# LIQUEFACTION EVALUATION OF A DAM FOUNDED ON SLIDE DEBRIS USING BECKER PENETRATION TESTS

by

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ABSTRACT

A review of construction records led B.C. Hydro's dam safety engineers to suspect that slide debris, which was used as fill and also to be found in the foundation of an earthfill dam of the Cheakamus Project, may be susceptible to liquefaction during earthquake loading. Several attempts, in 1983 and 1984 using conventional field testing methods, failed to quantify the liquefaction potential of the cobbly sand and gravel slide debris.

A new field testing procedure, the Becker Penetration Test (BPT), had been recently developed under the direction of Dr. H.B. Seed at the University of California to determine the liquefaction potential of a sand and gravel slope that had liquefied in Idaho. The soil in this slope is similar to the slide debris at the Cheakamus Project.

A test program was first performed at a test site in Squamish using two Becker drills, one similar to the one used in Idaho and the one normally used in B.C. Several mud rotary holes were also drilled, in which Standard Penetration Tests (SPT) were performed. Sufficient data was obtained in this test program to develop correlations to convert BPT information into equivalent SPT data.

Following the Squamish test program, thirteen BPT holes were drilled at the Cheakamus Project. The equivalent SPT data was then used to determine the liquefaction potential of the dam and foundation using empirical methods developed by Dr. Seed.

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## INTRODUCTION

Ongoing dam safety studies at B.C. Hydro required the determination of the liquefaction potential of well graded slide debris underlying and comprising part of Daisy Lake Earthfill Dam of the Cheakamus Project.

The Cheakamus Project, completed in 1957, is situated 110 km north of Vancouver, near the ski resort of Whistler, as shown on Fig. 1. The project consists of a number of dams which impound the water of the Cheakamus River to form Daisy Lake and Shadow Lake, an 11 km long tunnel and a 140 MW powerhouse situated on the Squamish River.

Daisy Lake Dam is the largest of the project dams, and consists of earthfill and concrete gravity dam sections as shown on Fig. 2. The earthfill dam section is approximately 460 m long with a maximum height of 29 m.

Landslide material was used to construct the earthfill section of and also forms it's foundation. The landslide material consists of a well graded silty sand and gravel matrix surrounding cobble and boulder particles. During a review of the dam's safety in the early 1980's it was decided that, because of the fine sandy matrix and its behaviour during placement in the embankment, portions of the soil could be subject to liquefaction during large earthquakes.

As a result, liquefaction investigations were carried out in 1984 and 1985 using in situ density testing and SPT testing. However, due to the coarse nature of the slide debris, the results obtained were limited and had a wide scatter, and were therefore considered inconclusive.

In 1986, with the assistance of Dr. H.B. Seed of the University of California, Berkeley, an in situ testing program using the Becker hammer drill was carried out at the dam.

This paper describes the Becker Penetration Test (BPT) and it's use in assessing the liquefaction potential of the soils at Daisy Lake Dam.

## SITE DESCRIPTION

The earthfill section of Daisy lake Dam is founded on a thick deposit of slide debris from an active slide area called the Barrier. The Barrier, located at the head of a tributary valley a short distance downstream of the dam, is a 200 m high near vertical cliff of volcanic rock deposited during an eruption of Clinker Mountain at a time when the Cheakamus and tributary valleys were infilled with glacial ice. Several catastrophic failures of the Barrier have occurred with the most recent being in 1855.

The earthfill section of the dam was founded on the thickest area of the Barrier slide debris (locally referred to as Rubble Creek wash) as this debris provided a more impervious foundation than the surrounding highly fractured basalt. The basis of the site selection and the difficulties encountered while constructing the dam on the slide debris are described in a report by Dr. K. Terzaghi (1954).

The earthfill section consists of a large impervious zone separated from a downstream rockfill toe by transitional material and filters as shown on Fig. 3. The impervious zone consists of Rubble Creek wash compacted in 0.6 m lifts.

## SOIL DESCRIPTION

Rubble Creek wash is a very well graded non-sorted andesitic sand and gravel with some cobbles and boulders and a trace of silt (GW-GM). The soil was deposited during a catastrophic failure of the Barrier and has not been reworked by either ice or water. Terzaghi[1] noted that the slide material, at the time of the slide, had the consistency of very wet concrete. It flooded the forest and there is evidence it flowed around some trees without breaking them. However at the toe of steep slopes accumulations of broken trees were observed.

Observations made in dam exploration records in 1954 regarding the density of the Rubble creek wash included:

> ...casings for the drillholes could be driven with ease by rapid strokes of the hammer to depths of more than 15 m below the surface of the Rubble Creek wash although the wash contains many stones with a diameter greater than that of the casing.
>
> ...in the bulldozer cuts it was noticed that a slight admixture of moisture suffices to convert the material again into a state of a thick slurry which flows like a glacier.

Various permeability tests in 1954 concluded that the Rubble creek wash has a permeability of about $10^{-4}$ cm/sec except for much higher values observed in contact zones around the perimeter of the slide.

It was also reported that in order to overcome the potential for segregation of the Rubble Creek wash fill, the fill in the lower portion of the dam was placed as a slurry by vibrating the fill with a bulldozer.

## LIQUEFACTION CONCERN

The Rubble Creek wash foundation and portion of earthfill dam placed in a slurry state was considered to have the potential for liquefaction because the soil is loose and non-cohesive. When shaken high pore pressures would be generated and would not rapidly dissipate because of the soil's low permeability.

Detailed field examination of exposures of Rubble Creek wash shows that a silty sand matrix completely envelopes the larger particle size. It is probable that this matrix will control to a large degree the liquefaction potential of the soil. Field examination suggests that the matrix has an upper size of a #10 sieve.

## THE BECKER PENETRATION TEST(BPT)

Dr. H.B. Seed was retained in 1984 by B.C. Hydro to provide assistance in developing a procedure to assess the liquefaction potential of both the embankment fills and foundation. As mentioned in the introduction, previous investigations involving in situ density testing (water displacement), Standard Penetration Test (SPT) testing (counting blows per inch and correcting for gravel) and some Becker drilling had provided limited and relatively inconsistent data.

A procedure for using a Becker hammer drill to obtain equivalent SPT blowcounts was under development at the time by Dr. Seed and Leslie F. Harder, Jr. and was completed in 1986 (Harder and Seed, 1986. The Becker Penetration Test (BPT) is a large scale penetration test suitable for testing soils containing gravel particles and/or cobbles.

