



Standard Penetration Test Driller's / Operator's Guide

DSO-98-17

Earth Sciences and Research Laboratory

May 1999



Standard Penetration Test: Driller's / Operator's Guide
DSO-98-17

by
Jeff Farrar

U.S. Department of Interior
Bureau of Reclamation
Dam Safety Office

May 1999

TECHNICAL NOTE
SPT DRILLER/OPERATORS GUIDE

by
Jeff Farrar
Earth Sciences Laboratory

INTRODUCTION

The purpose of this technical note is to review important aspects of the Standard Penetration Test (SPT). The intended audience is our drilling staff and field geology personnel involved with collecting the data. It also may be of interest to our engineering staff who interpret the data. There are many misconceptions regarding the test. This paper discusses - in plain terms - the significant aspects of the test and the pitfalls that can occur.

Reclamation uses the SPT to evaluate the earthquake liquefaction potential of soils under our dams. These determinations are very critical and the decisions that are made affect the lives of people downstream. The data you generate will be used to decide if multi-million dollar modifications are required for these structures. Reclamation uses the Earth Manual procedure USBR 7015 to run the test - and if you haven't read it you shouldn't run the test. These procedures are boring and only discuss the mechanics of the test. This document provides background on various factors involved in the testing.

Liquefaction is the process where water pressure builds up in granular soils during an earthquake. Soils which are most 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). In order to keep the terms simple, the term "sands" will be used to refer to these soils. The water pressure buildup results in strength loss, and possible dam deformation, slippage, and possible failure. Liquefaction is observed on level ground where water pressure vents to the surface in the form of sand boils or volcanoes. Researchers have collected SPTs at liquefaction sites and have developed a method to determine if a deposit is liquefiable. Figure 1 shows a summary of this data. The plot shows a graph of earthquake loading (cyclic stress ratio, CSR) versus a normalized N value $(N_1)_{60}$. Solid symbols on the graph are sites where liquefaction was observed while the open symbols show site with no liquefaction. The dividing line between liquefaction and non-liquefaction is shown on the graph for varying fines contents of the sands. From the figure, one can see that clean sands with $(N_1)_{60}$ values greater than 25 to 30 are likely not liquefiable. Dirty sands have lower N values than clean sands and the dividing lines are lower.

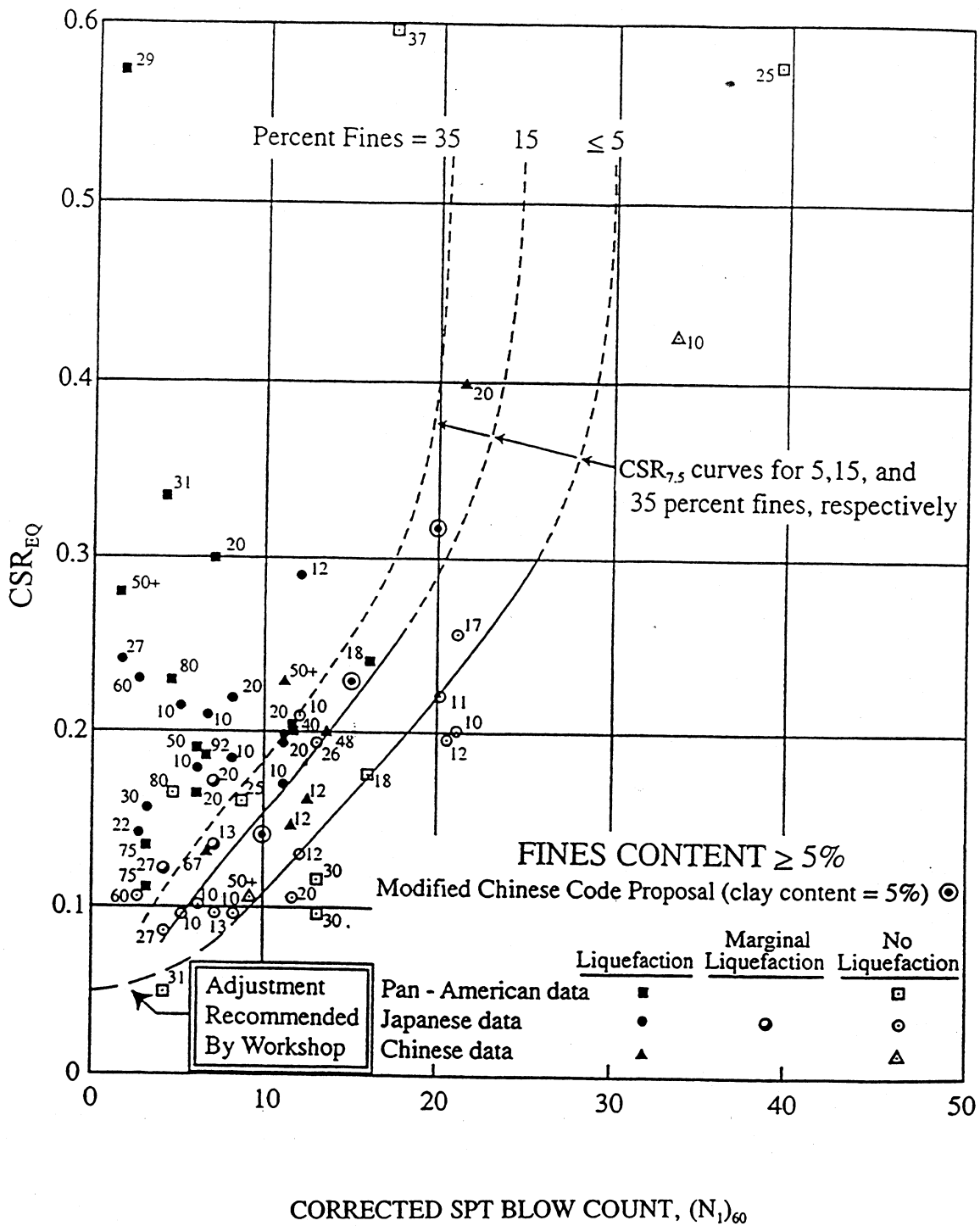


Figure 1 - Chart used to determine if sands are liquefiable.

This report illustrates the effects of drilling, test procedure, and energy transfer on SPT N values. The information given here is not all based in fact, some of it is based on experience. There are many things regarding the SPT that are still not known. For example, we will never be able to estimate drilling disturbance because it is a function of the geology and the drilling technique.

Difficulties Testing Cohesionless Soils

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

If you suspect that you have disturbed the sands, by all means be sure to report it, and take measures to avoid continued disturbance. It's easy to determine if the sand is disturbed. Perform depth checks to be sure of the depth of the sand at the bottom of the drill hole. These depth checks can be made by noting exactly where the sampler rests prior to testing. Depth checks that can be made during drilling will be discussed below. Take your time and do not drill at excessive rates. Signs of disturbance are, excessive slough in the SPT barrel, drill fluid in the sample, and a failure of the sampler to rest at the proper clean out depth. Slough is a term for disturbed material in the drill hole. Slough can consist of soil which caves from the sidewalls. Slough can include disturbed sand which heaves or flows upwards into the drill hole. Slough can also consist of cuttings which settle from the drill fluid prior to testing.

The SPT sampler must rest at the intended depth. This depth is the depth to the end of the clean-out bit, or the end of the pilot bit in hollow-stem augers. In our testing procedures we state that if the sampler rests at an elevation that is 0.4 ft different than the clean-out depth, disturbance may be occurring.

DRILLING METHODS

Fluid Rotary Drilling

Very early in the history of the SPT, data were collected that showed that rotary drilling with clear water resulted in N values that were much lower than those in which drilling mud was used. Two factors were involved, 1) the water from drilling was jetted into the test interval disturbing the sand, and 2) the water level in the borehole was allowed to drop and the sand would heave up the borehole when the clean out string was removed.

The best way to drill loose saturated sands is to use bentonite or polymer-enhanced drill fluid and drill bits that minimize jetting disturbance. The other important factor when drilling with fluid is to use a pump bypass line to keep the hole full of fluid as the clean-out string is removed from

the drill hole. The lack of a bypass line is one of the most frequent reasons sands are disturbed. If the soils are fine, use a fishtail-type drag bit with baffles that deflect the fluid upwards. Use of a tricone rockbit is acceptable if gravels or harder materials are present, but be aware of the downward jetting, and adjust your flow rates to minimize jetting.

