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Pattern recognition approach to evaluation of liquefaction potential: Exploration of Buller sites

Dou Yiqiang, J B Berrill, University of Canterbury

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RESEARCH REPORT

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1 INTRODUCTION

Since November 1989, a research project aimed at applying the pattern recognition technique to the problem of estimating soil liquefaction potential has been in progress at the University of Canterbury. This report describes results of the first stage of the project, the acquisition of field data for the calibration of the pattern recognition model.

The aim of our research is not only to conduct an exploration of liquefaction sites in the Buller region, but also, more importantly, to develop a new approach to the evaluation of soil liquefaction potential. The new approach is based on the hypothesis that any layer of soil suffering seismic load which has similar characteristics (soil properties, environmental factors, earthquake characteristics) to soils at other sites which have experienced past earthquakes, will behave in the present earthquake as they behaved in the past. In other words, the new approach is a kind of field performance approach. The new approach needs to solve two aspects of the problem: (1) how to characterize efficiently soils that have suffered seismic load, (2) how to perform a precise similarity comparison for soils in different states. Our research was designed to solve the problem in the following two steps: (1) setting up an information base which should contain as much information from historical liquefaction cases as possible; (2) developing a recognition system based on the information obtained to provide a reliable liquefaction evaluation for the soils of interest.

This report describes the first step: the field exploration of liquefaction sites, to set up an information base which can be used to design a recognition system for the evaluation of soil liquefaction potential. In order to set up a reliable information base, we need not only to utilize all of the current information about the liquefaction, but also to conduct investigations at both liquefied and unliquefied sites in regions of different shaking intensity in historical earthquakes.

The Buller Region on the West Coast of The South Island, New Zealand is an earthquake prone region. Since 1913, 4 strong earthquakes have occurred in the region (1913 Westport, 1929 Murchison, 1968 Inangahua, 1991 Westport earthquake), which caused extensive liquefaction. As shown in Figure 1, recent significant soil liquefaction phenomena in New Zealand were observed in the region [1]. In other words, the soils in the Buller region have attracted researchers interested in soil liquefaction in New Zealand.

From October 1990 to May 1991, 6 field trips were carried out. There were two field trips for preliminary explorations (from 1 October 1990 to 5 October 1990), two field trips for CPTU tests (from 19 November 1990 to 24 November 1990; from 13 May 1991 to 17 May 1991), one trip for SPT test (from 13 January 1991 to 18 January 1991), and one trip for investigation of liquefaction in the 1991 Westport (from 4 February to 5 February).

Our field study consists of two different forms: site investigation and detailed exploration.

The preliminary site investigation includes searching for liquefied sites and some preliminary exploration. The purpose of site investigation is to confirm the sites where liquefaction occurred in previous earthquakes in this century, or where liquefaction did not occur, and to perform preliminary exploration in both liquefied sites and unliquefied sites in order to choose proper sites for detailed exploration.

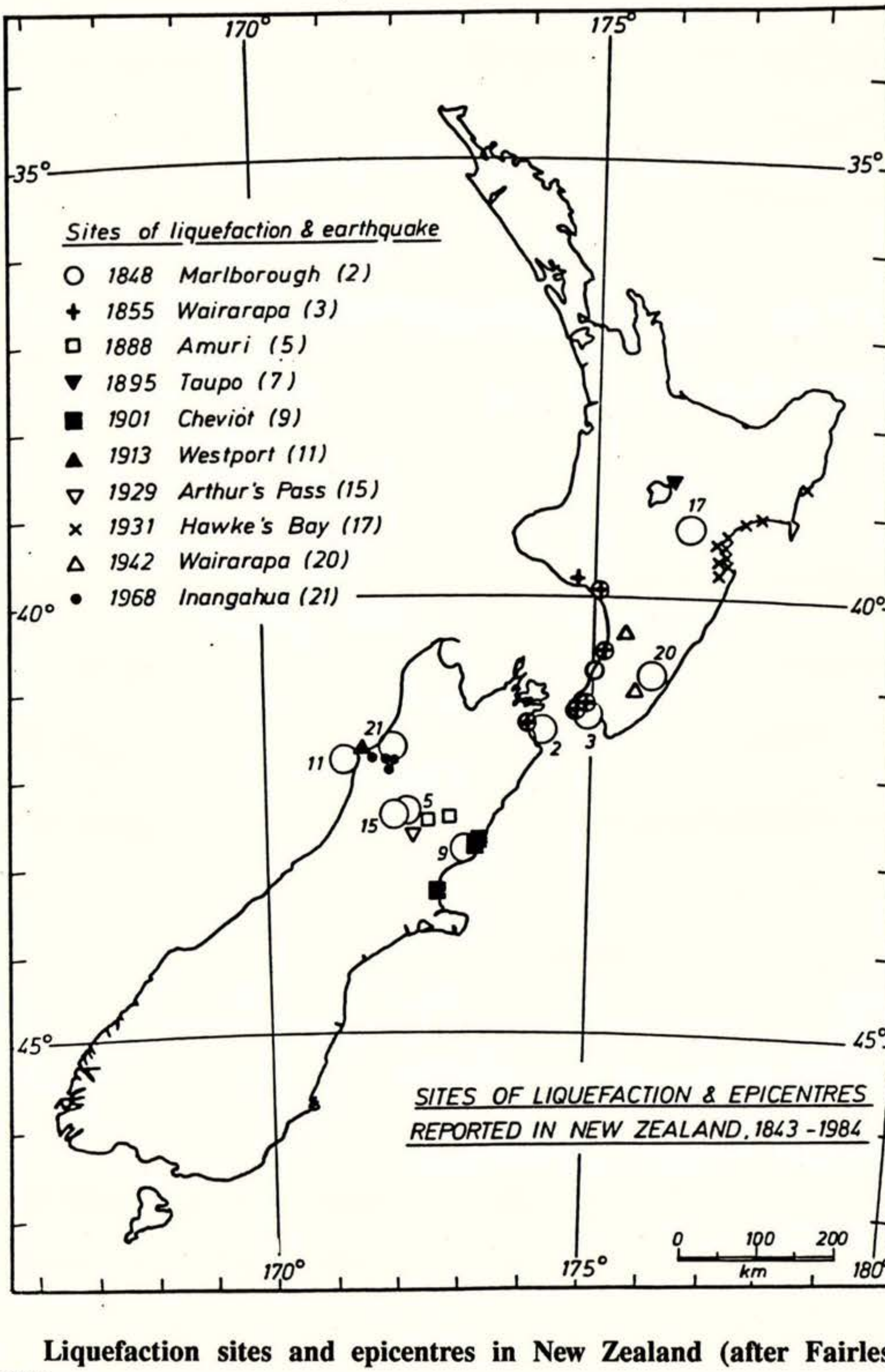

Figure 1 Liquefaction sites and epicentres in New Zealand (after Fairless and Berrill 1984).

Detailed explorations were performed at the chosen sites. The explorations included: CPTU testing, CPT testing, and drilling with SPT testing. The purpose of the detailed exploration was to understand the *in-situ* properties of soils at both representative sites of liquefaction and nonliquefaction so that an adequate data base could be set up for the recognition task.

2 INVESTIGATION OF LIQUEFIED SITES IN BULLER REGION

When we started this research, the 1991 Westport earthquake had not yet occurred. Well documented liquefaction phenomena were from the 1968 Inangahua earthquake and the 1929 Murchison earthquake. A number of papers and reports had been made on investigations of liquefaction related to the two earthquakes [3]. Table 1 gives a summary of liquefaction sites and evidence of liquefaction in the two earthquakes.

As liquefaction phenomena in the Buller region were well documented and the liquefied sites were well investigated, the purpose of our investigation was to conduct some complementary investigations and to find more sites for further detailed exploration, so that an information base could be set up combining results of previous research in the region and the current investigation. The emphasis of our investigation was placed on finding new sites representative of both liquefaction and nonliquefaction.

2.1 SOME REMARKS ABOUT LIQUEFACTION SITES IN THE 1968 INANGAHUA EARTHQUAKE

After the 1968 Inangahua earthquake, which at the time of writing is the most recent large earthquake in New Zealand, many researchers were involved in documenting the liquefaction phenomena during the earthquake and in exploring the characteristics of soils under liquefaction sites in the region. These studies provided the most detailed liquefaction information in New Zealand.

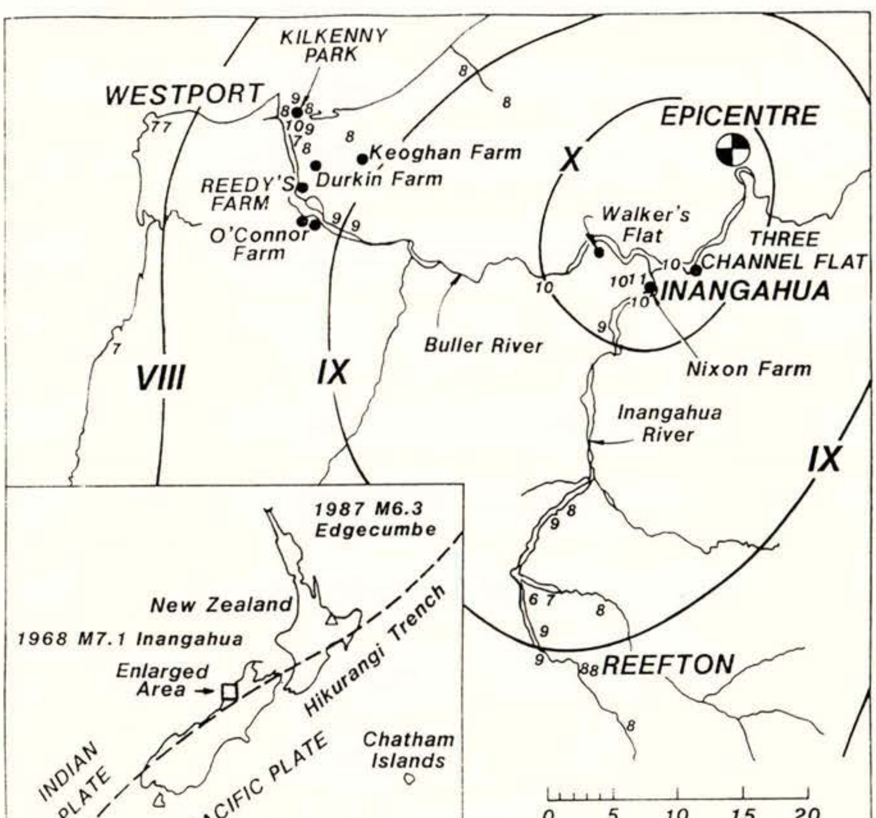

Figure 2a Epicentre and modified Mercalli intensities of the May 1968 Inangahua earthquake. Solid dots mark confirmed sites of liquefaction (after [2]).

Figure 2a shows the known liquefaction sites in the region during the Inangahua earthquake.

Our principal interest was to find discrimination information for liquefaction; in other words, to find the boundary between the liquefaction state and the non-liquefaction state of soils under seismic loads. This information may be found from samples taken from both liquefied sites and unliquefied sites.

Table 1 Sites of Liquefaction Found for the 1929 and 1968 Buller Earthquakes

SITE	EARTH-QUAKE	EPICENTRAL DISTANCE	EVIDENCE
1 Three Channel Flat Inangahua	1929 1968	23 km 10 km	Newspaper report Eyewitnesses, aerial photos
2 Nixon's Farm, Inangahua	1968	12 km	Eyewitnesses, aerial photos
3 Inwood's Farm, Inangahua	1968	11 km	Eyewitnesses, aerial photos
4 Walkers Flat, Buller Gorge	1968	12-15 km	Eyewitnesses, aerial photos
5 O'Connor's Farm, Westport	1968	30 km	Eyewitness report, MM Intensity Report
6 Durkin's Farm, Westport	1968	32 km	Eyewitness
7 Reed's Farm, Westport	1968	33 km	Eyewitness
8 Kilkenny Park North Beach Area, Westport	1968	34 km	Several eyewitnesses, Newspaper report and photographs
9 Keoghan's Farm, Sergeants Hill, Westport	1929 1968	45 km 29 km	Eyewitnesses
10 Corby Estate, Seddonville	1929	27 km	Eyewitness
11 Little Wanganui	1929	41 km	Eyewitnesses
12 Karamea School	1929	54 km	Several eyewitnesses
13 Kongahua Estuary, Karamea	1929	51 km	Indirect eyewitness report
14 Arapito, Karamea	1929	52 km	Eyewitness
15 Four Rivers Plain, Murchison	1929	8 km	Eyewitness
16 Grey Lagoon, Greymouth	1929	114 km	Newspaper report

(After Berrill, Bienvenu and Callaghan, 1988)

As the main evidence for liquefaction in the Inangahua earthquake was the ejection of sands [2,3] and since sand boils could be picked out on the aerial photographs taken after 5 days of the earthquake, we first carefully examined the aerial photographs. We noticed that there were some suspected liquefaction spots in the Reefton and Murchison areas besides many sand boils in the Inangahua area. So our site investigations related to the liquefaction induced by the Inangahua earthquake were conducted mainly in Inangahua, Murchison and Reefton areas. Figure 2b shows the sites investigated in this project, and serves to locate the more detailed site plans that follow.

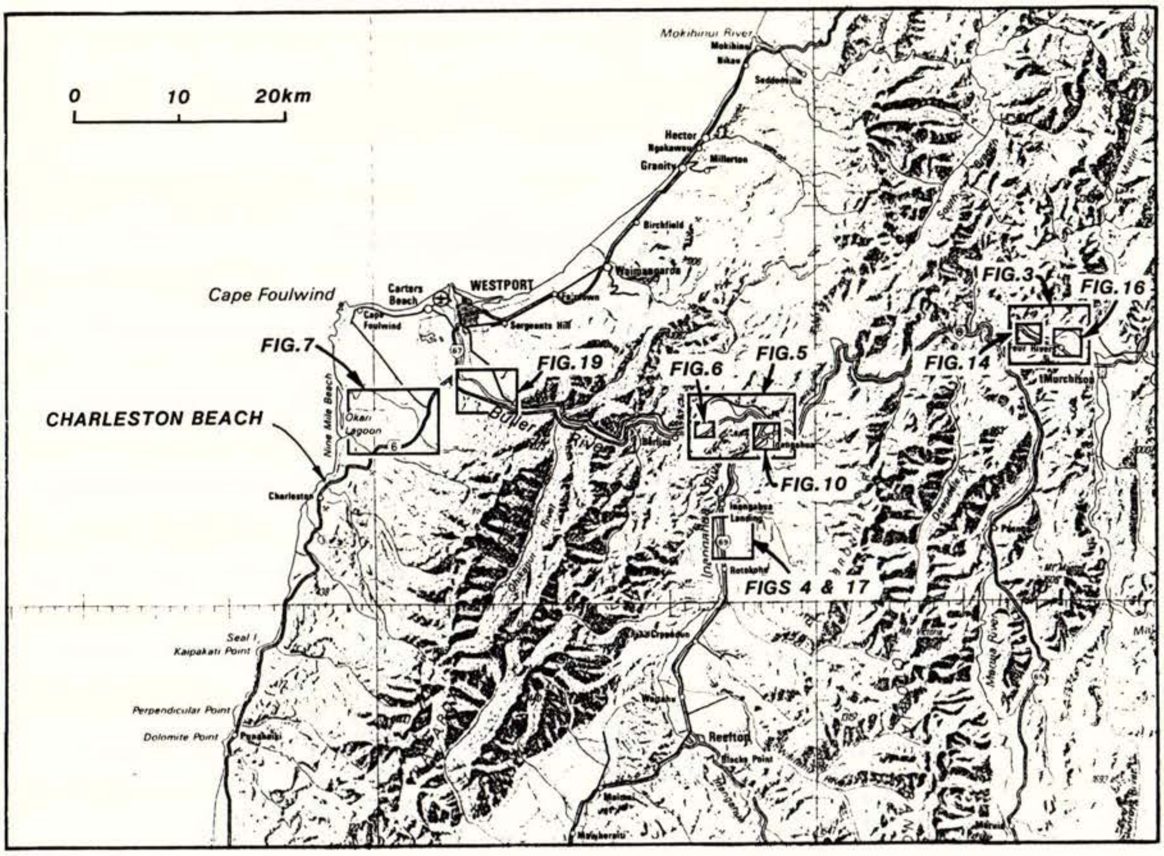

Figure 2b Location of detailed site plans in subsequent figures.

2.1.1 Peter Winfield's Farm at Fern Flat near Murchison

In October 1990 we visited the Murchison area in order to confirm if liquefaction had occurred in the area during the 1968 Inangahua earthquake.

At Fern Flat we visited Mr Peter Winfield, as there are some white spots in a grey background on the aerial photographs, which were suspected to be sand boils on his farm. After we showed him some photographs of sand boils, he confirmed that there were some sand boils ejected from the depth of ground in his farm and on the Fern Flat Road, and he even showed us a colour photograph (Plate 1) which shows some sand boils just on Fern Flat road where it runs though his farm. Then he pinpointed the spot where the photograph was taken. The place was one of the suspected liquefaction spots on the aerial photograph of the region (3086 Q/4). He also pointed out that there were other sand boils on his farm, but at that time he did not pay much attention to them, and could not remember their exact positions. Figure 3 shows confirmed liquefaction sites in the Murchison area. General location of the site plan, Figure 3, is shown in Figure 2b.)

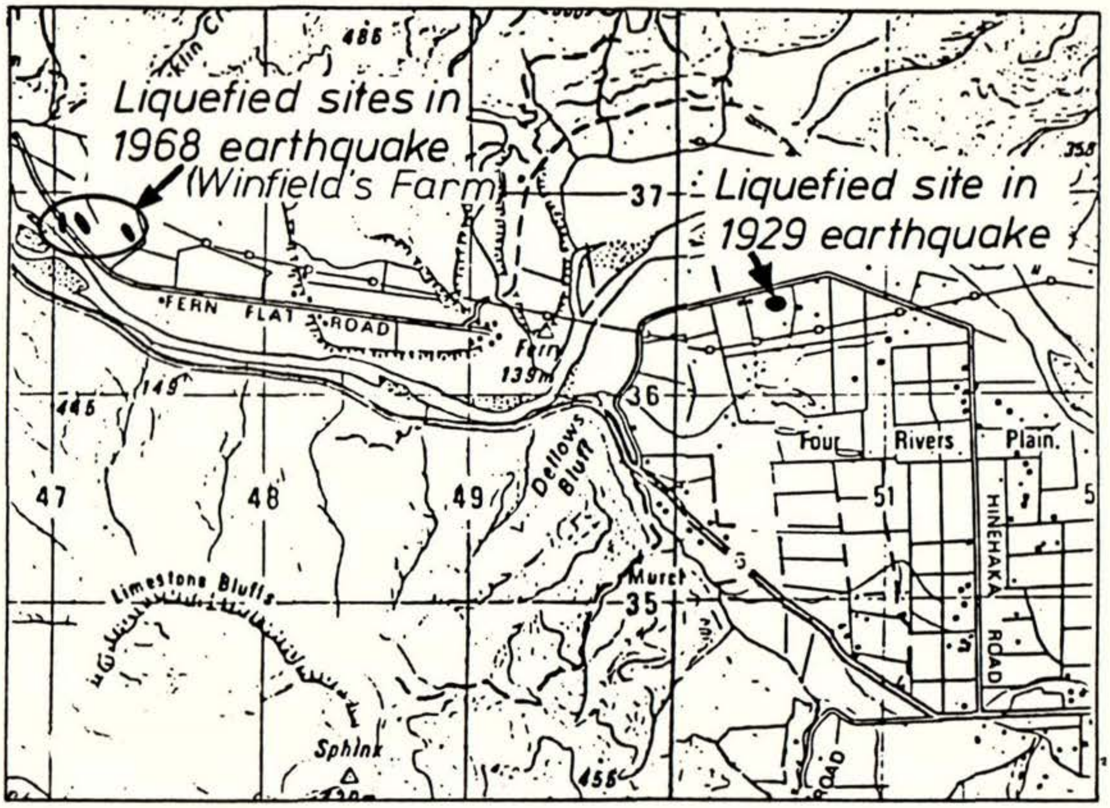

Figure 3 Location of sand boils observed in 1968 on Winfield's farm and in 1929 on Monahan's farm, near Murchison.

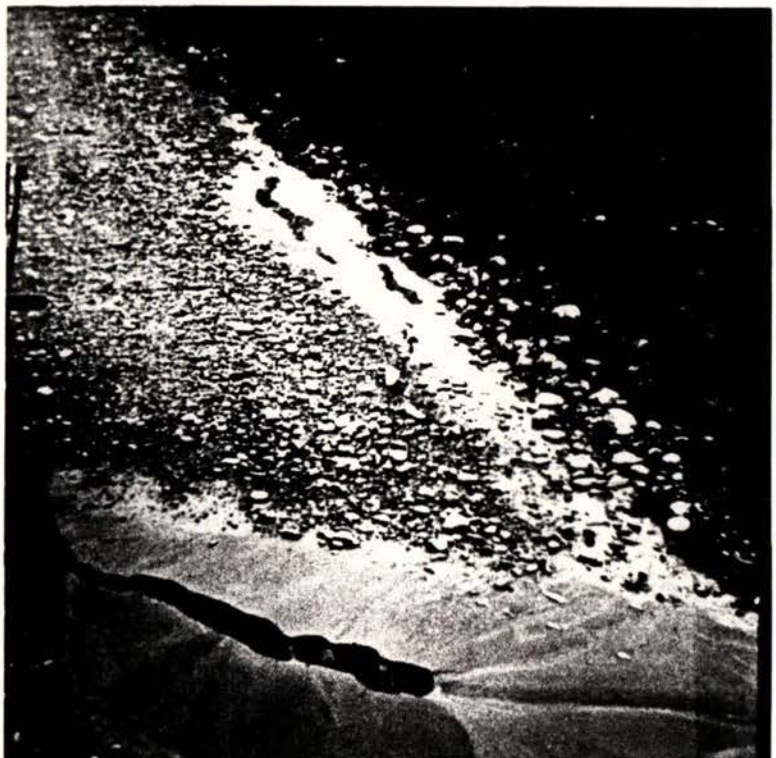

Plate 1 The sand boils ejected in the 1968 Inangahua earthquake at Peter Winfield's farm.

2.1.2 Van Vught's Farm at Reefton

In our first field campaign, we visited the suspected area adjacent to SH69 between Inangahua and Reefton. The suspected liquefaction spots [3] were indeed on Mr Van Vught's farm. As Mr Van Vught was not the owner of the farm and did not live there in 1968, he did not know what happened at his farm during the Inangahua earthquake. Fortunately, Mr Peter Bell who lived in a schoolhouse opposite Mr Van Vught's farm, could remember that there were some ejected sand boils on Van Vught's farm. The liquefaction spot pinpointed by Mr Bell was the same as the suspected liquefaction spot on the aerial photographs taken a few day after the earthquake. He also remembered that there were some ejected sands in Peter Schwass's farm which is to the south of Van Vught's farm. Figure 4 shows the confirmed liquefaction sites in this area.

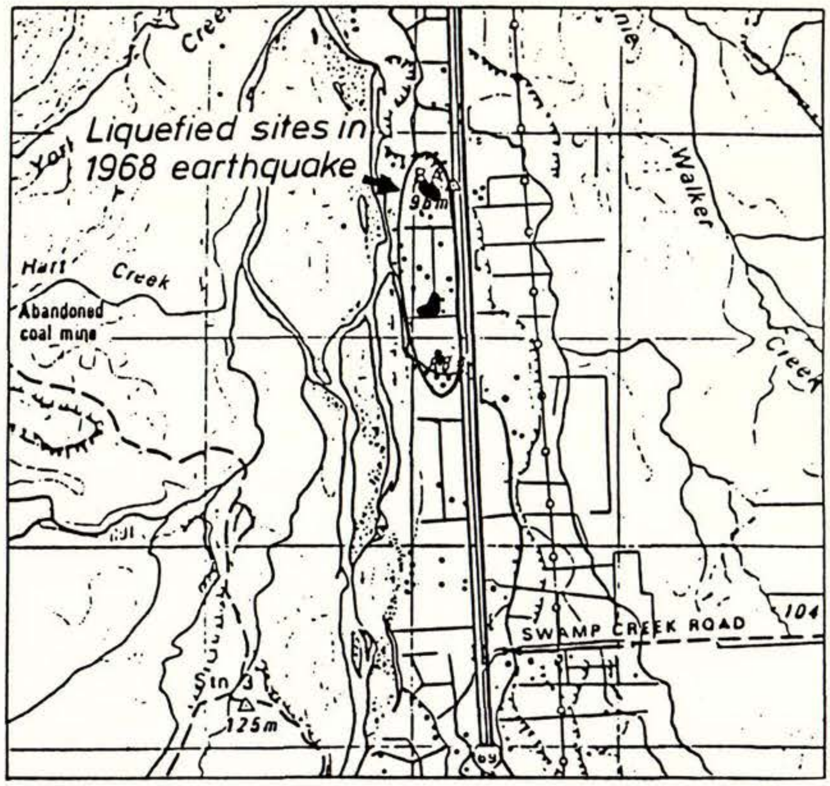

Figure 4 Locations of ejected sand at Van Vught's farm, between Reefton and Inangahua, seen in aerial photographs and confirmed by Mr Peter Bell, who lived near the site in 1968.

2.1.3 Wallace Turner's Farm at Walkers Flat, Inangahua

Walkers Flat is on a terrace of the Buller river around 3 km downstream from the junction of the Buller and Inangahua rivers. Because of its position, the sediments on the terrace comprising Walkers Flat were influenced by transportation of both the Buller River, and the Inangahua river, which carries more coarse material. The fields in the terrace belong to two farming families: Meddows and the Turners. The east part of the terrace belongs to Meddows; the west part of the terrace belongs to Turners.

As shown on aerial photographs (3086 C/11, 3086 D/9), there were many ejected sand boils on Walkers Flat after the Inangahua earthquake. After the Inangahua earthquake, Mr G. Meddows confirmed the occurrence of large number of sand boils in his farm [3,4], but Turner's farm was not visited by previous researchers, who had focused on Three Channel Flat. As most of sand boils in Walkers Flat were scattered in Tuner's farm according to the aerial photographs, we decided to visit Turners in order to confirm the occurrence of the liquefaction in Turner's farm and carry out necessary investigations. When we showed Mr Wallace Turner some typical photographs of sand boils and asked if he had seen any boils on his farm after the 1968 Inangahua earthquake, he answered that "*there were indeed many sand boils*," but he could not remember where they were. As Mr Turner never ploughed his fields, we thought that the sand boils may be found even now. We used survey instruments and aerial photography to locate one of biggest sand boils in Wallace Turner's liquefied site B shown in Figure 5. After some digging we found a thin sand lens covered by silty top soil (plate 2, plate 3). Then we could easily find more these kinds of sand lenses covered by silty top soil. Since the sand lens could not be found in places where aerial photographs showed no ejected sand, we were fairly sure they were indeed sand boils.

Plate 2 One of the sand boils covered by silty top soil at site B on Turner's farm which may have been ejected in the 1968 Inangahua earthquake.

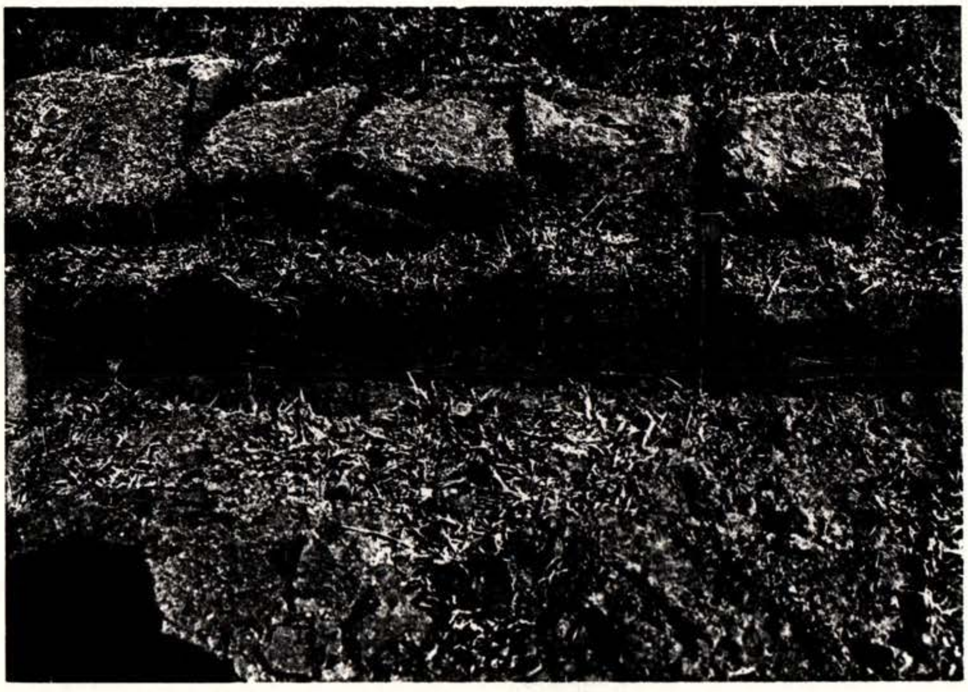

Plate 3 The edge of a sand boil at site B on Turner's farm which may have been ejected in the 1968 Inangahua earthquake.

Figure 5 shows liquefied sites in the Inangahua area. The most extensive liquefaction in the Inangahua area occurred in the terrace sediments of the Buller River at Walkers Flat.

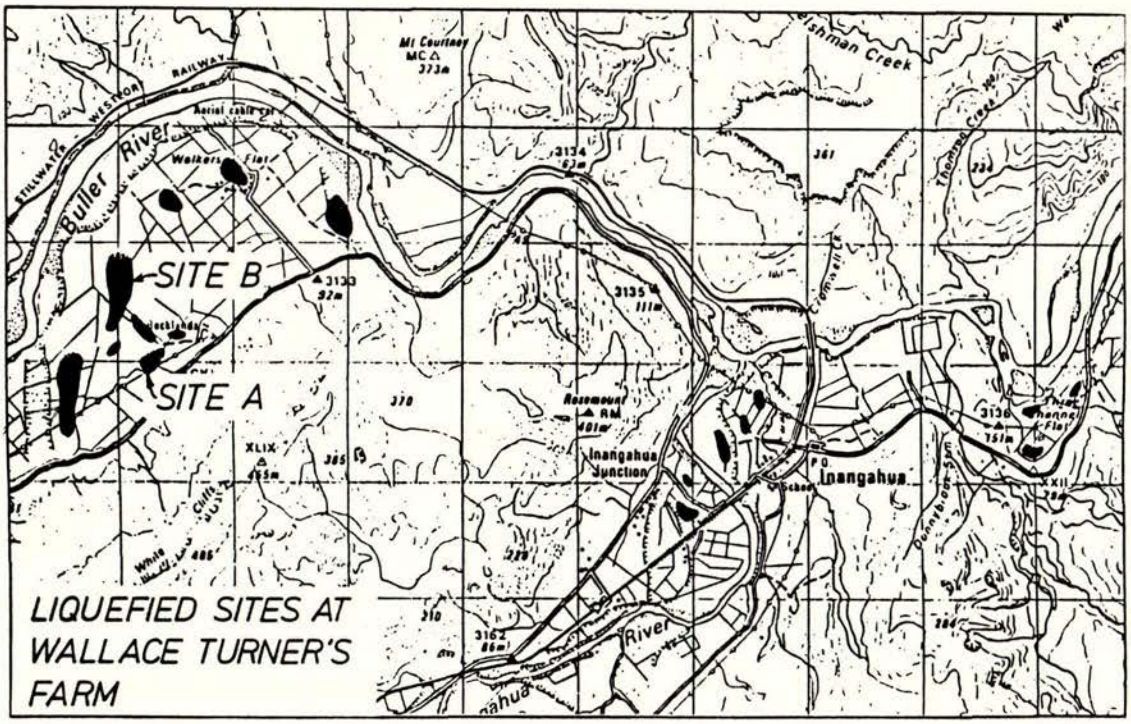

Figure 5 In the 1968 Inangahua earthquake, liquefaction occurred at the sites marked in black. In the 1991 earthquakes, there was liquefaction only at Turner's site A.

2.2 SOME REMARKS ABOUT LIQUEFACTION IN THE 1929 MURCHISON EARTHQUAKE

In October, 1990, we visited Mr Tom Monahan for more information about the liquefaction which had occurred on his farm during 1929 Murchison earthquake, and which he had mentioned to earlier investigators [3,5]. When we asked him if he could remember where sand boils were in his farm, he answered that he could not remember clearly. In the morning of the next day, his elder brother Mr Hugh Monahan came to Tom's home just after we had finished investigative tests in the field which, according to Tom, liquefied in the 1929 earthquake. The investigations of our campaign and of Bienvenu's campaign [5] revealed that soil condition under the sites pinpointed out by Tom was unfavourable to the occurrence of liquefaction). Hugh told us "*at the time of the 1929 earthquake, Tom was a school boy and was not yet home*". He saw sand boils in the field only after his return but that he, (Hugh), was in the fields when the earthquake occurred, and saw a geyser of sand and water erupting from the ground.