The BPT, as developed by Dr. Seed for use in the United States, involves the use of a supercharged Becker AP-1000 drill rig driving 168 mm O.D. double-walled casing into the ground. During the BPT, the number of hammer blows required to drive the casing and the average peak air pressure generated in the bounce chamber of the diesel hammer are recorded for each 305 mm of drilling. Using this data, the BPT blowcounts are converted into equivalent SPT blowcounts, which can then be used to determine the liquefaction potential of the soil using conventional methods.

As drill rigs and equipment used to develop the BPT in United States differed significantly from the Becker drill and equipment normally used by B.C. Hydro and others in B.C. it was decided that, prior to performing BPT testing at Daisy Lake Dam, a calibration test program would be carried out. By performing SPT and BPT testing (at the calibration site), with the drills normally used by B.C. Hydro and also with a supercharged Becker AP-1000 drill similar to the US drill it would be possible to establish correlations between the SPT and BPT for the two types of Becker drill rigs.

A calibration test site was selected in uniform deltaic sands at Squamish, British Columbia. A total of 6 SPT holes, 4 BPT holes using the local Becker HAV-180 and 4 BPT holes using the AP-1000 rig were drilled as shown on Fig. 4.

The SPT tests were performed using a mud rotary drill with a rope and cathead used for lifting the hammer. The hammer weighed 60.1 kg (132.3 lbs) and 2½ wraps of the rope around the cathead was used to give a measured rod energy ratio (ER) of 37.3%. The SPT results were converted to a rod energy ratio of 60% using the formula:

$$N_{60} = (ER/60) \times N$$

where $N_{60}$ = Equivalent SPT blowcount obtained using a rod energy equal to 60% of the free-fall energy of a 63.6 kg (140 lb) hammer falling 762 mm.

$ER$ = The measured rod energy ratio during the testing.

$N$ = Measured SPT blowcounts.

The energy measurements were performed for B.C. Hydro by the University of British Columbia.

The analysis of the BPT data involves the concept of the Constant Combustion Condition Rating Curve (Harder and Seed, 1986). The basis of this curve is that the combustion condition of a diesel hammer is not constant and can be influenced by fuel quantity and quality, atmospheric pressure and temperature, throttle setting and the penetration resistance of the ground.

To monitor the level of energy generated by the diesel hammer, the air pressure produced in the bounce chamber of the hammer is recorded. The air pressure in the bounce chamber acts as a spring returning the piston back to a firing position. Harder and Seed (1986) developed for the US AP-1000 drill a correction curve, based on field data and theoretical ratios of impact kinetic energy, to correct the Becker blowcounts for energy effects. The curve, as shown on Fig. 5, marked with symbols AA, is used to make corrections to the blowcounts for different combustion conditions.

At the Squamish test site, data was obtained to produce similar Constant Combustion Rating Curves for the two Canadian drills. Both drills were operated at full throttle setting and at a reduced throttle setting that represents less than efficient operation of the hammer. All blowcounts and corresponding bounce chamber pressures were plotted for the AP-1000 and HAV-180 drills as shown on Figs. 6 and 7 respectively.

Using the constant combustion curves for the two drills used at the test site, the Becker blowcount data was corrected for constant combustion. The corrected Becker blowcounts were then compared to the SPT results at the similar sampling depths and a correlation between Becker blowcounts and SPT blowcounts for the two Becker drills corrected was established as shown on Figs. 8 and 9.

## BECKER PENETRATION TESTS AT DAISY LAKE DAM

In April 1986 fourteen holes were drilled at Daisy Lake Dam using the two different Becker rigs. Approximately 900 blowcounts and corresponding bounce pressure readings were obtained during the drilling.

As the Constant Combustion Rating Curves developed for the Becker drills at the Squamish test site were for standard sea level pressure it is necessary to correct the bounce chamber data when BPT tests are performed at atmospheric pressures significantly different than sea level. During drilling at Daisy Lake Dam the atmospheric pressure was 972 mb, compared to sea level pressure of 1013 mb. To correct for this lower atmospheric pressure the bounce chamber data was increased by about 69 mb. (The actual amount of increase is determined by using theoretical ratios of impact energy.)

Once the atmospheric pressure corrections were made the Becker blowcounts were corrected for constant combustion efficiencies using the appropriate Constant Combustion Rating Curve. After these corrections were made, equivalent SPT blowcounts were obtained using the correlations between corrected Becker blowcounts and SPT blowcounts.

A final correction was applied to the equivalent SPT blowcount data obtained for depths of less than 3 metres. This correction consists of reducing the penetration resistance by 25% to allow for the effect of tension wave cut-off of energy due to the short casing length.

By way of example, a 305 mm column of soil at a depth of 29 m in the foundation of the earthfill dam, near its contact with the Main Concrete Dam was found to have a Becker blowcount of 14 blows/305 mm with a bounce chamber pressure of 827 mb. The bounce chamber pressure was corrected to 889 mb when converted to sea level pressure and, using the Constant Combustion Rating Curve, the Becker blowcount was corrected to 8½ blows/305 mm which equated to an SPT $N_{60}$ of 8½ blows/305 mm.

## LIQUEFACTION POTENTIAL

The potential for liquefaction of the slide debris was assessed by comparing the cyclic resistance of the slide debris to the shear stresses which would be induced in the foundation and embankment during the maximum design earthquake. As Daisy Lake dam has a high hazard classification* the maximum design earthquake was selected as the Maximum Credible Earthquake. It's estimated that this earthquake would produce a peak horizontal acceleration on bedrock at the dam site of 0.20 g.

The Cyclic Resistance Ratio (CRR) of the slide debris was obtained empirically using established relationships with the SPT blowcount.

Briefly, the procedure was as follow:

(a) Obtain equivalent SPT blowcounts, at 60% of the theoretical hammer energy, from the Becker data as previously described.

* Refers to downstream hazard from a dam breach and not to the condition of dam.

(b) Correct the SPT blowcounts for an effective overburden pressure of 95.8 KPa. This corrected blowcount is referred to as $(N_1)_{60}$. For Daisy Lake Dam a finite element program (ISBILD) was performed to determine the effective "overburden" stress in the dam with the reservoir at the level it was when the Becker drilling was carried out.

(c) Obtain the CRR using $(N_1)_{60}$ results and the fines content of the soil using established empirical relationships (Seed et al 1985). A Magnitude 7.5 earthquake was used to determine the number of significant cycles of earthquake accelerations.

The fines content (minus #200 sieve) of the slide debris is between 5 and 10% of the total weight of the soil. However the fines content of the fine matrix, which is believed to control the liquefaction resistance of the soil, is about 30%. This higher value was used in the empirical correlations.

