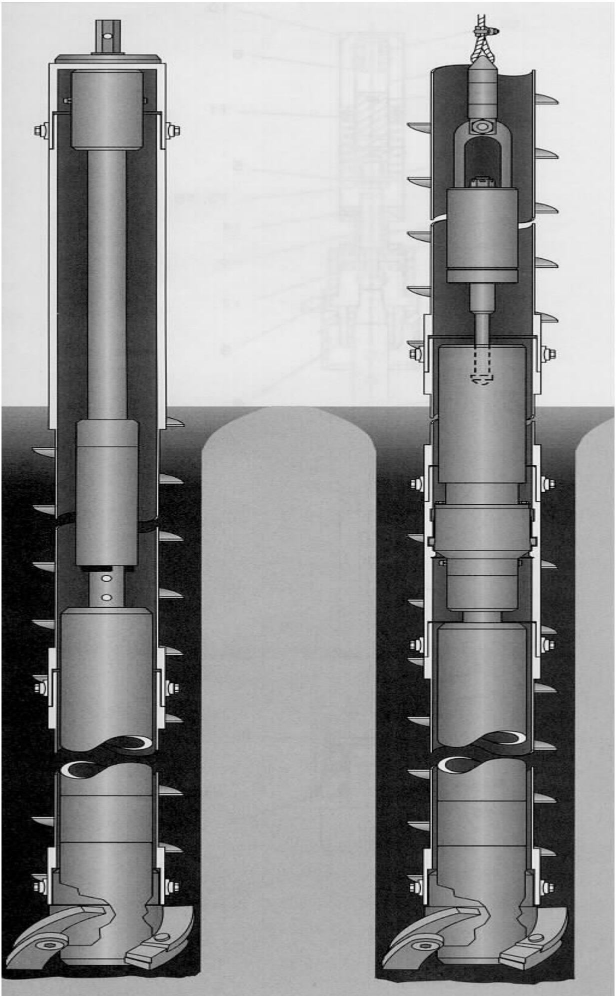


Figure 22-4.—Example of rod-type and wireline-type hollow-stem augers.

retracted ½ inch (1 cm) or so to re-latch bits or barrels. There is no need to release down pressure or retract the augers with rod-type systems.

- Add water to a level higher than the surrounding groundwater level before pulling the pilot bit or sampling barrel. In most cases, water can be added to the top of the augers without concern for disturbance. Add water by removing the drive cap using a hose from the bypass line. When removing the drive cap on rod-type systems, be careful to disconnect the drive cap bearing from the inner rods, or the pilot bit or sampler will be pulled prematurely before adding water. When using a wireline system, the latching device can be sent down the hole and latched before adding water.

The water level is not always maintained at the top of the column, especially if there is a thick layer of unsaturated soil above the test zone. Water can leak through the auger joints, and it may be necessary to add a lot of water.

Pulling the Sampler Barrel.—The sample barrel assembly is generally 5 feet (1.5 m) long. This barrel does not have much clearance with the inside of the augers, especially in the bushing at the base of the augers. With the augers full of water, reconnect the drive cap to the inner rods. Pull the barrel slowly up 0.1 to 0.3 foot (3 to 10 cm) and observe the water level in the augers. If water flows upward, out of the augers, there is a seal between the augers and the sampler, and the sampler barrel is acting like a syringe. If water flows from the top with rod type systems, rotate the barrel or work the barrel slightly down and up to try to break the seal and vent. For wireline systems, release the pulling force and re-apply. Pull slowly and attempt to break the seal. Once the seal is broken, remove the sampler **slowly**. Remember, with rapid withdrawal rates, suction can be created anywhere in the auger column. For rod systems, add water during pulling to account for water level drop. The same rule applies for wireline systems, but less water is needed.

Pulling the Pilot Bit.—Most pilot bits are seated flush in a brass bushing in the end (crown) of the augers. The pilot bit cutting teeth should be set to a lead distance the same as the outer cutting teeth, so that the body of the pilot bit sits correctly in the bushing. Do not drill with the pilot bit in advance of the outer cutting teeth. A useful procedure in heaving sands is to use a pilot bit one size smaller than the augers being used. For example, if a 4.25-inch (11-cm) inside diameter (ID) HSA is used, a 3.75-inch (9.5-cm) ID HSA pilot bit can be used to reduce vacuum and suction effects.

When drilling with the pilot bit, pull the bit back slowly about 0.1 to 0.2 foot (3 to 6 cm) to allow any seal in the bushing to vent. If the bit is withdrawn quickly, suction will likely occur. If water flows out the top of the augers, suction is occurring. If suction is occurring, rotate the pilot bit and work it down and up to try to break the seal. Once the bit clears the bushing, the tendency to bind is reduced. Withdraw the pilot bit **slowly** and add water, to account for water level drop as the rods are removed. Remember, with rapid withdraw rates, suction effects can be created anywhere in the auger column.

If sanding-in cannot be controlled with fluid or slow pulling, there are special flap valves that can be placed in the pilot bit seat. Drill without the pilot bit with flap valves.

Once the sampler has been inserted to the base of the boring, determine the depth to the sampler tip as a quality check. If there is more than 0.4 foot (12 cm) of slough or heave, the test may not be acceptable. This guideline is arbitrary, and it is possible to get a reliable test with as much as 0.5 foot (15 cm) or more slough as long as the vent and ball check of the sampler are not plugged. If the SPT barrel is used to test the bottom of the hole, the sampler will often penetrate loose slough or heave. Checks with a weighted tape may be more accurate in determining the depth to the slough. When using the HSA sampler barrel to core before testing, sand falling out of the barrel could be the cause of slough inside the auger. To avoid this problem, use catcher baskets in the HSA sampler barrel.

When testing at close intervals of 2.5 feet (75 cm) or less, it may be necessary to add water to the augers as the SPT sampling string is removed to avoid water level imbalance and possible heave.

It's a good idea to combine the continuous sampler of the HSA with SPT operations. If SPTs are at 2.5-foot (75-cm) intervals, perform the SPT and then sample the 2.5-foot (75-cm) and over-sample the 1.5-foot (45-cm) test interval. This adds some time, but allows continuous sampling. This sampling method provides a look at the soils between the test intervals. It is also helpful if recovery is low.

Rotary Casing Advancers

Rotary casing advancers can provide good SPT N values in sands. The casing advancer method uses drilling fluid (bentonite and water) as a circulation medium and is a fluid rotary drilling method. This method is successful because the large diameter outer rods remain filled with drill fluid and keep the sand down. The casing advancer normally has a diamond bit but can be equipped with tungsten carbide drag bits on the outside edge to over-cut soil. Typically, an HQ- or HW-size casing advancer is used with or without a pilot bit. The pilot bit can be a tricone bit removed via wire line. Suction is possible when a pilot bit is removed. If suction occurs, drilling without a pilot bit should be tried. An advantage of drilling with a wireline is that when the pilot bit is removed, the line takes up little volume and results in a minor drop in fluid level inside the rod column. Since a good fluid column remains in the rods, a fluid bypass is not needed. The only problem is that whenever adding rods to the SPT drill string, fluid flows out of the advancer.