Use of casing can help keep the borehole stable. But keep the casing back from the test interval a minimum of 2.5 ft and more if the hole can remain stable. Also, understand that with casing, the need for a bypass line is even more important. This is because if the water in the casing drops below natural ground water level, the imbalance is focused at the base of the casing, and the possibility for sand heave at the base is increased. So - keep the casing back as far back as possible to avoid the focusing effect. Under extreme cases, the casing will be need to be kept close to the test interval, under these conditions, set the casing at the base of the previously tested interval, prior to drilling to the next. Our test procedure says 2.5 ft SPT intervals are recommended at the closest spacing.

Reclamation procedures require the use of drilling mud when the SPT is performed for liquefaction evaluation. In order to have maximum stabilizing benefit, used of bentonite based drill fluid is required. Bentonite provides the maximum weight/density and wall caking properties to keep the drill hole stable. When mixing mud you must add enough bentonite for to the mud to be effective. There are two ways to test drill mud, either density or viscosity as indicated by the Marsh Funnel test. The Marsh Funnel test is the easiest. Water has a Marsh Funnel time of 26 seconds. Fine grained soils require Marsh Funnel times of 35 to 50 seconds. Coarser materials such as gravels, will require funnel times of 65 to 85 seconds to carry the cuttings to the surface. If using a mud balance typical drill mud should weight 10-11 lb/gal. Water weighs about 8 lb/gal.

Use of polymer based fluid or water has less benefit, and these methods are only recommended in special cases such as for a piezometer installation or when there are extreme environmental restrictions. In some cases use of polymer fluid or water may not keep the hole stable and bentonite drill mud must be used.

Often, there is a desire to complete an exploration holes with piezometers. Some instrumentation personnel have had bad experience in the past with old blue revertible drilling fluids. Today, these fluids have been improved and there are synthetic polymers which break down more reliably. If necessary, specific "breaker" compounds can be used to clean the borehole. If the borehole cannot be kept stable with polymer fluid, then bentonite mud should be used, and a second hole should be used for piezometer installation. We must not try to combine drill hole purposes if the data from SPT becomes unreliable.

Can we drill sands with clear water??? Sure, but we never recommend it. Drilling sands with clear water is possible; but, only if the driller is very experienced. Comparison studies have shown that as long a drilling is carefully performed, drilling with water can result in SPT N values close to those using mud. Disturbance can be avoided, but without drill mud, you have to be even more careful about jetting disturbance, cave, and sand heave due to fluid imbalance.

Another problem with sand is possible artesian conditions. If the water pressure in the sand layer is higher than the ground surface, sand heave is really going to be a problem. Under these conditions, use of heavy bentonite mud (80 to 100 sec marsh funnel) is required. Of course, the fluid bypass is required and you can work with an elevated casing or drill pad to hold down the sand. Some successful mud improvement is possible with Barite or Ilmenite additives. Bentonite 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 some cases it may not be possible to keep the sand stable in artesian conditions. In these cases, we can use other tests, such as the cone penetrometer to evaluate the sand.

When using drill fluids, check state and local regulations for allowable fluids and additives. Special considerations are needed if the aquifer being drilled is also used for public water supply. The National Sanitation Foundation (NSF) Standard 60-1988 provides requirements for drill fluids to be used when drilling in drinking water aquifers. If there are any questions or concerns regarding aquifer water quality it is best to stick with “un-benificated” bentonite, that is, bentonite without any additives.

Quality checks - to check for disturbance when using fluid rotary drilling, once the clean-out depth is reached, circulate to remove cuttings. Retract the cutting bit several feet. Cut fluid circulation. Go get a drink of water for a minute, then slowly/gently lower the bit and rest the bit at the bottom of hole. Check the depth to see if it is within 0.4 ft of the clean-out depth. This check will identify if there is settlement of cuttings, wall cave, or jetting disturbance.

Heave at the bottom of the borehole, normally occurs when the clean-out drill string is removed. To avoid problems it is essential that fluid be added to the drill hole as the clean-out string is removed. To check for disturbance once the sampler is placed, check the depth at which the sampler rests and compare it to the clean-out depth. Once again, an error of 0.4 ft is considered unsatisfactory. If sands or silty sands heave up into the borehole, often the SPT sampler will sink through most of the slough. The only way to check for this problem 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 - it's likely the SPT N value may have been affected.

The fluid rotary method is considered the best method for determining SPT N values in saturated sands. In the following sections two other acceptable drilling methods will be discussed. If you have trouble with these methods you must revert back to fluid rotary.

Hollow-stem Augers

Hollow-stem augers (HSA) have been used successfully to do SPT in loose saturated sands. A comparison study was performed between fluid rotary and HSA that showed that with the proper precautions hollow-stems could be used reliably in sands. Here are some problems with hollow-stem augers.

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 are removed in preparation for the SPT. We have seen numerous projects where, when the pilot bit or sampler is removed quickly, and suction is created at the base of the boring, resulting sand disturbance. Sometimes sand can heave 5 to 10 ft up inside the augers! These occurrences are not acceptable and SPT N values taken with this disturbance are un-reliable. In most cases, using fluid filled augers, if the pilot bit or HSA sampler are removed slowly to avoid the suction, these problems can be overcome.

There are two types of HSA systems shown on figure 2, 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. In Reclamation, use of the rod type HSA system is more prevalent. This is because for good sampling, the rod type system is best at preventing sample barrel rotation during soil sampling. In sanding in conditions, the wireline system is sometimes harder to operate, because the withdraw rate of the bit or HSA sampler is harder to control. Sanding in, also prevents re-latching of the wireline barrel. For this reason, the use rod type systems is recommended when drilling in heaving sands. For both systems, if sand heaves a considerable height into the augers, the auger will need to be cleaned or retracted in order to continue drilling. If you have to pull the augers up 3 ft to re-latch a pilot bit or sampler barrel, tremendous suction effects occur at the base of the boring, which possibly can disturb the next SPT test interval. HSA drilling can only be successful if sanding in is controlled.

Much like fluid rotary, when using HSA below the water table - they must be kept full of fluid. A water source and a bypass line are required. Here are some techniques for hollow-stem drilling in flowing sands that have been successful;

- 1.) When approaching the test interval, slow your 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 cause 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, this pressure should be relaxed, and the augers will need to slightly retracted, ½ inch or so to re-latch bits or barrels. There is no need to release down pressure or retract the augers with rod type systems.
- 2.) Before pulling the pilot bit or sampling barrel, add water to a level higher than surrounding ground water level. In most cases you can add water to the top of the augers without concern for

disturbance. Adding water to the top of the augers allows for disturbance to be evaluated when pulling the pilot bit or the sample barrel (discussed in the next bullets). Add water by removing the drive cap and add water with a hose (bypass line). When removing the drive cap on rod type systems, be careful to disconnect the connection of the drive cap bearing to the inner rods, or you will pull the pilot bit or sampler prematurely prior to adding water. When using wireline systems it is acceptable to send the latching device down hole and latch prior to adding water.

Maintaining water level at the top of the column is not always successful, especially if there is a thick layer of unsaturated soils above the test zone. Water can leak through the auger joints. It may be necessary to add very much water in these cases.

3.A.) *Pulling the Sampler Barrel* - The sample barrel assembly is generally 5 ft long. This barrel does not have much clearance with respect to the inside diameter of the augers, and 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 ft and observe the water level in the augers. If water flows upward, out of the augers, this means 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 barrel slightly down and up, to try to break the seal and vent. For wireline systems release the pulling force and re-apply to pull slowly and attempt to break the seal. Once the seal is broken remove the sampler slowly. Remember, with rapid withdraw rates, suction effects can be created anywhere in the auger column. For rod systems add water during pulling to account for water level drop when using the rod type systems. The same rule applies for wireline systems but less water is needed.

3.B.) *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, such 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.

When drilling the pilot bit, pull the bit back slowly about 0.1 to 0.2 ft 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 a 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. With the flap valves, you drill without the pilot bit.

4.) In accordance with our procedures, once the sampler has been inserted to the base of the boring, determine the depth to the sampler tip as a quality check. Reclamation procedures say that once you have more than 0.4 ft of slough or heave the test may not be acceptable. This

guideline is arbitrary, and it possible you can get a reliable test with as much as 0.5 ft or more slough as long at the vent and ball check of the sampler are not plugged. If you use the SPT barrel to test the bottom of the hole, often the sampler will penetrate loose slough or heave, so checks with a weighted tape may be helpful to find out what depth the loose slough is actually at. When using the HSA sampler barrel to core prior to testing, if sand falls out of the barrel, this slough could be the cause of high level of slough inside the auger. To avoid this problem use catcher baskets in the HSA sampler barrel.