The site pinpointed by Hugh was in the paddock to the east of Tom's house rather than on the western paddock, as Tom had indicated. The position of the new site is marked in Figure 3. Our later exploration revealed soil conditions at the new site were favourable to the occurrence of liquefaction.

2.3 LIQUEFACTION IN THE 1991 WESTPORT EARTHQUAKE

On 28 January 1991 universal time, two strong earthquakes shook the South Island and caused some damage of roads and residential properties in the Buller region. The strong ground motion was recorded at Westport, Inangahua, Reefton, Murchison and other places. Peak accelerations from the Westport earthquake of 29 January 1991 can be found in Table 2, (Cousins, pers. comm.). We visited the Buller region six days after the earthquake and confirmed that during the earthquakes liquefaction occurred at Wallace Turner's farm in the Inangahua area and at Virgin Flat near Westport. Local magnitudes of the two shocks on 28 January were 6.1 and 6.2 respectively. A third shock occurred on 15 February with M_L = 5.9 [10].

Table 2 Peak accelerations from the Westport earthquakes of 29 January and 15 February 1991.

(Note that scratch-plate sites do not have site numbers. Numbers given in brackets are preliminary values only.)

Event Date			28th January 1991		28th January 1991		15th February 1991	
Universal Time			12h 58m 48s UT		18h 0m 55s UT		10h 48m 11s UT	
Epicentral Coordinates			41.89S 171.61E		41.90S 171.73E		42.04S 171.59E	
SITE No.	SITE NAME	INSTRUMENT TYPE	EPICENTRAL DISTANCE (km)	PEAK ACCELERATION (g)	EPICENTRAL DISTANCE (km)	PEAK ACCELERATION (g)	EPICENTRAL DISTANCE (km)	PEAK ACCELERATION (g)
083A	Te Kuha	film	7.6	.207	9.4	.143	23.8	.028 S
051B	Westport Telephone Exchange	film	14.8	.152	19.2	.157	31.4	.108
	Westport Telephone Exchange	sp	14.8	*	19.2	(.18)*	31.4	(.1)
090A	Inangahua	film	28.9	.109	19.4	.182	36.5	.107
052A	Reefton Forestry Headquarters	film	32.8	.071	26.6	.183	24.0	.177
	Reefton Forestry Headquarters	sp	32.8	*	26.6	(.20)*	24.0	(.2)
122A	Murchison	film	58.6	.157	49.1	.256	65.0	nr
	Murchison	sp	58.6	*	49.1	(.30)*	65.0	(.1)
103A	Springs Junction Ranger Station	film	68.3	**	61.0	.039 S**(MO2)	58.8	**
	Greymouth	sp	70.9	***	75.1	(.02)***	55.8	***
057B	Hokitika	film	106.5	nr	110.8	.053 S	91.4	nr
	Hokitika	sp	106.5	***	110.8	(.08)***	91.4	***
104A	Kikiwa Line Depot (N.Z.E.D.)	film	106.7	nr	97.3	nr	112.9	nr
042A	Hanmer Springs	Dig.	122.9	.026	114.3	.030	115.5	.020
	Hanmer Springs	sp	122.9	***	114.3	(.02)***	115.5	***
049A	Branch River	film	134.3	nr	124.8	nr	139.7	nr
112A	Flock Hill Station	film	138.9	nr	137.2	nr	122.4	nr
	Motueka	sp	146.1	***	138.9	(.01)***	157.8	***
115A	Takaka	film	153.6	nr	148.0	.033 S	167.4	nr
045A	Nelson Telephone Exchange	film	155.2	nr	146.8	nr	164.5	nr
	Nelson Telephone Exchange	sp	155.2	***	146.8	(.01)***	164.5	***
	Coleridge	sp	163.7	nr	163.3	nr	147.0	nr
060A	Cheviot Post Office	film	171.0	nv	162.6	nv	162.8	nv
	Cheviot Post Office	sp	171.0	nv	162.6	nv	162.8	nv
	Kaikoura	sp	180.8	nr	171.1	nr	177.6	nr
	Harewood Airport, Christchurch	sp	192.0	nv	187.3	nv	177.5	nv
	Havelock	sp	192.0	***	183.1	(.01)***	200	***
502A	Canterbury University Arts Block	film	198.5	nv	193.8	nv	184.0	nv
048A	Blenheim Telephone Exchange	film	199.2	nr	189.7	nr	205	nr
501A	Christchurch Police Station	film	201	nv	196.1	nv	186.6	nv
503A	Canterbury Savings Bank	film	201	nv	196.3	nv	186.8	nv
918B	Seismological Observatory	Dig.	271	(.0020)	262	nr	277	nr
900B	Museum of New Zealand Site	Dig.	272	(.0048)	262	(.0069)	278	nr
642E	Physics and Engineering Lab.	Dig.	285	nr	275	(.0049)	291	nr

Legend:
- film — Film-recording accelerograph
- dig. — Digital accelerograph
- sp — Scratch-plate acceleroscope
- nr — No record
- nv — Site not yet visited in 1991
- S — S-wave triggering
- * — Scratch-plate record collected after second event. Records from both events of 28 January superimposed.
- ** — Record collected March 1991. No event time available and so record assigned to most probable causative event.
- *** — Scratch-plate record collected March 1991. All three events superimposed.

Last Update 22/05/91 W J Cousins

(Information given by W.J. Cousins in Engineering Seismology Section, DSIR, New Zealand.)

2.3.1 Sand Boils on Wallace Turner's Farm at Inangahua

Even though recorded maximum acceleration of ground motion at Inangahua in the 1991 Westport earthquake was just 0.182 g, the earthquake shaking still caused some landslides on mountains to the south of Walkers Flat (Plate 4) and liquefaction. Evidence of soil liquefaction on Wallace Turner's farm was ejected sand boils (Plate 5). The sand boils were conical in shape with a maximum diameter of 1 metre and height of 10 centimetres.

Plate 4 Rock slips on the slope of the mountain to the south of Walker's Flat after the 1991 Westport earthquake.

Plate 5 A sand boil at site A on Turner's farm which was ejected during the 1991 Westport earthquake.

As mentioned in the section above, there were extensive sand boils on Turner's farm and Meddows' farm at Walkers Flat during 1968 Inangahua earthquake. However, in the 1991 Westport earthquake, ejected sand boils were limited to only one paddock - site A at Turner's farm (shown in Figure 5). Using survey instruments, the ejected sand boils were mapped. Figure 6 shows the distribution of the sand boils in Wallace Turner's liquefied field A. The distribution of ejected sand displayed a random pattern.

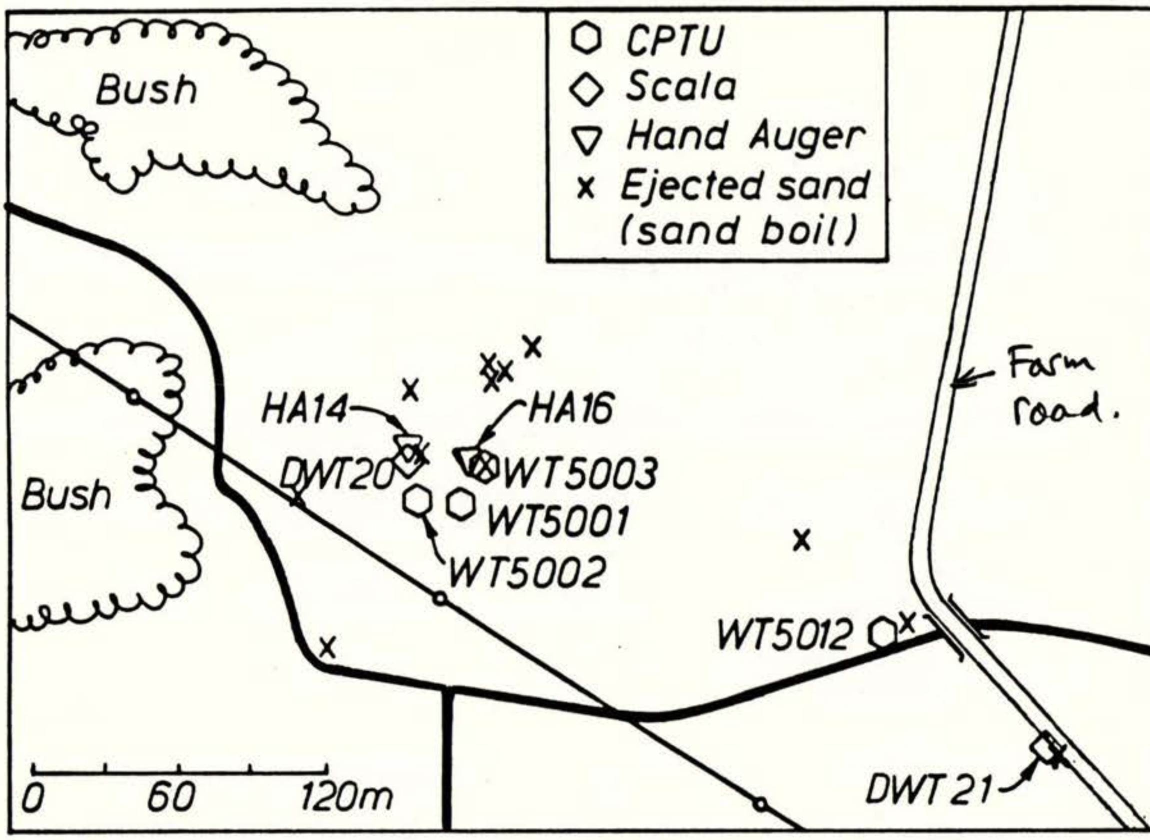

Figure 6 Location of sand boils and various *in-situ* test probes, at site A, Turner's farm, following the January 1991 earthquakes.

2.3.2 Liquefaction at Virgin Flat, Westport

At Virgin Flat about 13 km south-west of Westport, shown in Figure 7, liquefaction caused lateral spreads of a field and settlement of a road. Unfortunately, when we arrived a few days after the earthquake this liquefaction site and the settled road had already been fixed. Plate 6 and plate 7 display the fissures caused by lateral spreading.

2.3.3 Charleston Beach

Mr John Benn, of the West Coast Regional Council, reports having seen sand boils on Charleston Beach, about 35 km south of Westport.

Plate 6 The cracks caused by lateral spread at Virgin Flat during the 1991 Westport earthquake.

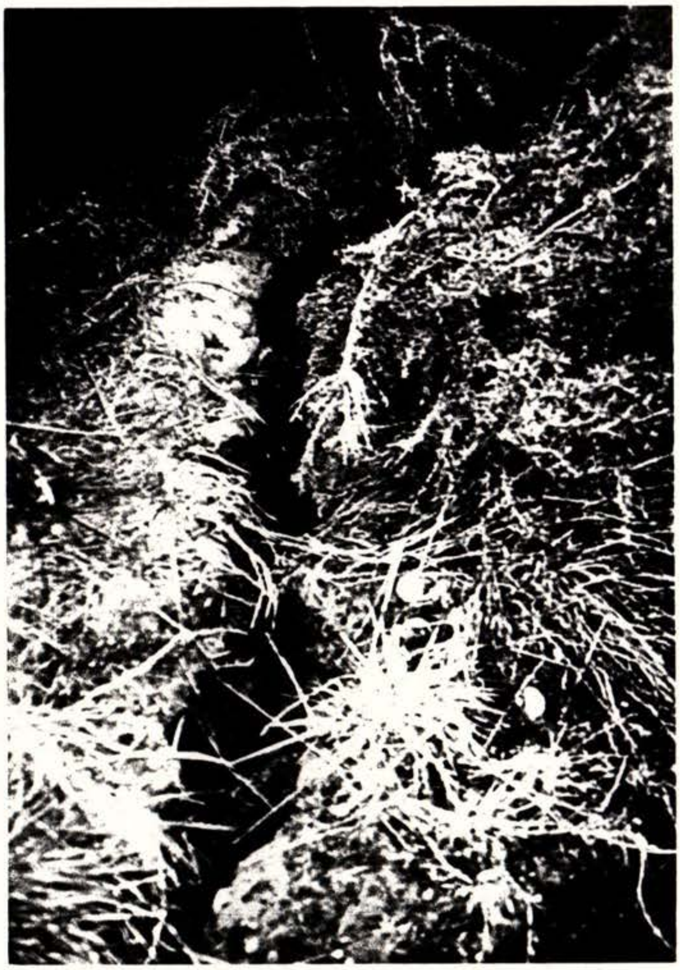

Plate 7 The cracks caused by lateral spread at Virgin Flat during the 1991 Westport earthquake.

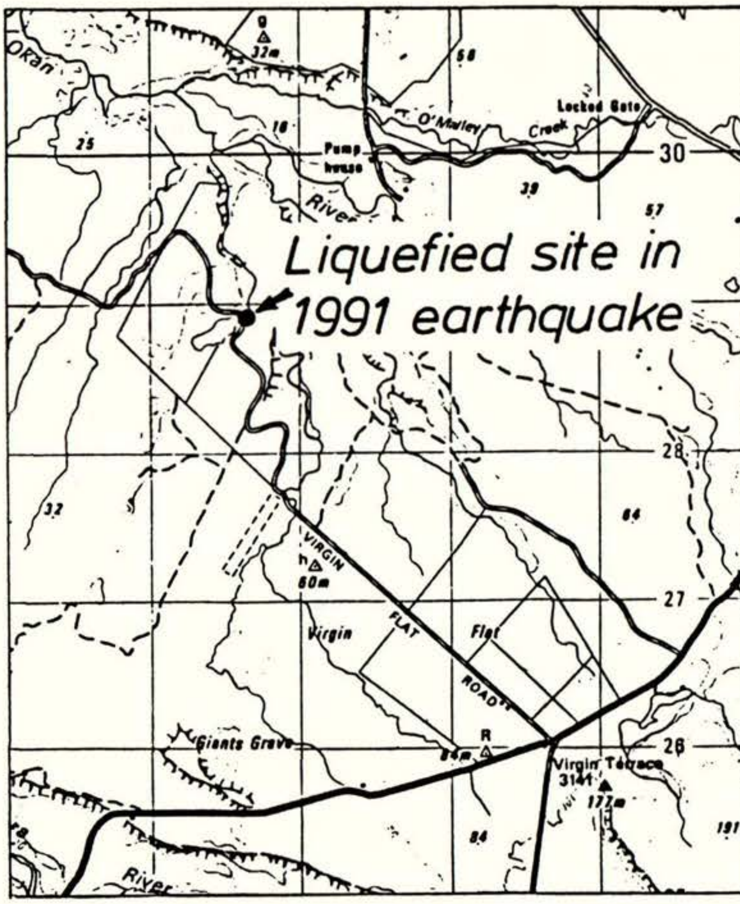

Figure 7 The site of lateral spreading in the January 1991 Westport earthquakes, at Virgin Flat near Westport, (see Figure 2b for general location).

3 PRELIMINARY EXPLORATION

The preliminary explorations were conducted in the Inangahua area, Reefton area, Murchison area, and Westport area. The exploration sites include

Inangahua area:	Three Channel Flat, Lee's Farm, Inwood's farm, Meddows' farm, Wallace Turner's Farm
Reefton area:	Van Vught's farm
Murchison area:	Peter Winfield's farm, Tom Monahan's farm, Taplin's farm, Lyall Foulsham's farm
Westport area:	Kilkenny Park, Westport Airport, O'Connor's farm, Reedy's farm.

The investigation apparatus used in preliminary exploration were: a Scala penetrometer and a hand auger.

The Scala penetrometer used in our investigation consists of a portable penetrometer with a series of rods (1 m long for each rod) and a 10 kg hammer falling 500 mm. The maximum depth of test is 10 metres. By counting the blow number to drive the penetrometer each 10 centimetres, the Scala penetration test can provide a quick test of the strata of the soil and a rough idea about the bearing capacity of the soils tested.

The hand auger is used to make a log of the soil profile and provide disturbed soil samples. The maximum boring depth of the hand auger is limited by three factors: total length of rods (6.5 metres), depth of underlying gravels and depth of collapse of the hole.

As the Scala test is normally used for bearing capacity test of soils at a shallow depth, we need to compare the test results with Standard Penetration Test performed in similar soils in the Buller region. In the Buller region, only three SPT test results were available before our campaign. Figure 9 shows the SPT test conducted in Kilkenny Park, Westport by Bienvenu's campaign [5]. A Scala test was conducted at this site. The result of the Scala test is shown in Figure 8. There seems to be a good correlation between the SPT N-value and the Scala value, though this depends on depth.

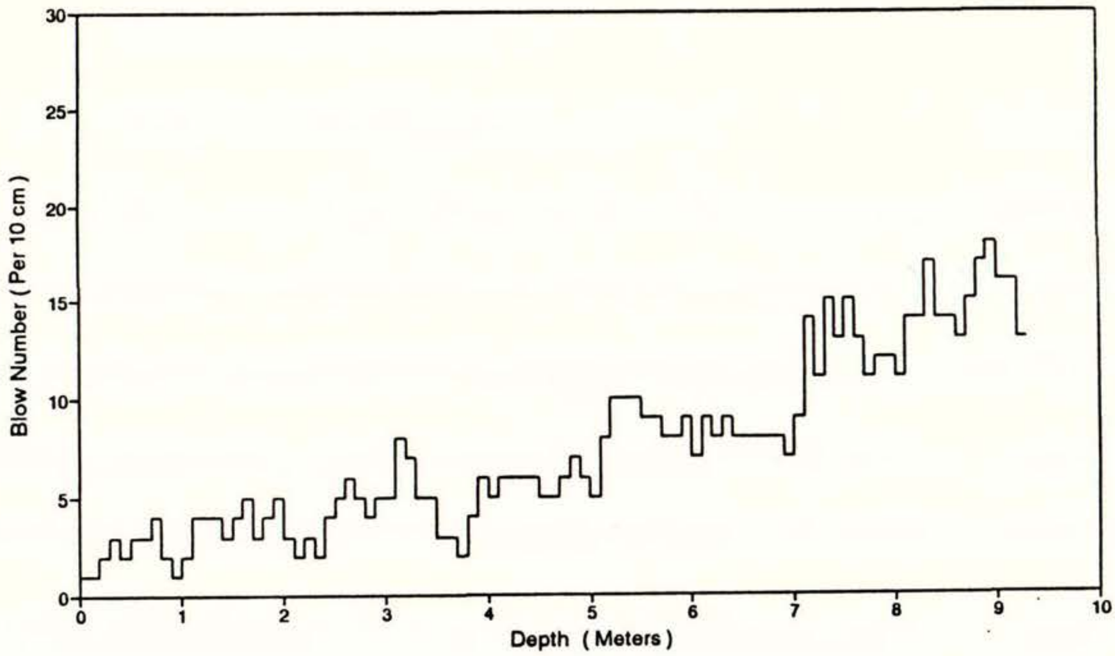

Figure 8 Scala penetrometer results from near Bienvenu's site D1 at Kilkenny Park, Westport.

The results of preliminary exploration include two aspects: (1) site investigation results for both liquefied sites and unliquefied sites, (2) choice of sites for detailed exploration. As the purpose of preliminary exploration was to choose proper sites for further detailed explorations, we display only the results of some preliminary explorations which have close relation with the choice of sites for detailed exploration. The hand auger logs made in our campaign are found in Appendix I, and results of the Scala tests in Appendix II.

3.1 THREE CHANNEL FLAT (INANGAHUA AREA)

Three Channel Flat is a low terrace of the Buller river located 3 km upstream of the junction of the Inangahua and Buller rivers. As extensive sand boils were confirmed by Mr M. Callaghan of the Ministry of Works and Development, Westport on the day after the Inangahua earthquake [5], many investigations have been performed at Three Channel Flat [1,2,3,4,5,6,7,8]. In our field trips, emphasis was not put on Three Channel Flat because so much previous exploration had been conducted there and also because the soils at Three Channel Flat had proven to be very soft, which would allow them to be liquefied in a lower seismic shaking intensity.

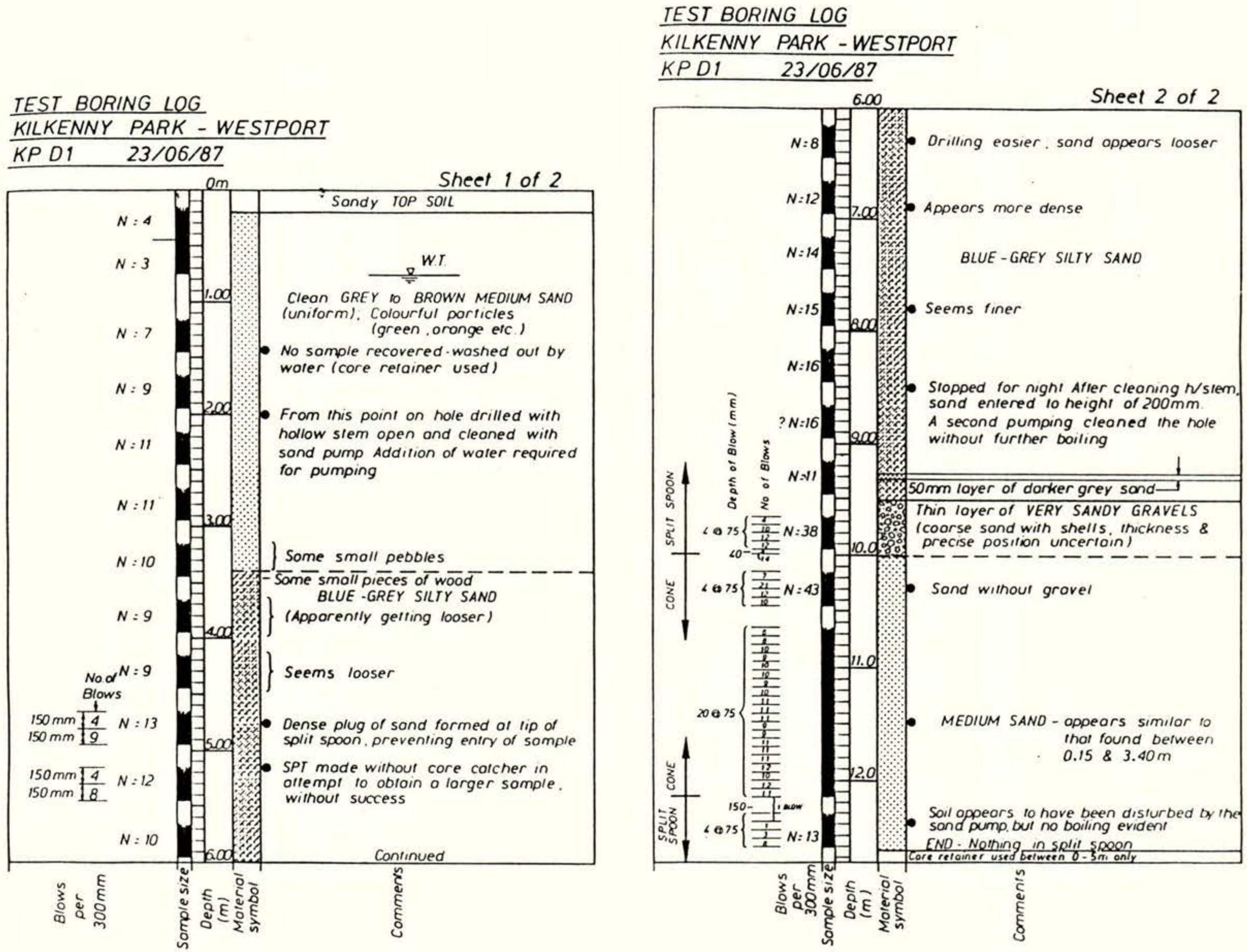

Figure 9a, 9b Logs of hollow-stemmed auger boring at Kilkenny Park, Westport (from Bienvenu [5]).

Only one hand auger, HA1, and two Scala tests (DT1, DT1a) were conducted at Three Channel Flat, to give a relative guide to further exploration. Figure 10 shows the positions of hand auger logs and Scala penetration tests performed in the Inangahua Junction area. According to the hand auger log HA1 (shown in Appendix I) the stratigraphy at Three Channel Flat is not complex: a 2.5 m thick layer of silt on the top, then a 0.5 m thick layer of sandy silt, followed by a 1 m thick layer of fine sand and a 0.5 m layer of fine-to-medium sand (because of hole collapse, drilling stopped at 4.5 m). The water table was 3.22 m on 2 October 1991.

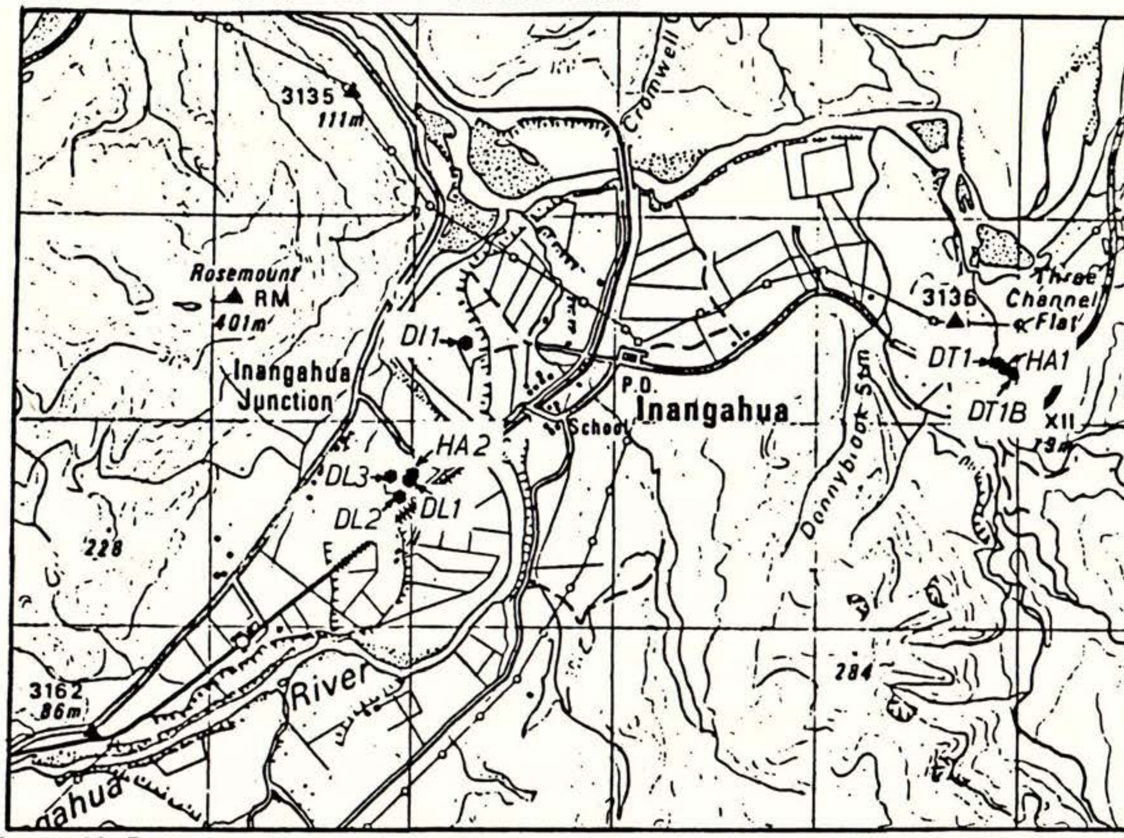

Figure 10 Location of preliminary hand auger borings and Scale penetrometer probes, near Inangahua.

Two Scala tests (DT1, DT1a) were conducted around the hand auger bore hole HA1. The Scala tests confirmed that the soils in Three Channel Flat are very loose (shown in Appendix II); the results of the two Scala tests were very consistent.

3.2 PRELIMINARY EXPLORATION ON TURNER'S FARM AT WALKERS FLAT

According to the interpretation of the aerial photographs taken a few days after the Inangahua earthquake, more than 60 percent of the liquefied area near Inangahua area was on Wallace Turner's farm. On the other hand, there were also some paddocks where there was no any sign of liquefaction according to the aerial photographs. The question arises as to whether they have different soil stratigraphy or a different geotechnical environment?

To answer this question, 7 hand auger and 6 Scala tests were conducted in Turner's farm. In three sites which liquefied during the Inangahua earthquake, five hand auger and four Scala tests were performed. In two sites which did not liquefy in the Inangahua earthquake, two hand auger and two Scala tests were conducted. Figure 11 shows the position of the hand auger and Scala tests.

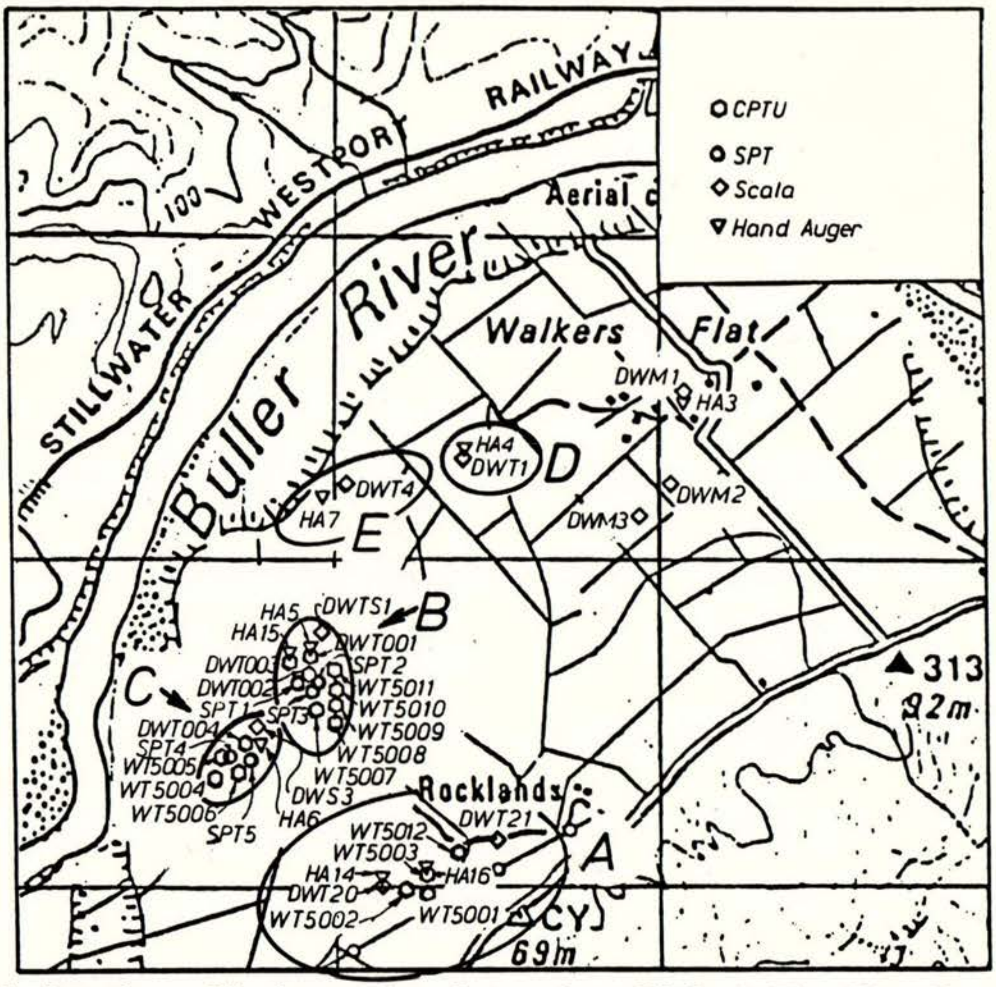

Figure 11 Locations of borings and probes made at Walker's Flat. Note that site A liquefied in both 1968 and 1991, whereas sites B and D produced sand boils in 1968 only. Sites C and E had no ejected sand.

3.2.1 Preliminary Exploration at Liquefied Sites

At Wallace Turner's farm, soil liquefaction was observed during two earthquakes: the 1968 Inangahua earthquake, and the 1991 Westport earthquake. In our campaign, preliminary explorations were conducted in only three liquefied sites, site A, site B, site D, even though there were more sites liquefied in the 1968 earthquake.

3.2.1.1 Preliminary exploration at site A

Site A is in the south-western corner of the terrace, Walkers Flat, as shown in Figure 5. Soils under site A were liquefied in both the 1968 Inangahua earthquake and the 1991 Westport earthquake. Two hand auger bore holes (HA14, HA16) were conducted on two different sand boils which occurred after the 1991 earthquake as shown in Figure 6. One Scala test DWT20 was conducted near the hand auger bore hole HA14. Another Scala test DWT21 was conducted on a sand boils on the path from the road into Turner's farm.

According to the information obtained from the hand auger HA16, and the Scala test DWT20 (shown in Appendix I and Appendix II), the soils under site A are a layer of silt (2 m thick) on the top, followed by a layer of loose fine sand (2 m thick) with some silt lens, a layer of loose medium sand (0.4 m thick), then gravels. The water table was 0.05 m on 4 February 1991 (just after the 1991 Westport earthquake) and had dropped to 0.5 m on 30 May 1991.