The casing advancer must be operated very carefully to avoid sand disturbance. Fluid is pumped down the casing and up a narrow annulus along the exterior of the casing. A casing advancer, especially without a pilot bit, is equivalent to a bottom discharge bit. If excessive fluid pressures are used or if circulation is lost, jetting or hydraulic fracturing the material in the SPT test interval is possible. Drilling the material with a slow advance rate and with low pressure while maintaining circulation is necessary to drill successfully with this system. If circulation return stops, blockage may be occurring; and if pump pressures increase, hydraulic fracturing could occur. If the advance rate is too fast, circulation will be blocked. Water is not an acceptable drill fluid with this method, and drill mud must be used.

Summary of Drilling Effects

Table 22-2 illustrates the effects of different drilling and mechanical variables on the SPT N value (items 1 through 5). A typical N value in clean quartz sand is 20 blows per foot (30 cm). The possible range of N for the material is shown if the material is subject to errors in testing.

Table 22-2 shows that drilling disturbance can have drastic effects on the N value. In fact, zero blows can be obtained. Zero blows may not be realistic because, in many cases, loosened sand settles back to the bottom of the hole. Also, very loose sand normally does not allow the sampler to settle under the weight of the assembly. Drilling disturbance usually results in a low N value. Low blow counts indicate loose, weak soils, and a weak foundation may be assumed. Erroneous low disturbed N values can result in costly over design of structures. The most important aspect of SPT testing is the way the hole is drilled.

Procedure Variables

The recommended 2.5-foot (75-cm) interval is to ensure that the next interval is not disturbed. If material that only has a few thin layers of sand is drilled, continuous sampling is possible, but difficult, and should not be attempted unless necessary.

Hammer Blow Rate

The blow count rate is important when soil drainage needs to be considered. Most test standards request SPT blows at a rate of 20 to 40 blows per minute (bpm). Blows at 55 bpm are not likely to have an effect on clean sand; but at some fines content, blows will be reduced by the lack of drainage. Blows should be between 20 and 40 bpm if a hammer with a controllable rate is used. Some hammer systems are designed to deliver blows at a faster rate. The automatic hammer is designed to deliver blows at a rate of 50 to 55 bpm. The hammer can be set to run at 40 bpm by adding a spacer ring to the impact anvil. If a hammer rate differs from 50 bpm, clearly note it on the drill logs.

Table 22-2.—Estimated variability of SPT N Values

Cause		Typical raw SPT value in clean sand N = 20	Typical raw SPT value in clay N=10
Basic	**Description**		
Drilling method	1. Using drilling mud and fluid bypass	20	10
	2. Using drill mud and no fluid bypass	0-20	8-10?
	3. Using clear water with or without bypass	0-20	8-10?
	4. Using hollow-stem augers with or without fluid	0-20	8-10?
	5. 8-inch (20-cm) diameter hole compared to 4 inches (10 cm)	17	8-10?
Sampler	6. Using a larger ID barrel, without the liners	17	9
	7. Using a 3-inch (7.6-cm) OD barrel versus a 2-inch (5-cm) barrel	[e]25-30	10
Procedure	8. Using a blow count rate of 55 blows per minute (bpm) as opposed to 30 bpm	[e1]20	[e1]10

Table 22-2.—Estimated variability of SPT N Values (continued)

Cause: Basic	Cause: Description	Typical raw SPT value in clean sand N = 20	Typical raw SPT value in clay N=10
Energy Transmission Factors			
Drill rods	9. AW rod versus NW rod	[e2]18-22	[e2]8-10
	10. SPT at 200 feet (60 m) as opposed to 50 feet (30 m)	[4]22	[e3]5
	11. SPT at less than 10 feet (3 m) as opposed to 50 feet (30 m) with AW rods	30	15
	12. SPT at less than 10 feet (3 m) as opposed to 50 feet (30 m) with NW rods	25	12
Hammer operation	13. Three wraps versus two wraps around the cathead	22	11
	14. Using new rope as opposed to old rope	19	9
	15. Free fall string cut drops versus two wrap on cathead	16	8
	16. Using high-efficiency automatic hammer versus two wrap safety hammer	14	7

Table 22-2.—Estimated variability of SPT N Values (continued)

Cause		Typical raw SPT value in clean sand N = 20	Typical raw SPT value in clay N=10
Basic	Description		
Energy Transmission Factors (continued)			
Hammer Operation	17. Using a donut hammer with large anvil as opposed to safety hammer	24	12
	18. Failure to obtain 30-inch (75-cm) drop height (28 inches [70 cm])	22	11
	19. Failure to obtain 30-inch (75-cm) drop height (32 inches [80 cm])	18	9
	20. Back tapping of safety hammer during testing	25	12

e = Estimated value.

1 = Difference occurs in dirty sands only.

2 = It is not known whether small drill holes are less or more efficient; with larger rods, N may be less in clay because of the weight.

3 = N in clay may be lower because of the weight of the rods.

4 = Actual N value will be much higher because of higher confining pressure at great depth. The difference shown here is from energy only and confining pressure was not considered.

Limiting Blow Counts

The Reclamation test procedure calls for stopping the test at 50 blows per foot (30 cm). Other agencies sometimes go to 100 blows per foot (30 cm) because the ASTM test standard D 1586 sets a 100-blow limit. The Reclamation standard is lower to reduce equipment wear.

Using the soil liquefaction criteria for sand at a depth of 100 feet (30 m), 50 blows would not be considered liquefiable. SPT data are corrected to a stress level of 1 ton per square foot (ton/ft^2). In a typical ground mass, a 1 ton/ft^2 stress level occurs at a depth of 20 to 30 feet (6 to 9 m), depending on the location of the groundwater table. Blow counts in a sand of constant density increase with depth. A correction factor is used to adjust for this overburden effect. In earthquake liquefaction clean sand N160 values greater 30 blows per foot (bpf) are not liquefiable. A blow count of 50 bpf at 100 feet (30 m) corrects to about 30 bpf at 1 ton/ft^2. Higher blow counts would not be considered liquefiable. If testing is deeper than 100 feet (30 m) it will be necessary to increase the limiting blow counts to 100. The refusal rule still applies; if there is no successive advance after 10 blows, the test can be stopped.

SPT N values in gravels generally are much higher than in sands. Liquefaction criteria for sands are not reliable criteria for gravels.

Penetration per Blow or Blows per 0.1 Foot (3 cm)

Penetration for each blow should be recorded when drilling in gravelly soils. If penetration per blow is recorded, sand layers can be resolved, and the N value of the sand can be estimated. The blow count in sand can be estimated from a graph of penetration per blow. The extrapolation is generally reliable if the blows start in sand. If the interval starts with gravel and then penetrates into sand, the extrapolation is less reliable because the sampler could be plugged by gravel.

The number of blows for 0.1 feet (3 cm) is the minimum penetration rate data that should be collected. If three people are present, it is very easy to record "penetration per blow," and these data are preferred over the coarser blows per 0.1 feet (3 cm). To record penetration per blow, make a form with three columns. In one column, list the blows 1 through 100. Mark the drill rods in 0.1-foot (3-cm) intervals or use a tape starting at zero from the edge of a reference point. In the second column, record the total penetration as the test is performed. This will require a reader to call off the total penetration. The reader can interpolate between the 0.1-foot (3-cm) increments, or the penetration can be read directly from a tape. After the test is done the incremental penetration can be calculated from the cumulative penetration data and recorded in the third column.

Equipment and Mechanical Variables

Sampler Barrel

The standard sampler barrel is 2 inches (5.1 cm) in OD and is the barrel that should be used. In private industry, 2.5- (6.4-cm) and 3-inch (7.6-cm) OD barrels are occasionally used. If sample recovery in coarse materials is poor, it is acceptable to re-sample with a 3-inch (7.6-cm) barrel equipped with a catcher.