(d) The CRR was corrected to make allowances for both the level of confining stress and shear stress within the embankment as suggested by Seed (1983, 1986). Parameters $K\sigma$ and $K\alpha$ were selected from Seeds charts and the CRR corrected by multiplying by both correction factors.

Using the previous example the $N_{60}$ of 8½ blows/ft was corrected using an overburden correction, CN, of 0.42, to give an $(N_1)_{60}$ of 3.6 blow/ft. From Seed's charts for silty soils the CRR was found to be 0.08. The parameters $K\sigma$ and $K\alpha$ were 0.84 and 1.0 respectively, giving a corrected CRR of 0.07.

The cyclic shear stresses that would be induced in the foundation and embankment during the design earthquake were determined using the computer program "SHAKE", which was a one-dimensional shear wave propagation method. The input earthquake record used in the SHAKE analysis was obtained on bedrock at the Caltech Seismological Laboratory in Pasadena, California during the February 9, 1971 San Fernando Earthquake. The East-West component of the record was used and the peak acceleration of 0.192 g was linearly scaled to 0.20 g.

The peak shear stresses obtained from the SHAKE analysis were multiplied by 0.65 to give an average shear stress. The Cyclic Stress Ratio (CSR) was determined by dividing this average shear stress by the effective overburden pressure. The factor of safety against liquefaction is the ratio CRR/CSR.

Using the previous example, the SHAKE analysis indicated the soil element in the foundation near the Main Concrete Dam would experience a peak shear stress of 41.1 kPa with an effective overburden pressure of 347 kPa giving a CSR of 0.077. The factor of safety of the example soil element is 0.070/0.077 or 0.91, indicating liquefaction under the design earthquake.

The data obtained from the fourteen Becker drill holes was analysed and it was found that only the portion of the earthfill dam and foundation adjacent to the Main Concrete Dam could be susceptible to extensive liquefaction. Rehabilitation studies are currently in progress to either densify or reinforce this limited portion of the dam.

## SUMMARY


Several attempts, using conventional soil testing techniques, to quantify the liquefaction potential of Rubble Creek wash underlying Daisy Lake Earthfill Dam gave inconclusive results.

The BPT Test was adopted by B.C. Hydro to test the soil as the large diameter casing driven by a diesel hammer would help to overcome the influence of gravel and cobbles.

The BPT; as developed by Dr. Seed and others at the University of California, Berkeley; employed a model of Becker hammer different from that normally used in B.C. Therefore a correlation was required between the two models of Becker drills for the BPT and the SPT Test. A calibration test program in Squamish lead to the development of Constant Combustion Condition Rating Curves for both Becker drills, so that the Becker blowcounts could be corrected for the operating efficiency of the diesel hammer. Correlation curves between corrected BPT blowcounts and SPT blowcounts were also developed from the test program.

Fourteen holes were drilled at Daisy Lake Earthfill Dam and the Becker data obtained was converted to equivalent SPT data. A liquefaction assessment of the earthfill dam and foundation using the equivalent SPT data concluded that one portion of the dam could liquefy during the design earthquake.

Notwithstanding the potential uncertainties and the assumptions associated with the above testing and analytical work, it is believed that there is a fair chance that the maximum design earthquake would cause liquefaction of portions of the Daisy Lake Earthfill Dam which in turn could lead to failure of the dam. Rehabilitation studies are presently underway to investigate methods of densification and reinforcing the slide material.

## REFERENCES


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4. Seed, H.B., Tokimatsu, K., Harder, L.F. and Chung, R.M., (1985). "Influence of SPT Procedures in Soil Liquefaction Resistance Evaluations", Journal, Geotechnical Engineering Division, ASCE, Vol. III, No. 12, December 1985.

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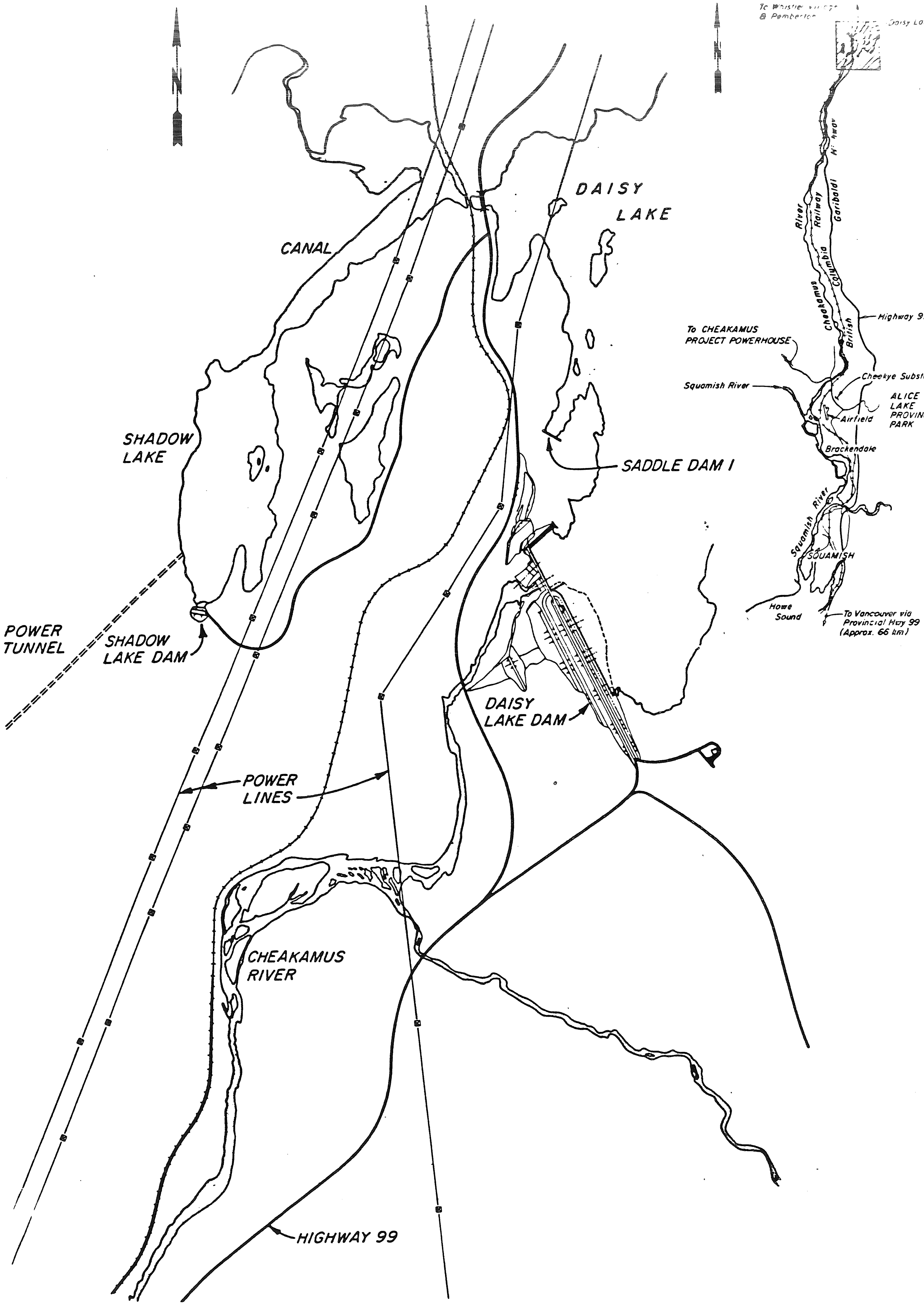