5.) After you perform the SPT, when testing at close intervals of 2.5 ft or closer, 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 hollow-stem auger with SPT operations. Let's say you are doing SPT's at 2.5 ft intervals. You perform the SPT and then sample 2.5 ft and over-sample the 1.5 ft test interval. This adds some time, but it allows you a continuous sampling hole. This sampling method allows you to look at the soils between the test intervals and it's also helpful if low recovery occurs.

Figure 3 is an example of what frequently occurs when drilling with hollow-stem augers in heaving sands. This is an actual recent example from Reclamation. During the drilling, the sand would consistently heave 5 to 10 ft up into the hollow-stem when the pilot bit was removed. The drillers would then use a high pressure water jet to clean out the heaved sand. The results of this disturbance are evident on Figure 3. Very low blow counts and poor recovery were obtained in the sands. As a result of the disturbance, a companion SPT hole was drilled using fluid rotary casing advancer. The true blows were much higher, and recovery was much better. If the hollow-stem data were reported this very dense sand deposit would be determined to be liquefiable in an earthquake. This site was actually a bridge site with only two borings. An engineer may have specified friction piles in construction, only to find they could not be driven due to dense sands. The would have caused very costly construction claims.

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. The reason this method is successful is the large diameter rods remain filled with drill fluid and keep the sand down. The casing advancer which normally has a diamond bit, 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 removed via wire line. The possibility still exists for suction effects when a pilot bit is removed. If this occurs you might have to try to drill without a pilot bit. Another positive aspect is that the pilot bit is removed by wireline, which takes up little volume and results in minor drop in fluid level inside the rod column. Since a good fluid column remains in the rods you do not need a

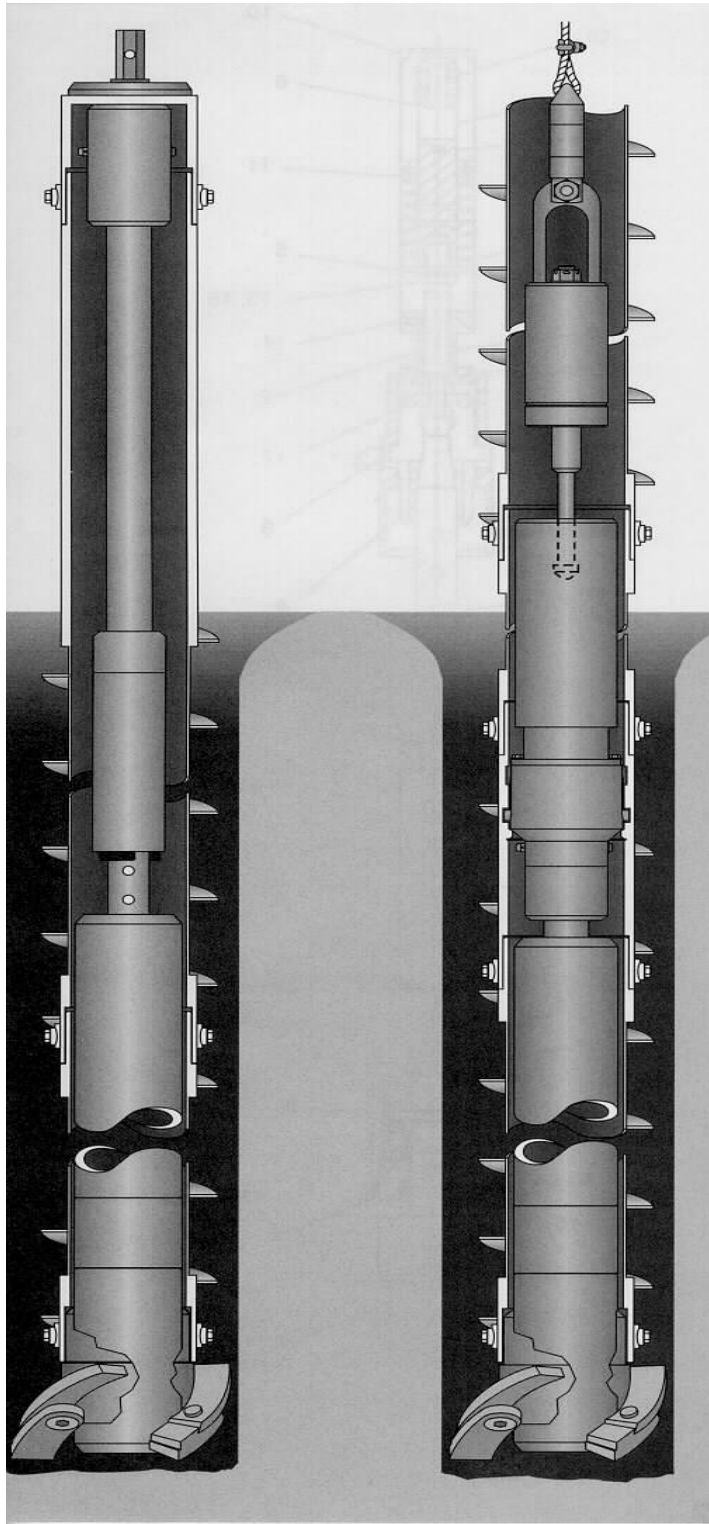


Figure 2 - Example of rod type and wireline type hollow-stem augers.

fluid bypass! The only problem is, every time you add 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 nothing but a bottom discharge bit. If excessive fluid pressures are used, or if circulation is lost, the possibility exists of jetting into or hydraulic fracturing occurring in the SPT test interval. To drill successfully with this system, you must drill with a slow advance rate with low pressures and maintain circulation. If circulation return stops, this is a sign of blockage, and if pump pressures increase hydraulic fracturing could occur. If you attempt too fast of an advance rate you are sure to block circulation. Water is not an acceptable drill fluid with this method and drill mud must be used.

Summary of drilling effects

Table 1 illustrates the effects of different drilling and mechanical variables on the SPT “N” value (items 1 through 5). In this table a typical N value in clean quartz sand is 20 blows per foot. The possible range of “N” for the material is shown if the material is subjected to errors in testing.

Examining Table 1, one can see that drilling disturbance can have the most 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 for the sampler to settle under the weight of the assembly.

Drilling disturbance usually results in a reduction in N value. This may be fortunate, because low blow counts, indicate loose, weak soils and therefore a flag is raised with the geologist or engineer. Those evaluating data may conservatively (and wrongly) assume a problem condition. The lower, disturbed N values, can result in more costly over design of structures.

The way you drill the hole is the most important aspect of SPT testing. We can control the mechanical and operator variables of the test, but it’s up to you to assure the hole is drilled with minimal disturbance.

Table 1 Summary of Factors in the Variability of SPT expressed in typical N values

Cause		Typical Raw SPT value in Clean Sand N = 20	Typical Raw SPT value in Clay N=10
Basic	Detailed		
Drilling method	1. Use of drilling mud and fluid bypass.	20	10
	2. Use of drill mud and no fluid bypass.	0-20	8-10?
	3. Use of clear water with or without bypass.	0-20	8-10?
	4. Use of hollow-stem augers with or without fluid.	0-20	8-10?
	5. 8-inch diameter hole compared to 4 inch.	17	8-10?
Sampler	6. Use of the larger ID barrel, without the liners	17	9
	7. Use of a 3-inch OD barrel versus a 2-inch barrel	25-30 ^e	10
Procedure	8. Use of a blow count rate of 55 bpm as opposed to 30 bpm	20 ^{e1}	10 ^{e1}
Energy Transmission Factors.			
Drill Rods	9. AW rod versus NW rod	18-22 ^{e2}	8-10 ^{e2}
	10. SPT at 200 ft as opposed to 50 ft	18 ⁴	5 ^{e3}
	11. SPT at less than 10 ft as opposed to 50 ft with AW rods.	30	15
	12 SPT at less than 10 ft as opposed to 50 ft 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 2 wrap on cathead.	16	8
	16. Use of high efficiency automatic hammer versus 2 wrap safety hammer.	14	7
	17. Use of a donut hammer with large anvil as opposed to safety hammer.	24	12
	18 Failure to obtain 30 inch drop height (28-in)	22	11
	19 Failure to obtain a 30 inch drop height (32 in)	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 rods are less or more efficient, with larger rods N may be less in clay due to weight.