Gravelly soils generally do not provide reliable SPT data for liquefaction evaluations that are based on sands. Other methods use larger samplers and hammers to evaluate the liquefaction potential of gravelly soils. The BPT is used at gravel sites. Often, the BPT is used at gravel sites after a first round of SPT testing shows considerable gravels present.

Sampler Shoe

The dimensions of the sampler shoe should meet ASTM D 1586 requirements. Some drill equipment catalogs claim to have special "heavy duty" sample barrels and shoes. The "Terzaghi" style does not meet the ASTM and Reclamation requirements. When buying shoes, check their dimensions to be sure they meet test requirements. Figure 22-1 shows both Reclamation and ASTM sampler requirements.

Shoe ruggedness can be improved by "carburizing" the metal. This is a process where the shoe is heated in a carbon gas to improve the surface hardness of the steel. This makes the shoe more rugged but also more brittle. Most drill manufacturers supply untreated low carbon steel such as 1040 alloy. Generally, a local machine shop can "carburize" the shoe, an inexpensive process.

Sample Retainers

A sample retainer should not be used for liquefaction studies except in desperation because the effects are unknown. If the sample cannot be retained, a sample may be taken with a large diameter split barrel sampler with a retainer re-driven through the test interval. The over coring procedure discussed earlier using HSAs could also be used.

There are several types of retainers available and some types are better than others. There is a flap valve device that actually looks like a toilet seat (a small one) that places a large constriction inside the barrel. This device is the least desirable of the retainers if the N value is important. The basket type catcher is made of curved fingers of steel, brass, or plastic. This type of retainer is only a minor constriction because the holding ring fits into the recessed area between the shoe and the barrel. The problem with this catcher is that the fingers may not always fall back into position to hold the core. A better variation of this catcher is the "Ladd" type retainer that combines the finger basket with a plastic sleeve. This retainer is the most successful at retaining flowing sand because the bag adds extra retaining capability.

Sampler Liners

Most of the SPT samplers in the USA accept liners, but the liner is usually omitted. To determine if the sampler will accept a liner, feel for an offset (increased diameter) inside the shoe. If an offset is present, the barrel is 1½-inch (3.8-cm) ID. Log whether a constant diameter or an enlarged diameter barrel is used because the sample type can effect recovery. For liquefaction evaluation, a constant ID barrel is recommended.

A sampler used without liners is actually better for recovery. Average recovery of a constant ID barrel is about 60 percent, and the average for the barrel without liners is about 80 percent. The difference in N value between constant and enlarged diameter barrels is not known, but an increase in blows in the range of 1 to 4 is likely with a constant ID barrel.

Sampler Length

A 24-inch- (61-cm-) long split barrel can normally accommodate any slough in the drill hole without plugging the ball check device.

Sampler Vent Ports

The required vent ports for the sampler top subassembly in ASTM and Reclamation test procedures are inadequate when drilling with mud. The ASTM standard requires two ⅜-inch (1-cm) diameter vents above the ball check. When drilling with mud, the fluid gets loaded with sand and can easily plug these ports. The sampler and rods fill with mud as they are lowered into the drill hole. A big column of drill mud may try to push the sample out if the ball check does not seat. Drill larger vent ports in the top subassembly to avoid this problem. Some drillers use a 0.5- to 1-foot (15- to 30-cm) drill rod sub just above the sampler with extra holes drilled in it to easily drain drill fluid from the rod column.

Hammers, Anvils, Rods, and Energy Effects

The variables in energy transmission are hammer type, hammer drop height, hammer drop friction, energy losses in impact anvil(s), and energy losses in rods. The energy in the drill rods is called the "Drill Rod Energy Ratio" or ERi.

Some hammers, especially donut (casing type) hammers with large anvils, deliver approximately 50 percent of the total potential energy of a 140-lb (63.6-kg) hammer dropping 30 inches (75 cm). The N value is proportional to the energy delivered, and the N values can be adjusted to a common energy delivery level. The current practice is to adjust SPT N values to 60-percent drill rod energy.

Safety Hammers

There are many kinds of SPT hammers. Pin-guided and donut type hammers were common in the past, but these hammers have generally been replaced by the “safety” hammer which has an enclosed anvil (figure 22-2). There are also new automatic hammers that improve the repeatability of delivered hammer energy to the sampler.

The safety hammer provides an economical and safe method of performing the SPT. The enclosed anvil removes hazards from flying metal chips, and operators cannot get their hands in the impact surface. Due to their inherent geometry, safety hammer energy transmission can vary only by about 20 percent as long as the hammers are operated correctly and consistently.

Safety hammers should be designed with a total stroke of about 32 inches (80 cm), and there should be a mark on the guide rod so the operator can see the 30-inch (75-cm) drop. The hammer weight should be 140 pounds (63.6 kg). These characteristics should be verified on the hammer. An easy way to weigh the hammer is to place the total assembly on a platform scale, get the total weight, then lift the outer hammer off the anvil, and weigh the guide rod and anvil. The difference in the two weights is the hammer weight. The hammer weight should be 140 +/- 2 lb (63.6 kg +/- 0.9 kg). Hammers should be stamped with an ID number. It is best to keep a given hammer for a specific drill, especially if the energy transmission of the drill has been measured in the past.

The assumption is that safety hammers deliver 60-percent drill rod energy with two wraps of rope around the cathead. Actually, the hammers deliver about 60 to 75 percent depending on their construction. The guide rod is one factor that affects the energy transmission.

Some safety hammers come with a solid steel guide rod, and others use a hollow AW drill rod. The solid guide rod absorbs energy, and the solid steel guide rod safety hammer will deliver lower energy than the hollow guide rod safety hammer. These differences are not enough to recommend one design over another. Another variable with safety hammers is a vent. Some hammers have vents near the top of the hammer. A vent allows some air to escape as the anvil moves toward the impact surface. These vents allow the best free fall possible.

Donut Hammers

These hammers are not recommended except in special cases such as when clearance is a problem. If the testing is for liquefaction evaluation, it may be necessary to measure the energy of the donut hammer used. The donut hammer is supposed to be inefficient, but if the hammer has a small anvil, efficiencies may be similar to the safety hammer. The larger anvil absorbs part of the hammer energy.

Rope and Cathead Operations

Most SPTs are performed using the rope and cathead method. In this method, the hammer is lifted by a cathead rope that goes over the crown sheaves. ASTM and Reclamation standards require two wraps of rope around the cathead. After the hammer is lifted to the 30-inch (75-cm) drop height, the rope is thrown toward the cathead, allowing the hammer to drop as freely as possible.

Three wraps will reduce the drill rod energy by about 10 percent and will result in a higher N value. As the rope gets old, burned, and dirty, there is more friction on the cathead and across the crown sheaves. New rope is stiffer and is likely to have higher friction than a rope that has been broken in. A wet rope may have less friction, but the energy differences are small enough that it is not necessary to stop testing in the rain. Rain should be noted on the drill report and log. Frozen rope may have considerably more friction. Under wet and freezing conditions, exercise the rope and warm it up prior to testing.

Consistent rope and cathead operations depend on having well maintained crown sheaves on the mast. Crown sheaves should be cleaned and lubricated periodically to ensure that they spin freely.