FIG. I
AREA MAP & GENERAL ARRANGEMENT

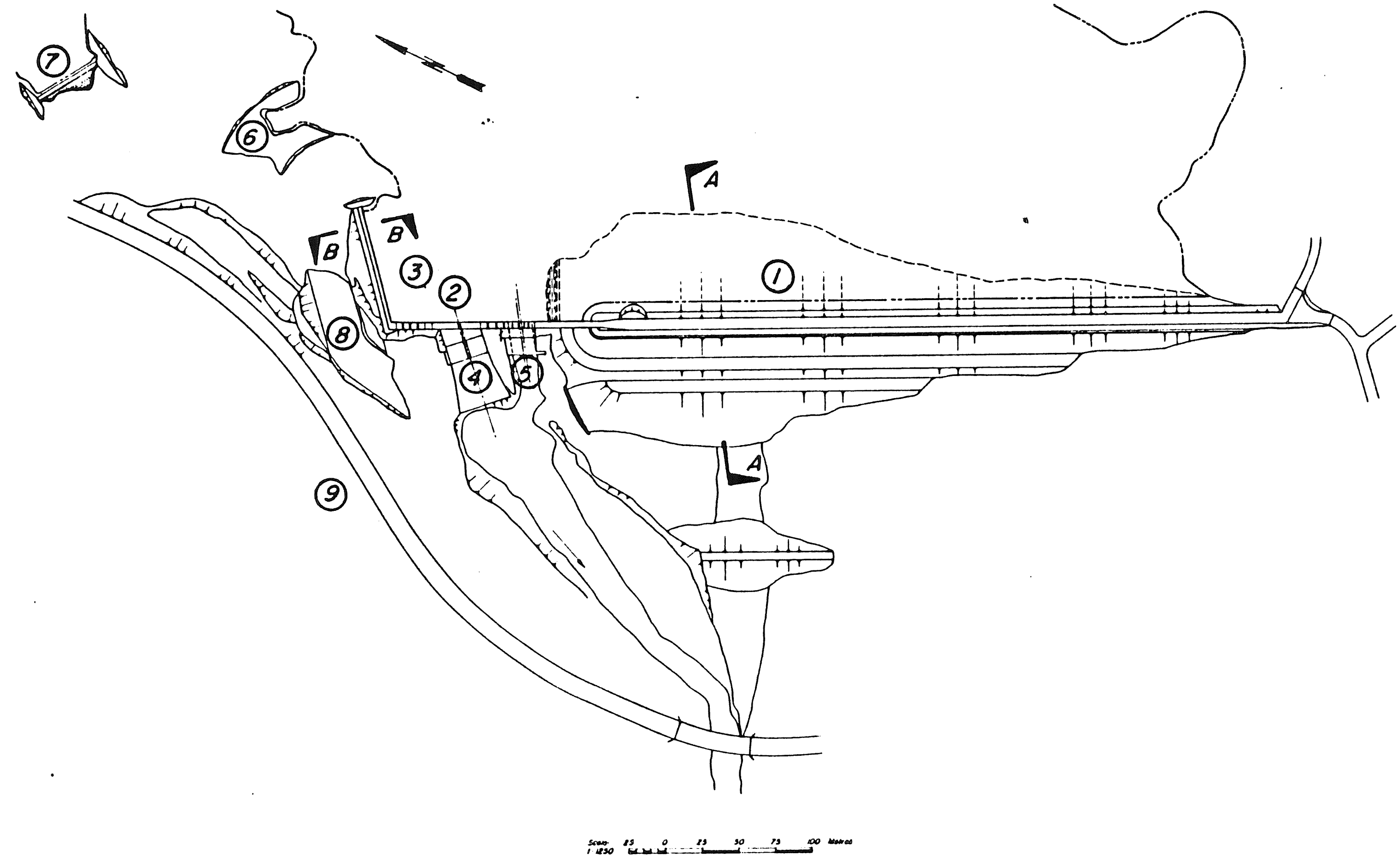



FIG. 2
DAISY LAKE DAM

(1) EARTHFILL EMBANKMENT
(2) MAIN DAM
(3) WING DAM
(4) SPILLWAY
(5) SLUICE
(6) OVERFLOW CHANNEL (ORIGINAL LOCATION OF SADDLE DAM 2)
(7) SADDLE DAM 1
(8) SIDE DISCHARGE CHANNEL
(9) HIGHWAY 99