3 = N in clay may be lower due to weight of the rods

4 = Actual N value will be much higher due to higher confining pressure at great depth, i.e the difference shown here is from energy only, and confining pressure was not considered

PROCEDURE VARIABLES

Testing Intervals

Reclamation's SPT procedure, USBR 7015, says the closest interval for testing is 2.5 ft. But you often get requests to do "continuous" SPT's!! What gives? The recommended interval of 2.5 ft is to try to assure that the next interval is not disturbed. We certainly can take SPT continuously. On some projects we have done this in sands with good results. The reason we did it was the sand layer was only 5 ft thick! So keep the interval at 2.5 ft, but if there is a layer that the exploration team is after then you can try closer intervals. If you are drilling on a project that only has a few thin layers of sand, this should be brought to the attention of the exploration team.

The SPT Liquefaction analysis method is most reliable in clean and silty sands and much less reliable in gravels and silts, so if the sand layers are thin you may need to tighten up the interval. Of course SPT can be used in all materials as an indicator of engineering properties. What we are trying to say here is the sands are of primary concern for liquefaction analysis. In other soils such as silts, clays and gravels the test is also performed, but there may not be a urgent need to tighten the test interval in these soils

Hammer blow rate

What is the difference in N value in a sand if the test is run at 50 blows per minute as opposed to 15 blows per minute? The answer is we don't know for sure. The SPT loading is much like an earthquake loading. That's why the test is often used for liquefaction evaluation. Both provide cyclic loading.

Blow counts are higher in clean sands because water pressures which develop, during the cyclic loading can be readily dissipated. A typical blow count for alluvial clean sand is 20 blows. When you add 30 % fines such as silty sand (SM), the drainage cannot occur and the blow count drops. A typical blow count in alluvial dirty sand is 15, and further, with even less drainage, soft clays may be 5 or 10.

The rate is important when drainage needs to be considered. Most test standards request SPT at a rate of 20-40 blows per minute. If you perform the test at 55 blows per minute, it is not likely to have an effect on clean sand, but at some fines content, blows will be reduced due to lack of drainage and the rate at which the blows are applied.

If you are using a hammer where you can control the rate, attempt to deliver between 20 to 40 blows per minute. Some hammer systems are designed to deliver blows at a faster rate. For example, the CME automatic hammer is designed to deliver blows at a rate of 50 to 55 blows per minute. The CME hammer can be set to run at 40 bpm, but you have to add a spacer ring to the impact anvil. If you use the hammer at 50 bpm clearly note it on the drill logs.

Limiting Blow Counts

Reclamations test procedure calls for stopping the test at 50 blows per foot when other agencies sometimes go to 100 blows per foot. This is because the American Society for Testing and Materials test standard D 1586 calls for the 100 blow limit. When we drafted the USBR standard we decided to see if we could lower this limit to avoid equipment damage.

Using the soil liquefaction criteria for sand, it appeared that a soil at a depth of 100 ft with 50 blows would not be considered liquefiable. SPT data are corrected to a stress level of 1 ton/ft². In a typical ground mass, 1 tsf stress level occurs at a depth of 20-30 ft depending on the location of the groundwater table. As you drill deeper and deeper blow counts in a sand of constant density increase. A correction factor is used to correct for these stress effects. Thus, at a depth of 100 ft you could have a raw blow count of 50 bpf that could correct to 30 bpf. In earthquake liquefaction clean sand N160 values greater 30 bpf are not liquefiable. So - it ends up a blow count of 50 bpf at 100 ft corrects close to 30 bpf at 1 tsf, and anything higher would not be considered to be liquefiable.

If you are drilling deeper than 100 ft it will be necessary to increase your limiting blow counts to 100. USBR 7015 states that if SPT is going deeper than 100 ft, to consult the exploration team. They would likely increase the maximum blow count for 1.5 ft to 100 blows.

And of course the refusal rule still applies. That is, 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 for use with gravels.

Penetration per Blow or Blows per 0.1 ft

When drilling in gravelly soils, you will be requested to record the penetration as the blows are applied.

The reason for recording partial penetration per blow is the engineer is looking for a sand layer, from which he can estimate the N value of the sand alone. Lets say you start out in a sand but hit gravel at a drive depth of one foot. From a graph of penetration per blow, the blow count in sand can be estimated. Generally, the extrapolation is fairly reliable if the blows start in sand. If the intervals starts with gravel and then penetrates into sand the extrapolation is be less reliable because the sampler could be plugged by gravel.

There is considerable debate on the way to record this information. In the Earth Manual procedure we require number of blows for 0.1 ft. This is the minimum penetration rate data we could collect. 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 ft. To record penetration per blow, make a tabular form with three columns, in one column are the blows 1 through 100. Mark the drill rods in 0.10 ft intervals or use a tape starting at zero from the edge of a reference point. In the other column record the total penetration as the test is performed. This will require a reader to call off the total penetration. The reader will find it fairly easy to interpolate between the 0.1 ft increments or they can read directly from a tape. After the test is done, the incremental penetration can be calculated from the cumulative penetration data.

EQUIPMENT/MECHANICAL VARIABLES

There are a lot of misconceptions regarding the SPT and the equipment that is used. Lets review some major points.

Sample Barrel

The standard sample barrel is 2-inches in outside diameter. In private industry, they also frequently use 2.5 and 3 inch outside diameter barrels. The question arises - will they give different blow counts??? The answer is we don't know! The only data I have are shown on Figure 3. On this figure, 2-inch and 3-inch samplers were tested at a bridge site in New York. It appears that there was not much difference in the samplers in the loose sand and dirty fill material. In gravelly soils, the 3-inch barrel had N values less than the 2-inch barrel as would be expected. In dense sand at the bottom of the boring, the 2-inch sampler had lower N values than the 3-inch barrel due to friction effects. The 3-inch barrel has more surface area, and in dense sand a large component of the penetration resistance is from friction. Table 1, item 7 estimates the effect of the larger sample barrel, and assumes some increase in a moderately dense sand due to friction, while N value in clay is not affected.

Due to the lack of data we need to stick with the 2-inch barrel. If we are in coarse materials, and we don't get good recovery, it is acceptable to re-sample with a 3-inch barrel equipped with a catcher to try to recover the material from the test interval.

Gravelly soils generally do not provide reliable SPT data for use of liquefaction evaluation based on sands. There are other methods using larger samplers and hammers for attempting to evaluate the density of gravelly soils. The Becker Penetration Test is now being used at gravel sites. Often you will see the BPT on gravel sites after a first round of SPT testing shows considerable gravels at the site.