Automatic Hammers

Automatic hammers are generally safer and provide good repeatability. Central Mine Equipment (CME) made one of the first automatic hammers commercially available in the United States. This hammer uses a chain cam to lift a hammer that is enclosed in a guide tube. The chain cam is driven with a hydraulic motor. The drop height of this hammer depends on the chain cam speed and the anvil length. Problems with this hammer system primarily result from the speed not being correctly adjusted. The hammer should be run at 50 to 55 bpm to obtain a 30-inch (75-cm) drop. There are blow control adjustments on the hammer, and there is a slot on the side of the hammer casing to observe the hammer drop height. Be sure the hammer is providing a 30-inch (75-cm) drop by adjusting the blow control.

The CME automatic hammer is designed to exert a down force on the rods. This down force from the assembly is about 500 lbs (227 kg). A safety hammer assembly weighs from 170 to 230 pounds (77 to 104 kg). In very soft clays, the sampler will more easily sink under the weight of the assembly, and with the automatic hammer, the blow counts will be lower.

The Foremost Mobile Drilling Company hammer "floats" on a wireline system. The drop mechanism does not depend on rate. Energy transfer is about 60 to 70 percent.

Energy transfer of some automatic hammers is significantly higher than rope and cathead operated hammers. The CME hammer can deliver up to 95 percent energy. This could result in very low blow counts in sands. Energy corrections are usually required for automatic hammers. The Mobile Drilling Company hammer is less efficient because of a large two-piece anvil.

If an automatic hammer is used, report detailed information on the hammer use. Report make, model, blow count rates, and any other specific adjustments on the drilling log. In liquefaction investigations, the energy transfer must be known. For some hammer systems, such as the CME and Mobile Drilling Company, the energy transfer is known if the hammers are operated correctly, but for some systems, energy measurements may be required.

Spooling Winch Hammers

Mobile Drilling Company developed a hammer called the "Safety Driver." This hammer system used a steel wireline cable connected to an automated spooling winch with magnetic trip contacts. The contacts sensed when the hammer was lifted 30 inches (75 cm), and the hammer then dropped with the spool unrolling at the correct rate for the dropping hammer.

Energy measurements of this hammer system show some extreme energy variations. Apparently, the contacts and spooling systems require continual adjustment to operate correctly. This type of hammer system is not recommended because of energy transmission problems.

Drill Rods

Any rod from AW to NW size is acceptable for testing. There is some concern about whipping or buckling of smaller AW rods at depths greater than 75 feet (23 m). In these cases, use BW rods or larger. There is not much difference in energy transfer between AW and NW rods. The type of rod changes a blow count in sand only by about two blows and maybe less.

SPT drill rods should be relatively tight during testing. Energy measurements on differing locations of the drill rods do not show significant energy loss on joints that are loose. There has to be a real gap on the shoulders to cause significant energy loss. This is because when the rod is resting in the hole, the shoulders of the joints are in contact. There is no need to wrench tighten joints unless rod joints are really loosening during testing. Be sure to firmly hand tighten each joint.

Drill Rod Length

When using very short rods, energy input to the sampler is attenuated early because of a reflected shock wave. The driller can usually hear this because there is a second hammer tap. The early termination of energy is a problem to depths of 30 feet (9 m), but the correction is small and is often ignored. The energy termination is also a function of the size of the drill rods. There is some energy loss for drill rod strings longer than 100 feet (30 m), and a correction is necessary. A constant density sand will have an increasingly higher penetration resistance as depths increase. This is because the confining pressure increases in the ground mass with depth.

Summary

How Good is the SPT Test

Figure 22-5 is a summary graph of a study performed in Seattle by the American Society of Civil Engineers (ASCE). In this study, several private geotechnical firms and agencies drilled SPTs at the same site. Six drills were used. Some had safety hammers, and others had automatic hammers. One drill was equipped with a 300-lb (136-kg) safety hammer.

The graph shows a wide variation in raw N value versus depth. The soil conditions at the site are not well documented. Some gravel layers are present. Note that the spooling winch system resulted in unreliably high SPT N values.

The variability of SPT drilling can be reduced if drillers are aware of the problems inherent to the SPT. Interpretation of the data improves if all unusual occurrences during SPTs are reported. **Drill logs should clearly describe in detail the equipment used.**

Liquefaction studies are done in loose sands below the water table. Unfortunately, this material is the hardest to drill without disturbance. Fluid rotary drilling is the preferred approach for keeping the sand stable. HSAs and casing advancer systems have also been successfully used.

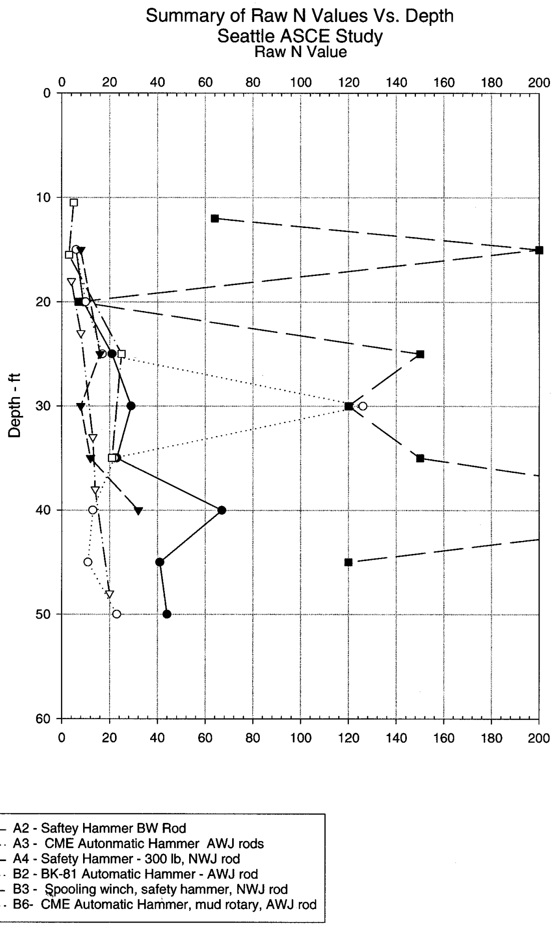


Figure 22-5.—Results of SPT with six different drills—ASCE Seattle study.

The drilling part of SPTs is the most important. Generally, disturbance from improper drilling technique results in lower N values.

Energy transfer effects can be important, especially if highly efficient automatic hammers are used.

Becker-Hammer Penetration Testing for Gravelly Soils

Introduction

The BPT is used to test the density of materials that are too coarse for the SPT or the CPT. Gravel can cause misleading results in the SPT and CPT. Because the diameter of the BPT penetrometer tip is much larger than that of the SPT sampler or the cone penetrometer, gravel-sized particles do not seriously affect the BPT.

The BPT consists of driving a plugged steel casing into the ground using a diesel pile-driving hammer. The blows per foot (30 cm) of penetration are recorded and adjusted for driving conditions. An empirical correlation is then used to estimate equivalent SPT values. The BPT is performed with a Becker Drills, Ltd. model AP-1000 or B-180 drill rig, equipped with an International Construction Equipment (ICE) model 180 closed-end diesel hammer. The standard configuration uses 6.6-inch (16.8-cm) OD double-wall casing and a plugged “crowd-out” bit. Some ICE 180 hammers are marked “Linkbelt.”