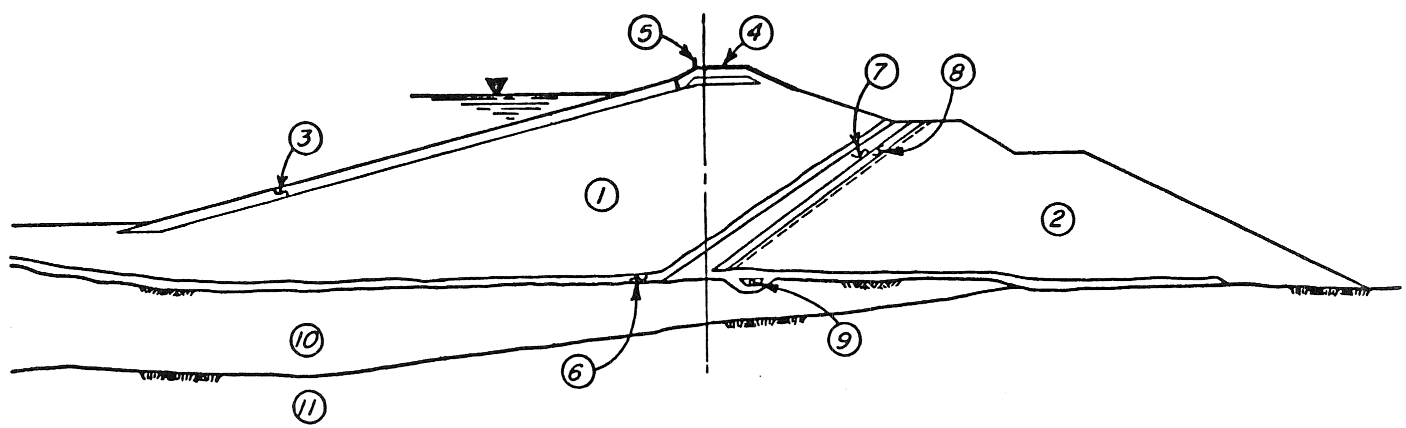
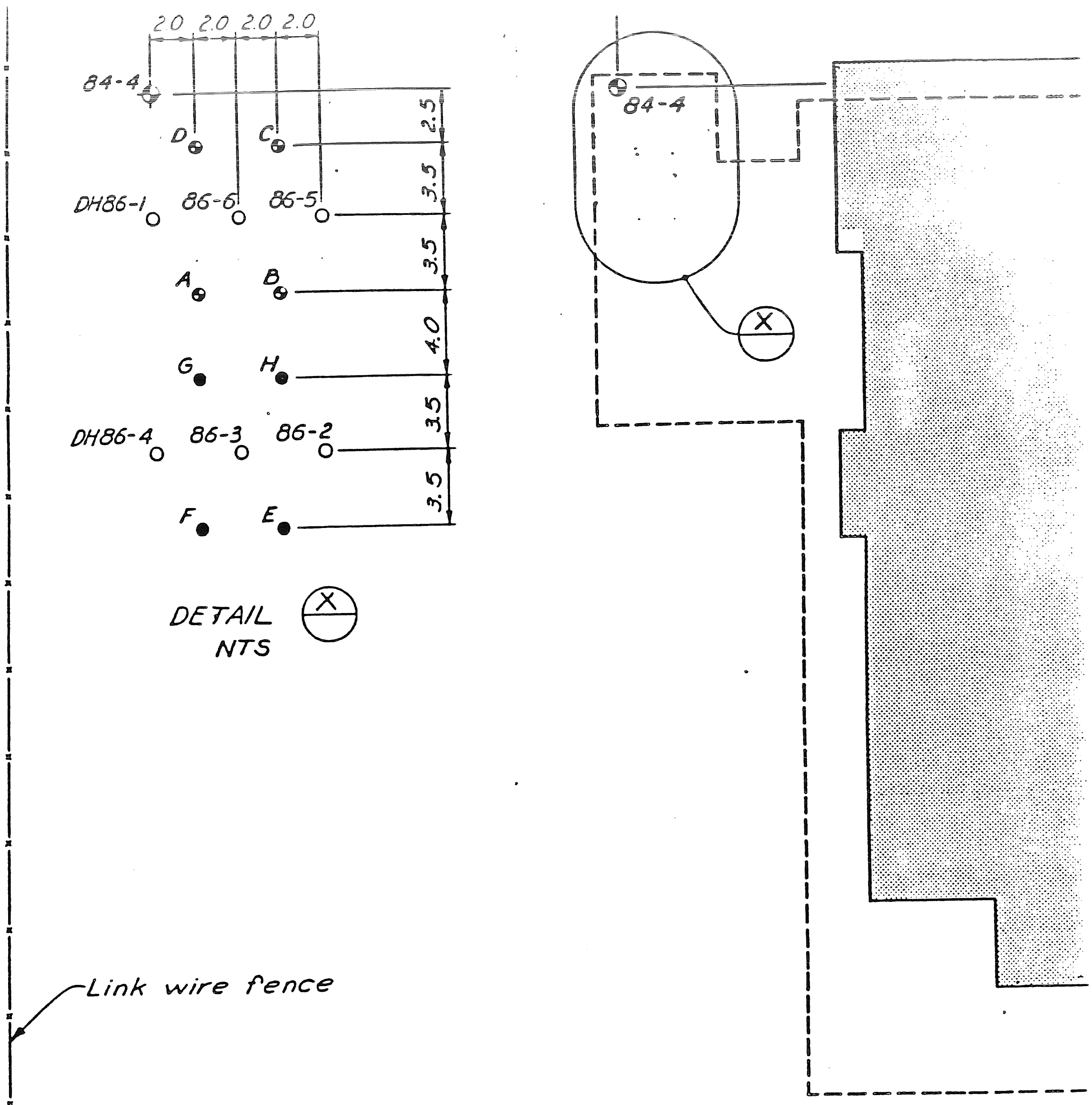



FIG. 3

EARTHFILL EMBANKMENT - SECTION A-A

1. IMPERVIOUS FILL - (COMPACTED SLIDE DEBRIS)
2. ROCKFILL
3. RIPRAP
4. CONCRETE CAP (0.15 m THICK)
5. SPLASH BARRIER
6. 'PREMIUM' IMPERVIOUS FILL
7. FINE FILTER
8. COARSE FILTER
9. DRAIN
10. FOUNDATION (SLIDE DEBRIS)
11. BEDROCK FOUNDATION




**DESCRIPTION OF HOLES**

| Hole No. | Type of Drill | Description |
|---|---|---|
| A | Becker HAV-180 | Full Throttle |
| B | | Full Throttle |
| C | | Full Throttle |
| D | | Reduced Throttle |
| E | Becker AP-1000 | Full Throttle |
| F | | Reduced Throttle |
| G | | Full Throttle |
| H | | Full Throttle |
| DH86-1 | | |
| -2 | | |
| -3 | Mud Rotary | SPT |
| -4 | | |
| -5 | | |
| -6 | | |