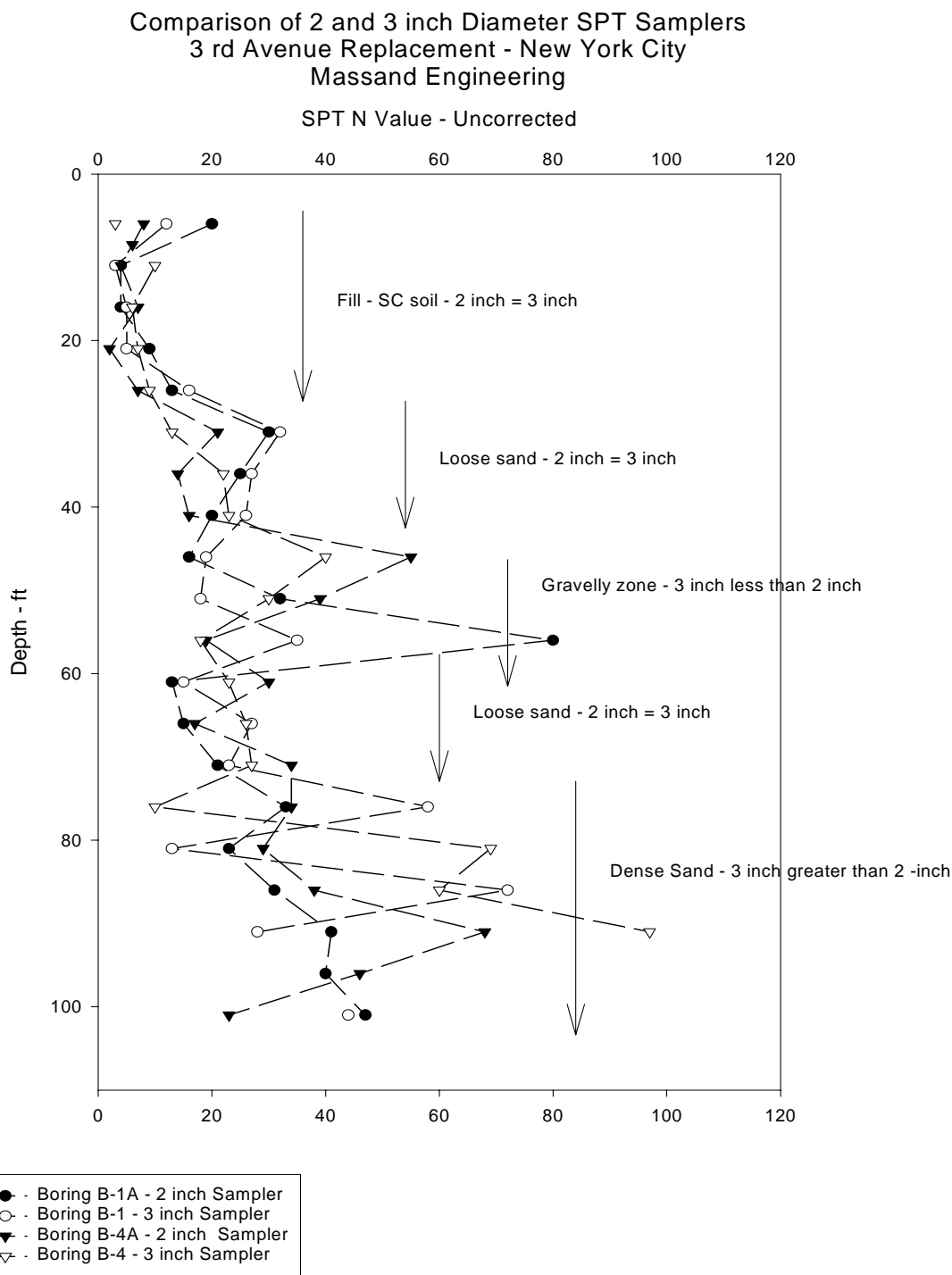


Figure 3 - Comparison of 2 inch and 3 inch diameter sample barrels - (courtesy of Massand Engineering, New York).

Sampler Shoe

The dimensions of the sampler shoe have been standardized by USBR and these are in accordance with ASTM D 1586 requirements. Some drill equipment catalogs claim to have special “heavy duty” sample barrels and shoes. There was once a shoe design called “Terzaghi” style (Acker Lynac) that does not meet the ASTM, and USBR requirements. When buying shoes, check their dimensions upon receipt to be sure they meet the test requirements. Figure 4 shows both USBR and ASTM sampler requirements. The dimension of the shoe is given there.

One way to improve the shoe ruggedness, especially in gravels, is to “carburize” the metal. This is a heat treatment process, where the shoe is heated in a carbon gas environment to improve the surface hardness of the steel. This makes the shoe more rugged. It also makes the shoe more brittle. Most drill manufacturers supply untreated low carbon steel such as 1040 alloy. Ask your local machine shop about “carburization” which is generally an inexpensive process.

Sampler Retainers

What is the effect of using sampler retainers? The answer is we don't know. There has never been a controlled study which shows the effect of using retainers. Since a retainer adds a constriction inside the sampler barrel, the use of one could result in slightly higher N values.

Until we know the effects, a sampler retainer should never be used. If it is impossible to retain the sample during SPT's, then a sample may be taken with a large diameter split barrel sampler with retainer, that is re-driven through the test interval. If you are using hollow-stem augers, you could use the over coring procedure discussed earlier.

There are several types of retainers available and some type are better than others. There is a flap valve device that actually looks like a toilet seat. This metallic valve places a large constriction inside the barrel and is the least desirable of the retainers if the N value is of concern. The basket type catcher is made of curved fingers of steel, brass, or plastic. This type of retainer places 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 the fingers may not always fall back into position to hold the core. A better variation of this catcher, is the “Ladd” type retainer which 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's in the USA are done with a sampler that was made to accept liners, but the liner is omitted. You can easily tell if you have sampler without liners. Stick your finger inside the shoe and feel past it, into the barrel. The shoe is always 1-3/8 inch inside diameter. If you feel an offset (increased diameter), the barrel is 1-1/2 inches. It is very important to be sure your drill logs report whether a constant diameter or an enlarged diameter barrel is used.

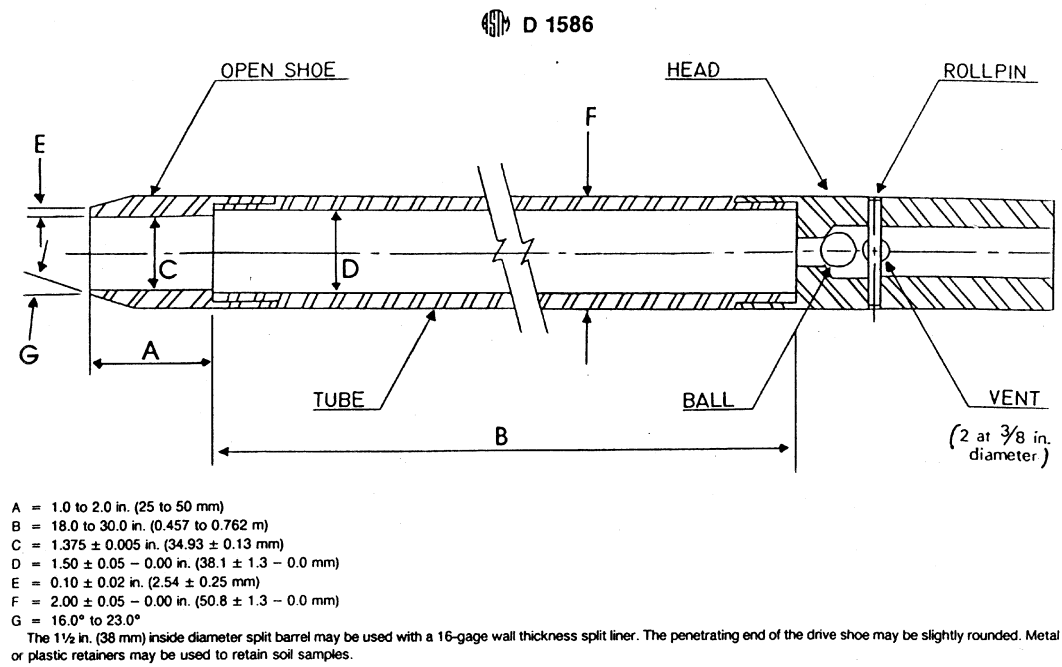
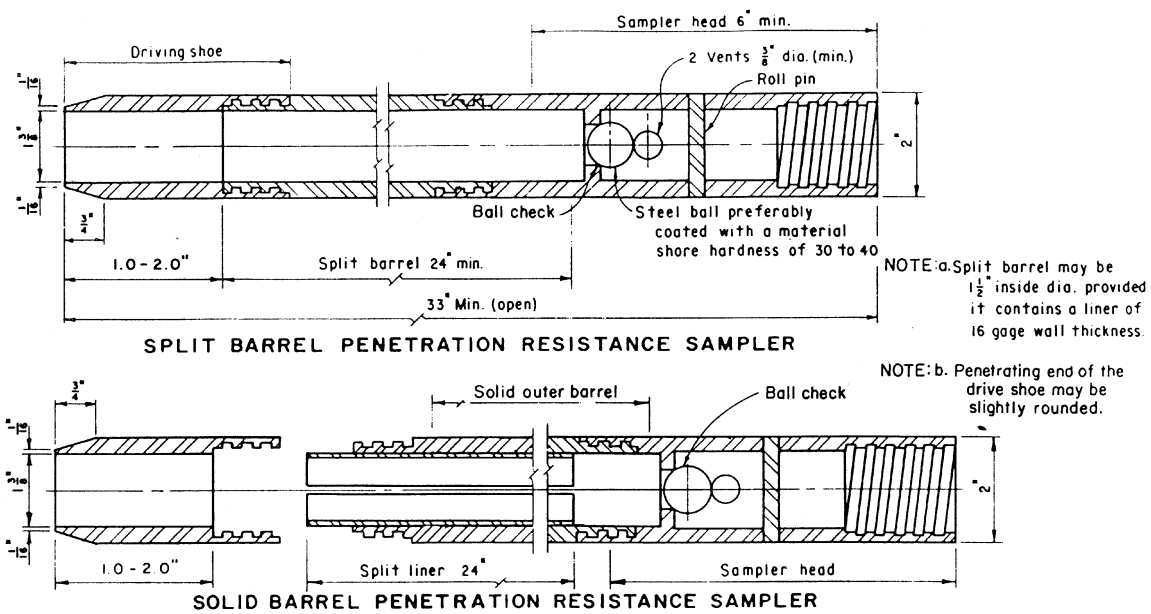


Figure 4 - ASTM and USBR SPT sampler requirements.