The BPT is rapid and economical to perform. Production can reach 500 feet (150 m) per day. A disadvantage is that no sample is retrieved with the BPT, so other sampling, such as SPT or coring, is also required. Another disadvantage is the uncertainty in interpretation of the data. Since the BPT is generally used to estimate equivalent SPT blow counts, significant uncertainty is introduced by that step, in addition to the uncertainty that exists in predictions of soil behavior from N values.

The penetration resistance of soils is influenced by a large number of factors, including soil type (grain-size distribution, plasticity, particle sizes, particle shapes), density, confining stress, energy delivered to the penetrometer, size and shape of the penetrometer, and friction on the sides of the penetrometer. The BPT differs from the SPT test in many ways, and correlation between BPT and SPT data is not consistent. The BPT is not performed in an open hole with a diameter greater than the rod diameter, and the penetrometer tip is not open like a SPT tip, so there is substantial friction on the drill string. This greatly complicates the analysis. Like the SPT, the BPT may give misleading results in soils containing boulders, cobbles, or even large amounts of gravel coarser than about 1½ inches (4 cm).

The effect of fines in the relationship between Becker penetration resistance and liquefaction potential has not been established by experiment or field performance. The effect of fines is generally assumed to be similar to what occurs with the SPT. Since the BPT does not return a sample, it is often necessary to estimate the fines content from nearby drill holes or to neglect the potential benefit of fines.

Role of BPT in Exploration

In soils containing gravel, measured SPT or CPT resistance may be misleadingly high, and there is potential for damage to CPT equipment. CPT equipment generally cannot be advanced through thick gravel layers with more than about 30 percent gravel, depending on the size of the gravel and the density of the soil. Results may be misleading with smaller gravel contents. BPTs are rarely performed at the start of an investigation and are generally done after SPTs or CPTs have been attempted and found to be inappropriate because of too much gravel. BPT testing generally should not be relied on as the sole basis for liquefaction evaluation without site-specific verification of the SPT-BPT correlation, corroboration by shear-wave velocities, or other liquefaction resistance predictors.

A Becker drill can also be used for other tasks such as installation of instrumentation or holes for geophysical testing. Some soil is compacted around each Becker hole, and the holes may be more prone to deviate from vertical than holes drilled by conventional methods. The extent of densification is not known, so if the holes are to be used for geophysical measurements (such as shear-wave velocity), vary the spacings to evaluate the effect of compaction around the hole. Rotary drilling can also be done inside the double-wall Becker casing to socket installations such as inclinometers into bedrock. This is more expensive than standard Becker testing because of delays and the need for a second rig. Becker rigs do not have rotary drilling capability.

Equipment

Becker drills can be operated with a variety of equipment configurations, but for penetration testing, the standard testing setup is as follows:

- Drill rig: Becker Drills, Ltd. model AP-1000 rig
- Hammer: Supercharged ICE model 180 diesel hammer

- Casing (rods): 168-mm (6.6-in) OD, double-wall

- Drive bit: Crowd-out plugged bit

The correlation between BPT and SPT data proposed by Harder and Seed relies on the use of the standard equipment configuration. The method proposed by Sy requires that at least the last two conditions be met. All four conditions should be met because analyses by the Sy method would probably be duplicated by the Harder-Seed method for preliminary calculations and/or verification. Harder and Seed determined that open-bit tests were inconsistent and erroneously low relative to the closed-bit standard. The older model B-180 and HAV-180 rigs, equipped with the same hammer, transfer about 50 percent more of the energy to the drill string than do AP-1000 rigs. This factor has been tentatively confirmed by energy measurements, but it is preferable to avoid the issue by specifying the use of AP-1000 rigs only.

The diesel hammer does not provide consistent energy to the drill string. This is because the energy depends on combustion conditions, which are affected by fuel condition, air mixture, ambient pressure, driving resistance, and throttle control. The closed-end diesel pile hammer is equipped with a “bounce chamber” where air is compressed by the rising ram after each blow; the air acts as a spring to push the ram back down for the next blow (unlike the more common open-ended diesel hammer that uses gravity alone to return the ram). Measuring the bounce-chamber pressure provides an indirect measure of combustion energy.

Harder-Seed Method of BPT Interpretation

The Harder-Seed method of interpreting the BPT uses measurements of bounce-chamber pressure as an indication of the energy imparted to the rods by each blow. The bounce-chamber pressure is used to adjust the blow count for the actual combustion condition to that produced by a hypothetical constant combustion condition. The measured bounce-chamber pressure must be adjusted at altitudes above 1000 feet (300 m). The throttle should be kept wide open and the supercharger should be operated any time data are being recorded. Some drillers prefer to use a smaller throttle opening or no supercharger at the beginning of driving when the blowcounts are smaller, producing high blow counts. If the blowcounts required for analysis are near the surface, the driller should be instructed to keep the throttle wide open. Instances where full throttle and supercharger are not used should be recorded in the field notes.

The bounce chamber pressure needs to be monitored continuously during testing. An electronic recording system is available to monitor the bounce chamber. The pressure gauge provided by the hammer manufacturer can be used to record the data manually, but the gauge reading is sensitive to the length of hose used to connect the gauge to the hammer.

If a B-180 or HAV-180 rig is used, the data can be adjusted by multiplying by the factor 1.5 to account for the difference in energy transmitted to the rods. This factor is supported by few data and is considered approximate. An AP-1000 rig is preferred.

Testing for the Harder-Seed Method of Interpretation

The Harder-Seed method requires that the number of blows to drive BPT rods each foot (30 cm) of depth and bounce-chamber pressure during that interval be recorded. Record the driving conditions and note if the drillers pull the rods back to loosen them up to reduce the driving friction.

Sy Method of BPT Interpretation

The method proposed by Sy and Campanella is more rigorous, but more costly and time-consuming. Friction on the sides of the rods may contribute a substantial portion of the driving resistance. A pile-driving analyzer (PDA) is used to record acceleration and rod force during individual blows of the hammer. The PDA also measures the driving energy for each blow. The force and acceleration histories are then analyzed to separate the resistance to driving contributed by the bearing capacity of the tip and by the side friction using a computer program called CAPWAP. PDA operation and CAPWAP analyses are usually done by the contractor.

The PDA measurement eliminates concern about the performance of the hammer, effects of altitude, or loss of energy between the hammer and the rods. At least in theory, analyses should eliminate the effects of varying amounts of side friction on the blow count. The primary drawback is the need for PDA measurements and special analyses. These substantially increase the cost of the testing program and slow the process of testing and interpretation.

The side friction can also be measured directly by pullback tests, where the force required to pull the rods back a few inches is measured by a load cell. This measurement can be substituted for some of the CAPWAP data, but it is not recommended that CAPWAP calculations be completely eliminated. CAPWAP data is the standard from which the method was developed.

Testing for the Sy Method of Interpretation

The Sy method requires:

Using the PDA, record rod force, acceleration, and transmitted energy. Record the number of blows for each 1-foot (30-cm) interval of BPT driving. Record driving conditions, and note if the drillers pull the rods back to loosen them up to reduce the driving friction.

Discussion of Methods

For routine investigations of typical alluvial materials that do not have dense material overlying them, a PDA is generally not necessary, and the Harder-Seed approach should usually be sufficient. In cases where drill rod friction is likely to be a problem (penetration through compacted fill or deep deposits), the Sy method may be better. BPTs can be done after pre-drilling and casing or after pre-driving the BPT with an open bit through compacted fill overlying the tested layers. This reduces the friction but does not necessarily provide valid predictions of SPT N_{60} with the Harder-Seed method and may cause them to be low.