3.2.1.2 Preliminary exploration at site B

Site B is at just north of site A and is the biggest liquefied site at Walkers Flat, as shown in Figure 5. Therefore the performance of the soils in earthquakes and the characteristics of soils under the site are very important to aid in the understanding of soil liquefaction in the region. During the 1991 Westport earthquake, there was no sign of liquefaction in site B according to our field investigation after the earthquake. However, during the 1968 Inangahua earthquake, soils under the site were extensively liquefied as shown by ejected sand boils. Three sand boils can be located with the aid of the aerial photographs taken 5 days after the 1968 Inangahua earthquake. As the field has not been ploughed, the old sand boils, covered by top soil, could be revealed by trenching.

In site B, two hand auger bore holes (HA5, HA15), and three Scala tests (DWT2, DWT2a, DWTS1) were conducted in site B. The four Scala tests were made at the same spot. The positions of hand auger and Scala tests are shown in Figure 11. The hand auger bore holes HA5 and HA15 were conducted at two different sand boils which were induced by the 1968 earthquake and covered by silty top soil. The Scala tests DWT2, DWT2a were conducted close to CPTU bore hole DWT003 and to HA15. The Scala test DWTS1 was conducted beside the hand auger bore hole HA5. Figure 12 shows the result of the Scala test DWTS1. According to the hand auger logs HA5, HA15 (shown in Appendix I) and Scala test DWTS1, the soil layers under the site are quite simple: a layer of silt (3.6 m thick) on the top, followed by 1 m of loose fine-to-medium sand, then a layer of medium to coarse sand (1 m thick) with fine gravels, followed by a layer of gravel at the bottom of the boring. The water table was 3.2 m on 4 October 1990 and 2.9 m on 30 May 1991.

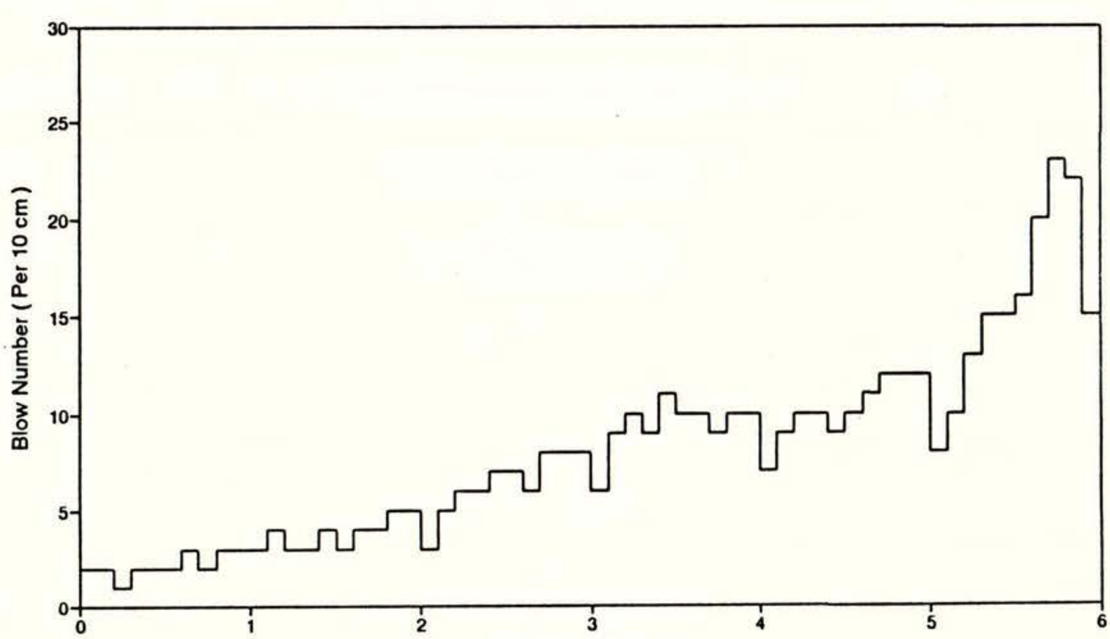

Figure 12 Scala penetrometer results from site B2, W. Turner's farm, corresponding to hand auger boring HA15 and CPTU test DWT003.

3.2.1.3 Preliminary exploration at site D

In the centre of Walkers Flat, there was a liquefied site to the north-east of site B as shown in Figure 5. We call it site D. One hand auger bore hole HA4 was conducted in site D as shown in Figure 11. According to the hand auger log HA4 (shown in Appendix I), soils under Site D are quite similar to those under site B. The soils under this spot comprise a layer of silt (2.8 m thick) on the top, followed by a layer of fine sand (0.9 m thick) and then a layer of medium sand (more than 1.1 m thick, as drilling in the layer was stopped by collapse of hole). The water table was 3.1 m on 3 October 1990. A Scala test DWT1 was conducted near the hand auger bore hole. Comparing the Scala tests in Three Channel Flat and in site B, soils under this spot seem to be more dense (see Appendix II). This is a good site for further exploration to search the boundary between liquefied sites and unliquefied sites. However, there will be some difficulty to bring the drilling truck to this spot. In other words, it is not a convenient exploration site for CPTU tests.

3.2.2 Preliminary Exploration at Unliquefied Sites

Even though there was wide spread ejection of sand over Walkers Flat in the 1968 Inangahua earthquake, there were still many paddocks in which no liquefaction occurred. In our campaign, preliminary explorations were performed at two unliquefied sites on Turner's farm, which did not display any sign of liquefaction in both the 1968 earthquake and the 1991 earthquake. One is to the north-east of site B; we call it site E. Another is to the west of site B, and we call it site C (see Figure 5 or 11).

3.2.2.1 Preliminary exploration at site E

On the aerial photographs, site C and site E display different tones. Site E has a light grey tone, which suggests the soils in the site are in a drier environment. Site C has nearly the same tone as liquefied site B, which suggests site C might have similar geotechnical conditions to site B.

One hand auger bore HA7 and a Scala test DWT4 were performed at site E as shown in Figure 11. According to the hand auger log HA7 (shown in Appendix I), the soil stratigraphy at site E is similar to that at site B. The significant difference is that the water table was still not found at a depth 6.4 m on 4 October 1991. The result of the Scala test DWT4 (shown in Appendix II) implies that soils under site E seem to be looser that soils under site B. The main reason for nonliquefaction in site E was clear - the water table was too deep. That is why on the aerial photographs Site E displays a lighter grey tone rather than a dark grey tone, and does not show any sand boils.

3.2.2.2 Preliminary exploration at site C

In our campaign, one hand auger boring, HA6 was made at site C as shown in Figure 11. A Scala test DWS3 was also conducted near the hand auger bore hole. Another Scala test DWTS2 was conducted 20 m south of DWTS3. Figure 13 shows the result of the Scala test DWTS3. According to the hand auger log HA6 (shown in Appendix I), the soils under site C comprise a layer of silt (2.9 m thick) on the top, followed by a layer of dense fine to medium sand (1 m thick), then a layer of coarse sand (more than 1.5 m thick, as drilling in the layer was stopped by collapse of hole), followed by a layer of gravels on the bottom. The water table was 3.5 m on 4 October 1990, and 2.97 m on 17 January 1991.

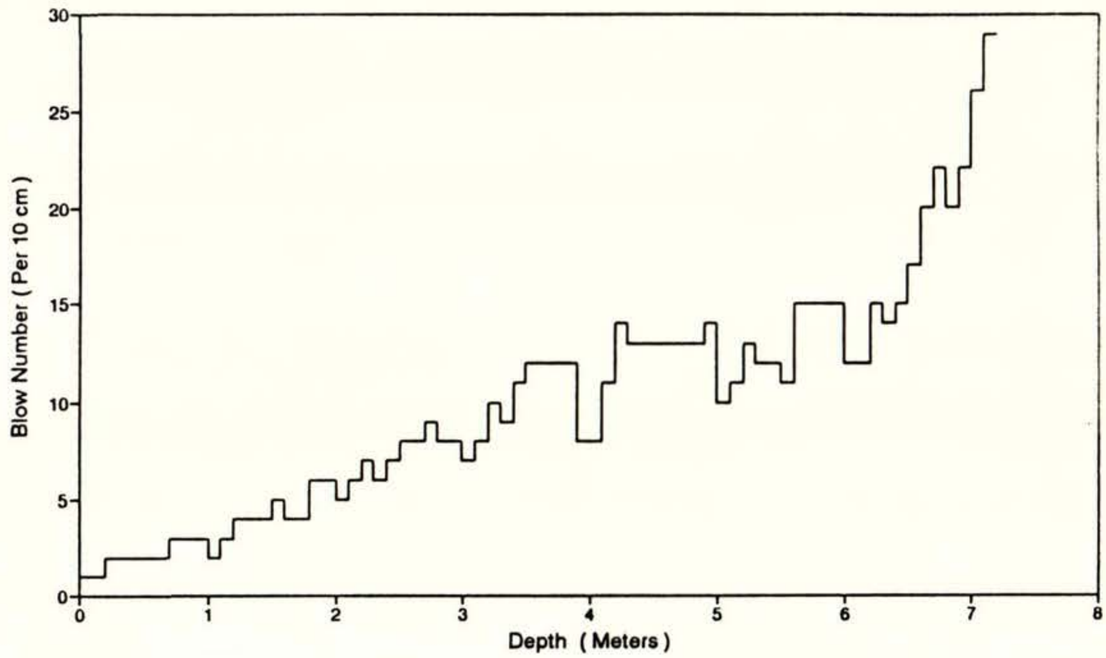

Figure 13 Scala penetrometer results from site C, Turner's farm. This site did not liquefy in 1968 or 1991.

The top layer of unliquefiable silty soil (2.9 m) at site C is thinner than that (3.65 m) at site B. The depth of water table in site C was nearly the same as that at site B. The main difference in soil conditions is that the sand at site C is more coarse and dense than the sand at site B, which can be seen by comparing the Scala tests DWTS3 with DWTS1. As site C has similar soil stratification and geotechnical conditions to site B, there should also be some sand boils at site C if soils under site C did liquefy in the Inangahua earthquake. According to the aerial photographs, there was no sand boil or sign of the occurrence of liquefaction in site C, so we can conclude that the soils under site C did not liquefy in the Inangahua earthquake.

3.3 PRELIMINARY EXPLORATION ON MEDDOWS' FARM AT WALKERS FLAT

Meddows' farm is located at the east side of Walkers Flat. The aerial photographs show that some liquefaction occurred on Meddows' farm and these sites are shown in Figure 5. On the easternmost side of the Walkers Flat terrace, there was a place where it looked as though lateral spreads occurred. In the paddock to the north of the Meddows' house, there were extensive sand boils showing on the aerial photographs. The sand boils were confirmed by Mr G. Meddows himself and by photographs taken in the paddock after the 1968 earthquake by Mr Meddows [4]. In our campaign, preliminary explorations were conducted in a liquefied site in the paddock on the northern side of the Meddows' house, and at two unliquefied sites.

3.3.1 Preliminary Exploration at the Liquefied Site

We made one hand auger boring, HA3, in Meddows' liquefied northern paddock just nearby Meddows' house as shown in Figure 11. One Scala test DWM1 was conducted beside the hand auger. The hand auger log (in Appendix I) shows that the soils under the this site are quite complicated. A layer of silt (1.7 m thick) is overlaying a layer of fine sand (1 m thick) with silt lenses, then a layer of silty-to-fine sand (1 m thick) over a layer of gravel. The gravel layer is at 4 m depth. The water table was at 3.2 m on 3 October 1990. The Scala test shows that the soils under this site could be looser than those in site B. As the gravel layer is at the shallow depth of 4 m, we did not conduct any detailed exploration.

3.3.2 Preliminary Exploration at Unliquefied Sites

On the central part of the terrace at Walkers Flat, some paddocks belonging to Meddows did not display any sign of liquefaction. Two Scala tests (DWM2, DWM3) were performed in the unliquefied sites in Meddows' farm as shown in Figure 11.

The Scala test DWM2 was in an unliquefied paddock near the liquefied paddock as shown in Figure 5. The Scala probe in test DWM2 reached gravels at a depth of 3.2 m. According to the Scala test DWM2 (shown in Appendix II), there is probably a layer of dense sand at a depth of 1.5 m to 3.2 m which is covered by a layer of silt 1.5 m thick. At another unliquefied site, the Scala test DWM3 was stopped by meeting gravels at a depth of 1.7 m.

As in both Scala tests in unliquefied sites on Meddows' farm, the Scala probe quickly reached gravel layers above the water table which meant that the gravel layers could prevent the deep liquefied soil rising to the surface to form sand boils or that there was really no liquefaction happening under the site. Anyway, the unliquefied sites seem to be unsuitable for conducting further CPTU, CPT tests.

3.4 PRELIMINARY EXPLORATION ON LEE'S FARM AT INANGAHUA JUNCTION

The liquefied sites in Lee's farm were located on a high terrace of the Inangahua river. The evidence for liquefaction again came from sand boils showing on the aerial photographs. As Lee's farm has been ploughed since 1968, no sand boils could be found now.

At a sand boil site shown on the photographs, a hand auger bore hole, HA2, was conducted as shown in Figure 10. A Scala test, DL1, was conducted near HA2. According to the hand auger log HA2 (shown in Appendix I) and the Scala test DL1 (shown in Appendix II), it is very clear that the silty sand at a depth of 1.55 m to 3.13 m is very loose and the coarse sand with small gravel at depth of 3.1 m to 4.3 m is very dense. Gravel was found at a depth of 4.3 m. The water table was 3.05 m on 3 October 1991.

Another two Scala tests, DL2 and DL3, met gravels at a depth of 2.8 m. As the gravel layer was found at such a shallow depth no detailed exploration was conducted in Lee's farm.

3.5 PRELIMINARY EXPLORATION ON INWOOD'S FARM AT INANGAHUA JUNCTION

Mr Inwood has two farms. One is at Three Channel Flat; the other is on the alluvial terraces bounded by the Inangahua and Buller Rivers and the railway line at Inangahua. We refer to his farm at Inangahua.

There were some sand boils appearing on both low and high terraces on Inwood's farm, according to the aerial photographs. Liquefied sites on Inwood's farm inferred from these photographs are shown on Figure 5.

A Scala test, DI1, was performed in the field of the low terrace of Inwood's farm. The results, (shown in Appendix II), suggest that soils at this place are very loose and that a gravel layer is at a very shallow depth (only 2 m). This means this site is not suitable for further CPTU testing.

3.6 PRELIMINARY EXPLORATIONS ON PETER WINFIELD'S FARM (MURCHISON)

At Peter Winfield's farm, one hand auger boring, HA10, was conducted in a paddock, immediately to the north of Fern Flat Road, which liquefied in the 1968 Inangahua earthquake, as shown in Figure 14. A Scala test, WINF2, was conducted near the hand auger bore hole.

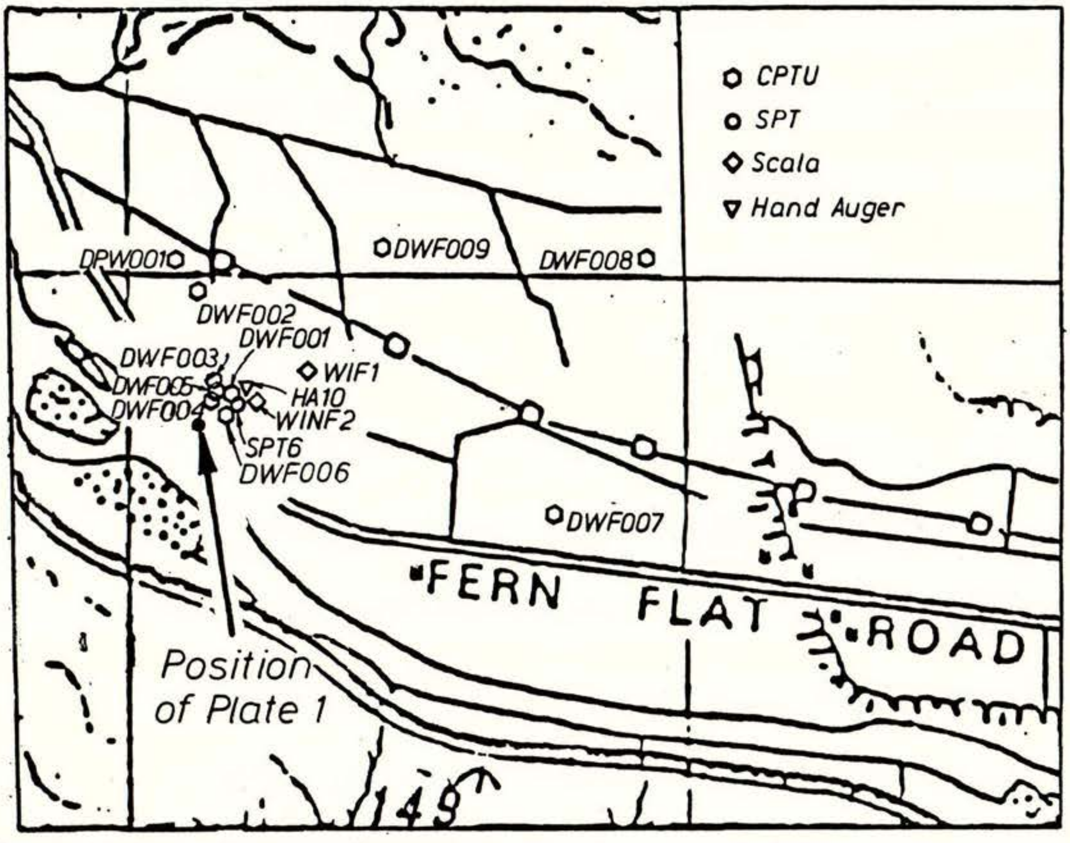

Figure 14 Probe location, Peter Winfield's farm at Fern Flat, near Murchison.

As displayed by the hand auger log, HA10, (in Appendix I), and the Scala test, WINF2, (in Appendix II), the soils at the site comprise a layer of silt (3.3 m thick with fine sand lenses) followed by a thin layer of loose fine sand (0.2 m), and a layer of dense medium sand (1.5 m) followed by a layer of coarse sand (1 m), then a layer of gravels on the bottom. The gravel layer was found at a depth of 6 m. The water table was at a depth of 4 m on 10 March 1991.

Another Scala test, WIF1, was conducted at another liquefied site on Peter Winfield's farm as shown in Figure 14. The Scala test, WINF1, was stopped at a depth of 3.3 m as gravels were met (see Appendix I).

3.7 PRELIMINARY EXPLORATION ON TOM MONAHAN'S FARM (MURCHISON)

According to Mr Tom Monahan's recollection, there were some ejected sand boils on his farm after the 1929 Murchison earthquake, but no sand boils occurred in the 1968 Inangahua earthquake [5]. However, three bore holes made by Bienvenu to the west of the farm house, at the site indicated by Mr Monahan showed that soil conditions seem to be unfavourable to the occurrence of liquefaction as seen in Figure 15. But according to the recollection of Hugh Monahan, (Tom's bother), while Tom Monahan was in school at the time of the earthquake, Hugh Monahan was on their farm and saw the eruption of water and sand when the 1929 earthquake occurred at various locations. Hugh got a very strong impression of the occurrence of ejected sand boils or occurrence of liquefaction in his farm.

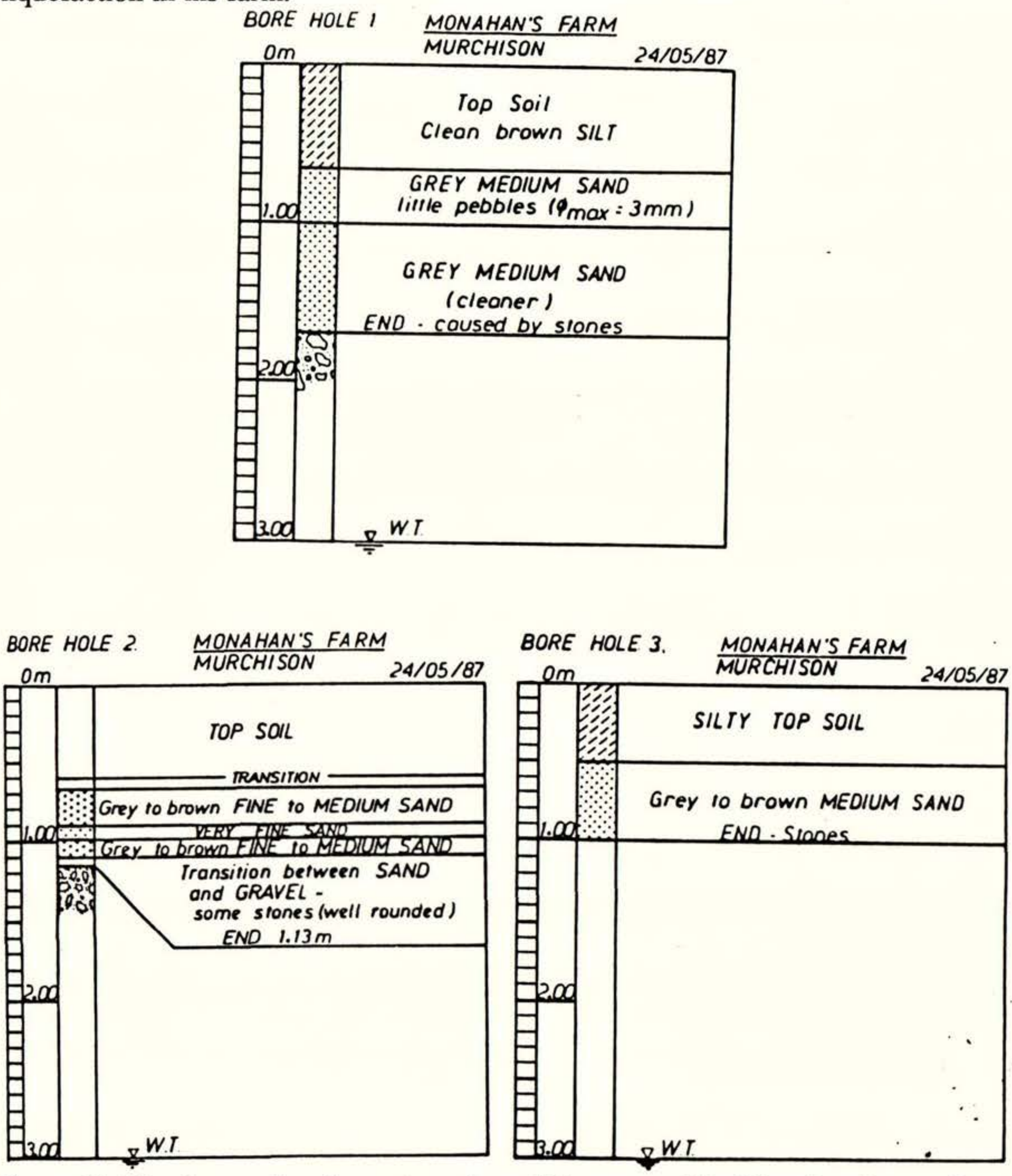

Figure 15 Hand auger logs from sites about 100 m west of the Monahan house (from Bienvenu, 1988).

At a paddock to the east of Tom Monahan's house, one hand auger, HA9, was conducted at the spot pinpointed by Hugh Monahan, (41 m south of the road), where soils and water had erupted during the 1929 earthquake according to the recollection of Hugh Monahan. Figure 16 shows the positions of the exploration conducted on Monahan's farm.

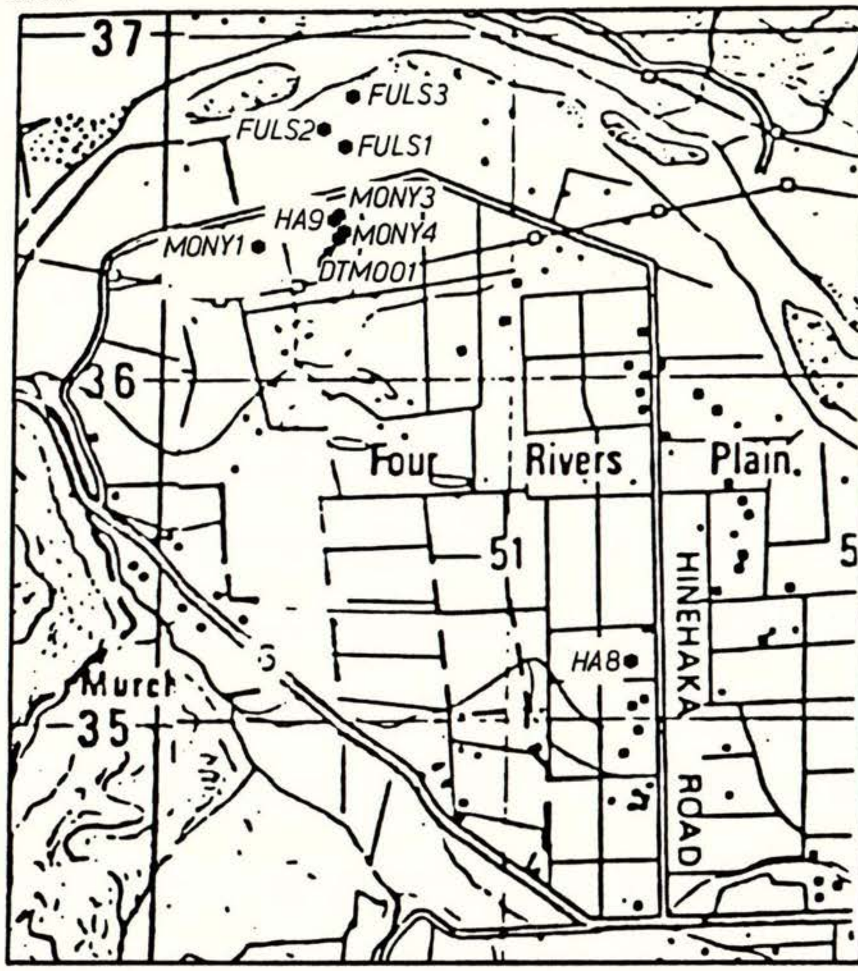

Figure 16 Location of probes on the Monahan and Foulsham farms, Four Rivers Plain, Murchison.

The water table was at 1.9 m on 30 October 1990. Under the water table, a layer of very loose medium to coarse sand was found at a depth of 2 m. The bore hole, (shown in Appendix I), reached a depth of only 2.7 m before collapsing. A Scala test, MONY3, was conducted beside the bore hole, HA9, and revealed that gravels were found at a depth of 4.4 m (shown in Appendix II). A Scala test, MONY2, conducted 10 m to the north of MONY3 met gravel at a depth of 3 m. Another Scala test, MONY4, conducted 20 m to the south of the hand auger HA9 was stopped by gravels at a depth of 5.3 m.

In the paddock to the west of Monahan's house, one Scala test, MONY1, was conducted. In this paddock, a gravel layer was found at the shallow depth of 1.7 m (see Appendix II). The result of the Scala test was similar to the results of the explorations conducted by Bienvenu [5].

3.8 PRELIMINARY EXPLORATION ON FOULSHAM'S FARM

Foulsham's farm is located to the north of Hinehaka Road, just to the north of Monahan's farm, (Monahan's farm is located on the south side of the road). As the two farms are separated by a road, we were curious to know what the soil condition was under Foulsham's farm as no evidence of ejected sand was seen in the 1968 aerial photographs.

On Foulsham's farm, three Scala tests, (FULS1, FULS2, FULS3) were conducted as shown in Figure 16. A gravel layer was found at a depth of approximately 3.2 m (see Appendix II). The soils under Foulsham's farm are very loose, as shown by Scala tests (FULS1, FULS2, FULS3). Perhaps the difference in behaviour was due to a much lower water table. (The Scala penetrometer does not detect the water table.)

3.9 PRELIMINARY EXPLORATION ON TAPLIN'S FARM

Taplin's farm is on the south part of Four Rivers Plain (to the west of Hinehaka Road) and close to Highway 65. Since there is a white spot on the 1968 aerial photographs at the position of Taplin's farm, we suspected that it might be a sand boil caused by the 1968 earthquake. We asked Mr Taplin, the owner of the farm, whether he remembered any ejected sand in 1968. He was adamant that there were none but we conducted a hand auger boring, HA8, at the suspected *"liquefaction"* spot on Taplin's farm anyway. The hand auger bore hole, HA8, revealed that there was a gravel layer was at a depth of 1.2 m and that no water was found at that depth (as shown in Appendix I), confirming Mr Taplin's belief that no liquefaction had occurred there.

3.10 PRELIMINARY EXPLORATION ON VAN VUGHT'S FARM (BETWEEN INANGAHUA AND REEFTON)

At Richard Van Vught's farm, one hand auger boring, HA13, was made in the paddock which liquefied in the 1968 earthquake as shown in Figure 17. A Scala test, VUGHT1, was performed close to the bore hole.

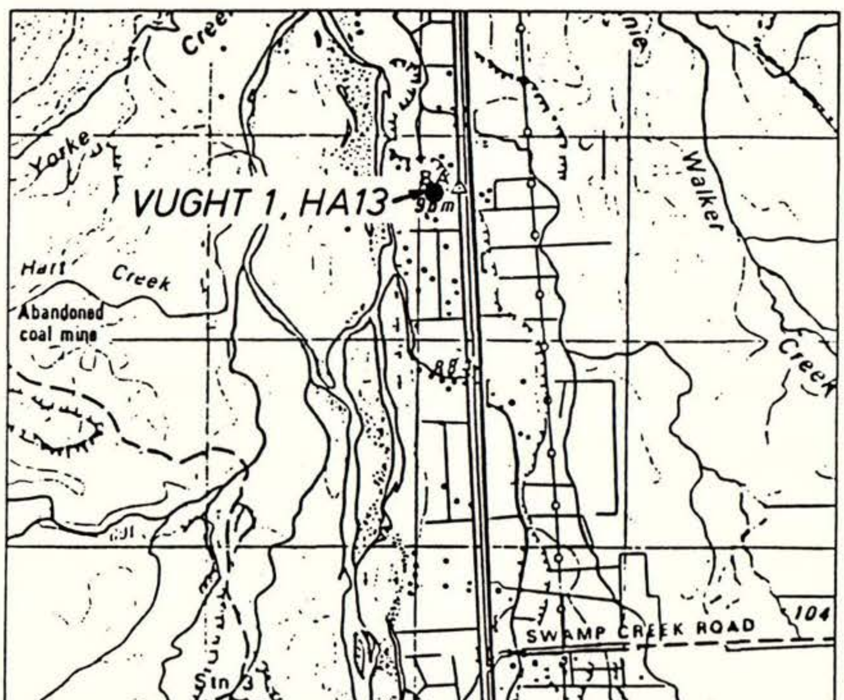

Figure 17 Van Vught's farm, adjacent to SH69 between Reefton and Inangahua.

According to the hand auger log, (Appendix I), and the result of the Scala test (in Appendix II), there is a layer of very loose fine sand (0.4 m thick) covered by silt, and a layer of loose medium sand (0.3 m thick) below the fine sand layer. Gravels were found at a depth of approximately 1.4 m. The water table was 0.9 m on 11 January 1991. As the gravel layer was found at a very shallow depth the site was not suitable for further exploration.

3.11 PRELIMINARY EXPLORATION IN KILKENNY PARK (WESTPORT)

To test the reliability of the Scala testing, four Scala tests, (KILK1, KILK2, KILK3, KILK4) were conducted in Kilkenny park as shown in Figure 18, where soil liquefaction occurred in the 1968 earthquake. KILK1 and KILK2 were performed in nearly the same place (within 10 m of one another). The results seem to be consistent as shown in Appendix II.