Figure 4: General Layout of Drill Holes at the Squamish Test Site

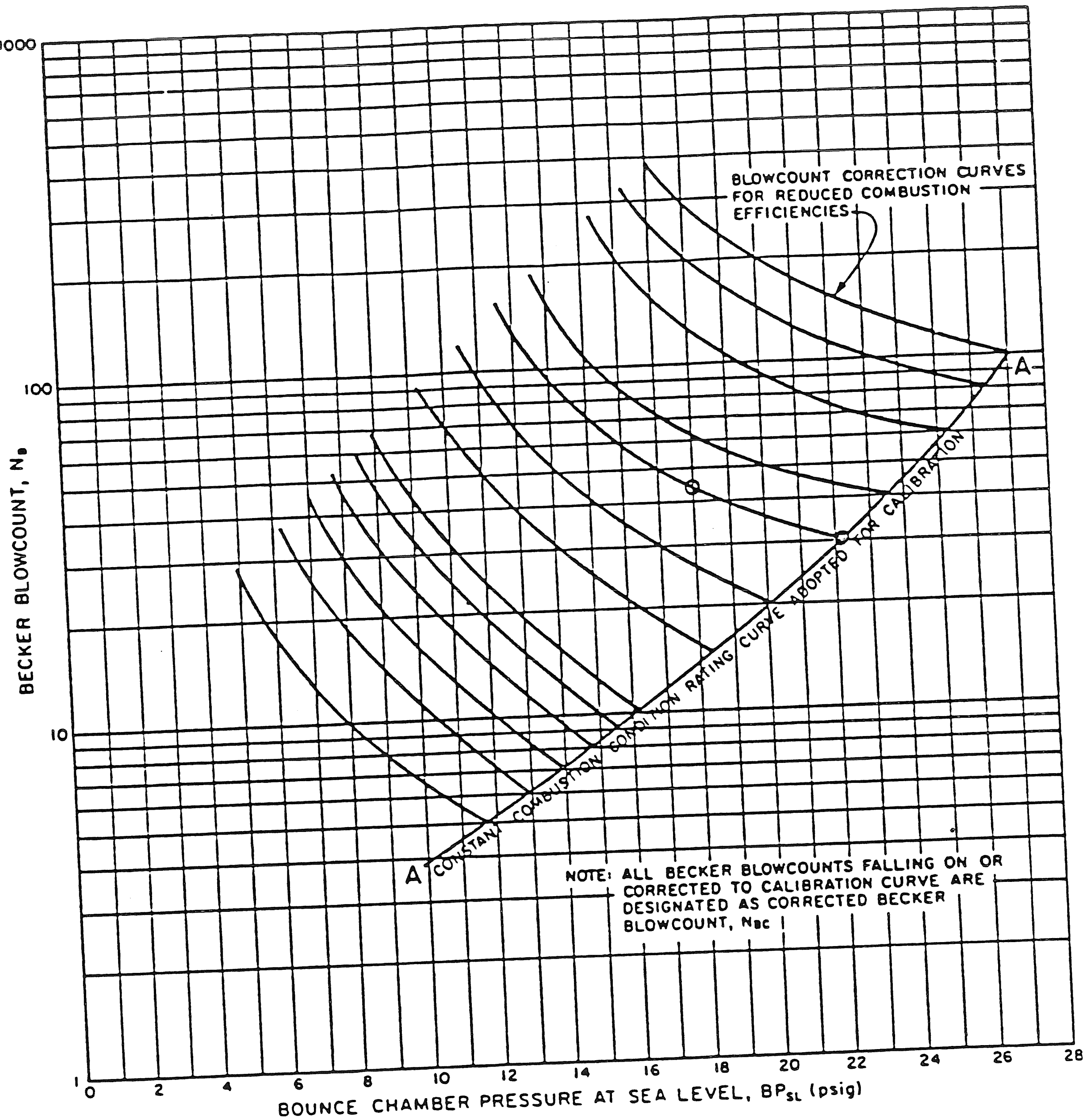



Figure 5: Correction Curves Adopted to Correct Becker Blowcounts to U.S. AP-1000 Full Throttle Constant Combustion Conditions (after Harder and Seed, 1986)

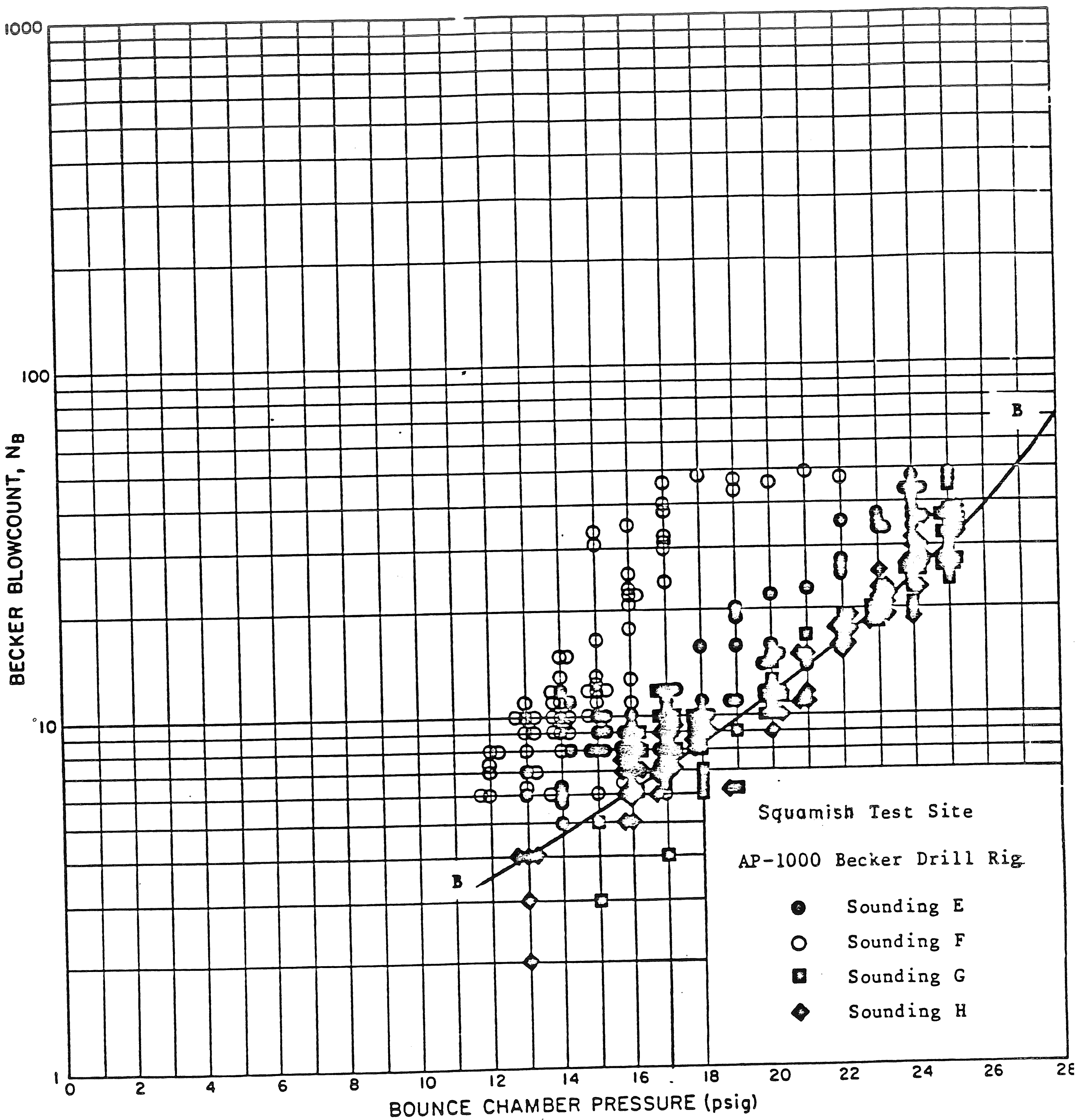



Figure 6: Becker Blowcount Data for Full and Reduced Throttle Conditions Obtained with AP-1000 Drill Rig at Squamish Test Site (after Harder, 1986)