With either method, the field notes should mention any time that the drillers pull back the rods to reduce the friction. There is no way to explicitly account for this in the Harder-Seed method. When using the Sy method, the locations for calculations should be selected with the pullbacks in mind. Ideally, pullbacks should be done only before and after critical layers are penetrated. This way, the rod friction can be interpolated between analyzed zones with no pullbacks between them to invalidate the interpolation. Zones to be tested and pullbacks should be discussed with the drillers prior to each hole. Substantial uncertainties exist both in the correlations to estimate the equivalent SPT N_{60} and in the correlations to estimate soil behavior from the SPT blow count.

Contracting for Becker Drilling Services

In addition to the usual specifications requirements, the work statement for BPT should address:

- Work requirements — explain general work requirements.
- Purpose and scope — state which portions of the work are for liquefaction assessment and which are for instrumentation or other purposes.
- Local conditions and geology — describe anticipated drilling conditions and potential problem areas.
- Equipment and personnel to be furnished by the contractor — specify complete details on the equipment: rig model numbers, hammers, superchargers, and double wall pipe for rods. See above for details.
- Drilling requirements — list special considerations such as staking, calibration requirements, and refusal criteria.
- Hole completion — describe all hole completion or abandonment procedures.
- Driller's logs — list requirements for the driller's report, including forms to be used.
- Field measurement — specify method of measurement of depths for payment.

In the contract for PDA work, specify the following:

- Purpose and scope of testing.
- Estimated number of feet of driving to be monitored by PDA.

Cone Penetration Test

Test History

The CPT was introduced in northern Europe in the 1930s to facilitate the design of driven pile foundations in soft ground. Early devices were mechanical penetrometers that incrementally measured the cone tip resistance. In the 1960s, mechanical cones, known as Begemann friction cones, were developed. This penetrometer measured both the tip resistance and the side resistance along a sleeve above the cone tip (figure 22-6). At about this same time, the CPT was introduced in North America. Using technology from the rapidly advancing electronics industry, an electric cone penetrometer was developed that used electrical transducers to measure the tip and side resistance (figure 22-7). Most of the work today is performed with electronic cone penetrometers, and the manual does not discuss mechanical systems. The use of electronics allows the incorporation of additional sensors in the cone system, including those for pore water stress, temperature, inclination, acoustic emissions, down-hole seismic, and resistivity/conductivity. In the 1990s, sensors such as laser or other energy-induced fluorescence spectroscopy sensors, membrane interface probes, and even video cameras have been added to detect groundwater contamination. Penetrometers capable of measuring dynamic or static pore water pressures are called piezometric cones or piezocones (CPTU). CPT

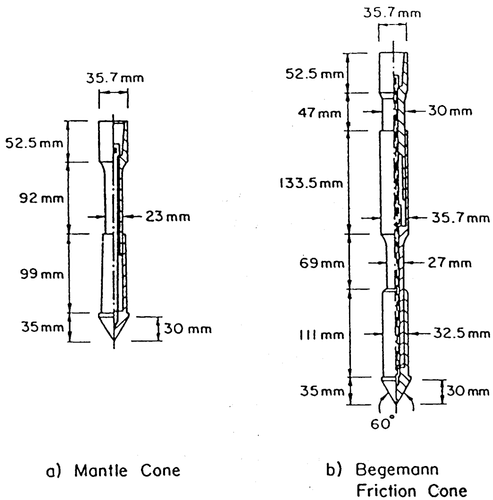


Figure 22-6.—Mechanical cone penetrometers.

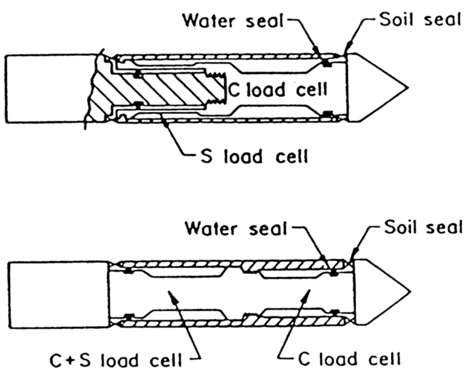


Figure 22-7.—Typical electrical cone penetrometers.

has continued to gain wide acceptance as an effective site investigation tool in North America.

Test Procedure

The procedures for performing CPTs are standardized in Reclamation procedures USBR 7020 and 7021 and ASTM D-5778 and D-6067. The test is highly reproducible as opposed to SPTs. Test standards call for a cone tip 35.7 mm in diameter with a 10-square-centimeter (cm^2) projected area and an apex angle of 60 degrees. The friction sleeve is 150 cm^2. Larger diameter penetrometers of 15-cm^2 projected area are sometimes used in very soft soils. Smaller diameter penetrometers are sometimes used for laboratory studies of soils.

The cone is advanced at a constant rate of 20 mm per second. Since the penetration resistance depends significantly on the advance rate, the push rate must be checked in the field. The basic equipment required to advance any cone penetrometer is a hydraulic jacking system. Trucks or vehicles built for CPT are typically used; but, in some cases, the hydraulics of rotary drill rigs are used. Semi-portable equipment has been developed for remote site testing. Rigs can be mounted on trucks, tracked vehicles, trailers, barges, or diving bells, depending on accessability. The capacity of cone rigs varies from 100 to 200 kilonewtons (kN) (11.2 to 22.4 tons). The upper bound is the maximum allowable thrust on the cone penetration rods.

Electronic cone penetrometers have built in load cells to measure the tip and side resistance simultaneously (Figure 22-7). Bonded strain gauges typically are used in the load cells because of their simplicity and ruggedness. The load cells commonly have a range of 90 kN (10 tons) for tip resistance and 9 kN (1 ton) for side resistance. The load cell capacity can be varied, depending on the strength of the soils to be penetrated. The load cells are usually connected by an electric cable passing through the drill rods to a data acquisition system at the surface. Cordless models are also available that transmit sonically and “Memo” cones that store the data internally until retrieved at the surface. Data are recorded digitally, which greatly enhances the use of CPT results in engineering applications. The data can be sent in daily by e-mail to the engineer and geologist.

Nearly all electronic cone penetrometers are equipped with a pore pressure element. This pore pressure sensor is typically located between the tip and the friction sleeve. The element can record dynamic water pressure as the cone is being pushed, as well as static water pressures during pauses in testing. The typical capacity of the water pressure transducer is 2.2 kN (500 lb/in^2), and the accuracy of water pressure head is about ± 3 cm (0.1 foot). Cones are almost always equipped with inclinometers. The inclinometers are used to monitor rod bending during push and are an essential part of protecting the cone from damage. The inclinometer can be monitored by computer, and pushing can be stopped if bending is excessive. Cone rods can bend as much as 10 to 20 degrees. If the cone is used to detect bedrock or hard layers, this error can be significant. The inclinometer is not directional, so the error from bending can only be estimated.

Advantages and Disadvantages

The CPT has several advantages over other routine in place tests. The tests are rapid and inexpensive compared to other geotechnical profiling techniques. Penetration rates of 3 feet (1 m) per minute are common in many soils. Penetration is stopped only to add sections of push rods, except when pore water stress dissipation measurements are made with the piezocone. With electrical equipment, continuous profiles are recorded and plotted as penetration progresses, and operator effects are minimized. As discussed below, the test results have been correlated to a variety of soil properties. Digital data acquisition with electrical cones enhances interpretation and provides continuous profiles of soil property estimates.