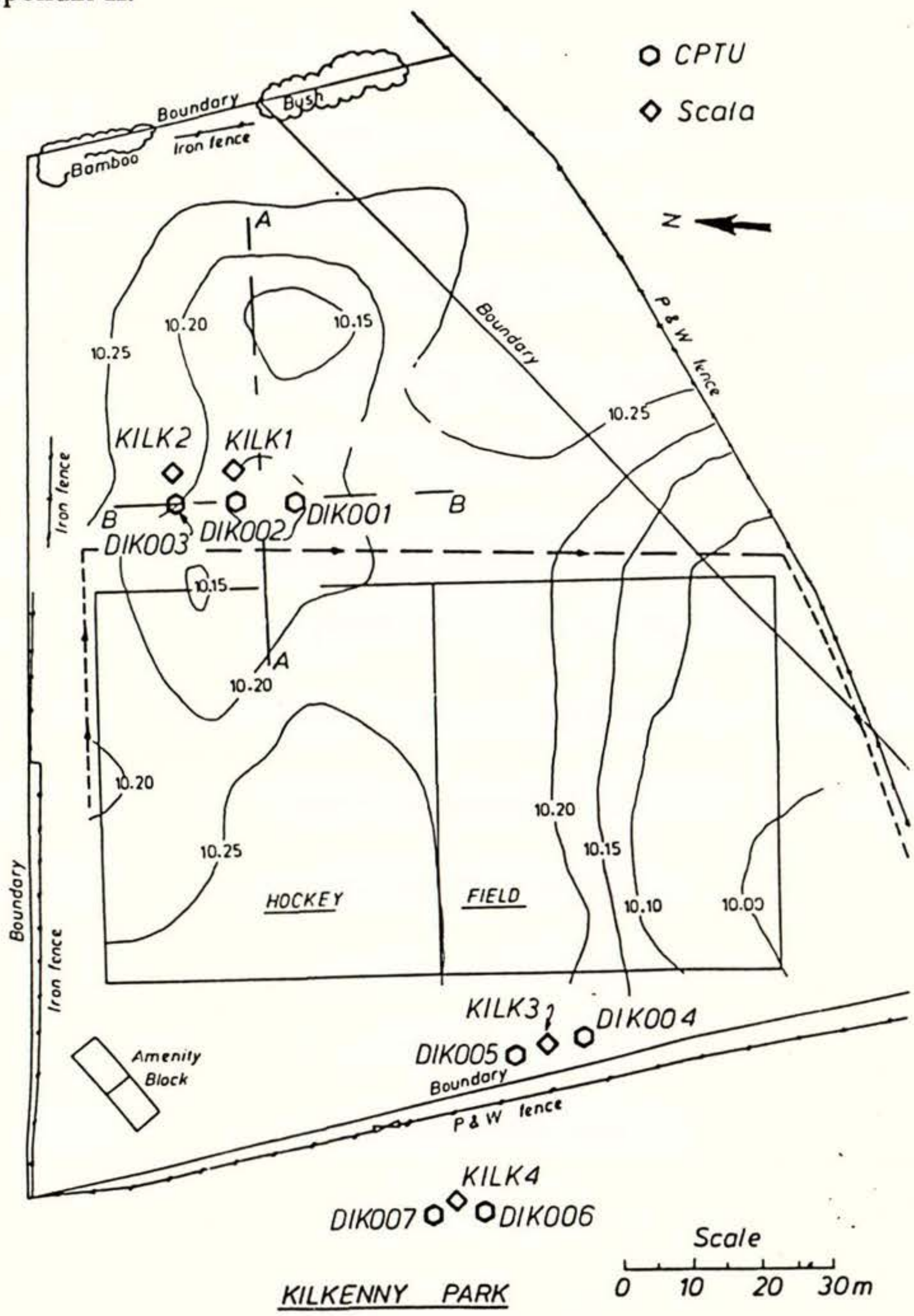

Figure 18 Kilkenny Park, Derby Street, Westport.

3.12 OTHER PRELIMINARY EXPLORATION NEAR WESTPORT

At the south-eastern corner of Westport airport, a hand auger bole, HA11, and a Scala test were made in an area where there was no report of the occurrence of liquefaction in the 1968 earthquake. The hand auger bore and the Scala test revealed that gravels were found at a shallow depth.

At O'Connor's farm, at the western liquefied site [3]; (Mr O'Connor reconfirmed and pinpointed the site that liquefied in the 1968 earthquake), a hand auger, HA12, was made to reveal the soil condition as shown in Figure 19. A Scala test, OCON1, was conducted at the same position as HA12. The hand auger log, HA12, (in Appendix I) and the result of the Scala test, OCON1, revealed a layer of silt (0.6 m thick) overlaying a layer of very loose fine to medium sand (more than 2 m thick as the hole collapsed while drilling). Gravels were met at a depth of 4.2 m. The water table was 1.9 m on 31 October 1990. Another Scala test was conducted 10 m east of HA12 and met gravels at a depth of 5.1 m. The site was liquefied twice, in both the 1968 Inangahua earthquake and the 1963 Westport earthquake [5]. It is a very good site for further detailed exploration.

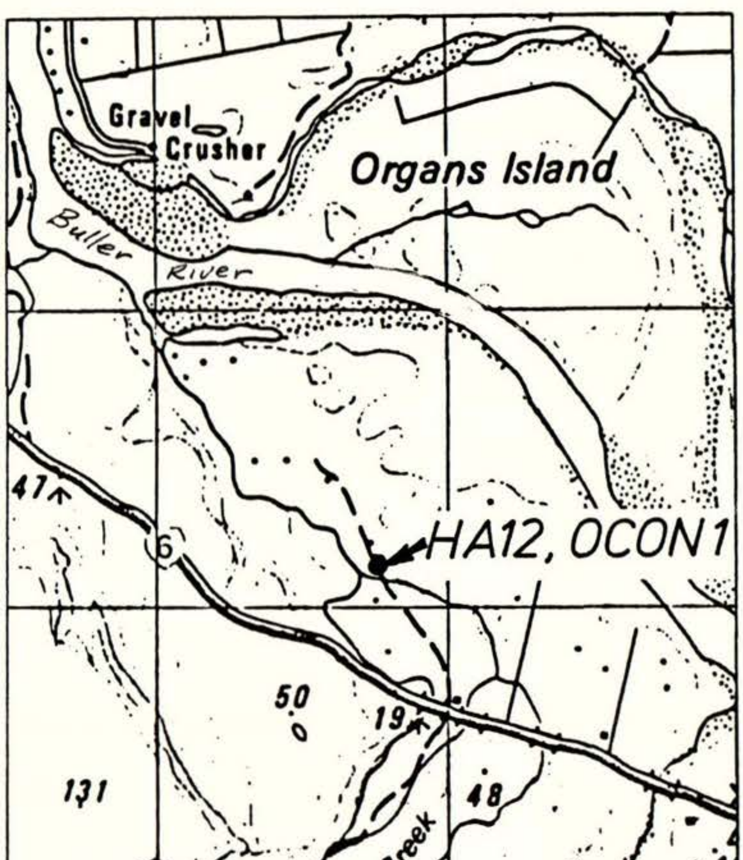

Figure 19 O'Connor's farm at the mouth of the Buller Gorge, adjacent to SH6.

At Reedy's farm, two Scala tests, REEDY1 and REEDY2, were conducted.

4 THE SPT TESTS

In this campaign, SPT tests were performed at liquefied site B, unliquefied site C at Wallace Turner's farm; and at the liquefied site on Peter Winfield's farm.

In our SPT tests, both the usual split spoon and a cone of similar external dimensions were used. Normally, the spilt spoon was used to obtain both penetration resistance and samples of soils tested. As bentonite drilling mud was not used in our tests, the bore hole stability was lost at certain depths below the water table (i.e. boiling occurred at the bottom of the hollow stem auger hole when the central plug was withdrawn). Some SPT tests can provide only an approximate estimate of the in-situ properties of the soils tested.

The SPT test results at Turner's farm show that both grain size and penetration resistance of soils under liquefied site B are significantly different from those of the soils under unliquefied site C.

4.1 THE SPT TESTS AT LIQUEFIED SITE B AT TURNER'S FARM

At liquefied site B on Wallace Turner's farm, three SPT bore holes (SPT1, SPT2, SPT3) were conducted as shown in Figure 11.

Figure 20 shows the results for SPT1, the first hollow stemmed auger hole in our explorations. The first SPT test was conducted from 3.4 m to 3.7 m. It was just at the boundary of the silt layer and fine sand as shown in Figure 20. In the silt layer the blow number was two for 250 mm, while in the top fine sand layer the blow number was one for 50 mm. After the first test water rose to 3.1 m in the hole. The second SPT test was made at a depth of 4.35 m. As sand boiled into the auger at a depth of 4.2 m, we had to lift the auger, then put it down again. This meant the sand layer on top (around the 4.2 m depth) was disturbed. The blow number for the second test was six. For every two blows the sampler was driven down 100 mm. The soil at the testing depth was loose grey clean fine to medium sand. Then, when we tried to do the third test at a depth of 5.3 m, sand rose to 2.7 m and the test had to be abandoned.

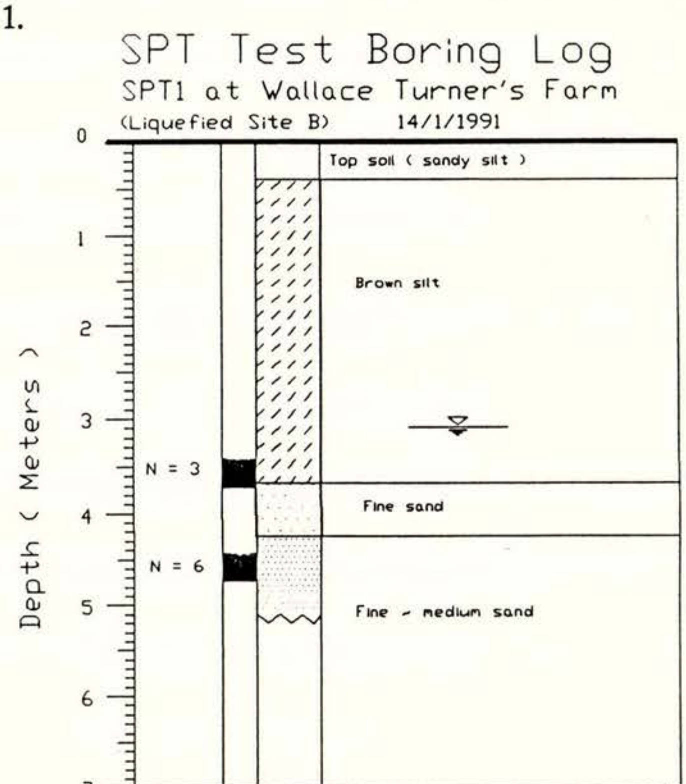

Figure 20 Note that for the lower SPT, sand had boiled into the hollow-stemmed auger (see text, p.30).

Five metres east of bore hole SPT1, another auger boring, SPT2 was made. Figure 21 shows the results of SPT2. The water table was at 2.7 m on 15 January 1991, 0.4 m higher than its position on 14 January 1991. Three SPT tests were conducted in bore hole SPT2. The first test was at a depth of 3.95 m to 4.25 m in the loose fine sand layer. Its blow count was four (the first two blows drove 200 mm and the remaining two blows drove 100 mm). The second test was made at a depth of 4.75 m to 5.05 m in loose medium sand. When lifting the centre plug of the hollow-stemmed auger at a depth of 3.7 m the sand boiled up inside the auger. The auger was lifted then dropped slowly and the second test was made. The blow number for the second test was nine. At a depth of 5.3 m, a 45° cone was used to do a SPT test. For the first 100 mm, the blow count was three; for the second 100 mm the blow count was seven and for the third 100 mm the blow count was 13.

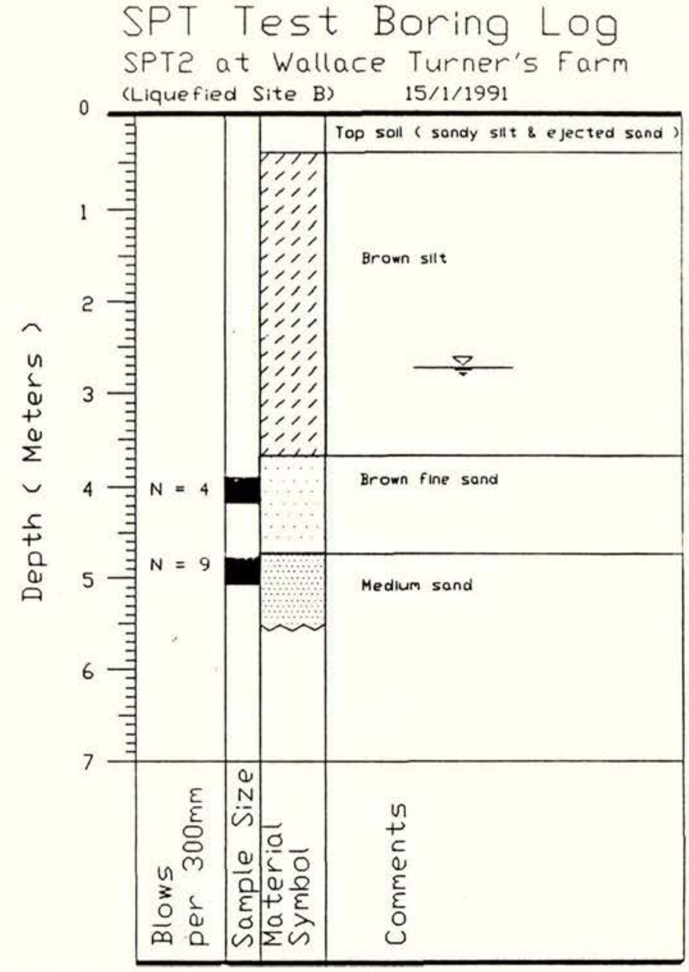

Figure 21 Hollow-stemmed auger boring made 5 m east of SPT1 (Figure 20). Again, the blow count in the medium sand is unreliable due to boiling.

Figure 22 shows the results of SPT3, which was conducted at liquefied site B close to SPT1 and SPT2. The water table was 2.4 m on 16 January 1991. Only one test was made at the 4.17 m to 4.47 m depth in the fine to medium sand layer. The blow count was nine (for first 150 mm the sampler was driven down by three blows; for the following 75 mm, three blows; for the last 75 mm, three blows). When lifting the centre at depth 4.95 m, sand boiled inside the auger up to 2.9 m. After lifting the auger, sands dropped (caved) to depth 3.6 m.

Figure 23 provides the results of the particle size distribution of soils under site B at different depths. The samples were mainly taken from the SPT tests which were conducted at site B. The D_{50} of the sands under site B is mainly below 0.2 mm.

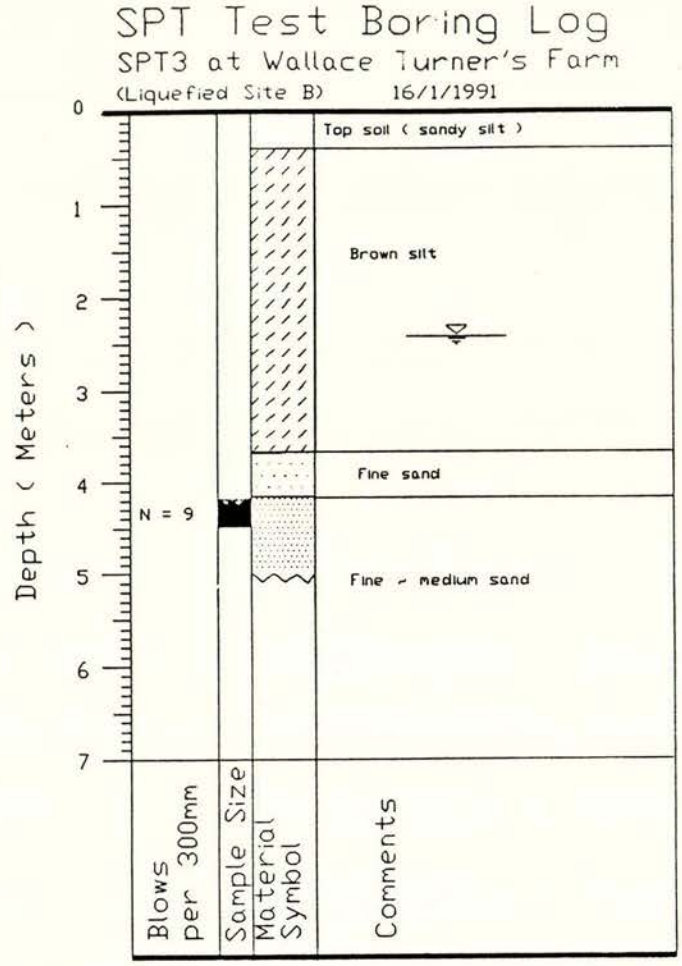

Figure 22 Third boring at site B, Turner's farm. The value of N=9 is probably a lower bound; 6 blows were required for the final 150 mm, giving N=12.

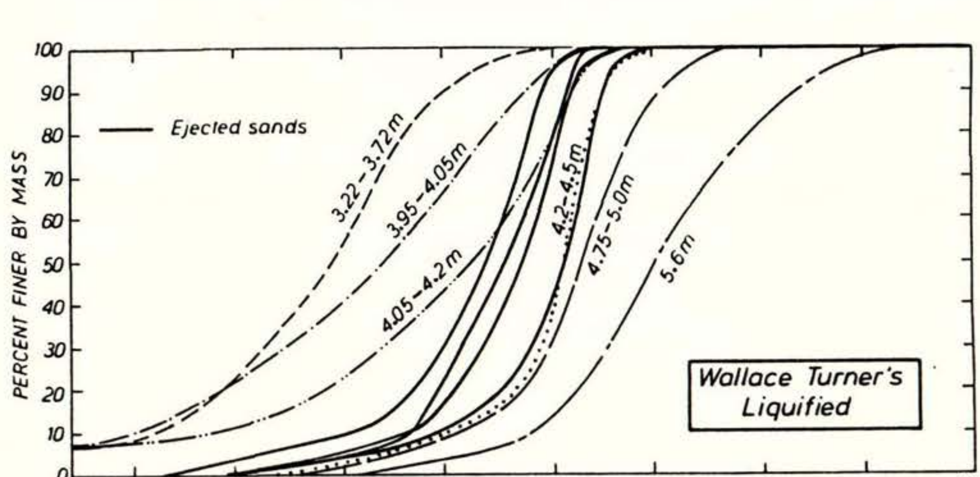

Figure 23 Particle size distribution of soils under site B at Walkers Flat.

4.2 SPT TESTS AT UNLIQUEFIED SITE C

At unliquefied site C on Wallace Turner's farm, two hollow stemmed auger borings (SPT5, SPT6) were made at the site shown in Figure 11.

The result of SPT5 is displayed in Figure 24. The first test was made at a depth of 3.26 m to 3.56 m in loose grey fine to medium sand. The blow count was eight (two blows every 75 mm). The second test was made at a depth of 3.85 m to 4.15 m in dense, medium to coarse sand. The blow count for the second test was 19 (five blows for first three 75 mm core sections and four blows for the last 75 mm sample). At a depth of 4.74 m an attempt to make another SPT test failed, as sands heaved up inside the auger to 3.43 m. The water table was 3.04 m on 17 January 1991.

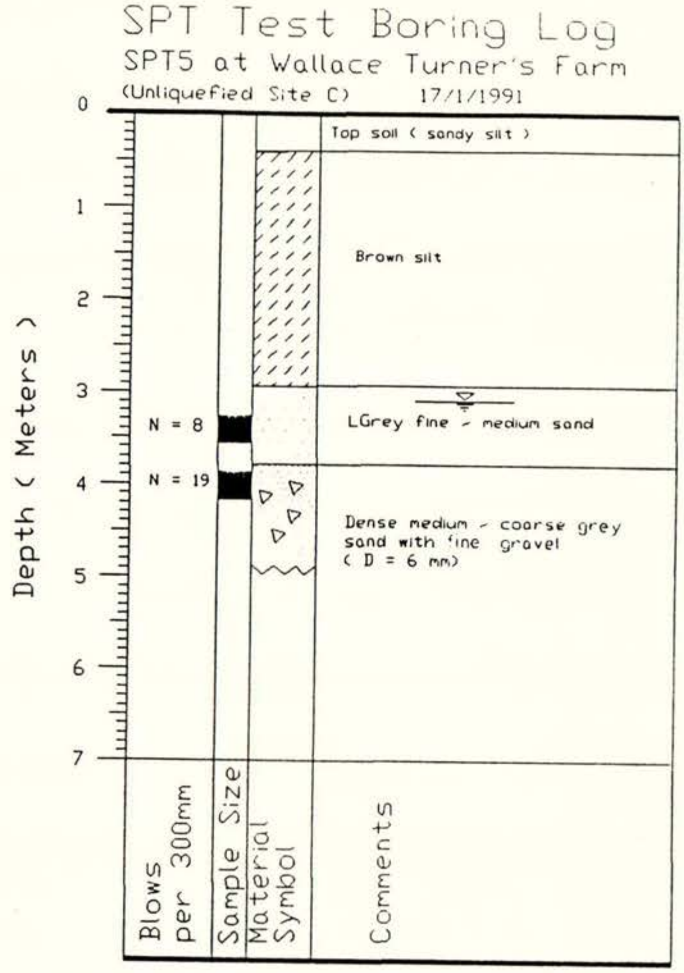

Figure 24 Hollow-stem auger boring SPT5, at site C (no liquefaction) at Turner's Farm.

Two SPT tests were performed in bore hole SPT6, 20 m west of bore hole SPT5 in unliquefied site C. The test results of SPT6 are shown in Figure 25.

The first test was made at a depth of 4.1 m to 4.4 m in the dense medium to coarse sand layer. The blow count for the first test was 15 (three blows for the first 75 mm sample four blows for the second, third and fourth 75 mm samples). As sand heaved up to 200 mm at the seating drive depth of 3.95 m, the auger was lifted then slowly dropped to a new seating drive depth. The second test was made at a depth of 4.62 m to 4.92 m in a dense medium to coarse grey sand layer with fine gravels. The blow count was 16 (four blows for each 75 mm). As sand heaved up at the seating drive depth, the auger was lifted 200 mm then dropped again to do the SPT test. The water table at the site was 2.97 m on 17 January 1991.

Figure 26 shows the particle size distribution of the soils under the site C. The D_{50} of the sands under site C is mainly larger than 0.3 mm.

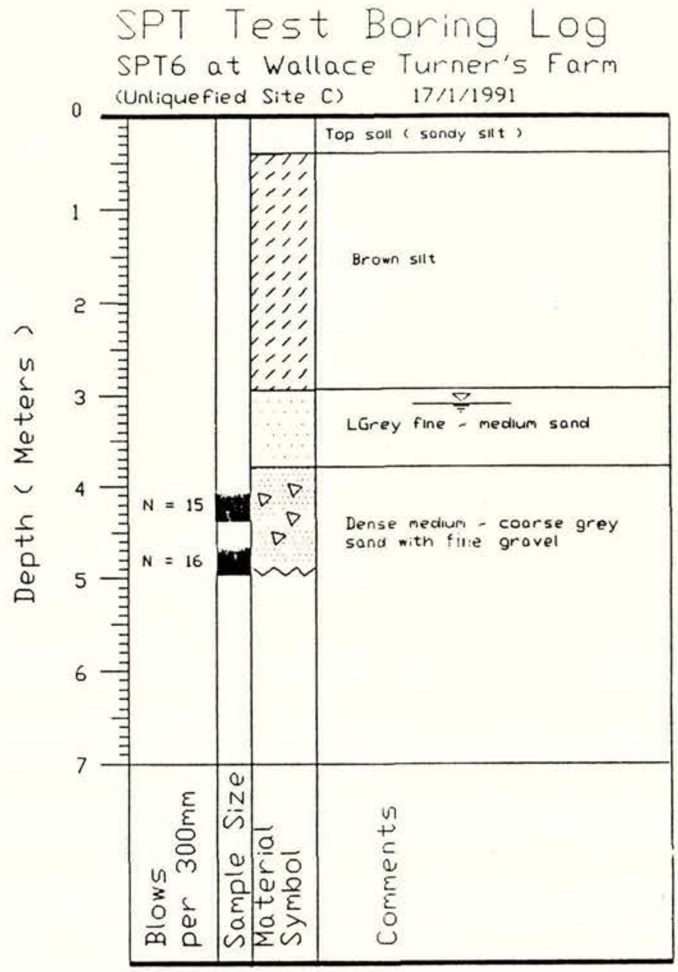

Figure 25 Second boring at site C, Turner's farm 20 m west of SPT5. Heaving of sand occurred before both SPT tests, thus the N values must be treated with doubt.

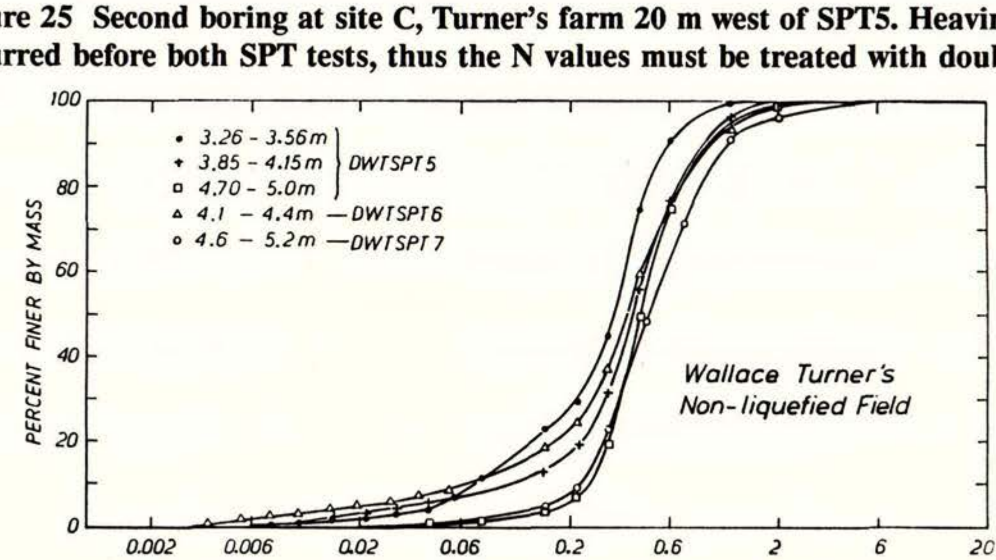

Figure 26 Particle size distribution of soils under site C at Walkers Flat showing clean medium sands.

4.3 THE SPT TESTS ON PETER WINFIELD'S FARM

Only one bore hole was drilled on Peter Winfield's farm at a site which liquefied in the 1968 Inangahua earthquake, at the location shown in Figure 14. Three SPT tests were made in the bore hole. The first test was made at a depth of 3.5 m to 3.8 m in both the silt and fine sand layers as shown in Figure 27. The blow count was eight. The test at the

3.5 m to 3.7 m depth, in silt, required a blow count of four while the 3.7 m to 3.8 m test, in fine sand had a blow count of four. The second test was made at a depth of 4.65 m to 4.95 m in the grey, medium to coarse sand layer. The blow count was 17 (four blows for first and second 75 mm samples, five blows for the third and four blows for the last 75 mm sample). The third test was made at a depth of 5.75 m to 6.05 m in the coarse sand layer. The blow count was 20 (four blows for the first and second 75 mm samples and six blows for the third, fourth and fifth 75 mm samples). As sand heaving occurred in the third test, the auger was lifted. After releasing the auger, the heaved sand still remained inside the auger 150 mm. We had to penetrate the sand inside the auger, then do the third SPT test.

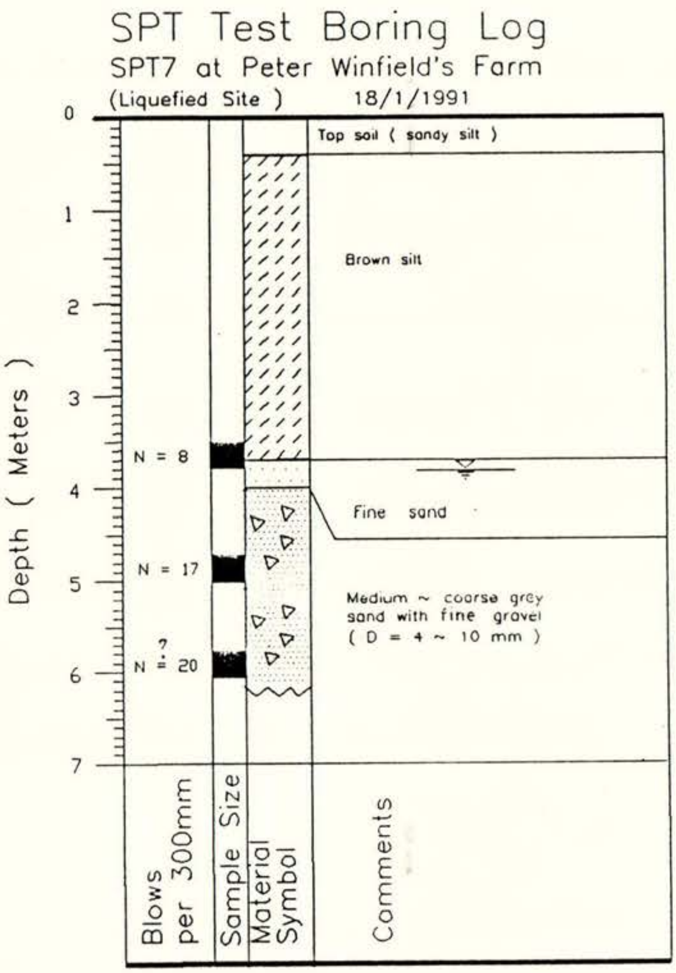

Figure 27 Hollow-stem auger boring at Winfield's farm. First two SPTs are reliable; heaving occurred in removing plug for third test.

Figure 28 displays that particle size distribution of sands under the site. The samples were taken from the SPT tests. In the first test at a depth of 3.5 m to 3.8 m the D_{50} of the sands is below 0.2 mm. In the second and the third tests at 4.8 and 5.9 m the D_{50} of the sands are larger than 0.3 mm.

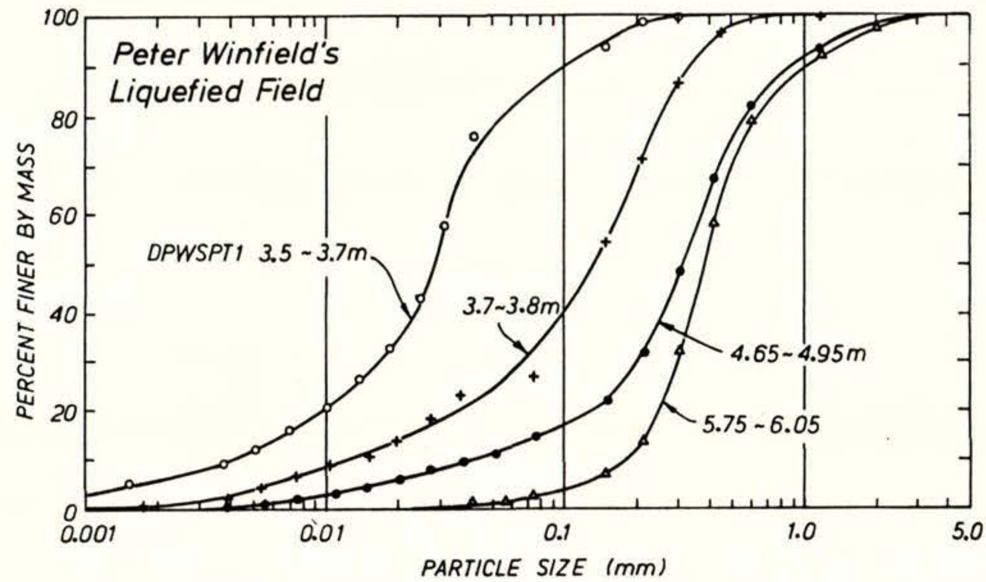

Figure 28 Particle size distribution at liquefaction site on Winfield's farm.

5 THE CPTU TESTS

The apparatus used for the CPTU tests was a Fugro 50 kN piezocone penetrometer driven by a truck-mounted drilling rig which was developed by the soil mechanics group of the Civil Engineering Department at the University of Canterbury. The piezocone can measure pore pressure, point resistance, sleeve friction, cone inclination, and penetration rate in soils up to a depth of 20 m. This piezocone penetrometer has a standard 60° apex cone at the head of the penetrometer (diameter 35.7 mm, projected area 10 cm^2) with a 5 mm thick porous element mounted 5 mm behind the shoulder of the cone, and a 150 cm^2 friction sleeve. De-airing of the piezocone was performed in a container of water connected to a vacuum pump to create a vacuum in the container. The extent of de-airing of the piezocone depends on the de-airing time and the vacuum pressure in the container. Normally, de-airing time was 30 minutes at -0.9 atmospheres.

In our campaign, 20 CPTU tests were conducted at liquefied site A, liquefied site B, unliquefied site C on Wallace Turner's farm; on Peter Winfield's liquefied site and at Kilkenny Park. The CPTU tests performed at liquefied sites and the unliquefied site on Turner's farm display significant differences in both cone resistance and pore pressure. An anomalous distribution pattern of pore pressure has been observed in the liquefied site at Turner's farm and at the liquefied depth at Kilkenny Park. Only a few CPTU tests will be discussed here. All of the CPTU test results can be found in Appendix III.

5.1 CPTU TESTS ON WALLACE TURNER'S FARM

On Wallace Turner's farm, 15 CPTU tests were conducted at three different sites (site A liquefied in both the 1968 Inangahua earthquake and the 1991 Westport earthquake; site B liquefied only in the 1968 earthquake; site C did not liquefy in either earthquake).

5.1.1 The CPTU Tests at Site A

Four CPTU tests were performed in site A. They were labelled WT5001, WT5002, WT5003, WT5012. The precise positions of the tests are mapped on Figure 6.

The most significant characteristics of the CPTU tests here are a very low cone resistance in the liquefied fine sand layer (8 bars to 30 bars; i.e. 0.8 to 3 MPa) and the different distributions of pore pressure in different soils. In the silt layer, the pore pressure measurements display mainly positive and stable values. In the fine sand layer from about 3 m to 3.8 m, which liquefied in both the 1968 earthquake and the 1991 earthquake, pore pressure measurements display an oscillatory pattern with large amplitude and medium period. In the medium sand layer, pore pressure measurements display a little oscillation, with small amplitude and relative high frequency. In the gravelly sand layer, the pore pressure is closer to the hydrostatic value, reflecting freer drainage. Figure 29 shows the result for one, (WT5003), of the four CPTU tests, which were conducted on a sand boil ejected in the 1991 earthquake.