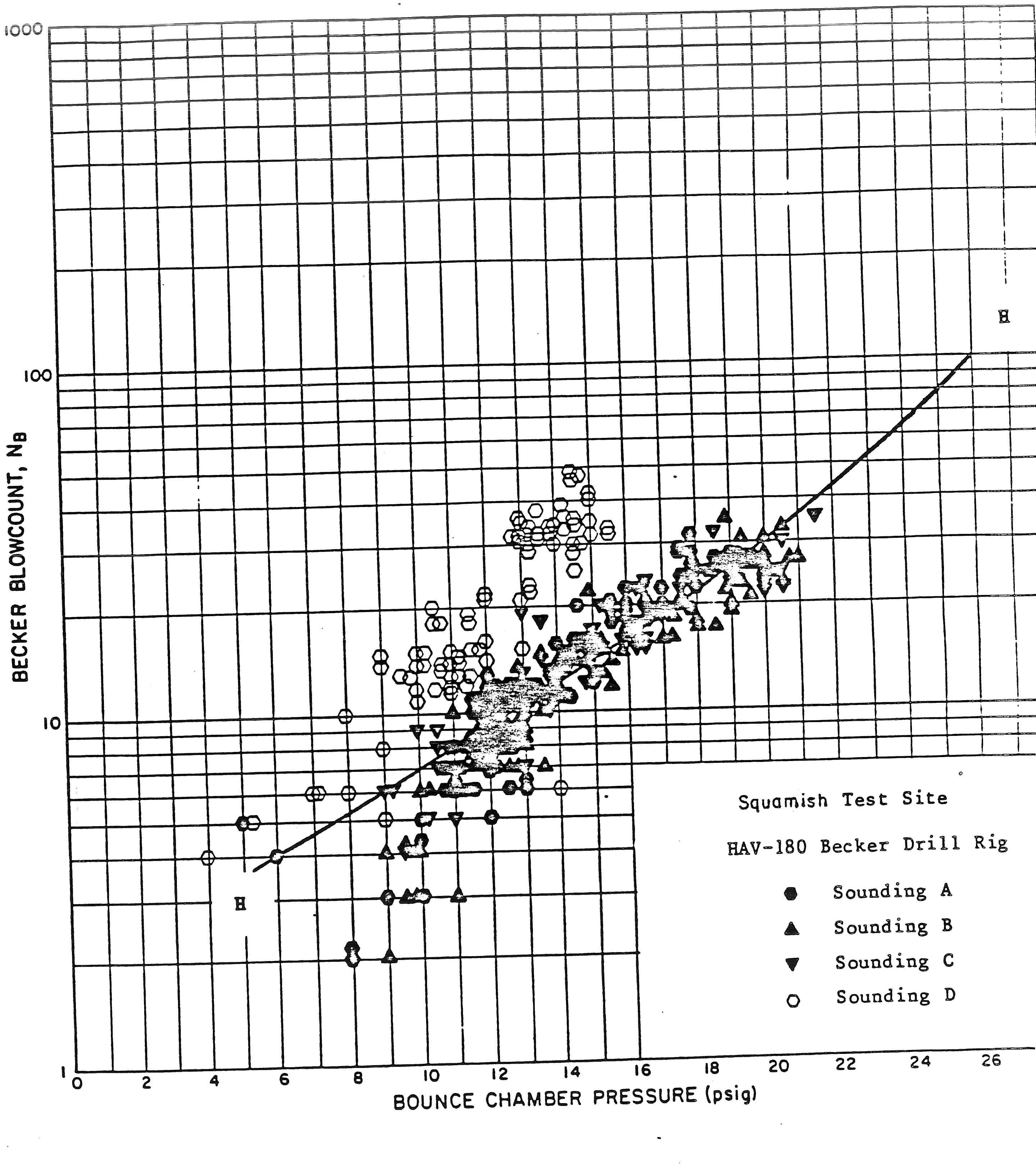



Figure 7: Becker Blowcount Data for Full and Reduced Throttle Conditions Obtained with HAV-180 Drill Rig at Squamish Test Site (after Harder, 1986)