Although the tests are applicable to a wide range of soil conditions, penetration is limited in certain ground conditions. Well-cemented soils, very stiff clays, and soils containing gravel and cobbles may cause damage to the penetrometer tips.

The CPT can be used at nearly any site because portable devices are available. Portable hydraulic jacking systems can be used for soft soils in locations not accessible to standard rigs.

The CPT has several disadvantages. The test does not provide soil samples. The test is unsuited for well-cemented, very dense and gravelly soils because these soils may damage the relatively expensive penetrometer tips.

Local experience with this test is less than that with the SPT. Although the test is rapidly gaining acceptance in the United States, some drilling contractors do not have the equipment or experience necessary to perform the test. The equipment is expensive and may not be available in some locations. Maintaining the electronics for the CPT and CPTU equipment may be a problem in some test locations.

Data Obtainable

The CPT is primarily a logging tool and provides some of the most detailed stratigraphic information of any penetration test. With electronic cones, data are typically recorded at 5-cm-depth intervals, but data can be recorded at closer spacings. Layers as thin as 10 mm can be detected using the CPT, but the tip resistance can be influenced by softer or harder material in the layer below the cone. Full tip resistance of an equivalent thicker layer may not be achieved. The penetration resistance of the soil is a function of the drainage conditions during penetration. In sands that are drained, the penetration resistance is high, but in clays that are undrained, the penetration resistance is low.

A typical CPT data plot is shown in figure 22-8. CPT plots should show all recorded data (i.e., Tip Resistance, q_c , Sleeve Resistance, f_s , Pore pressure, u, and for this example, cone inclination and temperature). CPT data should be plotted to consistent scales on a given project so that the plots can be more easily evaluated.

The CPT does not obtain a soil sample. However, the soils may be classified by comparing the tip resistance to the ratio of tip to sleeve resistance which is known as the friction ratio, F_r . Friction ratio should also be shown on the summary plots. Figures 22-9 and 10 show commonly used relationships to estimate the “soil behavior type.” Clay soils have low tip resistance and high friction ratio, while sands have high tip resistance and low friction ratio. Mixed soils fall in zones 4 through 7. There are also classification methods that incorporate the dynamic pore water pressure generation. The CPT cannot exactly classify soil according to the Unified Soil Classification System. Experience at many sites shows that soils give consistent signatures; and even though the soil behavior

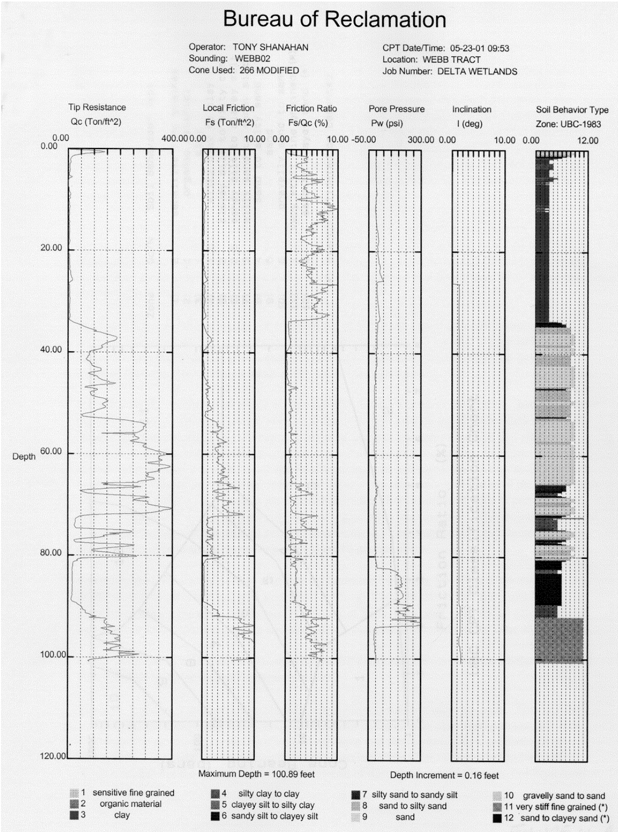
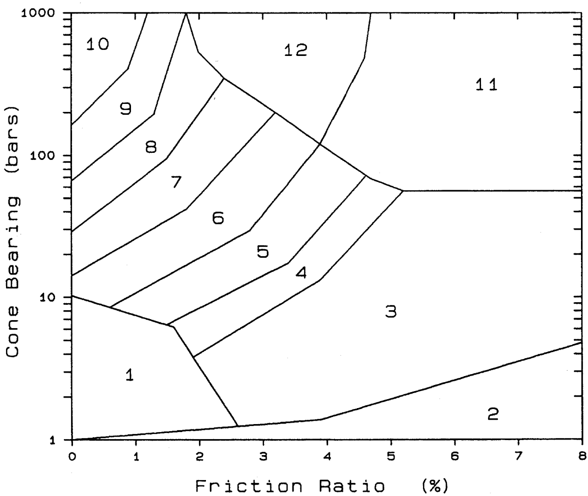


Figure 22-8.—Example CPT data plot.



UBC CPT Classification Chart

Zone	Qc/N	Soil Behaviour Type
1)	2	sensitive fine grained
2)	1	organic material
3)	1	clay
4)	1.5	silty clay to clay
5)	2	clayey silt to silty clay
6)	2.5	sandy silt to clayey silt
7)	3	silty sand to sandy silt
8)	4	sand to silty sand
9)	5	sand
10)	6	gravelly sand to sand
11)	1	very stiff fine grained (*)
12)	2	sand to clayey sand (*)

(*) overconsolidated or cemented

Figure 22-9.—Chart for estimating the soil behavior type.

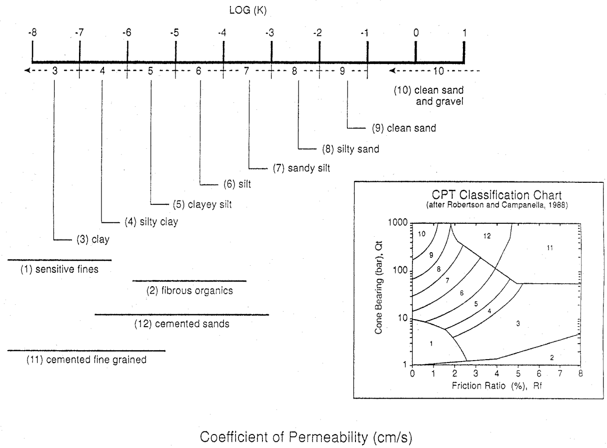


Figure 22-10.—Chart for estimating the soil behavior type and the coefficient of permeability.

type is generally correct, the soil types should be confirmed with a sample boring. Soil behavior type prediction in the unsaturated zone is less reliable but often still useful. The summary plot in figure 22-8 also shows the soil behavior group on the right side bar.

Soil permeability can be estimated from CPT because the tip resistance is a function of drainage during penetration. The permeability estimate is generally within an order of magnitude, which is suitable for most groundwater and seepage studies (figure 22-10).

Numerous correlations of CPT data to strength and compressibility of soils have been developed. These correlations are based primarily on tip resistance but are also supplemented by sleeve friction and dynamic pore water pressure data.