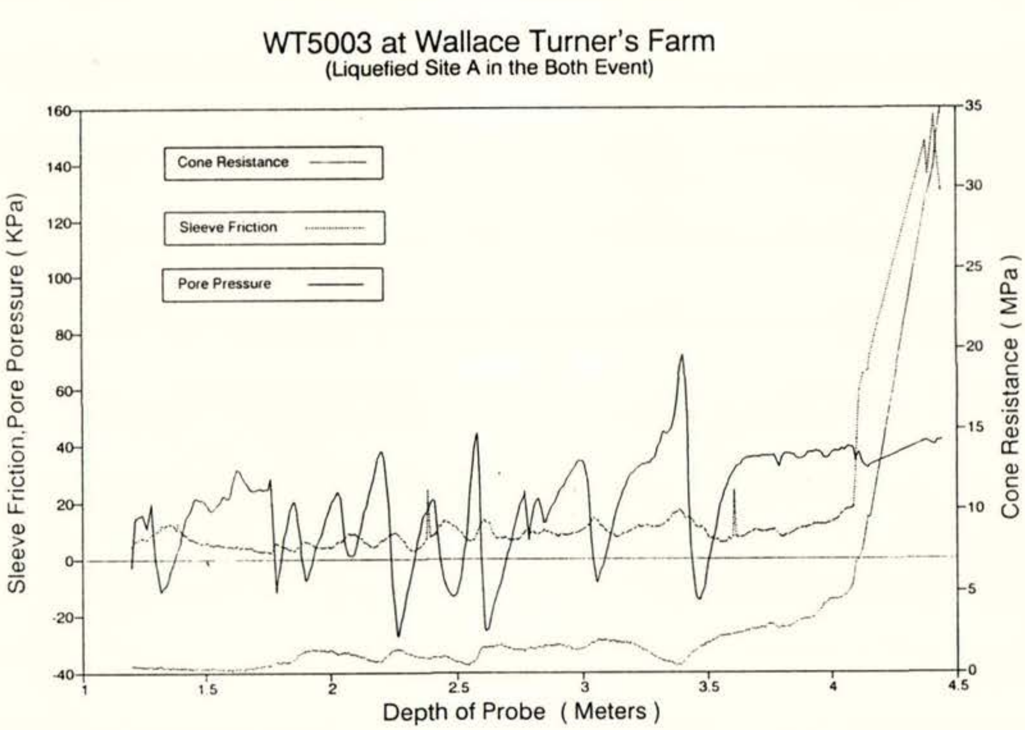

Figure 29 Typical CPTU results for site A, Turner's farm.

Using the soil behaviour type classification chart proposed by Robertson [9] (Figure 30), it can be estimated that at the test site there are two layers of clay to silty clay at a depth above 1.8 m and 3.3 m to 3.4 m; a layer of variable silty sand and sandy silt between 1.8 m and 3.7 m; and a layer of gravelly sand at a depth between 3.7 and 4.1 m.

A hand auger bore hole was conducted at the same position as WT5003. The particle size distribution of the samples taken from the hand auger bore and the sand boils ejected in the 1991 earthquake is shown in Figure 31. The PSD shown in Figure 31 displays very good consistence with the interpretation of the CPTU test WT5003. On the other hand, particle size analysis of ejected sands show that the ejected sands seem to be from the fine sand layer at a depth of 1.9 m to 3.7 m but that their grading is much cleaner. The point of resistance at a depth of 1.8 m to 3.7 m is from 8 bars to 27 bars, (0.8 to 2.7 MPa).

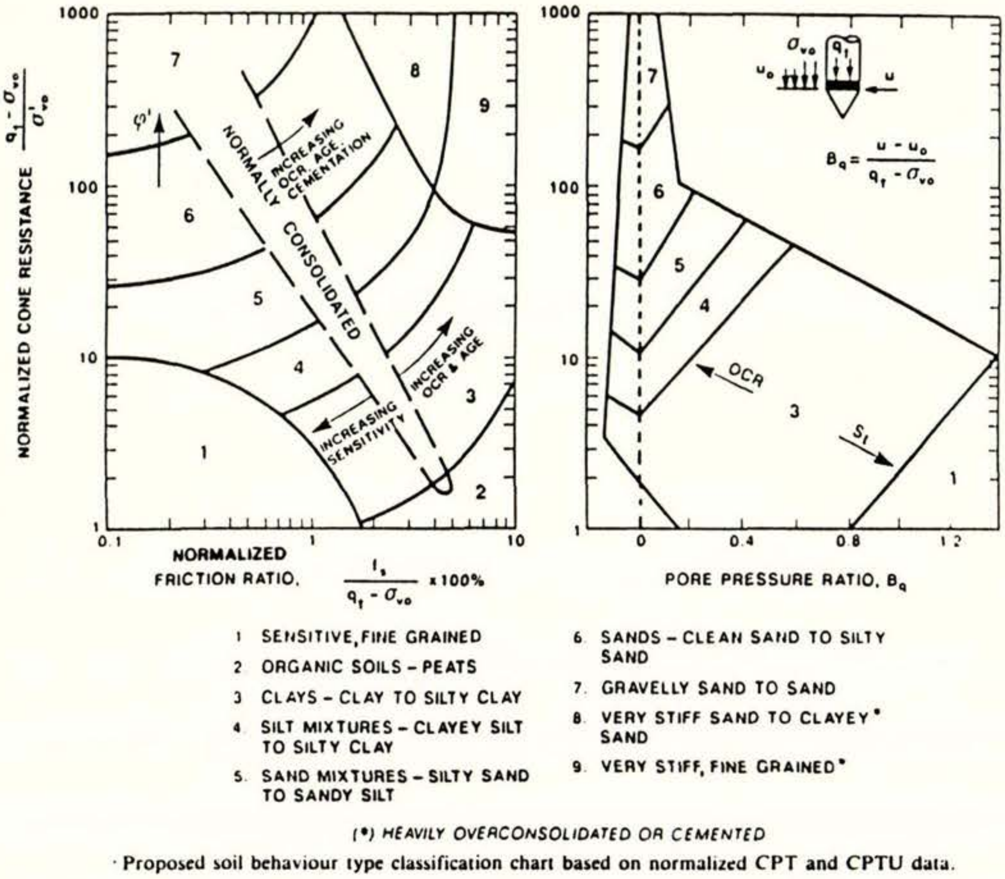

Figure 30 Robertson's soil classification chart for CPTU results.

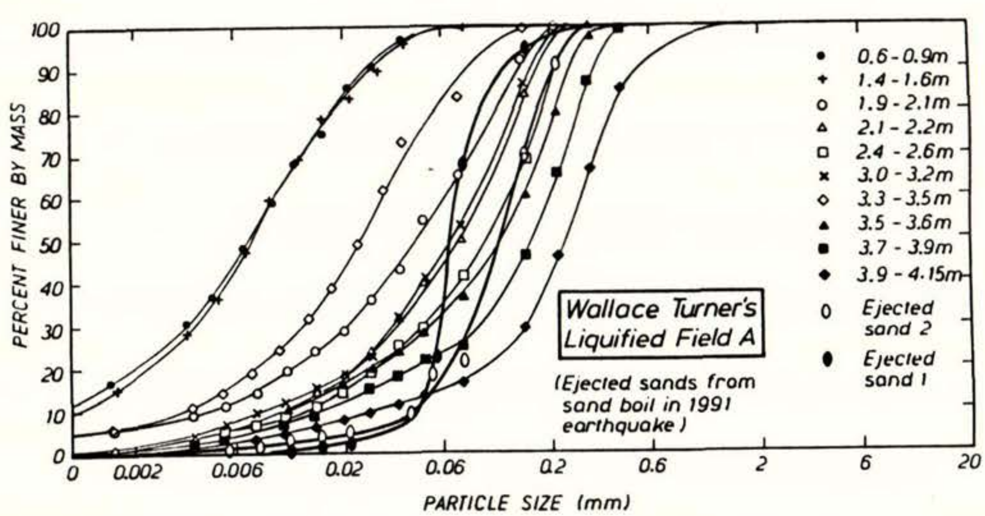

Figure 31 Particle size distribution of soils under site A at Walkers Flat.

5.1.2 The CPTU Tests at Site B

In site B, eight CPTU tests were performed in our exploration. They were labelled DWT001, DWT002, DWT003, WT5007, WT5008, WT5009, WT5010 and WT5011. The locations of the tests are shown in Figure 11. The disk record of DWT001 was damaged so that only the paper record of the test is available, which has a very similar pattern to DWT002.

Figure 32 shows one of the CPTU tests, WT5008, conducted in site B. The most interesting characteristic of the CPTU tests in site B is the pattern of the pore pressures. In the silt layer, pore pressure oscillated at a level much higher than hydrostatic pore pressure. In the fine sand layer which liquefied in the 1968 earthquake, pore pressure oscillated at a level much lower than the hydrostatic pore pressure. In the medium sand layer, which did not liquefy in the 1968 earthquake, the pore pressure is quite stable near the static pore pressure, and only varied slightly with small amplitude and higher frequency around the hydrostatic value. Since these test started above the water table, there may have been a loss of saturation in the upper layers, leading to unreliable pore pressure measurements in the fine-grained soils.

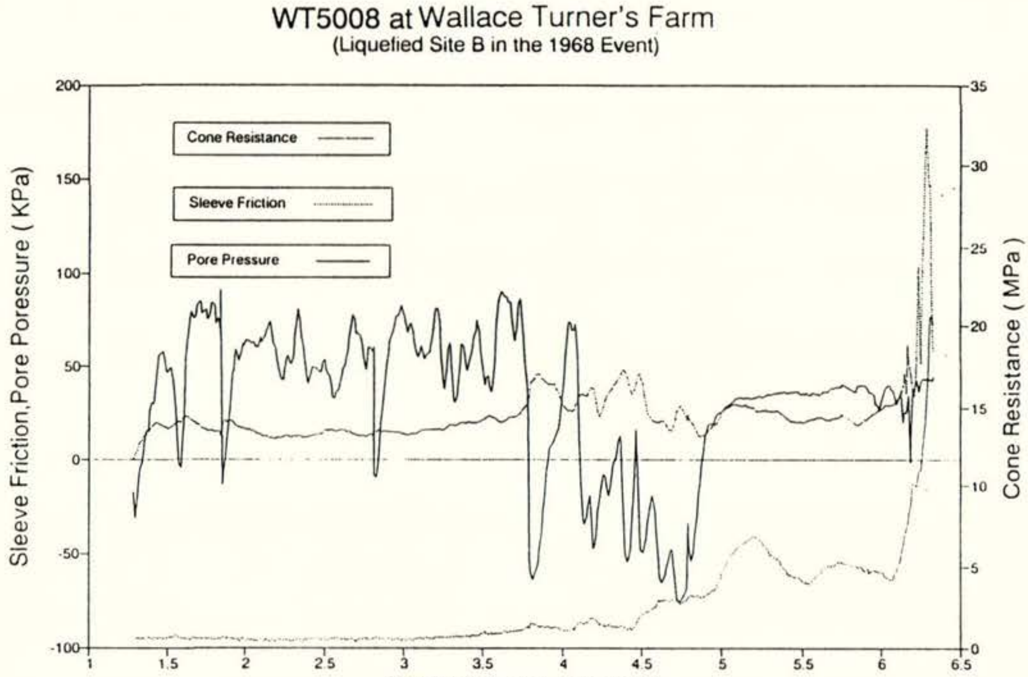

Figure 32 CPTU results from site B, Turner's farm.

5.1.3 The CPTU Tests at Site C

Site C did not liquefy in either the 1968 earthquake or the 1991 earthquake. Hand auger boring revealed that the soil stratigraphy is same as site B and that most sand layers are under water table. The results of the Scala and the SPT tests conducted in site C show that the sands under site C are denser than sands under sites A and B. The grain size analysis shows that the D_{50} values of the sands under site C are larger than those under site A and site B, or in other words, sands under site C are more coarse.

To make a continuous measurement of in-situ properties of soils under site C, four CPTU tests were conducted in the site. They are DWT004, WT5004, WT5005, WT5006. Figure 33 shows the result of the CPTU test WT5005 at site C, which was conducted in saturated sand layers, from a hole prebored to below the water table. The pore pressure measurement shows a stable rising pattern as depth increases, following the hydrostatic pore pressure. Figure 34 shows another CPTU test (WT5004) in site C, which started in the silt layer above the water table; water was poured into the predrilled hole to help prevent air get into the filter. The pore pressure measurement in WT5004 is quite similar to that in WT5005.

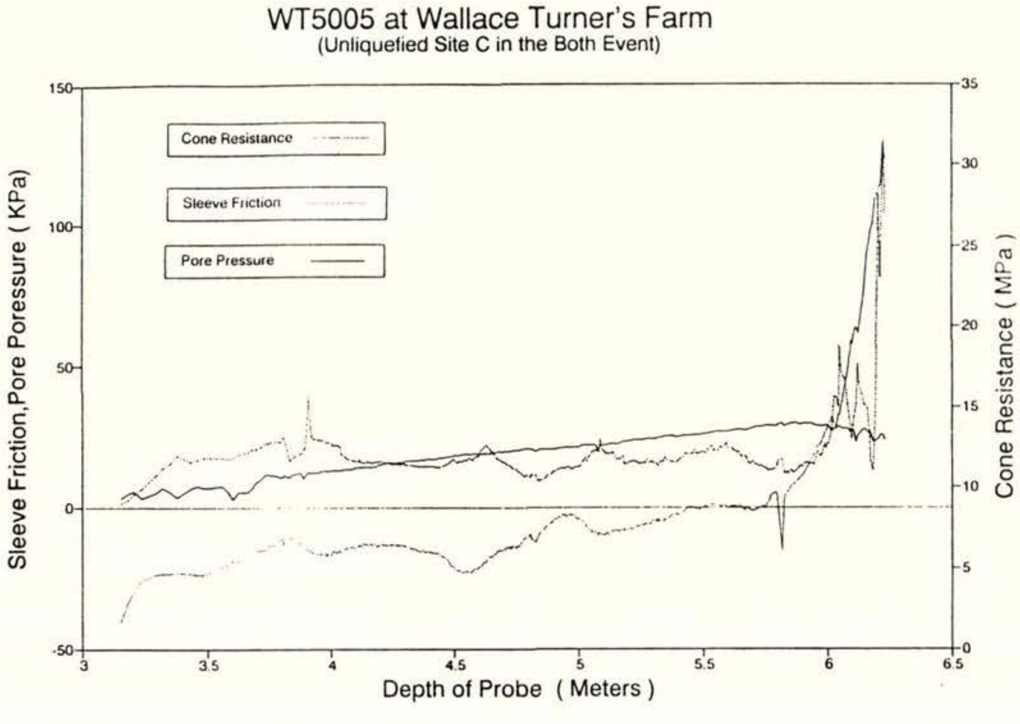

Figure 33 Site C, Turner's farm. Note the near-hydrostatic pore pressure trace in the generally coarser sands that did not liquefy in either the 1968 or 1991 earthquakes.

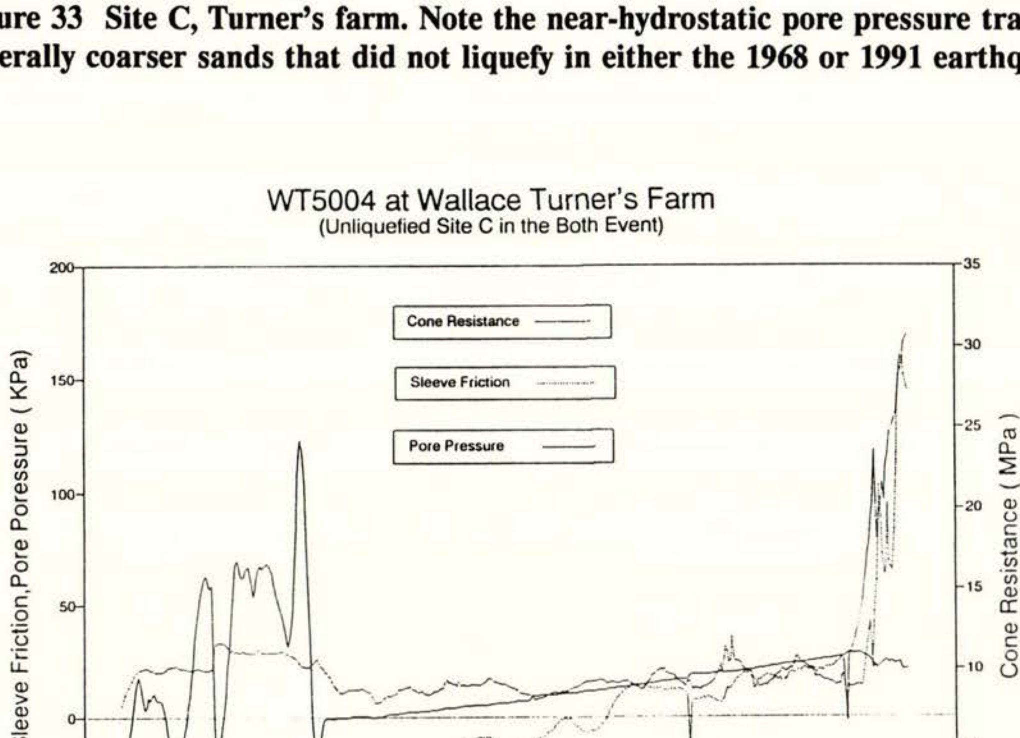

Figure 34 CPTU near site of probe shown in Figure 33, but without pre-drilling to water table.

5.2 THE CPTU TEST AT PETER WINFIELD'S FARM

Only one CPTU test was conducted in the liquefied site in Peter Winfield's farm, DWF005, the first CPTU test conducted in our exploration. The position of the CPTU test is shown in Figure 14. Figure 35 shows the results of the CPTU test. The pore pressure measurement oscillated heavily at a level below static pore pressure. Another interesting characteristic is that the amplitude and frequency of the oscillation of the pore pressure measurement seems to be related to the oscillation of the measurement of the point of resistance. This suggests that the fluctuations correspond to fine details of the soil layering. In this CPTU test, the predrilled hole (4.2 m deep) was not filled with soil, so that vibration of the rods might also cause the pore pressure oscillation.

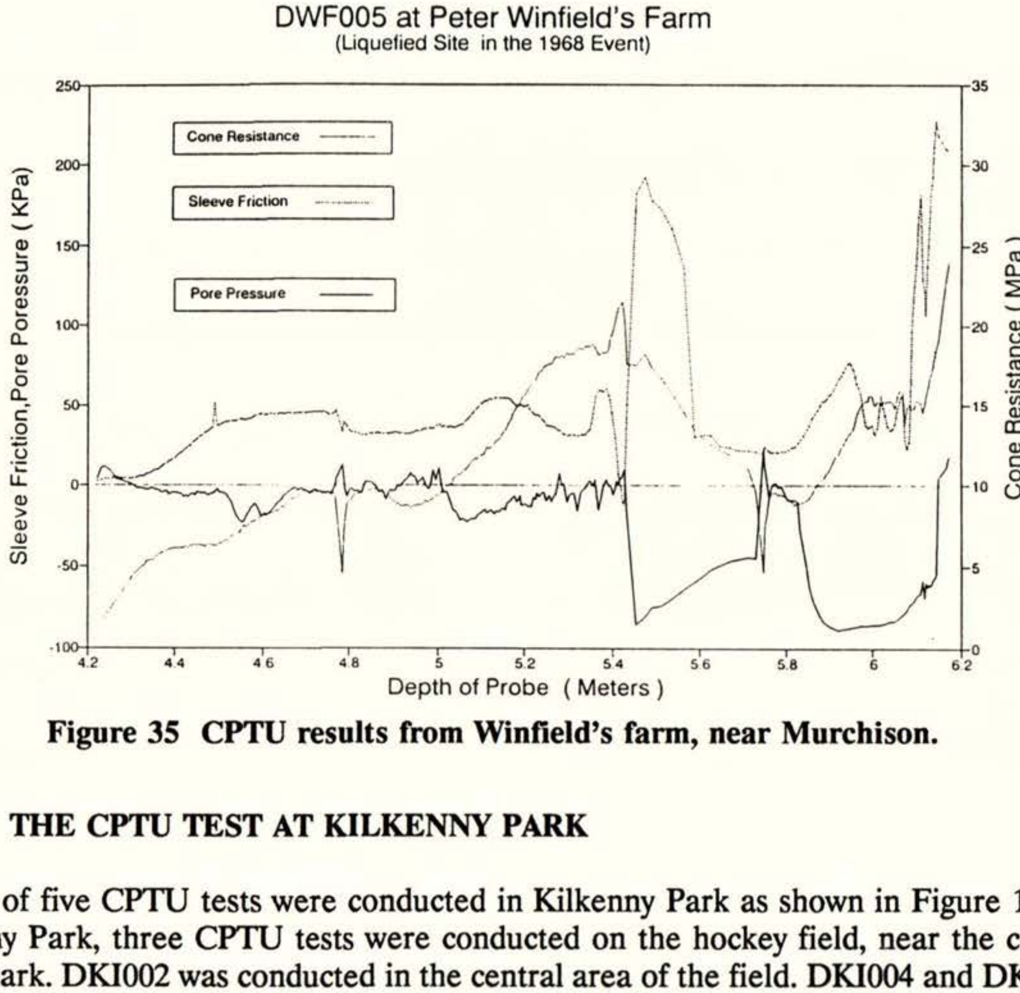

Figure 35 CPTU results from Winfield's farm, near Murchison.

5.3 THE CPTU TEST AT KILKENNY PARK

A total of five CPTU tests were conducted in Kilkenny Park as shown in Figure 18. In Kilkenny Park, three CPTU tests were conducted on the hockey field, near the centre of the park. DKI002 was conducted in the central area of the field. DKI004 and DKI005 were conducted at the western edge of the hockey field close to the SPT bore hole drilled during Bienvenu's exploration [5].

In the paddock across Derby Street on the western side of Kilkenny Park, which liquefied in the 1968 earthquake two CPTU tests, (DKI006, DKI007) were conducted. Here photographs in *The Nelson Evening Mail* of 28 May 1968 [3], show power poles leaning heavily off vertical. However, the disk record of DKI007 was damaged and only the backup paper record can be utilized for DKI007.

Figure 36 shows the results of the CPTU test DKI002. The pore pressure measurements display an oscillating tendency which add to a background of increased hydrostatic pore pressure. The oscillation normally happens at a lower level than hydrostatic pore pressure.

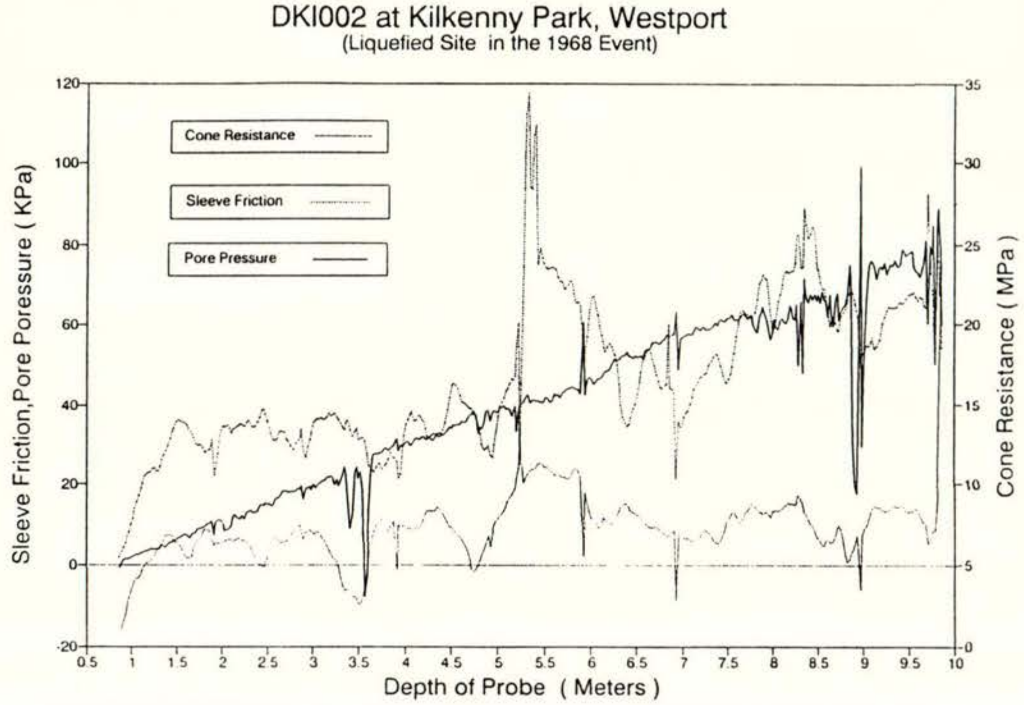

Figure 36 CPTU results from near the centre of Kilkenny Park, Westport. A large sand boil was observed at the location in 1968.

5.4 DISCUSSION OF REASONS FOR PORE PRESSURE OSCILLATION

Observations of pore pressure in our CPTU testing have suggested that there are two different types of oscillations in pore pressure as shown in Figure 37. This is an enlarged graph showing results from CPTU test DKI002 at Kilkenny Park, Westport. One kind of oscillation was caused by a sudden stress change in the soils under the probe of the piezocone during the sudden loading/unloading procedure of changing the rod, (Oscillation A) and that caused by soil properties in normal drilling, (Oscillation B).

Oscillation A, in a very simple form at around 1.9 m is depicted in Figure 37. During unloading, pore pressure rises quickly when the drilling speed drops. During loading, the pore pressure rises a little, drops quickly to a lower level and then rises again to the same level as before unloading. The procedure causes a pulse of pore pressure. The amplitude of the pulse appears to be dependent on the static pore pressure and the amplitude of the stress change. The frequency component of the pulse seems to depend on the bearing capacity of soils. The pulses in loose soils are more likely to have a low frequency component while the pulses in dense soils seem to have a greater high frequency component.

The forms of oscillation B are very complicated. Most of them have very small amplitude and a dominating high frequency component but some of them have large amplitude and a greater low frequency component as shown in Figure 37. As the drilling penetration speed is almost the same, except when changing rods, this means that during drilling the strain rate of the soil just under the probe of the piezocone depends on the soil structure. Therefore, the amplitude of oscillation B should bear some relationship to the bearing capacity of the soil. The amplitude seems to be more closely related to the change in the permeability of soil layers according to analysis of the pore pressure pattern displayed in Figure 37.

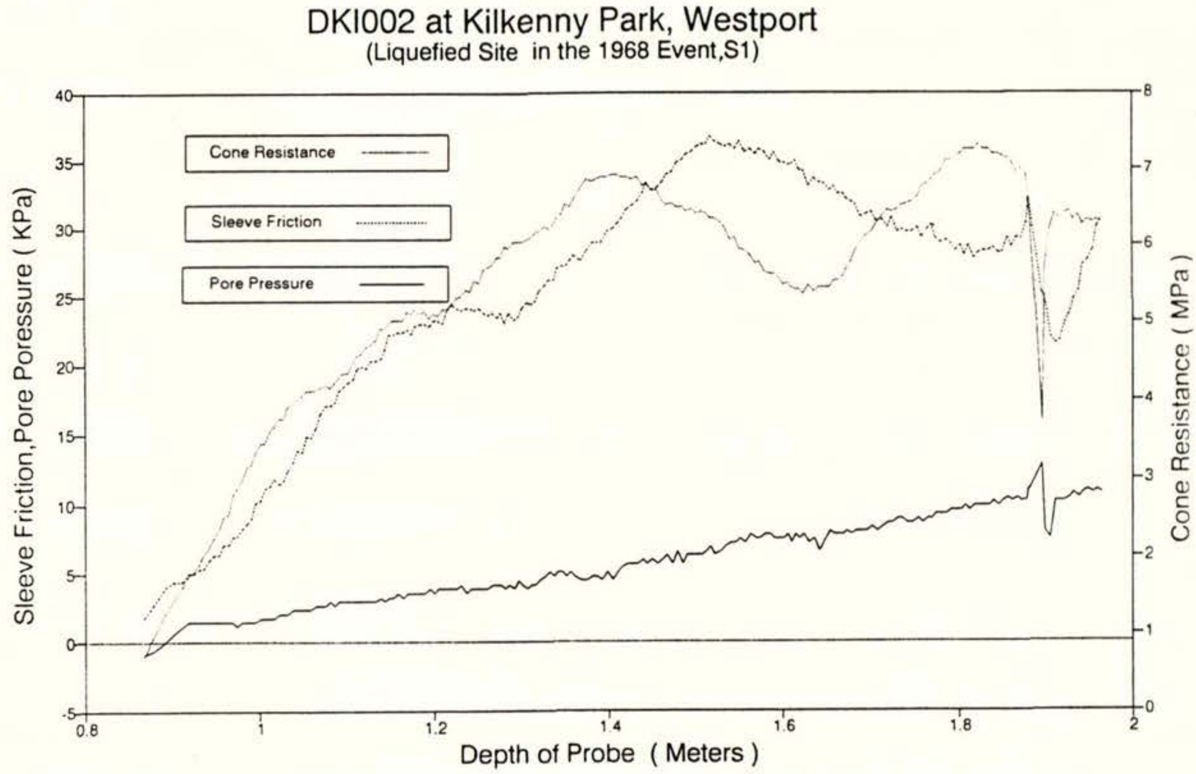

Figure 37 (1) Expanded plot of CPTU probe DKI 002, illustrating fluctuations in pore pressure trace with both minor and major changes in stratigraphy and with rod changes.

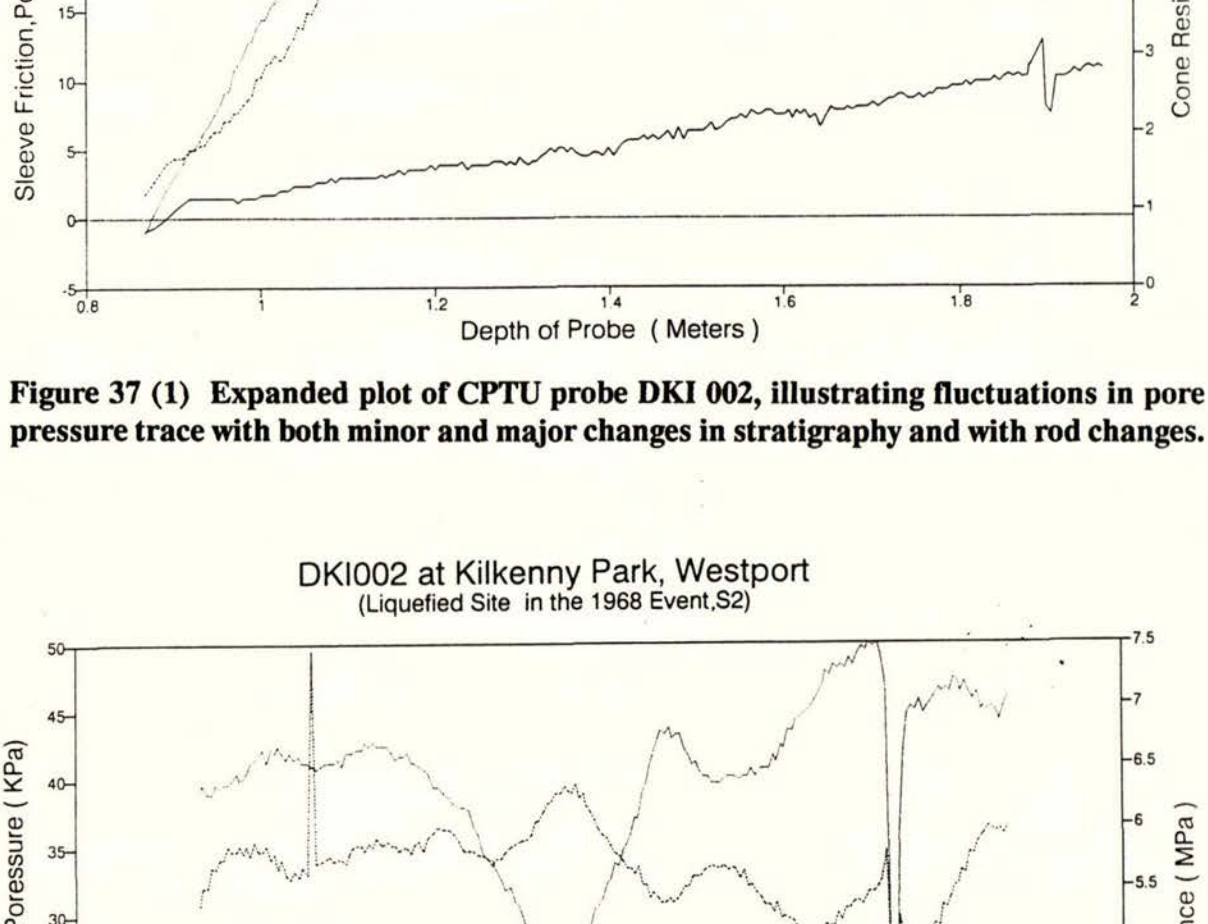

Figure 37 (2) Expanded plot of CPTU probe DKI 002, illustrating fluctuations in pore pressure trace with both minor and major changes in stratigraphy and with rod changes.