When the SPT was developed the liners were frequently used, but this practice was slowly dropped in the USA in the 1960's. Now, most all major manufacturers sell a barrel made to accept liners - and it's hard to find liners or someone who sells a constant ID barrel. Meanwhile, all of the foreign countries kept the constant ID sampler. For liquefaction evaluation, the experts recommend that we go back to the constant ID barrel. Reclamations test procedure calls for a constant ID barrel. Some regional offices have found sources for either liners or a constant ID sampler.

The use of a sampler without liners is actually better for recovery. Average recovery of a constant ID barrel is about 60%, and the average for the barrel without liners is about 80%.

The difference in N value between constant and enlarged diameter barrels in the soils we are testing is not clear. A study using side by side drilling in Japan indicates the differences are 10% in softer soils (clays) and up to 25% in high blow count soils (sands). In a loose dirty sand with a blow count of 10, the constant ID barrel may only increase the count by 1 or 2 blows. In a clean sand with blow count of 20, the difference may be 4 or 5 blows (see Table 1, item 6).

Sampler Length

USBR procedures require a 24 inch split barrel. These are easy to obtain. The purpose of the extra length is to 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 USBR test procedures are woefully inadequate when drilling with drill mud. The ASTM standard requires two 3/8 inch diameter vents above the ball check.

When drilling with drill fluid, the fluid gets filled with sand and can easily plug these ports. As the sampler and rods are lowered into the drill hole, they fill with mud. After driving, if the ball check does not seat, you may have a big column of drill mud trying to push the sample out! To avoid this problem, drill larger vent ports in the top subassembly. Some drillers use a 1 to 0.5 ft drill rod sub just above the sampler, and drill extra holes in it to easily drain drill fluid in the rod column.

HAMMERS, ANVILS, AND RODS - ENERGY EFFECTS

In the last 30 years, engineers began to study the mechanical aspects of the SPT. Early on, measurements were made of the hammer drop height and velocity. These measurements showed the effects of such variables as the number wraps on the cathead on hammer energy.

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. Since we want to know what energy is delivered to the sampler, a logical place to measure energy would be in the rods just above the sampler. This was not very feasible, so the measurements were made at the top of the drill rods just below the impact anvil. The energy content in the drill rods is called the “Drill Rod Energy Ratio”, ERI.

Energy measurements on the drill rods were being made in the 1980's. These measurements showed that some hammers, especially donut (casing type) hammers with large anvils delivered very low energy on the order of 50% of the total potential energy of a 140 lb hammer dropping 30 inches. Studies were performed to compare N values from different hammers. It was shown that the N value, was proportional to the energy delivered and the N values could be adjusted to a common energy. The current practice is to adjust SPT N values to 60% drill rod energy.

Reclamation participated in these energy measurements and had about eight drill rigs measured in the early 1980's.

These energy measurements are not easy. The equipment must measure forces of up to 60,000 lb in a period of 10 milliseconds. Different force transducers were used, and some were suspected of giving erroneous data. Then in the 1990's methods using accelerometers were developed. These measurements are sometimes in disagreement with older measurements, and the engineers are now scratching their heads trying to resolve this issue. None-the-less the energy is important, and sometime in the future you may see these measurements being made on your drill.

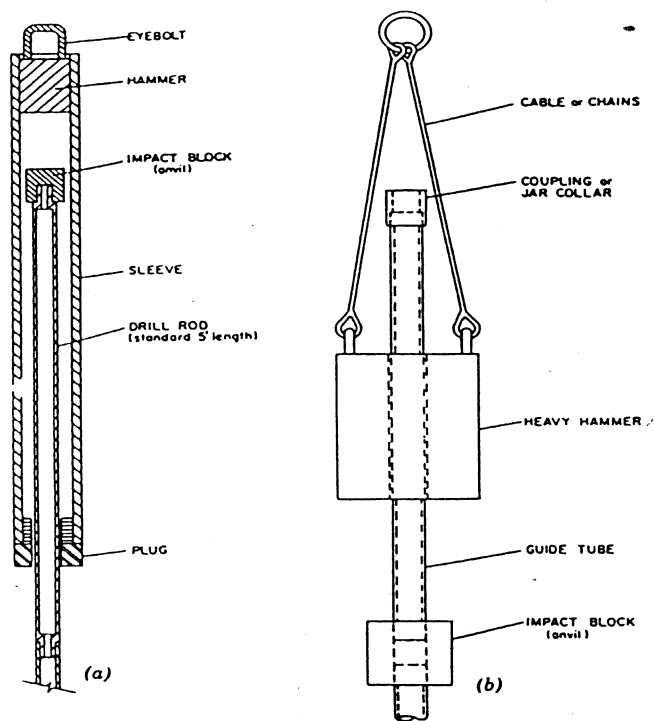
Hammers

There are many kinds of SPT hammers. In the early days people used pin-guided and donut type hammers. Figure 5 shows some donut and safety hammers. The donut hammer has lost favor in the USA to the “safety” hammer with the enclosed anvil. There are also new automatic hammers today which help improve the repeatability of delivered hammer energy to the sampler.

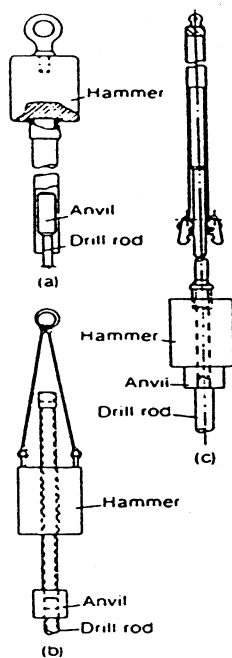
Safety Hammers

The safety hammer provides an economical and safe method of performing the SPT. The enclosed anvil removes hazards from flying metal chips, and of operators getting their hands in the impact surface. Due to their inherent geometry, safety hammer energy transmission can only vary by about 20 % as long as they are operated correctly and consistently.

Safety hammers should be designed with a total stroke of about 32 inches, and there should be a mark on the guide rod so the operator can see the 30 inch drop. In the past we have encountered hammers with a total stroke of only 30-inches, and hammers with more or less than the required 140 pound mass. These characteristics should be checked for the hammer you buy or use. An easy way to measure the hammer is to place the total assembly on a platform scale, get the total



—Configuration of SPT Hammers (Adopted from Ref. 48): (a) Safety Hammer; (b) Donut Hammer



SPT hammers: (a) old standard; (b) donut; (c) trip

Figure 5 - Examples of donut and safety hammers for SPT.

mass, and the lift the outer hammer off the anvil, and weigh the guide rod and anvil. The difference in the two weights is the hammer mass. The hammer mass should be 140 +/- 2 lb. Hammers should be stamped with an ID number. It is desirable to keep a given hammer for a specific drill, especially if the energy transmission of the drill has been made in the past.

One nice thing about safety hammers is we assume they deliver 60% drill rod energy with two wraps on the cathead. Actually the hammers deliver about 60 to 75 % depending on their construction. One factor affecting the energy transmission is the guide rod. Some safety hammers come with a solid steel guide rod, while others use a hollow AW drill rod. The solid guide rod acts as an energy trap and the solid steel guide rod safety hammer will deliver lower energy than the hollow guide rod safety hammer. These differences are not significant enough for us to state that one design is preferred over another. Another variable with safety hammers is a vent. Some hammers have vents near the top of the hammer and some do not. A vent will help allow some air to escape as the anvil moves toward the impact surface. These vents appear desirable to allow the best free fall possible.

Donut Hammers

These hammers are not recommended. We have had to use them in special cases, such as when clearance has been a problem (Lake Tahoe investigation in a covered bridge). 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 small anvil it may have efficiencies maybe close to the safety hammer. The larger anvil traps part of the hammer energy.