CPTs in clean sands have been performed in large calibration chambers where the density and confining pressure have been controlled. Based on the chamber data, the relative density and friction angle of sand can be estimated using relationships such as those shown in figure 22-11. The tip resistance at a constant relative density increases with increasing confining pressure. Once the relative density is estimated, the friction angle

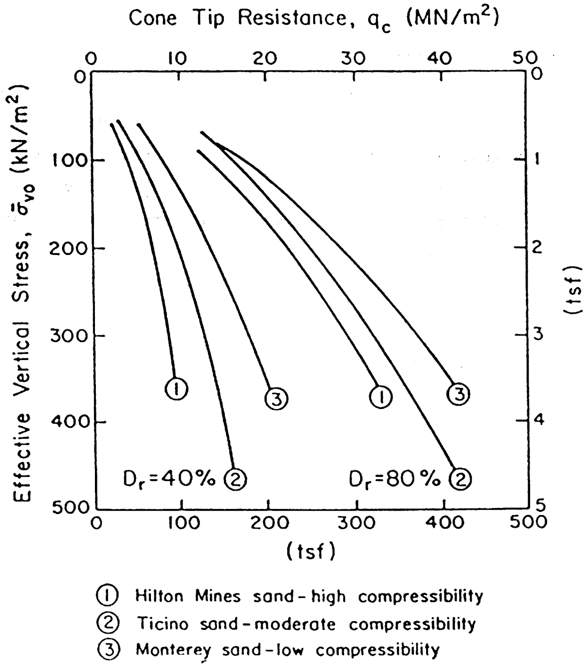


Figure 22-11.—Relationships between cone tip resistance, relative density, and effective vertical stress.

can be estimated. The compressibility of the sand depends on the mineralogy of the sand particles. Highly compressible sands may contain soft particles. If mica is present in the sand at percentages as low as 5 percent, the compressibility will increase. Samples of the sand to determine mineralogy may be necessary. These estimates for sands are not applicable to sands containing more than 10 percent fines.

The CPT can be used to estimate the undrained strength, S_u, for clays because the CPT is like a cone bearing test in rapid, undrained loading. Figure 22-12 shows that the cone factor, N_k, must be estimated for clay. Typically, a factor of 12 to 15 is used. The factor can be refined by cross correlating with sampling and unconfined compression testing or by vane shear testing.

Compressibility of soils can be estimated by the CPT test, but the consolidation behavior should be confirmed by sampling and laboratory testing.

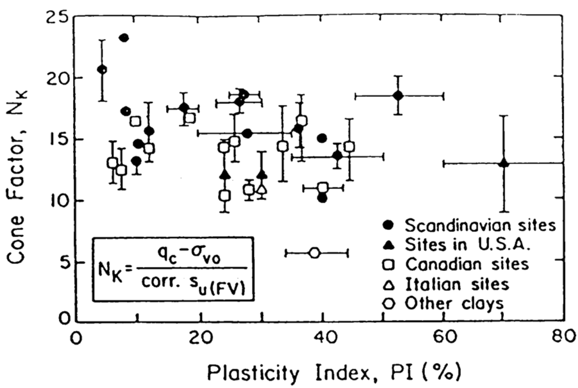


Figure 22-12.—Empirical cone factor, N_k, for clays.

The CPT is the best method for estimating the liquefaction resistance of sandy soils. The SPT is also used but has many problems in drilling and with equipment. The CPT tests the sand in place without disturbance, and the test is highly repeatable. Figure 22-13 shows the chart used to estimate liquefaction triggering. The chart is based on "clean sands," but the method includes conversion of dirty sands for evaluation. If the CPT can be used for liquefaction evaluation, it should definitely be considered in the exploration plan. SPT should still be performed at a few sites, but the CPT can be used to rapidly and economically

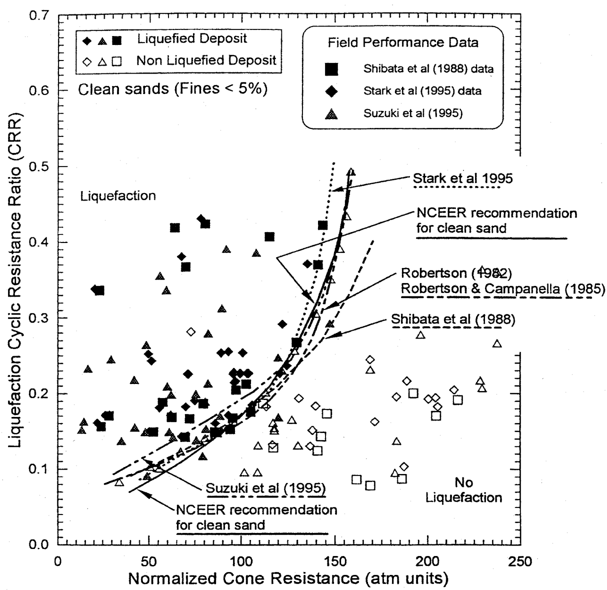


Figure 22-13.—Comparison of various cyclic resistance ratio (CRR) curves and field data.

map the extent of liquefiable strata. CPT is also used extensively for evaluating ground improvement of liquefiable deposits.

The cone is like a miniature pile and is used for evaluating pile capacity. CPT tests are often performed at the abutments of bridges for pile design. Numerous methods exist for estimating pile capacity.

Economics

Equipment costs for CPT range from low for mechanical devices to high for piezocones, and generally two technicians are required to perform CPTs. These personnel should have a working knowledge of the equipment, but highly trained technicians are not required. The equipment mobilization is similar to that required for the SPT, but portable devices can be used for remote locations. Unit costs are difficult to estimate because the tests provide continuous or nearly continuous measurements. Rig costs are comparable to costs for the SPT, with an added capital cost to convert a conventional drilling rig for CPT testing. However, 200 feet (60 m) of penetration per day is typical; and in some cases, maximum production of 400 feet (120 m) per day is possible. This cost is the lowest of any geotechnical drilling, sampling, and logging method.

Bibliography

Harder, L.F., *Application of the Becker Penetration Test for Evaluating the Liquefaction Potential of Gravelly Soils*, NCEER Workshop on Evaluation of Liquefaction Resistance, held in Salt Lake City, Utah, 1997.

Harder, L.F. and Seed, H.B., *Determination of Penetration Resistance for Coarse-Grained Soils Using the Becker Hammer Drill*, Report No. UC/EERC-86-06, NTIS PB87-124210, Earthquake Engineering Research Center, College of Engineering, University of California, Berkeley, California, May 1986.

Peck, Ralph B., *Foundation Engineering*, Second Edition, John Wiley & Sons, 1973.

Rausche, F., Goble, G.G., and Likins, Jr., G.E., *Dynamic Determination of Pile Capacity*, Journal of Geotechnical Engineering, ASCE, Vol. 111, No. 3, pp. 367-383, 1985.

Sy, A. and Campanella, R.G., *Becker and Standard Penetration Tests (BPT-SPT) Correlations with Consideration of Casing Friction*, Canadian Geotechnical Journal, 31(3): 343-356, 1994.

Sy, A., Campanella, R.G., and Stewart, R.A., *BPT-SPT Correlations for Evaluation of Liquefaction Resistance of Gravelly Soils, Static and Dynamic Properties of Gravelly Soils*, ASCE Special Publication 56, M.D. Evans and R.J. Fragazy, Editors, American Society of Civil Engineers, New York, New York, 1995.