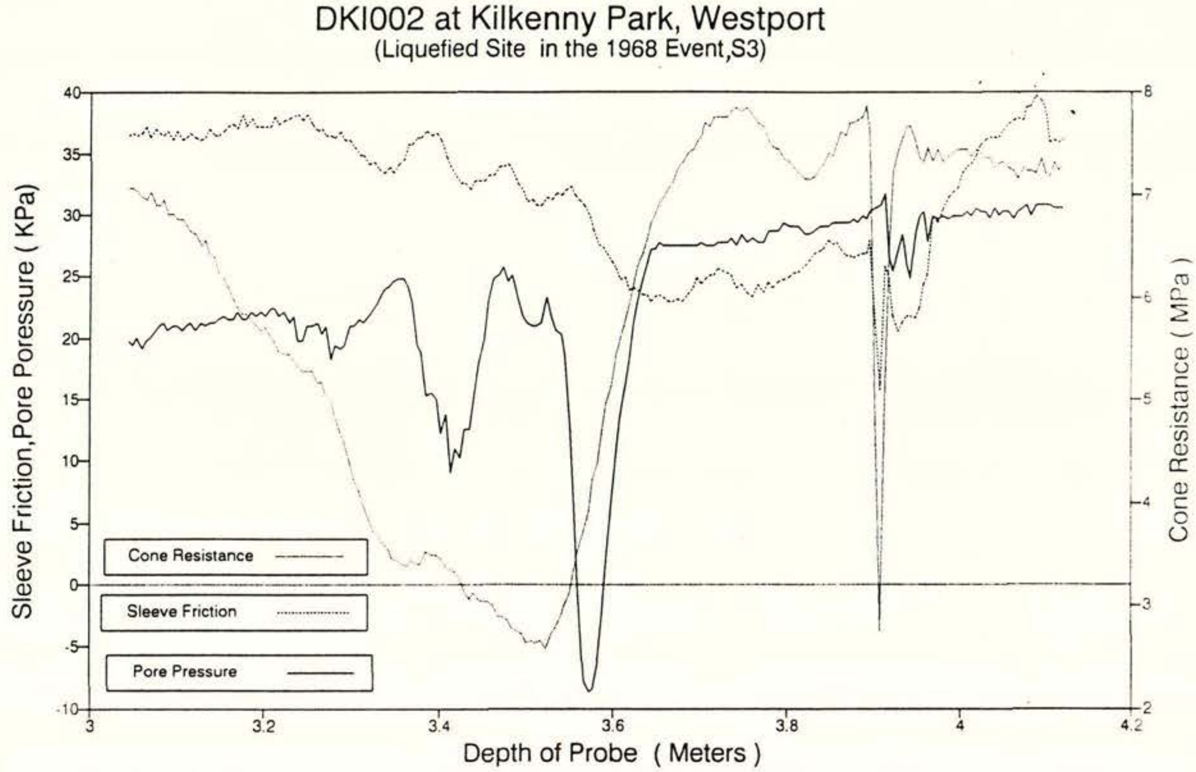

Figure 37 (3) Expanded plot of CPTU probe DKI 002, illustrating fluctuations in pore pressure trace with both minor and major changes in stratigraphy and with rod changes.

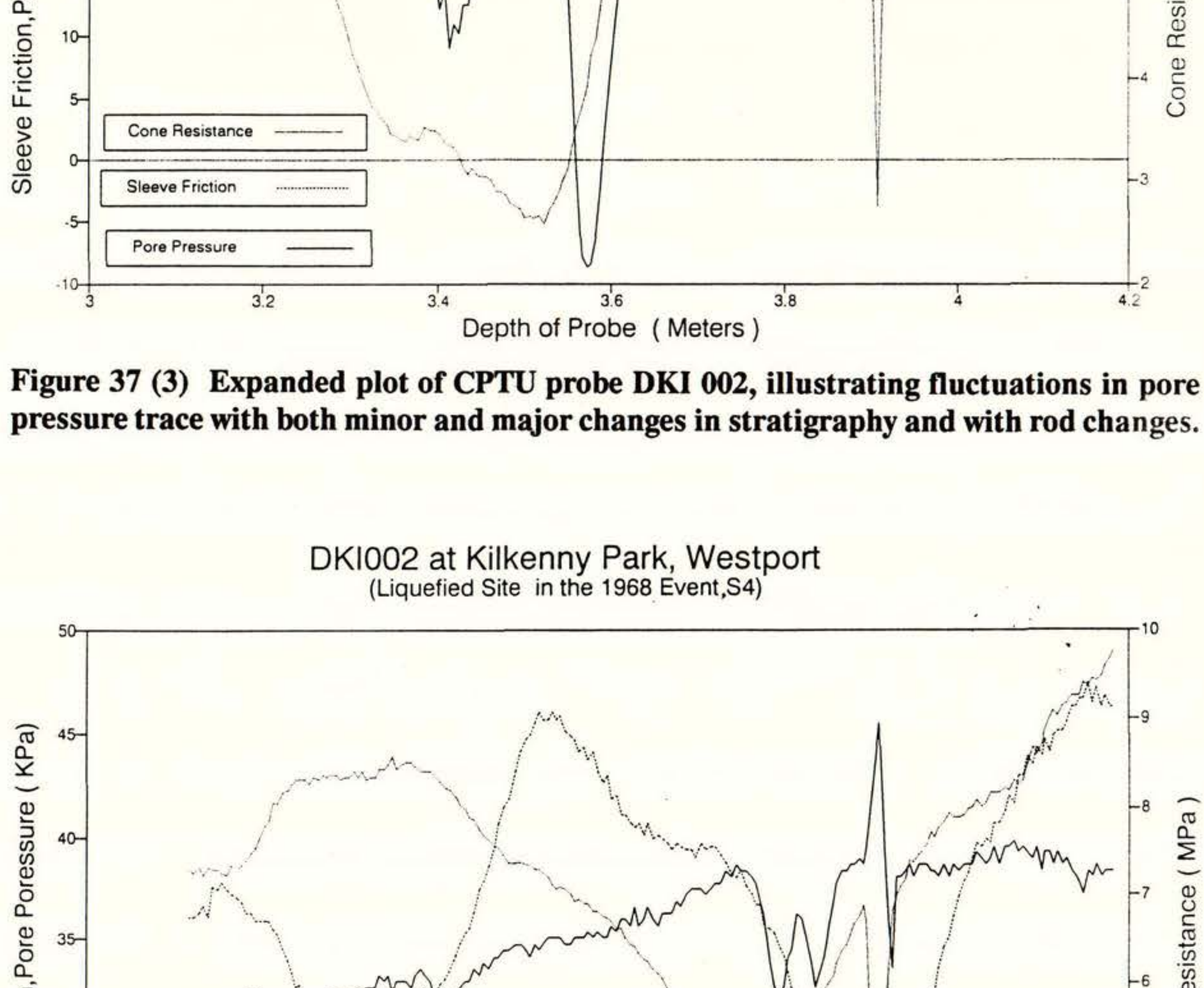

Figure 37 (4) Expanded plot of CPTU probe DKI 002, illustrating fluctuations in pore pressure trace with both minor and major changes in stratigraphy and with rod changes.

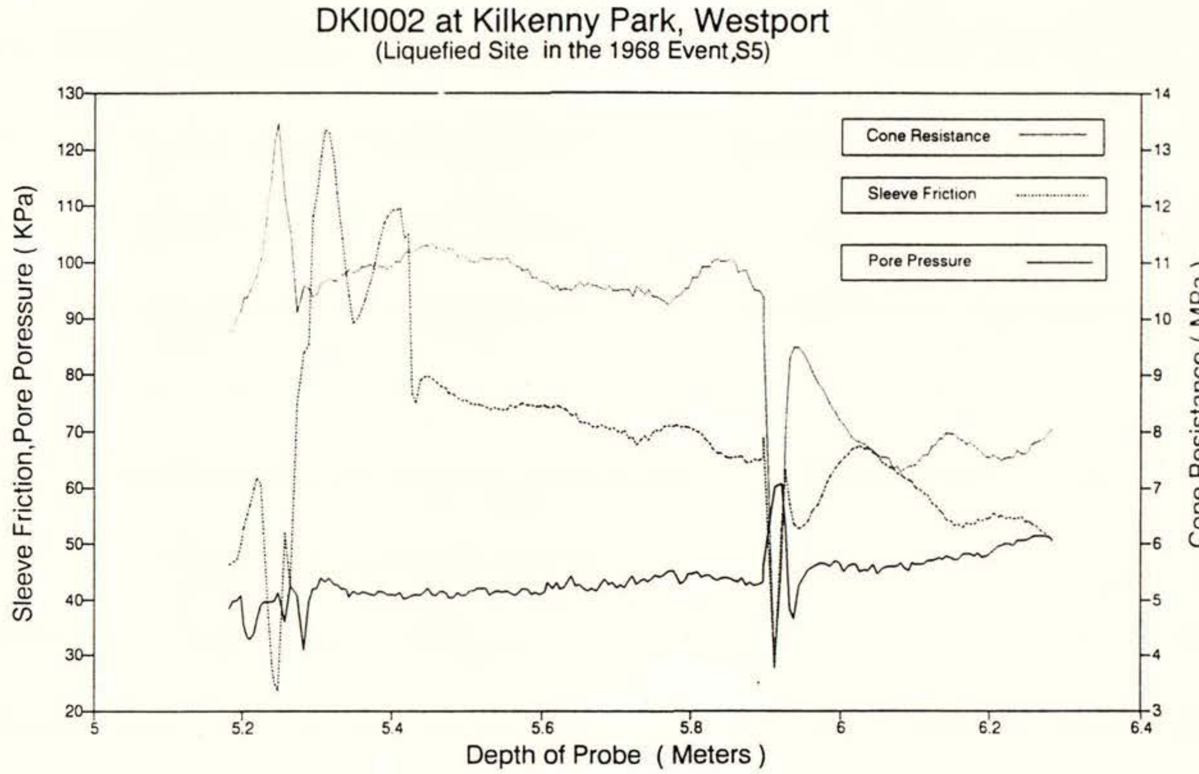

Figure 37 (5) Expanded plot of CPTU probe DKI 002, illustrating fluctuations in pore pressure trace with both minor and major changes in stratigraphy and with rod changes.

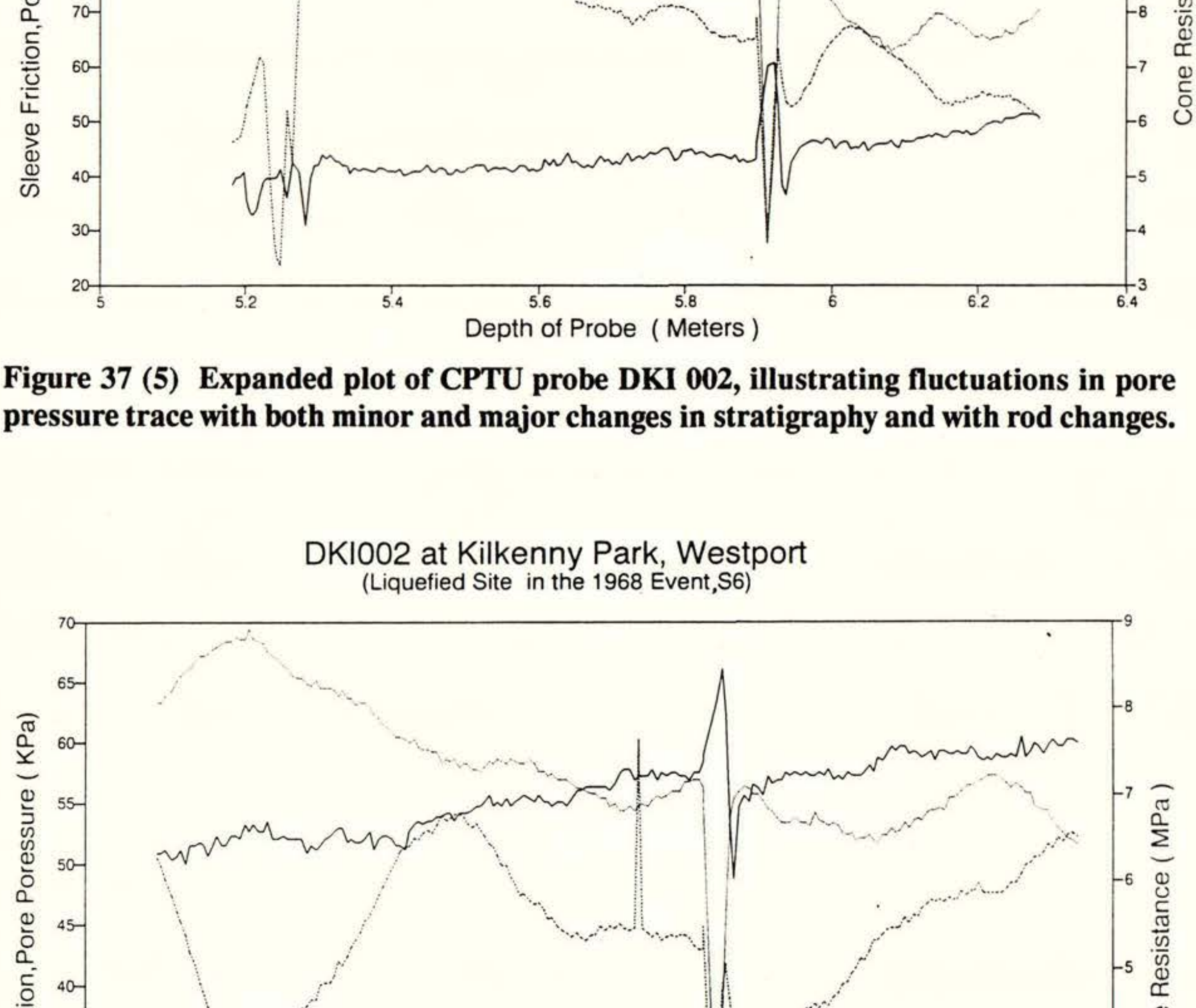

Figure 37 (6) Expanded plot of CPTU probe DKI 002, illustrating fluctuations in pore pressure trace with both minor and major changes in stratigraphy and with rod changes.

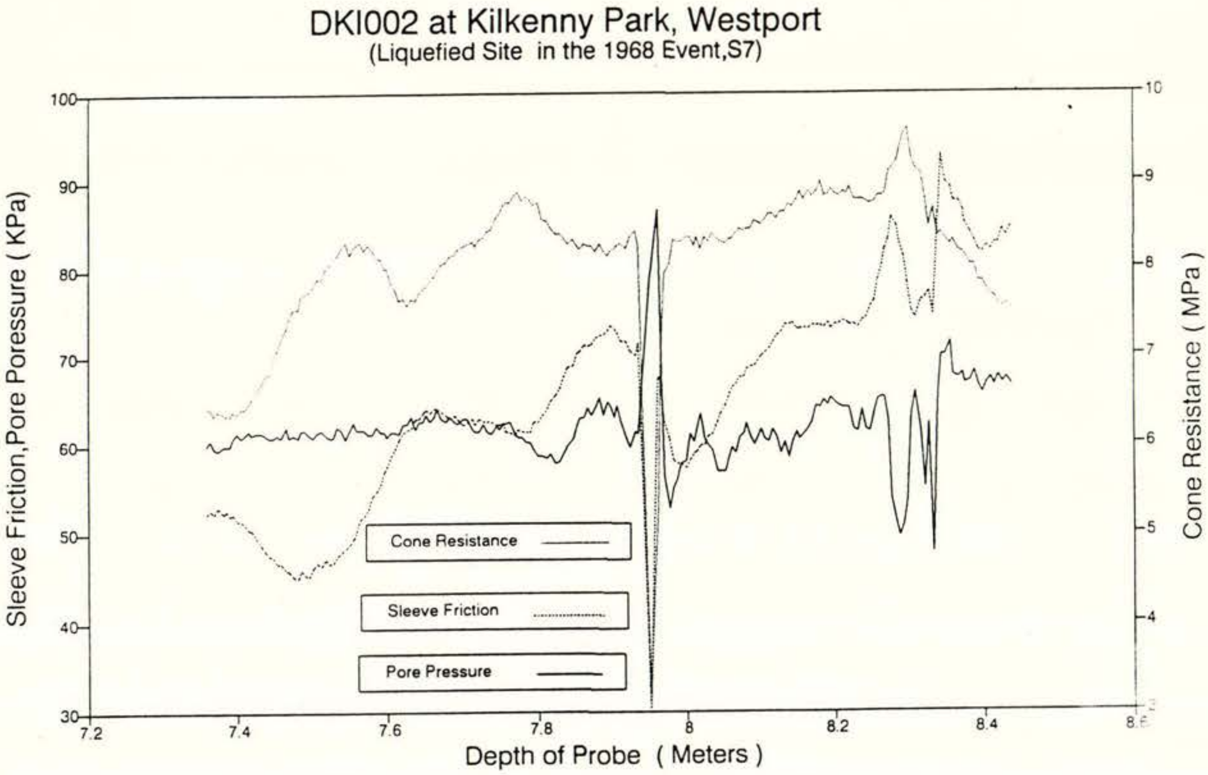

Figure 37 (7) Expanded plot of CPTU probe DKI 002, illustrating fluctuations in pore pressure trace with both minor and major changes in stratigraphy and with rod changes.

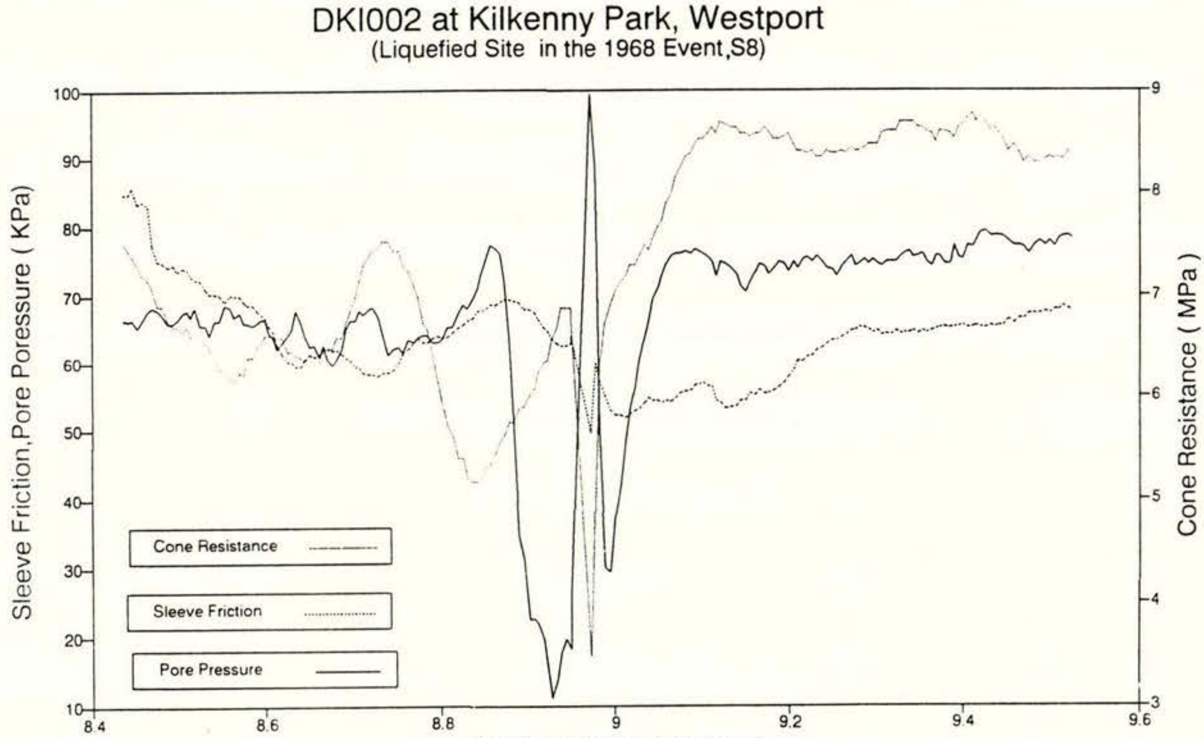

Figure 37 (8) Expanded plot of CPTU probe DKI 002, illustrating fluctuations in pore pressure trace with both minor and major changes in stratigraphy and with rod changes.

Figure 32 shows a very good example of oscillation B. From the depth of 1.4 m to 3.7 m, the mean value of oscillation B is positive and bigger than the static pore pressure, (Oscillation B1). From a depth of 3.7 m to 4.8 m, the mean value of the oscillation B is negative and much lower than static pore pressure, (Oscillation B2). At depths of 4.8 m to 6.4 m, the mean value is positive but very close to static pore pressure, (Oscillation B3). It is obvious that oscillations B1 and B3 display oscillations within the normal range of pore pressure (B1 is common in silt or clay; B3 is more usual in sand and/or gravel), and oscillation B2 is anomalous.

In CPTU test, DKI002, at Kilkenny Park, Westport, two obvious anomalous oscillation occur at depths around 3.5 m and 9 m. Figure 37 shows the detailed characteristics of recordings from DKI002. At the 3.3 to 3.6 m depth, an anomalous oscillation occurs and there is a similar oscillation from the 8.75 m to 8.95 m depth.

We noticed that the anomalous oscillation of pore pressure always occurs in loose sand, (or silty sand with a large enough static pore pressure), or in a situation where there is a relatively dense sand or gravelly sand layer under the loose sand or silty sand layer. This means that the anomalous oscillation occurs when the soils tested have relatively low resistance to liquefaction or the strain rate of soils become larger. The deformation of soil immediately under the probe is generally limited or concentrated in the loose soil layer. The deformation in the dense soils below is very much smaller. In this situation, soils tested might be liquefied and mixing of soils and water might occur around the probe so that suction and disturbance may cause the mean value of the oscillation to appear much smaller than the static pore pressure.

6 THE CPT TESTS

In our campaign, the CPT tests were conducted using the same Fugro piezocone, but without de-airing or preboring.

In our exploration, 12 CPT tests were conducted on Winfield's farm, Monahan's farm and Kilkenny Park. Plots of the results are presented in Appendix IV. (Note that the pore pressure traces are unreliable since the transducer system has not been de-aired.

On Winfield's farm, because the water table was very deep, the main exploration was with the CPT rather than CPTU. Four CPT tests were performed at the liquefied site, DWF001, DWF003, DWF004 and DWF006. The test sites are shown in Figure 14. Although the tests were performed at very close spacing, (within 20 m), they display quite different *in-situ* properties of soils at the same depth.

Five CPT test were conducted at the unliquefied sites on Peter Winfield's farm, DWF002, DWF007, DWF008, DWF009, DPW001. The disk records of DWF007 and DWF008 were damaged.

On Monahan's farm, one CPT test, (DTM001), was conducted. A layer of loose fine sand was found at a depth of 1 m to 2.3 m, over a layer of dense sand at a depth of 2.3 m to 2.6 m, followed by another layer of loose sand at a depth of 2.6 m to 3.9 m. The water table was 1.68 m on 18 January 1991.

In Kilkenny Park, two CPT tests, (DKI001 and DKI003), were performed to observe the influence of different de-airing conditions.

7 CONCLUSION

For the 1929 Murchison earthquake, the exploration conducted in our campaign confirmed that soil conditions on Monahan's farm, (in the paddock on the east of Tom Monahan's house), were favourable to the occurrence of liquefaction.

In the 1968 Inangahua earthquake the most extensive liquefaction appeared on Wallace Turners's farm at Walkers Flat. In addition, the earthquake shaking also induced liquefaction (sand boils) on Winfield's farm at Fern Flat, Murchison and on Van Vught's farm at Reefton beside the previously known liquefaction sites.

Our field investigation confirmed that the 1991 Westport earthquake also caused liquefaction on Wallace Turner's farm at Walkers Flat and at Virgin Flat and Charleston Beach, near Westport. The liquefaction on Walkers Flat was limited to one small area only in the 1991 earthquake. Most of the sites liquefied in the 1968 earthquake did not liquefy in the 1991 earthquake.

The results of SPT, CPTU tests at liquefied sites on Wallace Turner's farm display a significant difference to those at unliquefied sites. The difference can be seen not only in the cone resistance but also in the pore pressure measurements, reflecting density and permeability of the soils.

Through our explorations, more information about liquefaction occurrence in the soils in Buller region has been obtained, and more knowledge about the in-situ properties of the soils in both liquefied sites and unliquefied sites in the region has been accumulated. These results will form the basis for the development of a pattern recognition system for the evaluation of soil liquefaction potential based on New Zealand data, which can be perfected by involving more cases and more data from the whole world.

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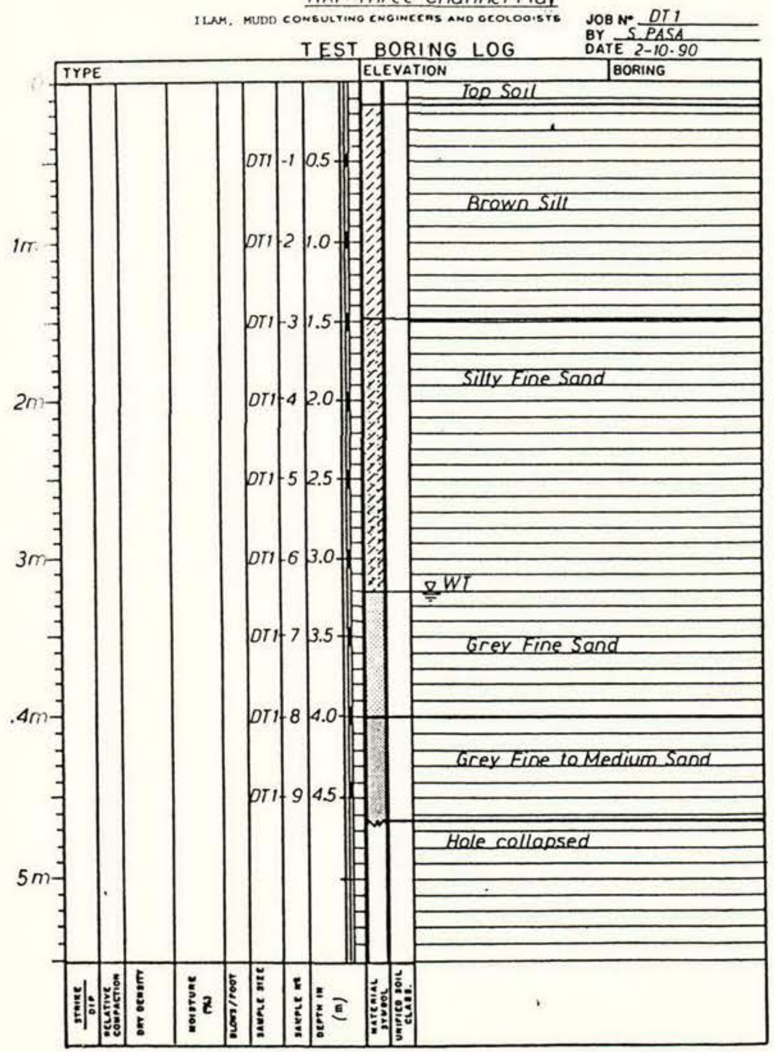
8 Dodd, T.A.H., 1970, Earth structure, **Canterbury Engineering Journal**, No.1, pp. 23-43.

9 Robertson, P.K., 1990, Soil classification using the cone penetration test, **Canadian Geotechnical Journal**, Vol. 27, pp. 151-158.

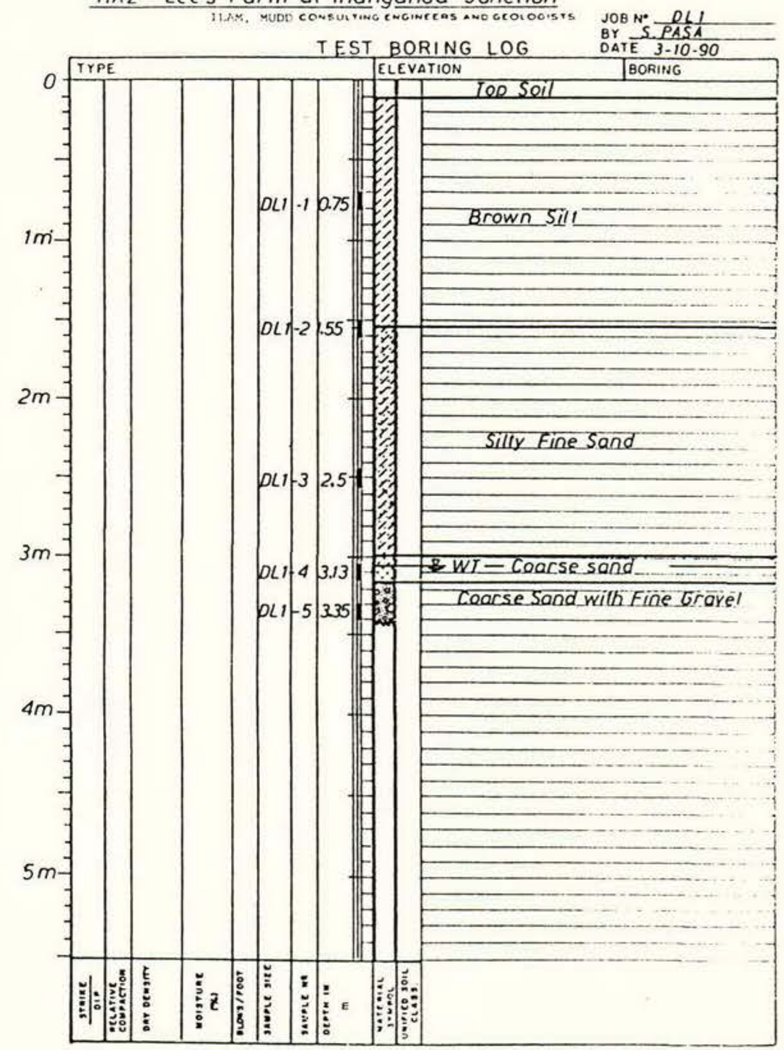
10 Cousins, W.J., R.T. Hefford, G.H. McVerry, S.M. O'Kane and D.E. Baguley, 1991, Computer Analyses of N.Z. Earthquake Accelerograms, DSIR Physical Sciences, Lower Hutt, Vol. 7.