Rope and Cathead Operations

A majority of SPT's are performed using the rope and cathead method. In this method, the hammer is lifted by a cathead rope which goes over the crown sheaves. ASTM and USBR standards require 2 wraps on the cathead. After the hammer is lifted to the 30-inch drop height, and the rope is thrown toward the cathead allowing the hammer to drop as freely as possible. When performing the rope and cathead method it is important to avoid getting too close to the cathead.

Table 1 item #13 shows the effects of using three wraps around the cathead. Three wraps will reduce the drill rod energy by about 10 % and will result in a higher N value, for example a value of 22 in sand. Also shown on Table 1 are the effects of not obtaining an 30-inch drop height (items #18 and 19) and the effect of backtapping the sampler (item #20).

As the rope gets old, burned, and dirty there is more friction on the cathead and across the crown sheaves (Table 1, item #14). This effect has not been studied, but we suspect energy effects less than 5%.

Automatic Hammers - Reclamation encourages the use of automatic hammers. These hammers are generally safer, and provide good repeatability. There are several manufacturers.

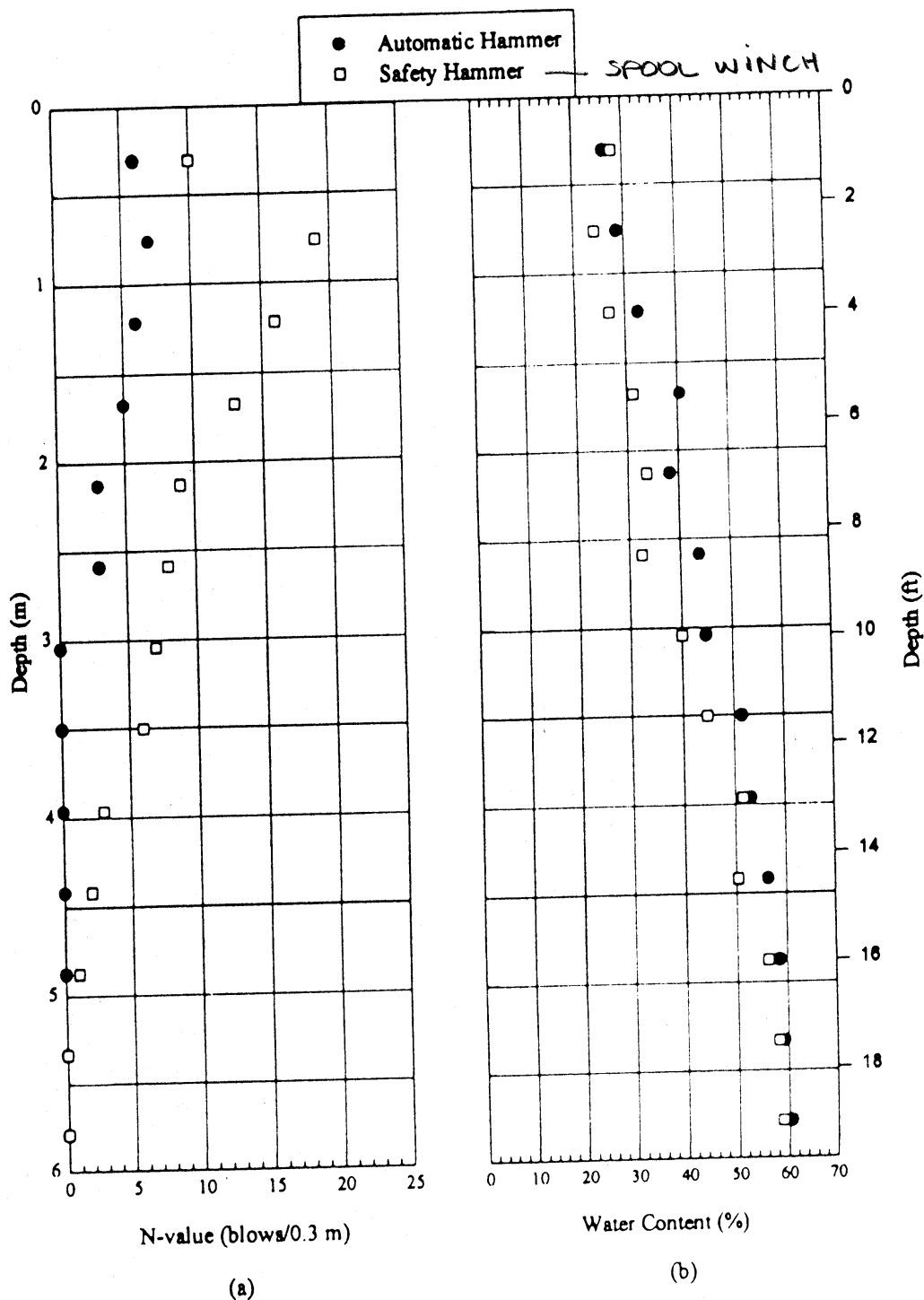
Central Mine Equipment (CME) made the first automatic hammer in the USA. This hammer uses a chain cam to lift the hammer. The hammer is enclosed in a guide tube. The chain cam is driven with a hydraulic motor. The drop height of this hammer depends on the chain cam speed and the anvil length. We have had numerous problems with this hammer system, primarily because the speed is not correctly adjusted. The hammer should be run at 50 to 55 blows per minute to obtain a 30-inch drop. There are flow control adjustments on the hammer and there is a slot on the side of the hammer casing where you can look at the hammer drop height. Be sure this hammer is providing a 30-inch drop by adjusting the flow control. The TSC will send out another operational bulletin on this hammer with more details.

The CME auto hammer is also designed to exert a down force on the rods. This down force from the assembly mass is about 500 pounds. A safety hammer assembly weights range from 170 to 230 pounds. In very soft clays, during the SPT, the sampler will sink under the weight of the assembly much easier with the automatic hammer. This effect is illustrated in Figure 6. Figure 6 shows much lower blowcounts in a very soft clay, due to the weight of the automatic hammer assembly. The safety hammer blows are higher, but be careful because the safety hammer was driven with an inefficient spooling winch system (see section to follow). In cases where this occurs it is advisable to try some tests with a safety hammer, and note these effects on the drilling log.

Another automatic hammer was manufactured by Foremost Mobile Drilling Company. This hammer “floats” on a wireline system. The drop mechanism is not rate dependent. One problem with this hammer is noise. If you have this hammer - hearing protection is required. Foremost Mobile has dropped production of this hammer because of the noise problem and now equips their drills with an automatic hammer manufactured by Diedrich Drill.

Energy transfer of some of these automatic hammers is significantly higher than rope and cathead operated hammers. The CME drill can deliver up to 95% energy. This could result in very low blows counts in sands (see Table 1 #16, N=14 in sand). Energy corrections are usually required for automatic hammers. The Mobile hammer is less efficient due to a large two piece anvil. There are not many measurements on the Diedrich hammer.

If you are going to use an automatic hammer, be sure you let the exploration team know, and be sure you report detailed information on it's use. For example, report make, model, blow count rates, and any other specific adjustments on the drilling log. Questions regarding use of automatic hammers can be directed to the Earth Sciences Laboratory, D-8340. In liquefaction investigations the energy transfer must be known. For some hammer systems such as the CME and Mobile we know the energy transfer - if they are operated correctly. But for some systems we may be required to perform energy measurements.



National Geotechnical Experimentation Site, Amherst, Mass.: (a) Uncorrected Blow Count Data; (b) Water Content Data

Figure 6 - Example of an automatic hammer and safety hammer in soft clay.

Spooling Winch Hammers

Mobile drilling developed a hammer called the “Safety Driver.” This hammer system used a sand line cable connected to an automated spooling winch with magnetic trip contacts. The contacts sensed when the hammer was lifted 30 inches, and then it dropped the hammer with the spool unrolling at the correct rate for the dropping hammer.

Energy measurements of this hammer system have shown that it is subject to extreme energy variations. Apparently the contacts and spooling systems required continual adjustment to operate correctly. This type of hammer system is not recommended for use due to energy transmission problems.

Figure 7 shows a comparison of 6 drills doing SPT at the same site in Seattle. Note that the use of the spooling winch system result in very high blow counts. These blow counts are not reliable for engineering evaluation.