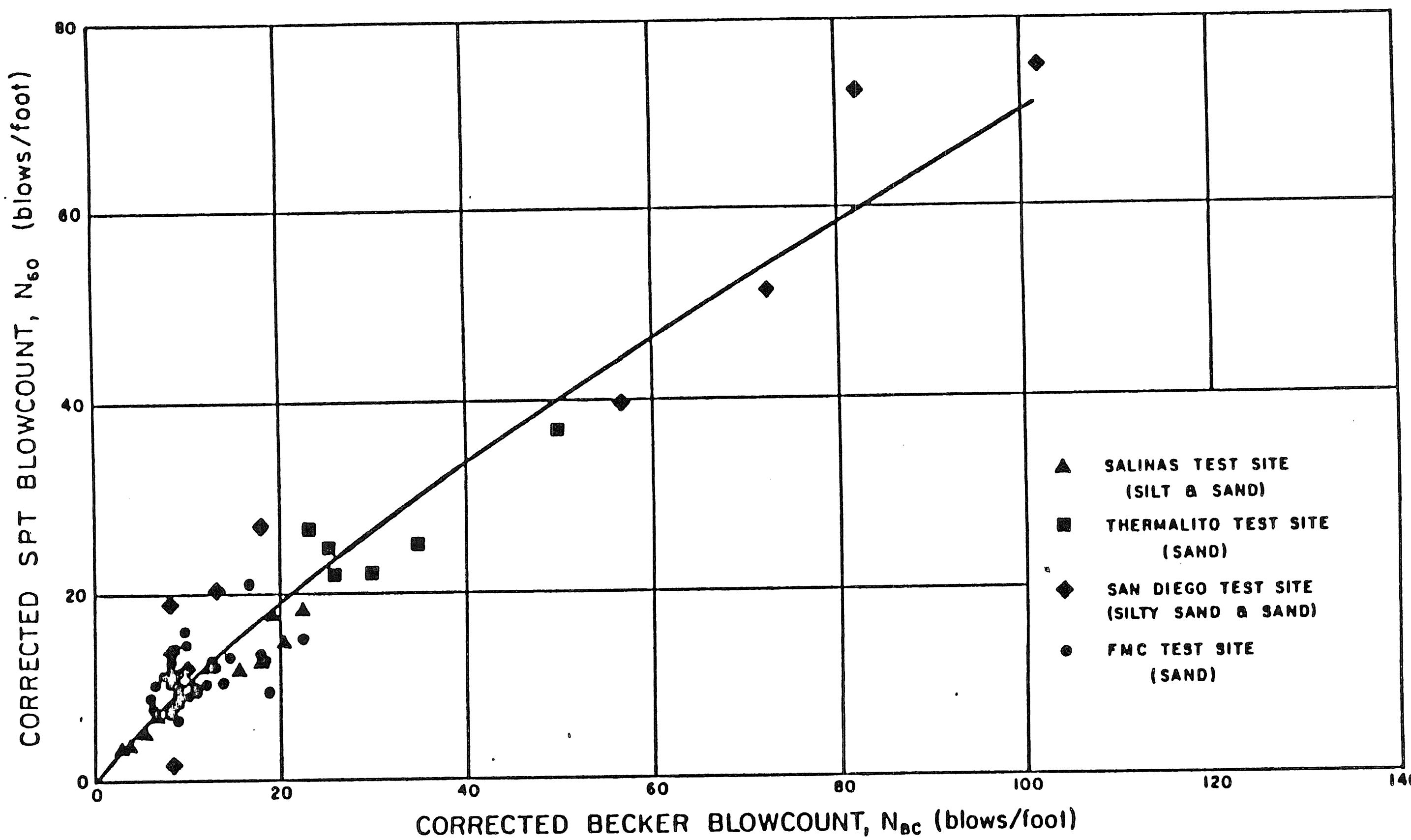
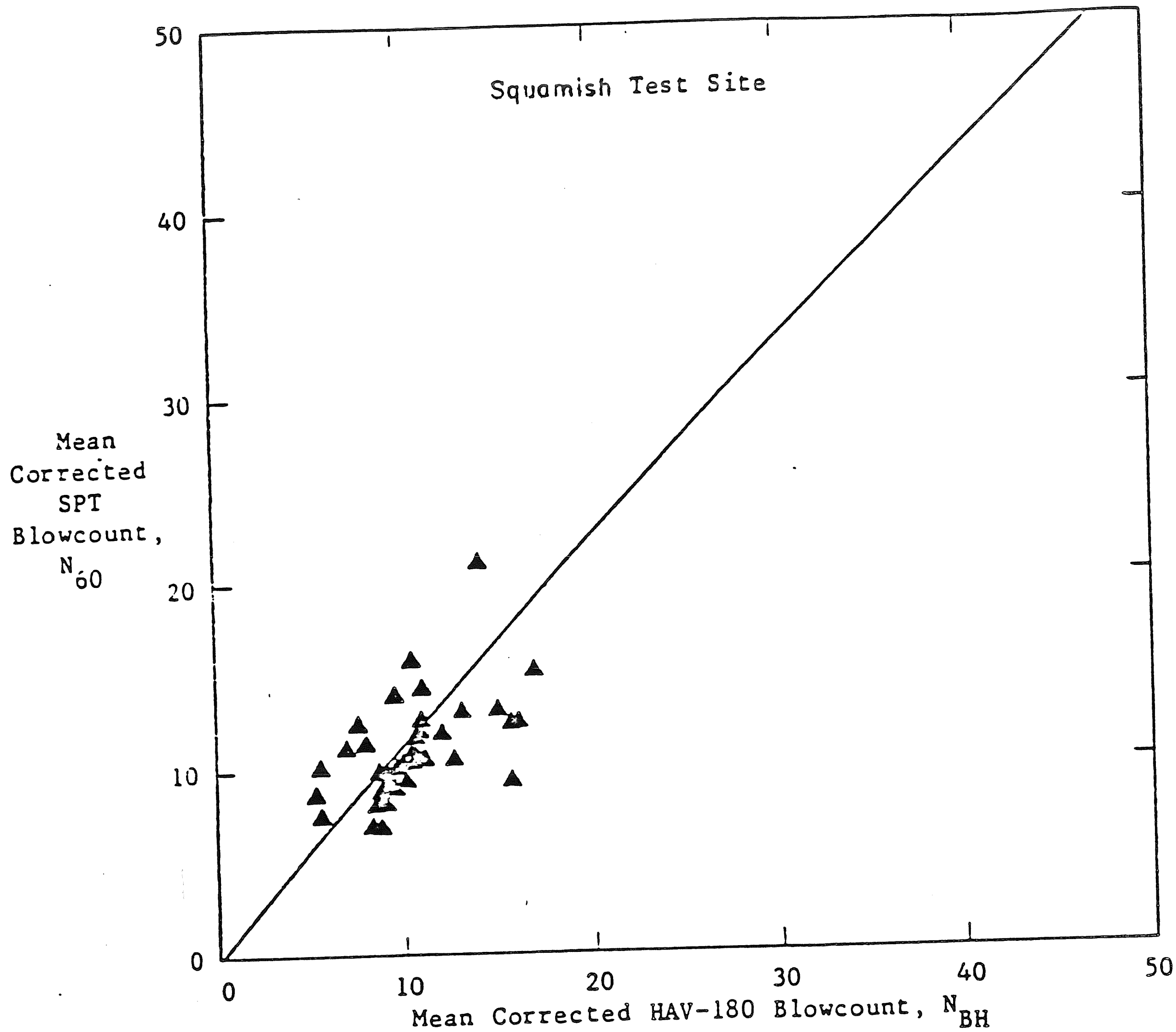



Figure 8: Correlation Between Corrected SPT and AP-1000 Becker Blowcounts (U.S. Rating Curve) Supplemented with Data Obtained at the Squamish Test Site (after Harder, 1986)




Note: $N_{BH}$ denotes HAV-180 Becker blowcount corrected to the FMC HAV-180 full throttle rating curve (Curve HH).

$N_{60}$ denotes SPT blowcount corrected to 60% of the free-fall energy of a 140-lb. hammer falling 30 inches.

Figure 9: Correlation Between Corrected SPT and HAV-180 Becker Blowcounts (Squamish Rating Curve) Developed with Data Obtained at the Squamish Test Site (after Harder, 1986)