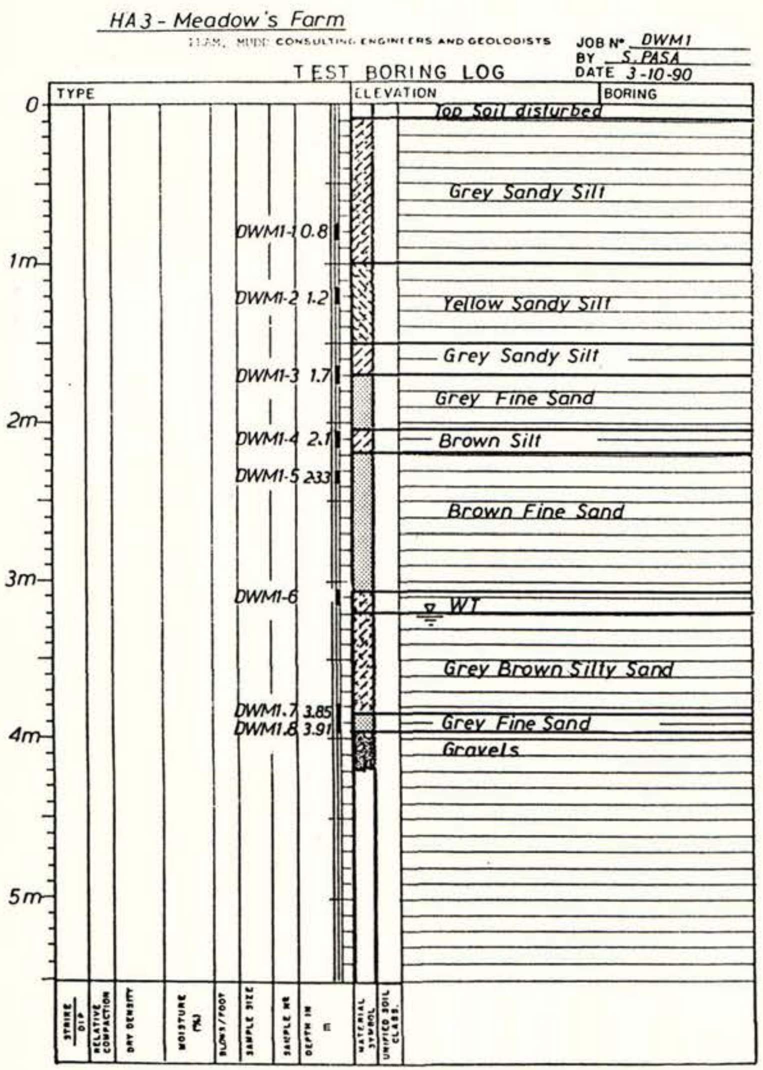
APPENDIX I

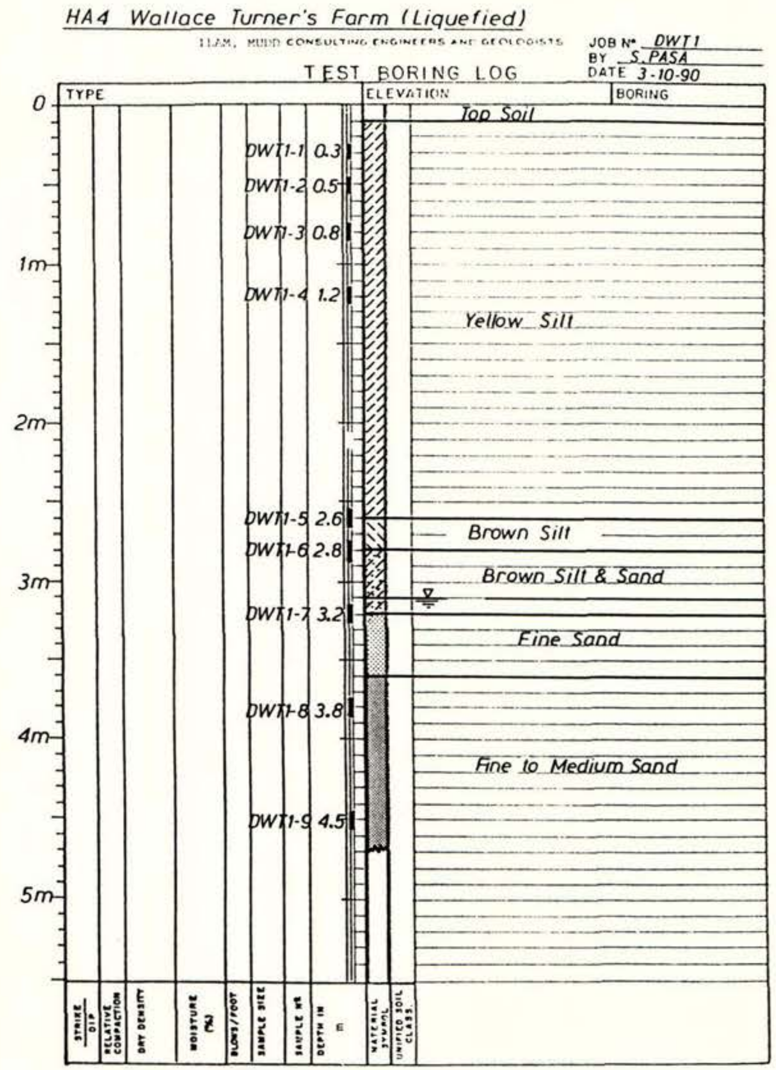
HA1 - Three Channel Flat



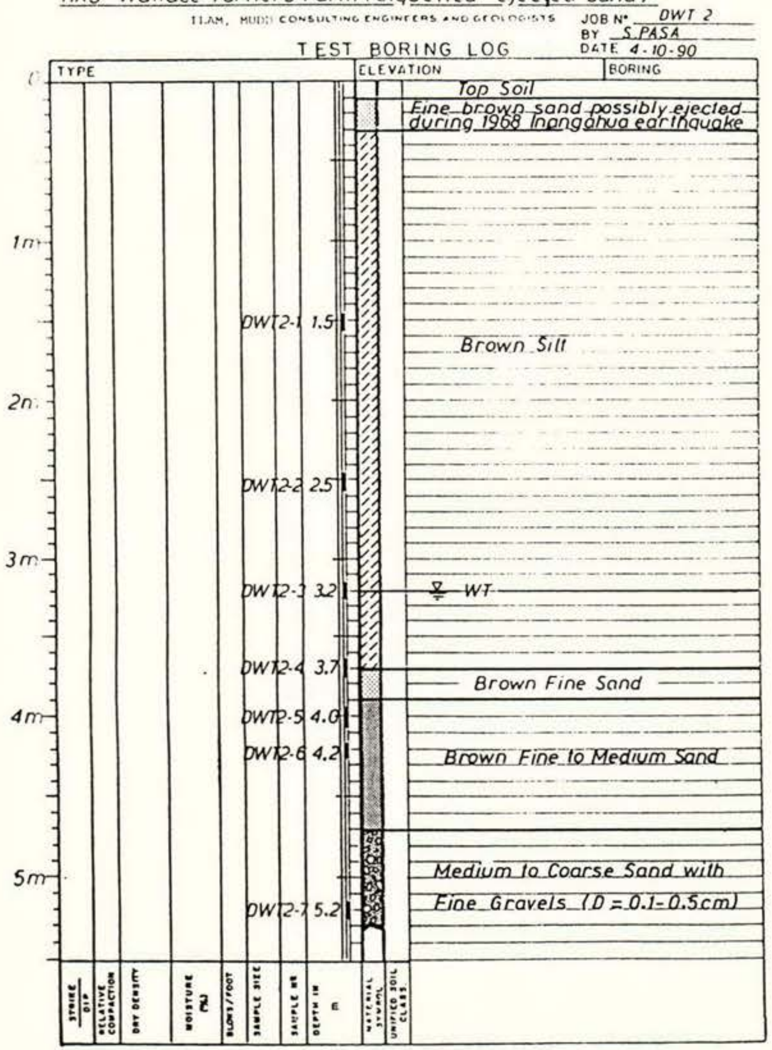
HA2 - Lee's Farm at Inangahua Junction



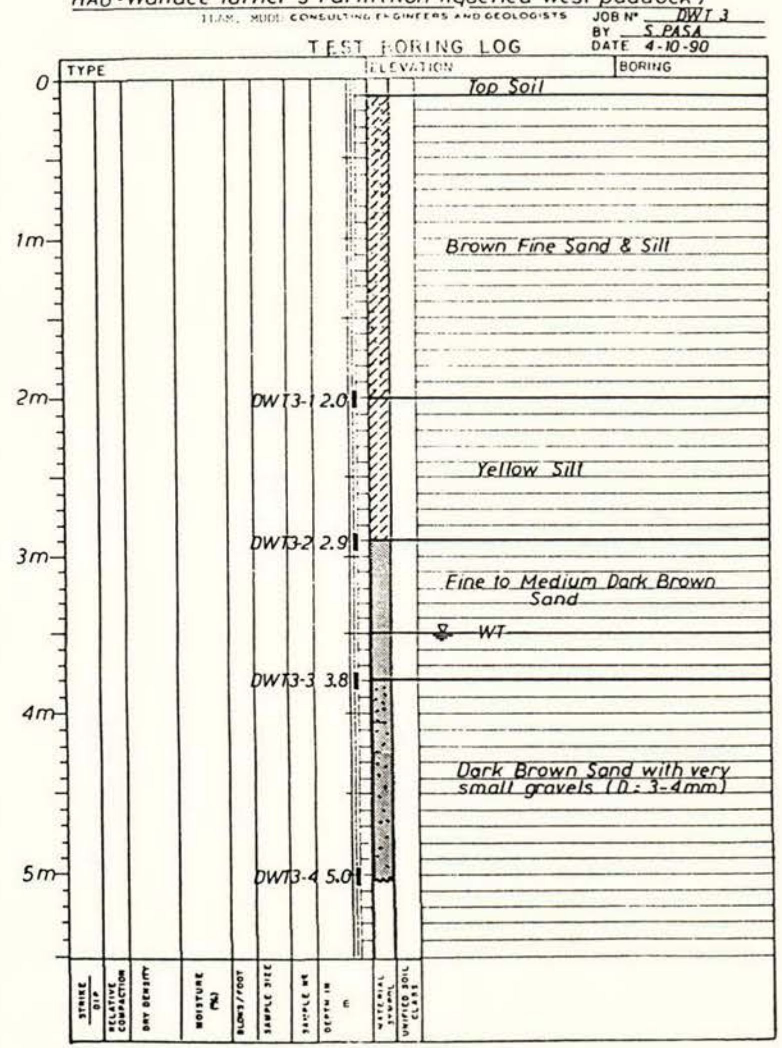

HA3 - Meadow's Farm
ILAM, MUDD CONSULTING ENGINEERS AND GEOLOGISTS
JOB Nº DWM1
BY S. PASA
DATE 3-10-90
TEST BORING LOG
TYPE
ELEVATION
BORING
Top Soil disturbed
Grey Sandy Silt
DWM1-1 0.8
Yellow Sandy Silt
DWM1-2 1.2
Grey Sandy Silt
DWM1-3 1.7
Grey Fine Sand
DWM1-4 2.1
Brown Silt
DWM1-5 2.33
Brown Fine Sand
DWM1-6
WT
Grey Brown Silty Sand
DWM1.7 3.85
DWM1.8 3.91
Grey Fine Sand
Gravels
0
1m
2m
3m
4m
5m
STRIKE / DIP
RELATIVE COMPACTION
DRY DENSITY
MOISTURE (%)
BLOWS/FOOT
SAMPLE SIZE
SAMPLE Nº
DEPTH IN m
MATERIAL SYMBOL
UNIFIED SOIL CLASS.


HA4 Wallace Turner's Farm (Liquefied)
ILAM, MUDD CONSULTING ENGINEERS AND GEOLOGISTS
JOB Nº DWT1
BY S. PASA
DATE 3-10-90
TEST BORING LOG
TYPE
ELEVATION
BORING
Top Soil
DWT1-1 0.3
DWT1-2 0.5
DWT1-3 0.8
DWT1-4 1.2
Yellow Silt
DWT1-5 2.6
Brown Silt
DWT1-6 2.8
Brown Silt & Sand
DWT1-7 3.2
Fine Sand
DWT1-8 3.8
Fine to Medium Sand
DWT1-9 4.5
0
1m
2m
3m
4m
5m
STRIKE / DIP
RELATIVE COMPACTION
DRY DENSITY
MOISTURE (%)
BLOWS/FOOT
SAMPLE SIZE
SAMPLE Nº
DEPTH IN m
MATERIAL SYMBOL
UNIFIED SOIL CLASS.

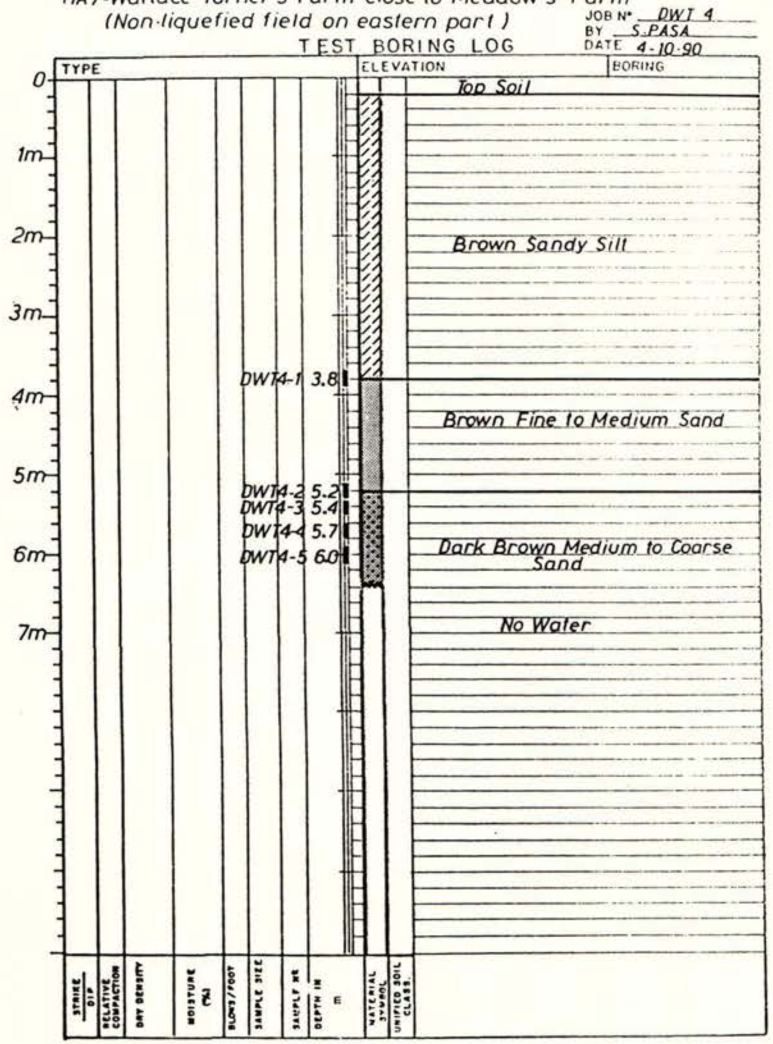
HA5 - Wallace Turner's Farm (Liquefied - ejected sand)



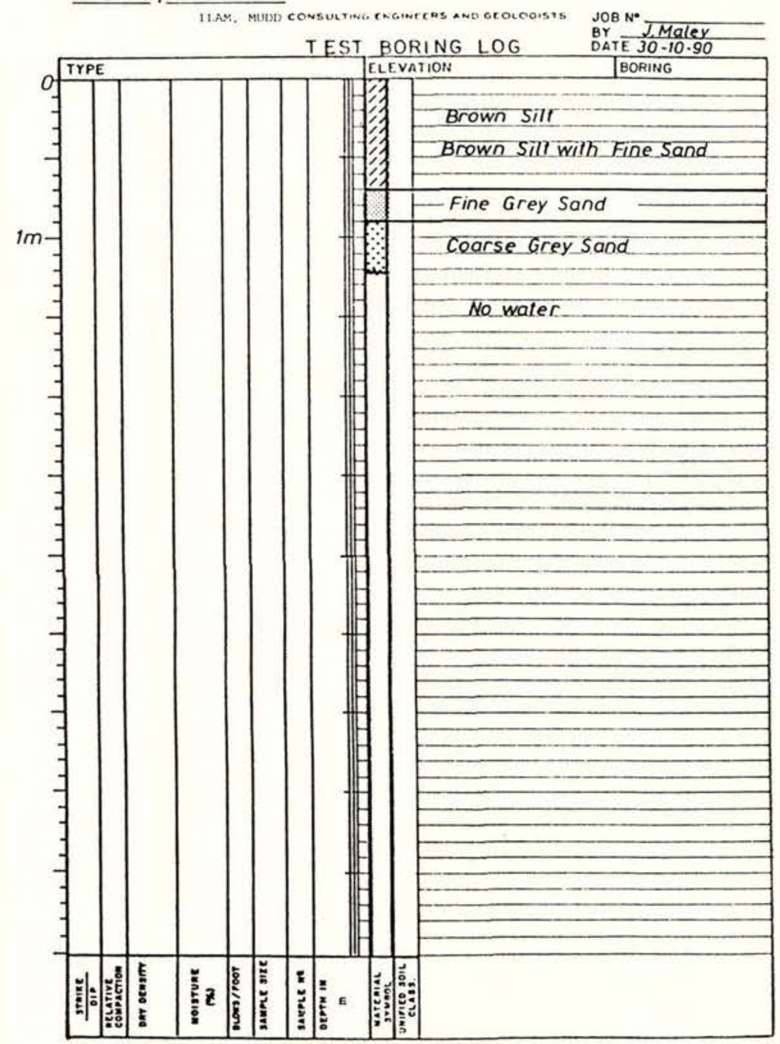
HA6 - Wallace Turner's Farm (Non liquefied west paddock)



HA7-Wallace Turner's Farm close to Meadow's Farm
(Non-liquefied field on eastern part)



HA8 Taplin's Farm



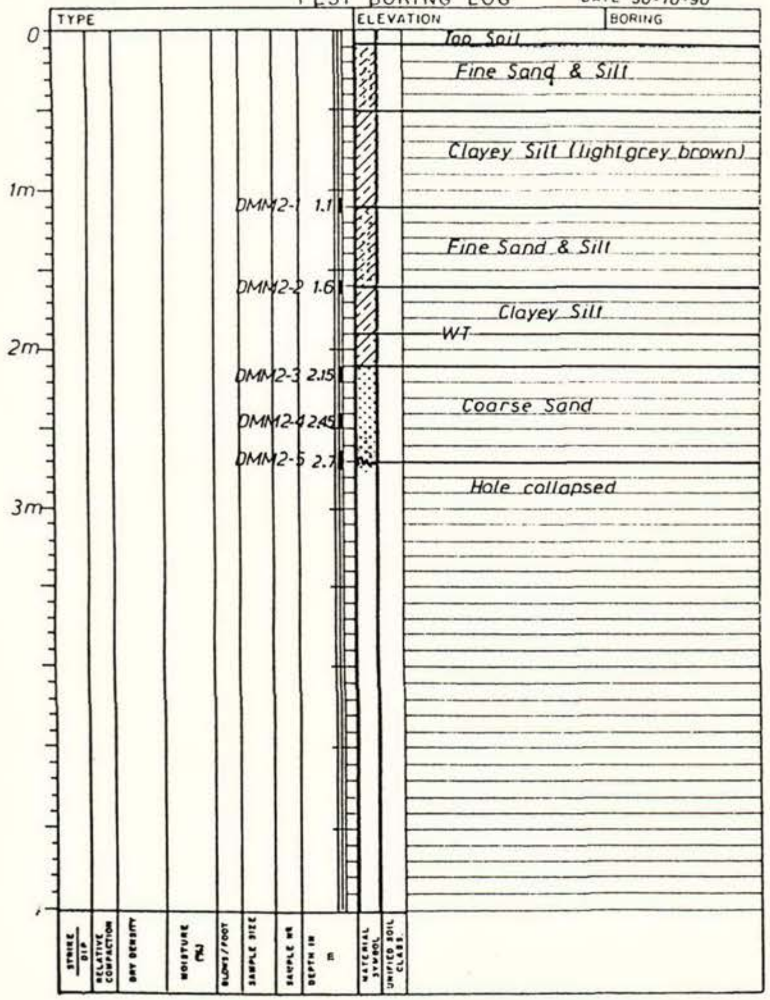
53

HA9 Tom Mon han's Farm

TILAM, MUDD CONSULTING ENGINEERS AND GEOLOGISTS

JOB Nº DMM2
BY J. MALEY
DATE 30-10-90

TEST BORING LOG

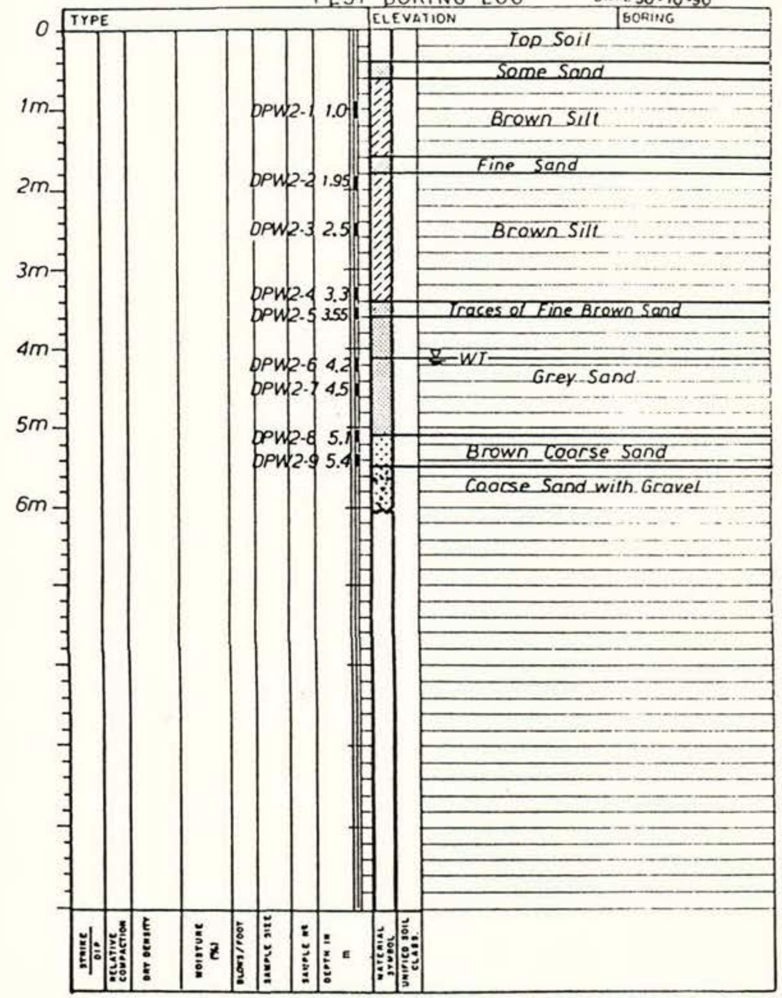


HA10 - Winfield's Farm, Fern Flat (Liquefied Field)

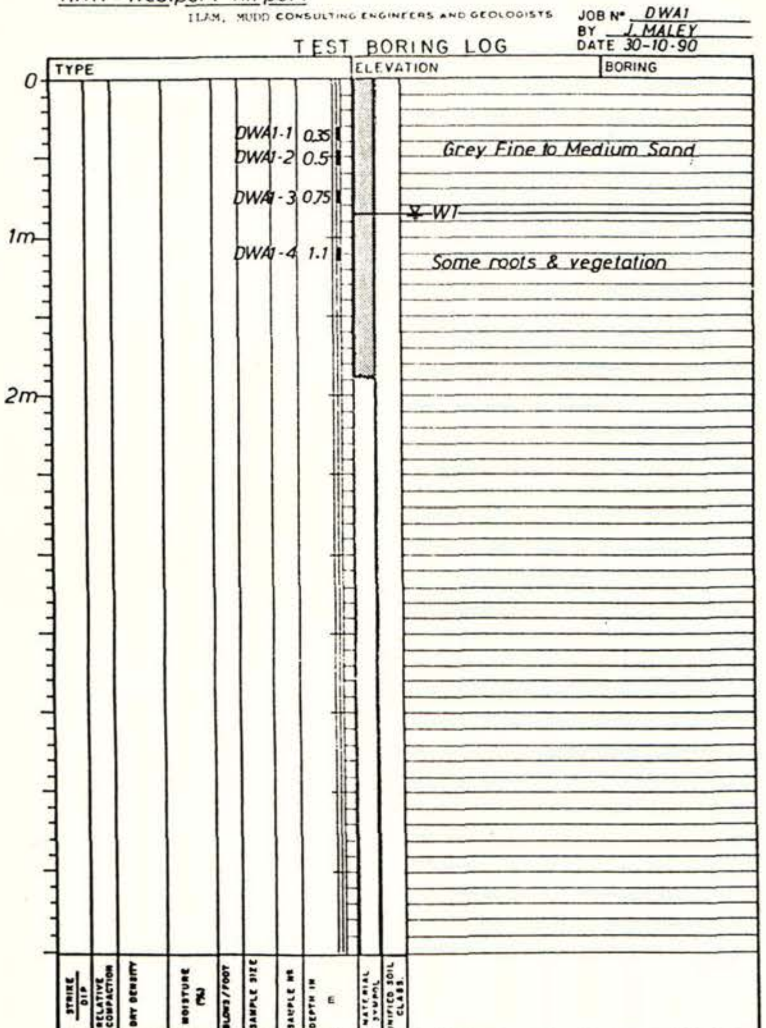
TILAM, MUDD CONSULTING ENGINEERS AND GEOLOGISTS

JOB Nº DPW2
BY J. MALEY
DATE 30-10-90

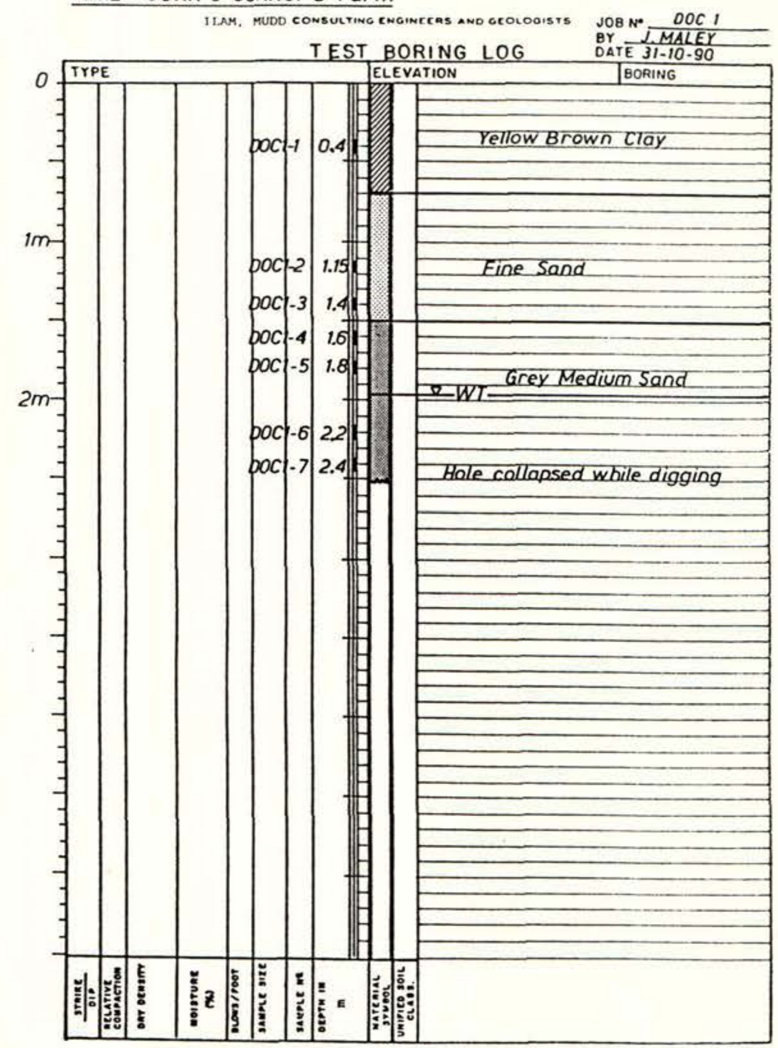
TEST BORING LOG



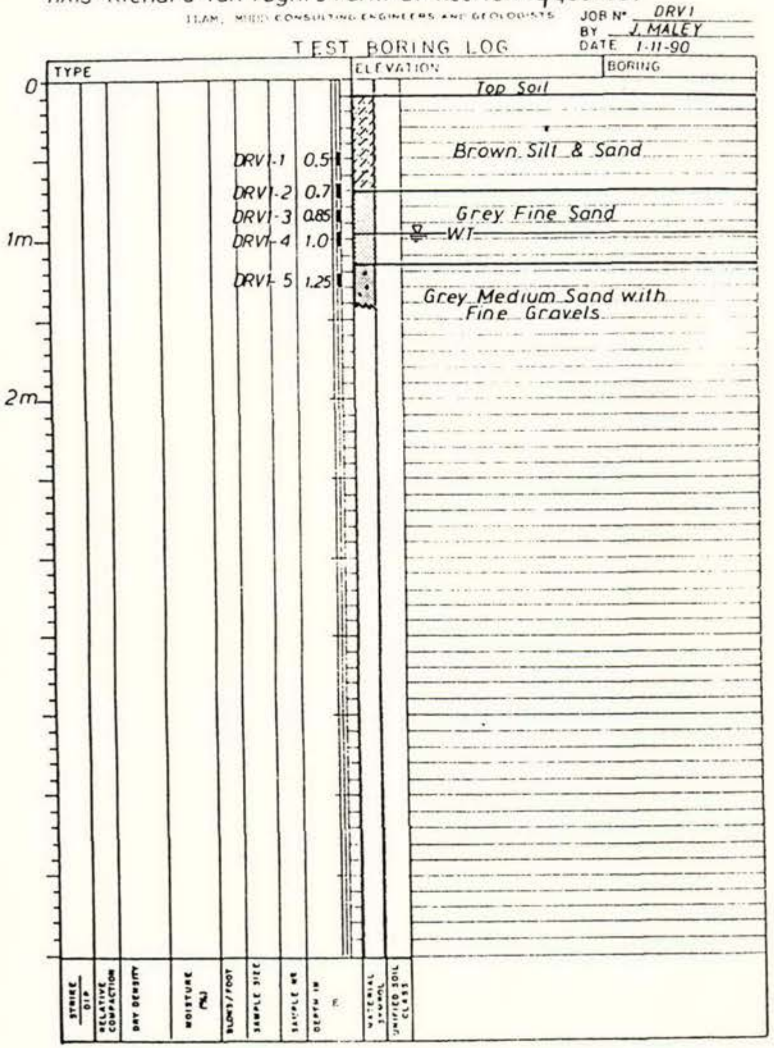
HA11 - Westport Airport



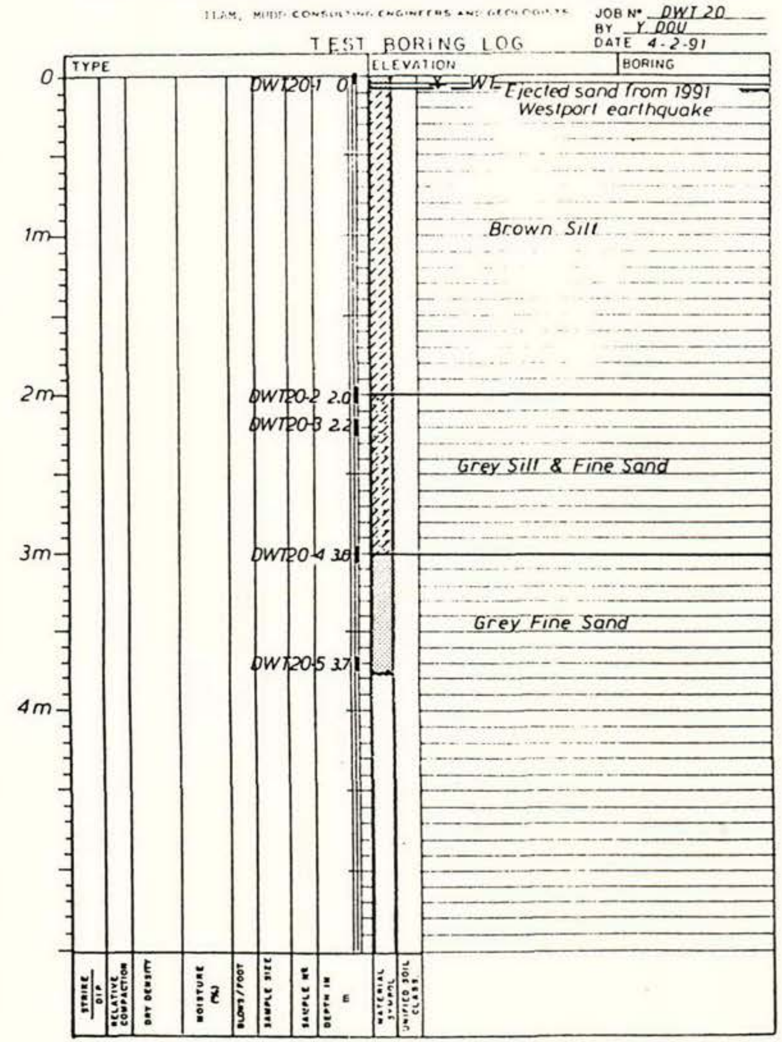
HA12 - John O'Connor's Farm



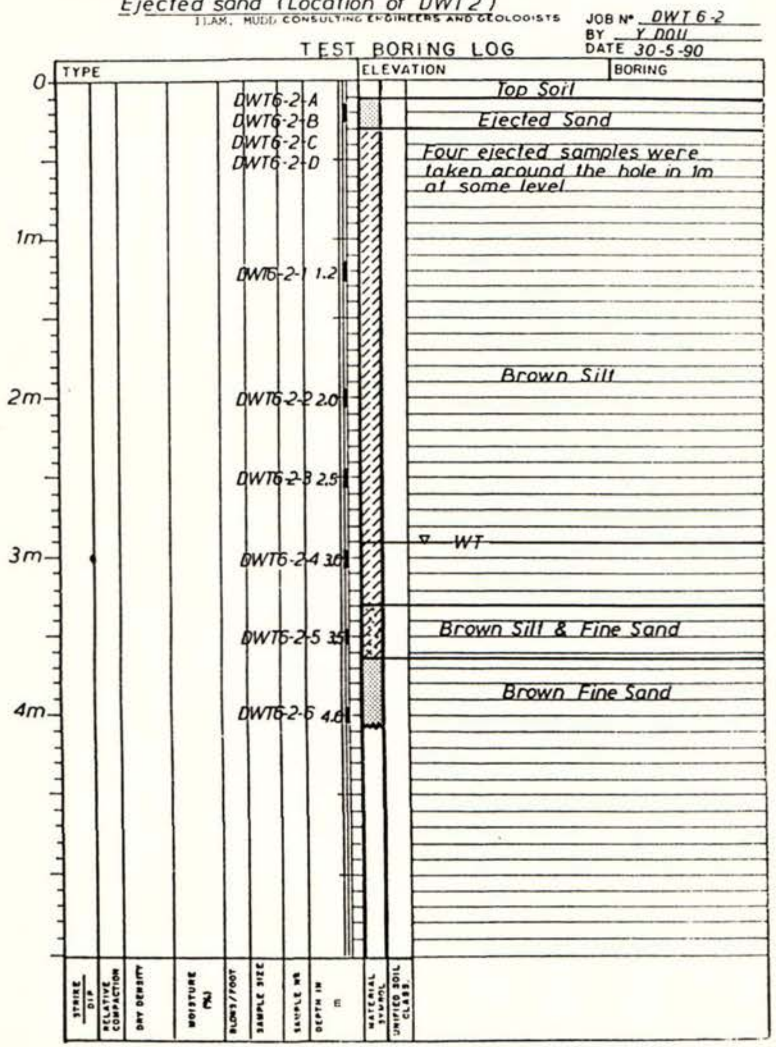
HA13 - Richard Van Vught's Farm at Reefton (Liquefied)