Drill Rods

Reclamation began using NW rods for SPT in the early 1980's. Actually, for SPT's, any rod from AW to NW is acceptable for testing. There is some concern about whipping or buckling of smaller AW rods at depths greater than 75 ft. In these cases it is recommended to use BW rods or larger. There has never been a conclusive study that shows significant energy transfer losses in buckling.

There is not much difference in energy transfer between AW and NW rods. One estimate is that the differences are less than 10 % drill rod energy ratio. But there has not been any conclusive study which shows one rod is more efficient than the other. So, on Table 1 #9 we show N value ranging from 18-22 blows. This means that the type of rod only changes a blow count in sand by 2 blows. Recent work indicates that this effect may even be smaller. If you are tired of hauling that NW rod around, it would be acceptable to use AW or BW rod for testing.

SPT drill rods should be tight during testing. Often, with the new taper lock rods, we only hand tighten the joints and when we remove a string, we see some loose joints. Energy measurements on differing locations of the drill rods do not show significant energy loss on joints that are just 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. So - there is no need to wrench tighten joints unless a rod joint is really loosening during testing. What is really loose? Lets say more than a 1/8 inch gap when the rod is removed. Be sure to firmly hand tighten each joint so this is not a concern.

Drill Rod Length

When using very short rods, energy input to the sampler is terminated early due to a reflected wave. The engineers normally will take SPT at less than 10 feet and multiply it by a factor of 0.75. Actually, the early termination of energy is a problem to depths of 30 feet, but the correction is smaller, and it is often ignored. The energy termination is also a function of the size of the drill rods. On Table 1 Items # 11 and 12 illustrate the higher N values which occur at shallow depths.

What about those jobs where you are on a 300 foot tall embankment drilling through the shells? Ever wonder if the energy makes it all the way down the rods? Well there are some losses, and a correction will be made for drill rods greater than 100 ft. At this time we are not sure if there differences between AW and NW rods. The deeper we drill, a sand at the same density will have increasingly higher penetration resistance. This is because the confining pressure increases in the ground mass. On Table 1, item #10, we show an SPT N value in sand of 18, which does not account for the increase due to the confining pressure, and it means that there was a 10% reduction in energy from 100 to 200 ft depth.

Human Factors

The SPT is highly dependent on the training, professionalism, and attention of the whole crew, especially the driller. If you are in a hurry, cold, wet, upset, hungover, angry, etc., the results can vary in large and un-measurable ways.

Your attitude is very important. If you are in a hurry to complete a job and go home, the tendency is to overlook many of the problems we have discussed in this paper. You are encouraged to be sure all problems are noted and discussed in your reports.

Reclamation drilling operations are a team effort. It is important that geologist and drilling staff work to together to obtain the highest quality data possible. Try to be cognizant of the factors we have discussed in this paper. If there are ever uncertainties on the quality of the data be sure to discuss these problems with your supervisors or the exploration team requesting the drilling.

SUMMARY - HOW GOOD IS THE SPT TEST?

The SPT is a very difficult test to perform and the engineer is posed with serious decisions on how to use the data you provide him. Just how reproducible is the SPT in practice? Figure 7 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 we asked to drill SPT's at the same site. Six drills were used. Some had safety hammers, and other had automatic hammers. One drill was equipped with a 300 lb 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, and this supports our recommendations not to use these systems. Looking at the graph one wonders how an engineer could even utilize this test for design purposes!

The variability of SPT in Reclamation drilling, can be much better if our staff is aware of the problems with the test. It is hoped that this paper will help make our testing much more reliable than the example given above. This can only be accomplished with careful attention to equipment and procedures when performing the test.

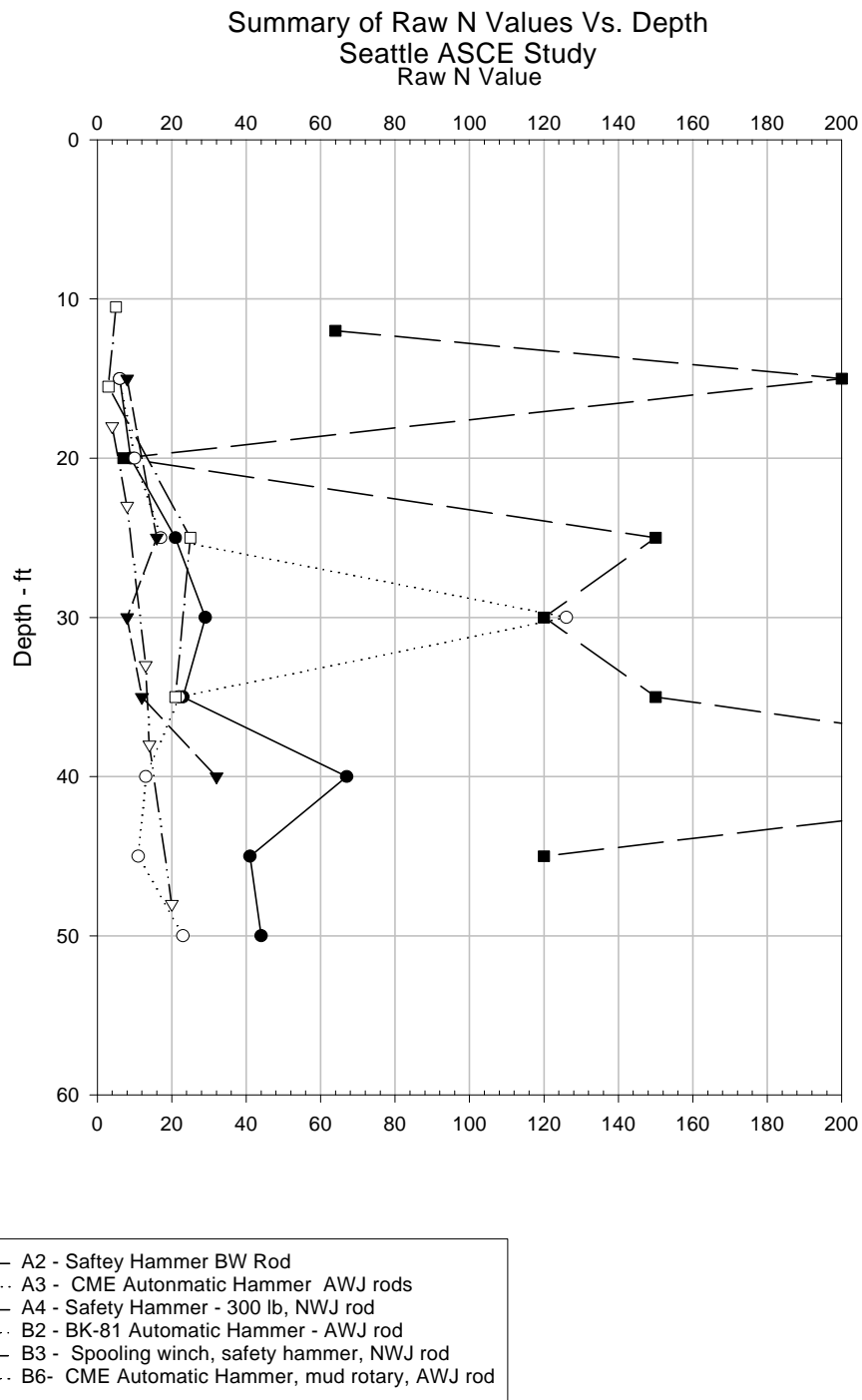


Figure 7 - Results of SPT with six different drills - ASCE Seattle study.

CONCLUSIONS

In this report we have tried to review many of the important aspects of SPT testing. The SPT is used extensively by Reclamation. One of the more important applications is the use in our Safety of Dams investigations. It's up to you our field staff to be sure the SPT is performed correctly.

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. Hollow-stem augers, and casing advancer systems have also been successfully used.

The drilling part of SPT is the most important. **Generally, disturbance from improper drilling technique results in lower N values.** It's up to you to give us the best drilling possible. Perform the quality checks to be sure disturbance does not occur. Report all cases of disturbance.

We have also discussed some procedure issues, such as testing intervals, blow count rate, limiting blow counts, and recording of partial penetration. The effects of changing technique are not always well known.

Issues regarding the sampler are addressed. Users should carefully order and inspect sample barrels. We have recommended increased venting capability.

Energy transfer effects can be important especially if we use highly efficient automatic hammers. We are currently having difficulty with energy measurements but you will see more of these measurements in the future.

And always, if there are questions please contact your drill foreman, the exploration team, or us at the Earth Sciences Lab if you have any questions.