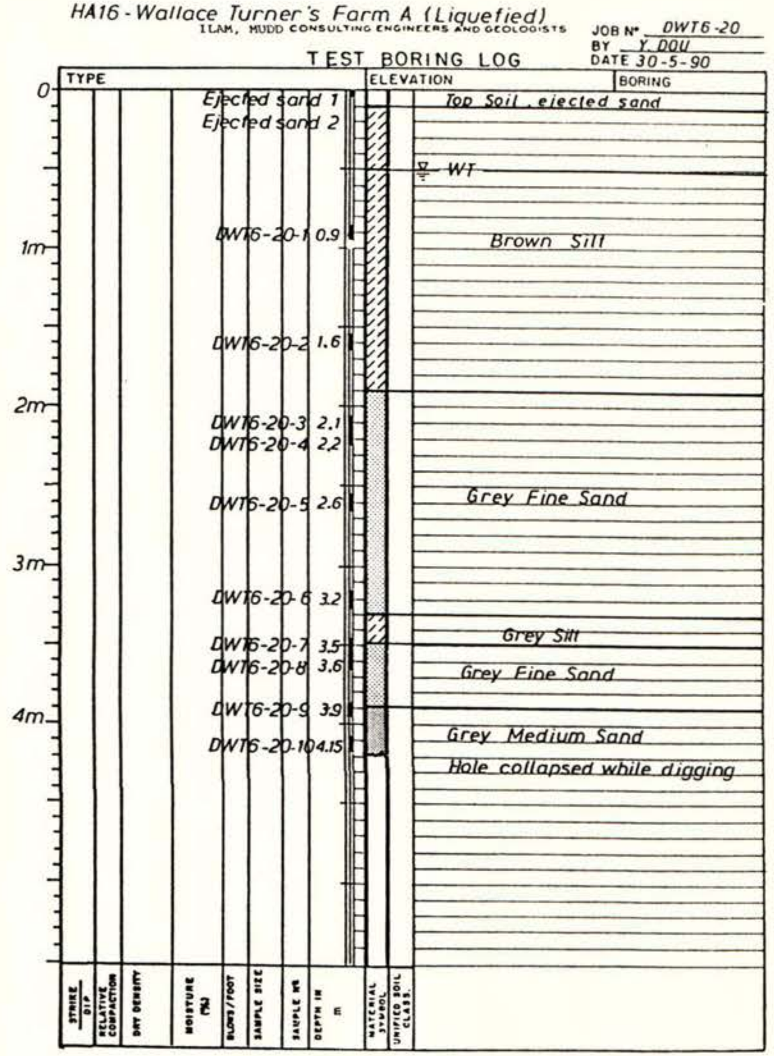
HA14 - Wallace Turner's Farm A (Liquefied) On ejected sand boil



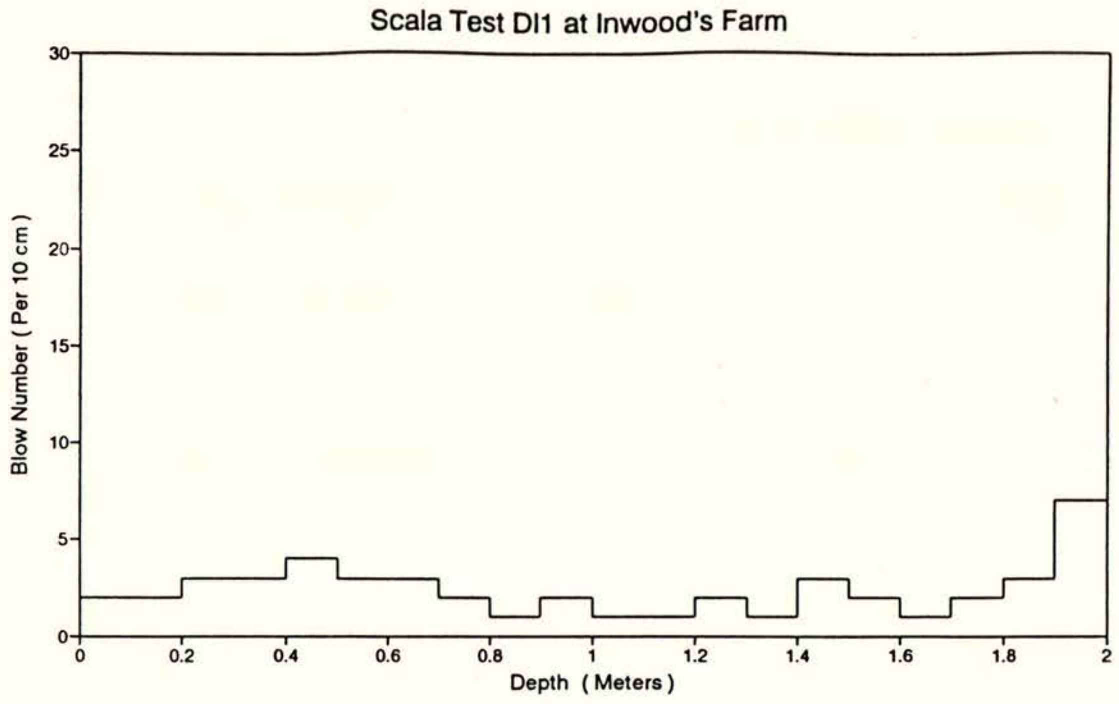
HA15 - Wallace Turner's Farm B (Liquefied)
Ejected sand (Location of DWT2)

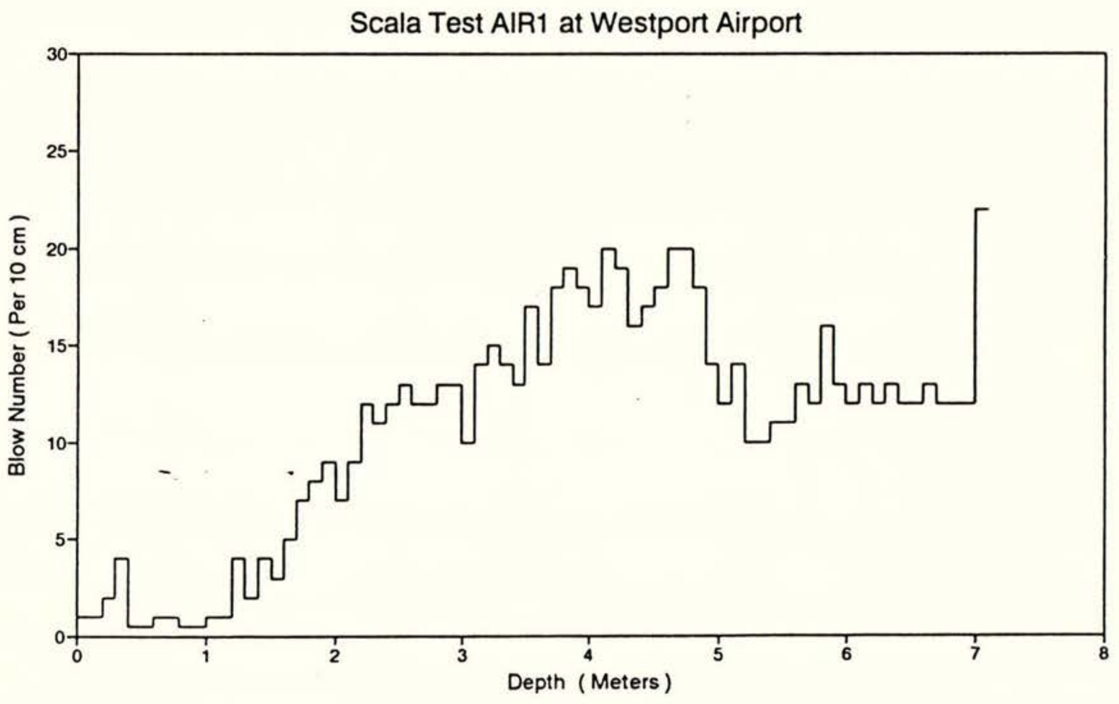


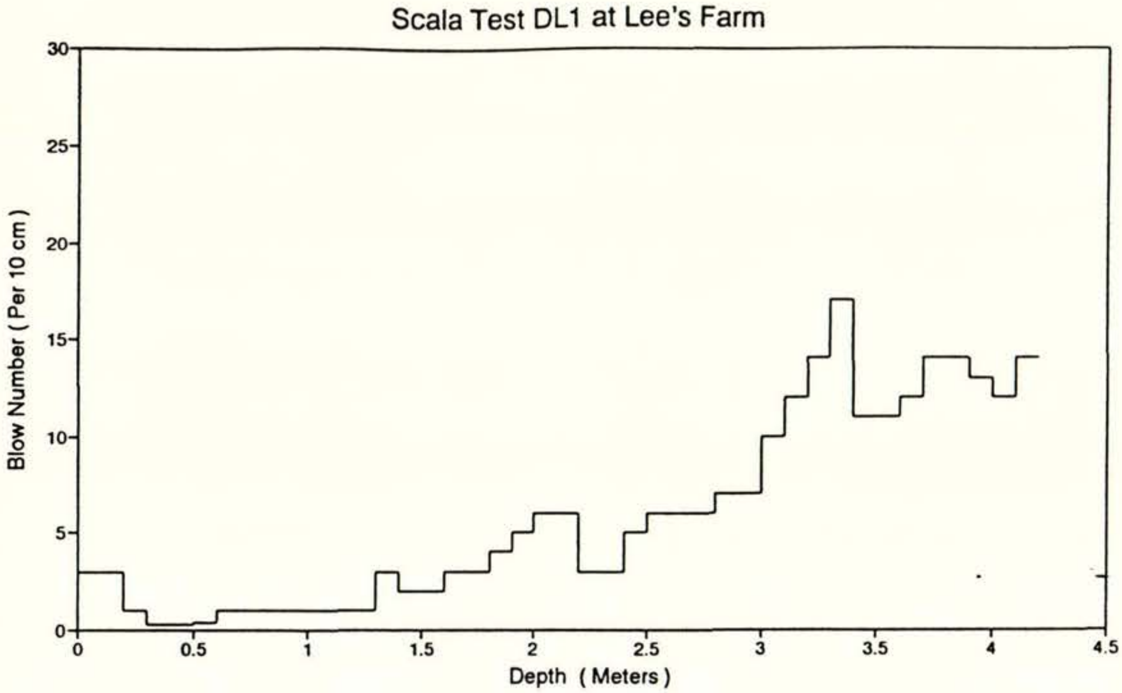
HA16 - Wallace Turner's Farm A (Liquefied)

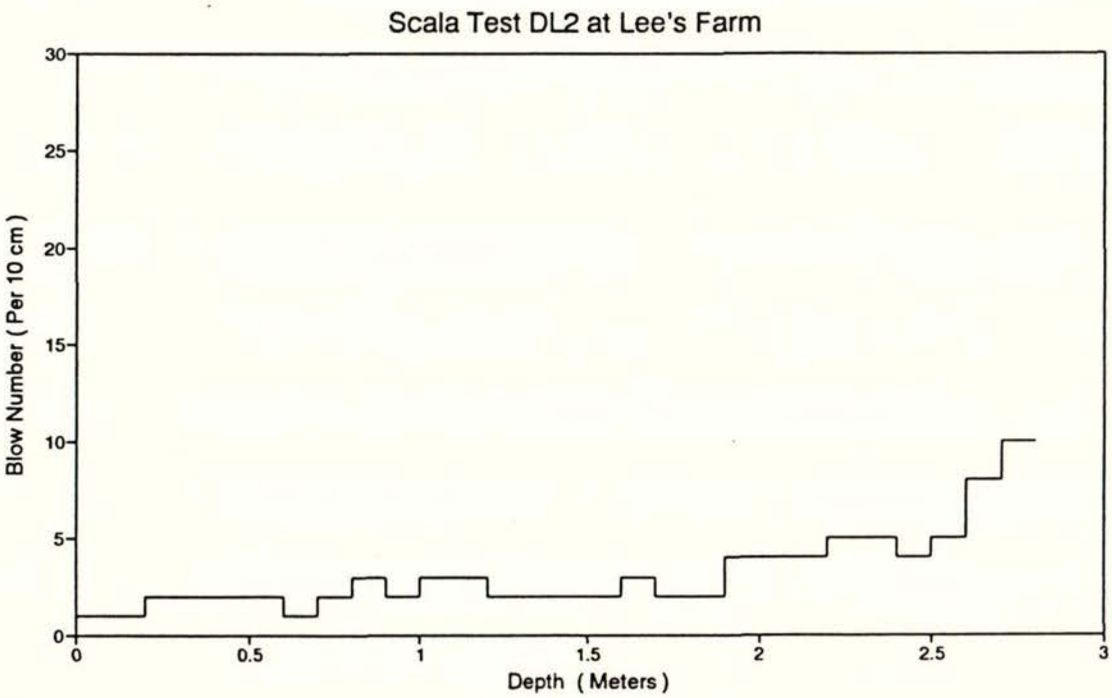


APPENDIX II

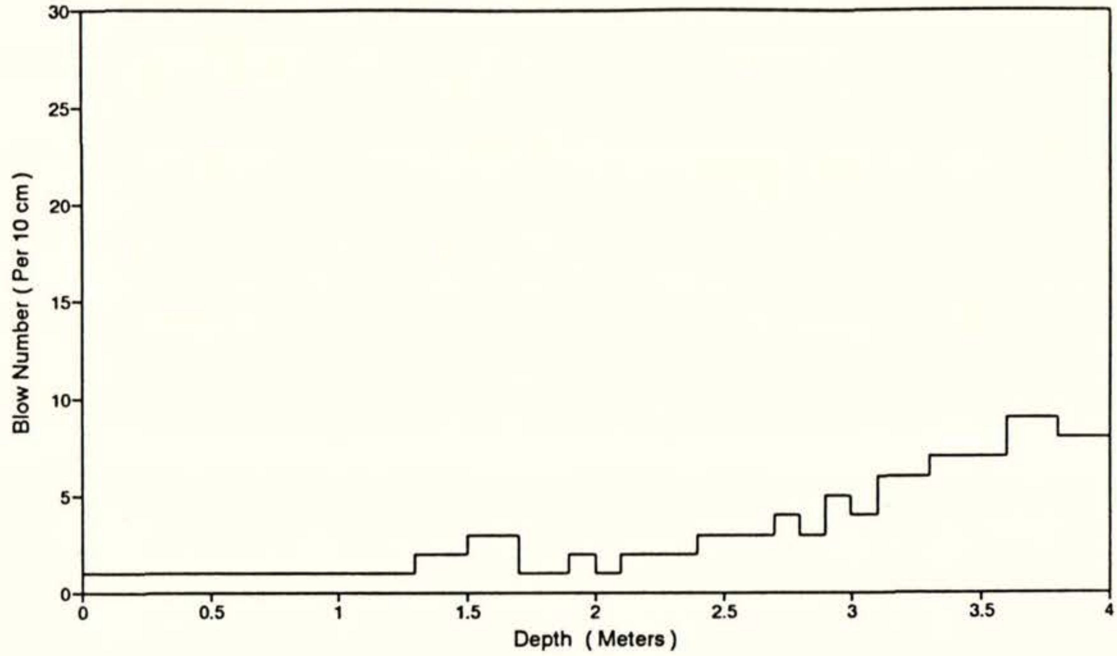

Scala Test DI1 at Inwood's Farm
Blow Number (Per 10 cm)
Depth (Meters)
0
5
10
15
20
25
30
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2


Scala Test AIR1 at Westport Airport
Blow Number (Per 10 cm)
Depth (Meters)
0
5
10
15
20
25
30
0
1
2
3
4
5
6
7
8

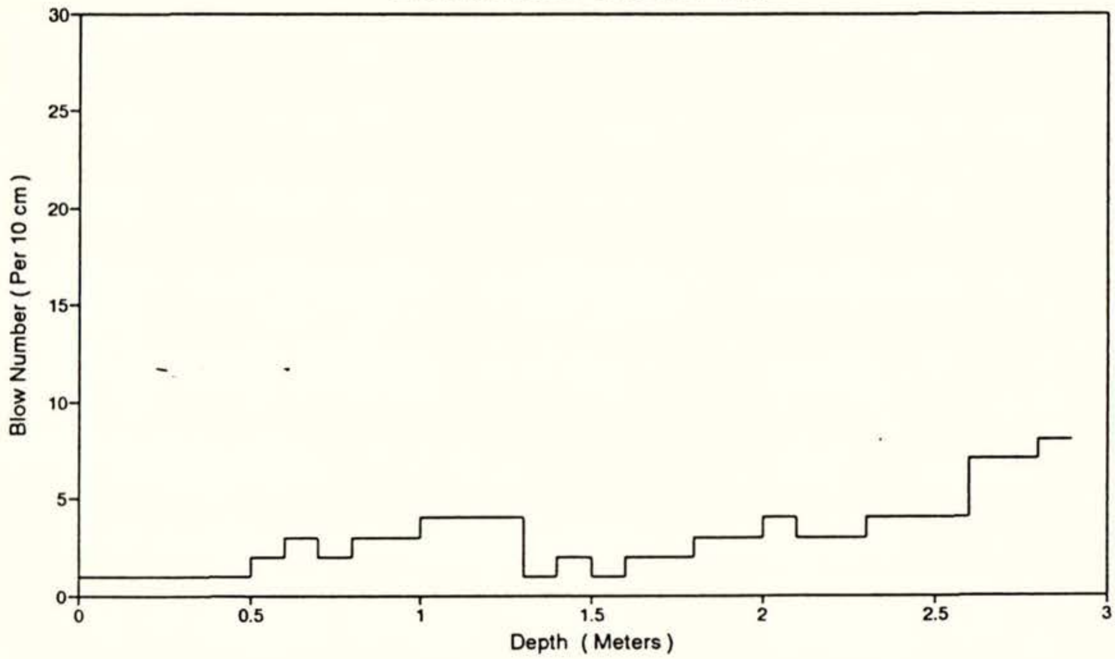

Scala Test DL1 at Lee's Farm
Blow Number (Per 10 cm)
Depth (Meters)
0
5
10
15
20
25
30
0.5
1
1.5
2
2.5
3
3.5
4
4.5

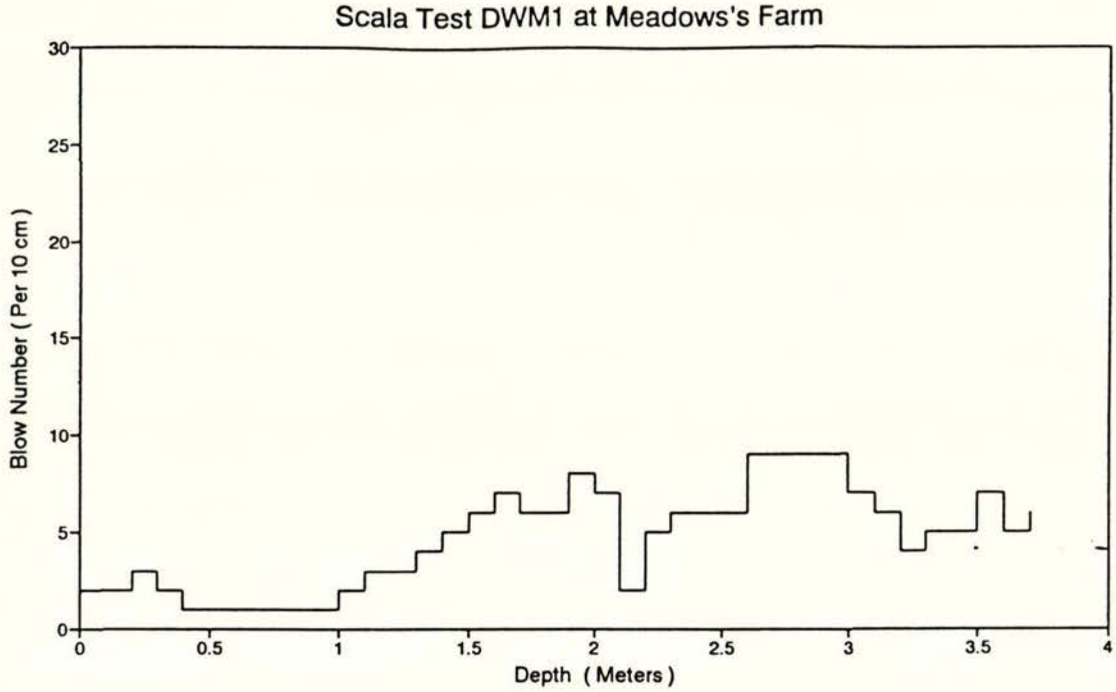

Scala Test DL2 at Lee's Farm
Blow Number (Per 10 cm)
Depth (Meters)
0
5
10
15
20
25
30
0.5
1
1.5
2
2.5
3

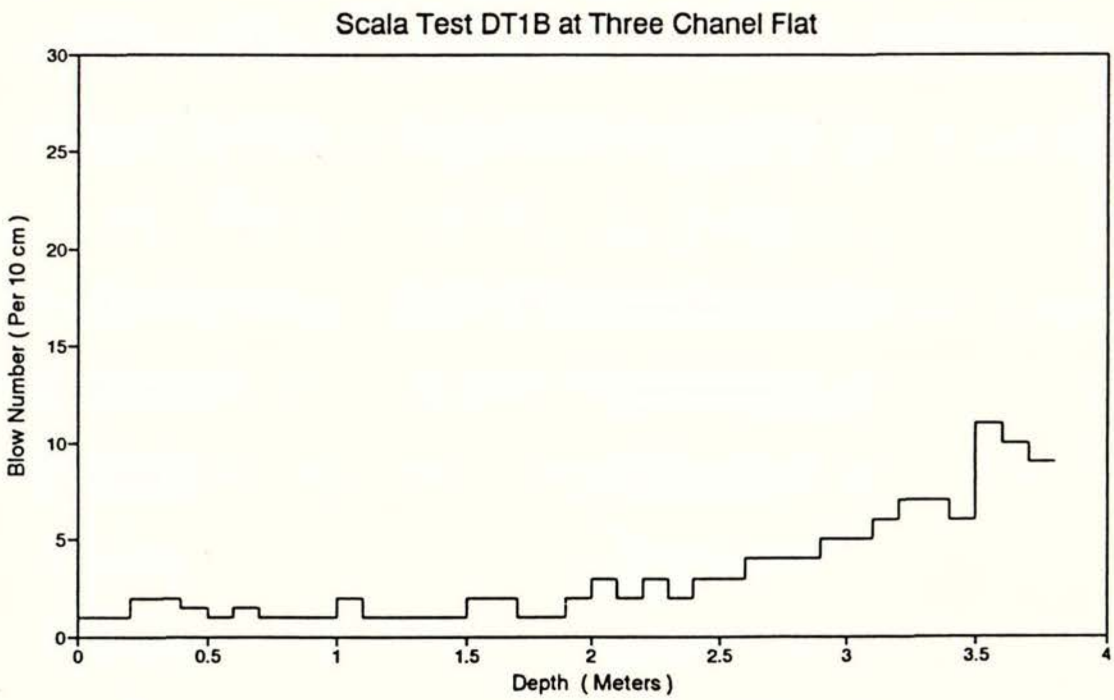
Scala Test DT1 at Three Chanel Flat



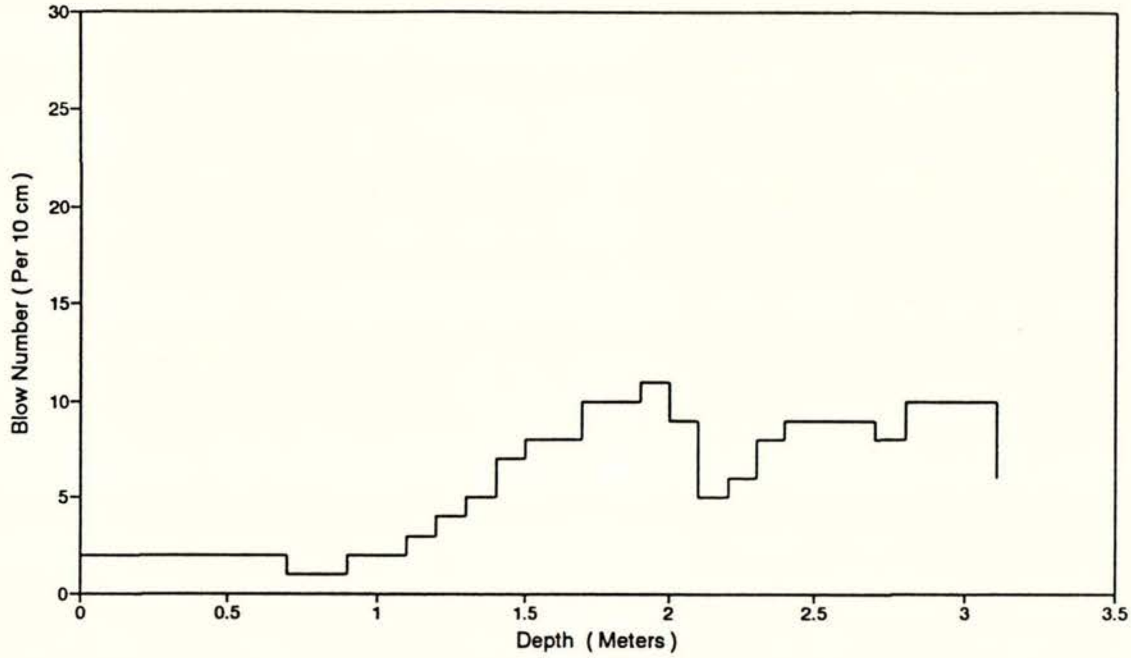
Scala Test DL3 at Lee's Farm



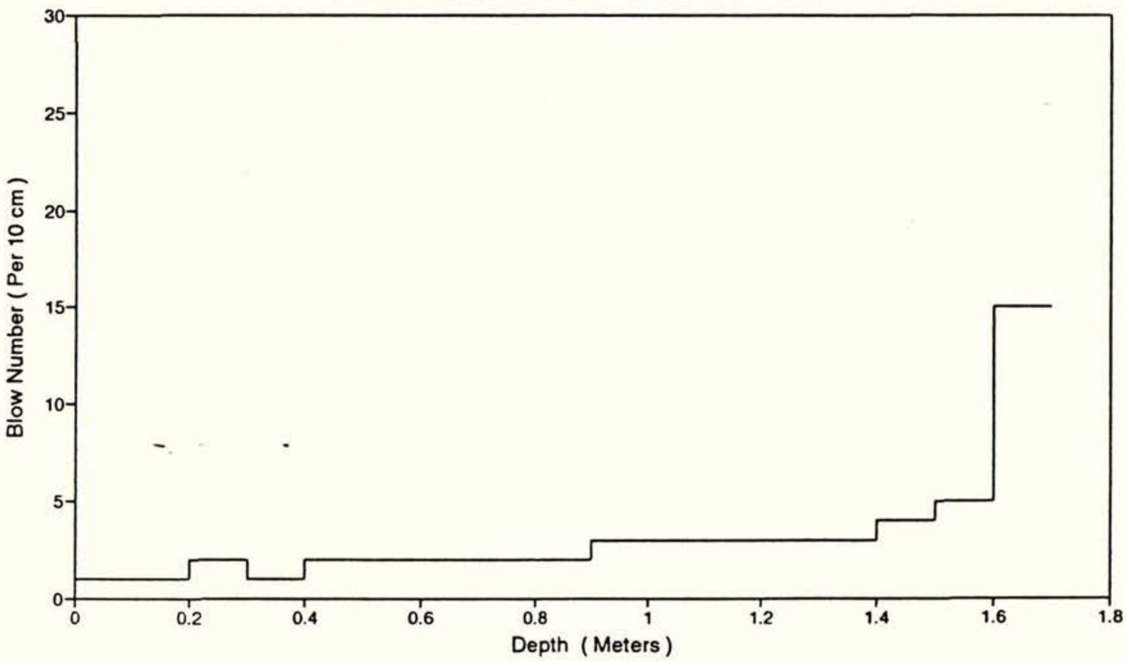

Scala Test DWM1 at Meadows's Farm
Blow Number (Per 10 cm)
Depth (Meters)
0
5
10
15
20
25
30
0
0.5
1
1.5
2
2.5
3
3.5
4

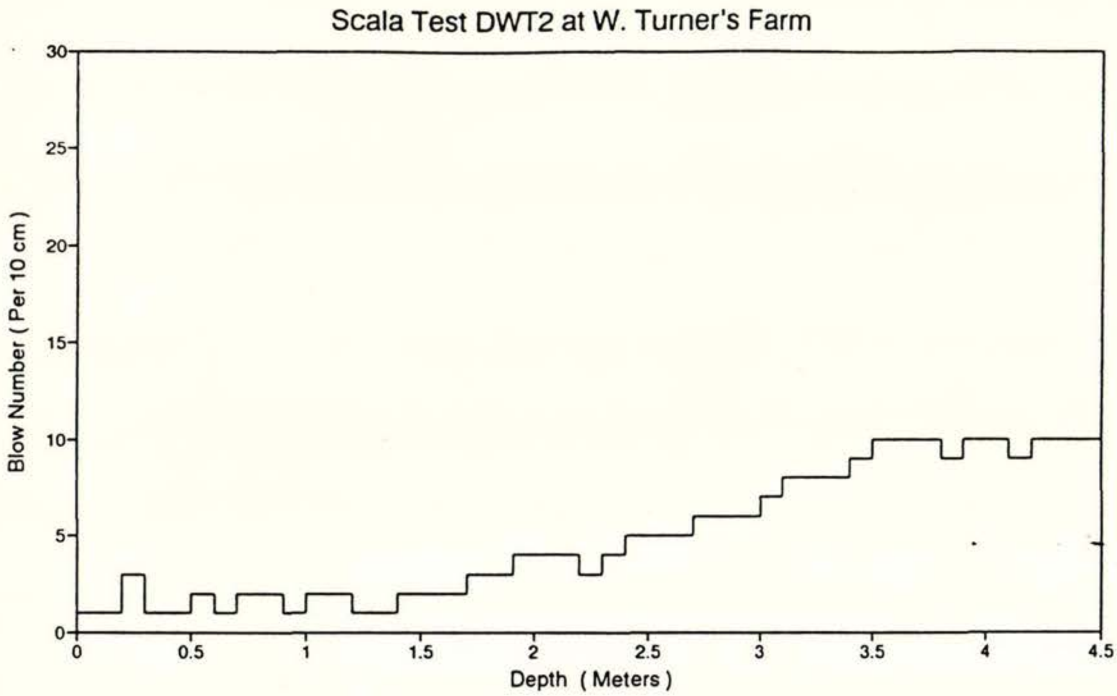

Scala Test DT1B at Three Chanel Flat
Blow Number (Per 10 cm)
Depth (Meters)
0
5
10
15
20
25
30
0
0.5
1
1.5
2
2.5
3
3.5
4

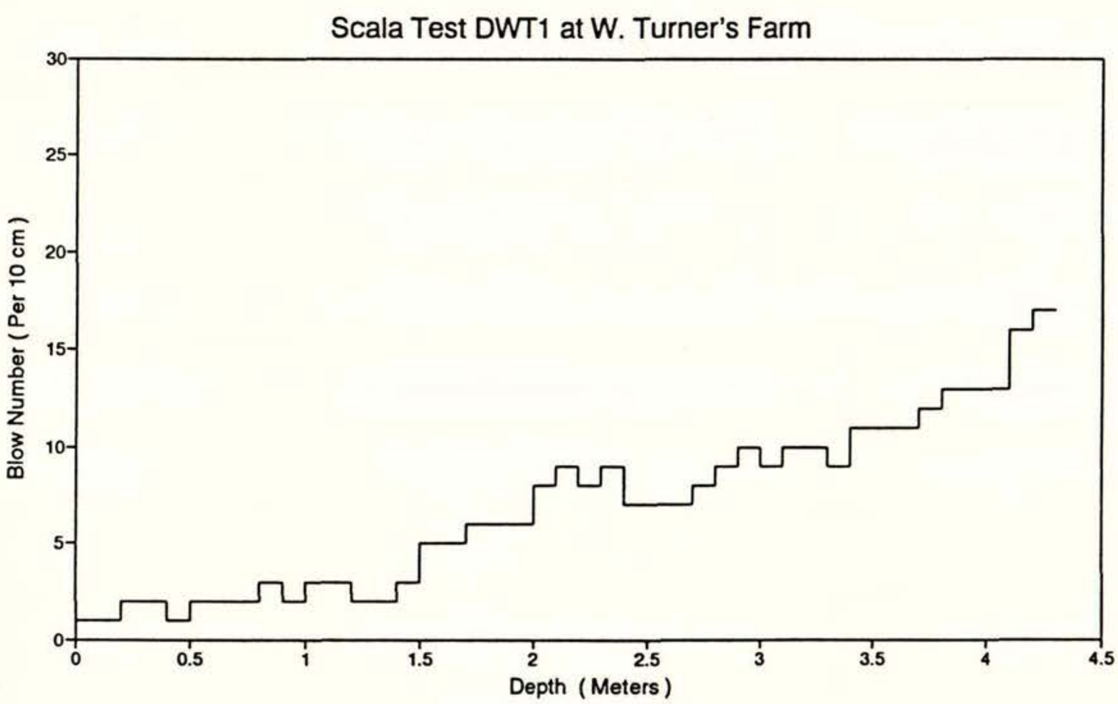
Scala Test DWM2 at Meadows's Farm

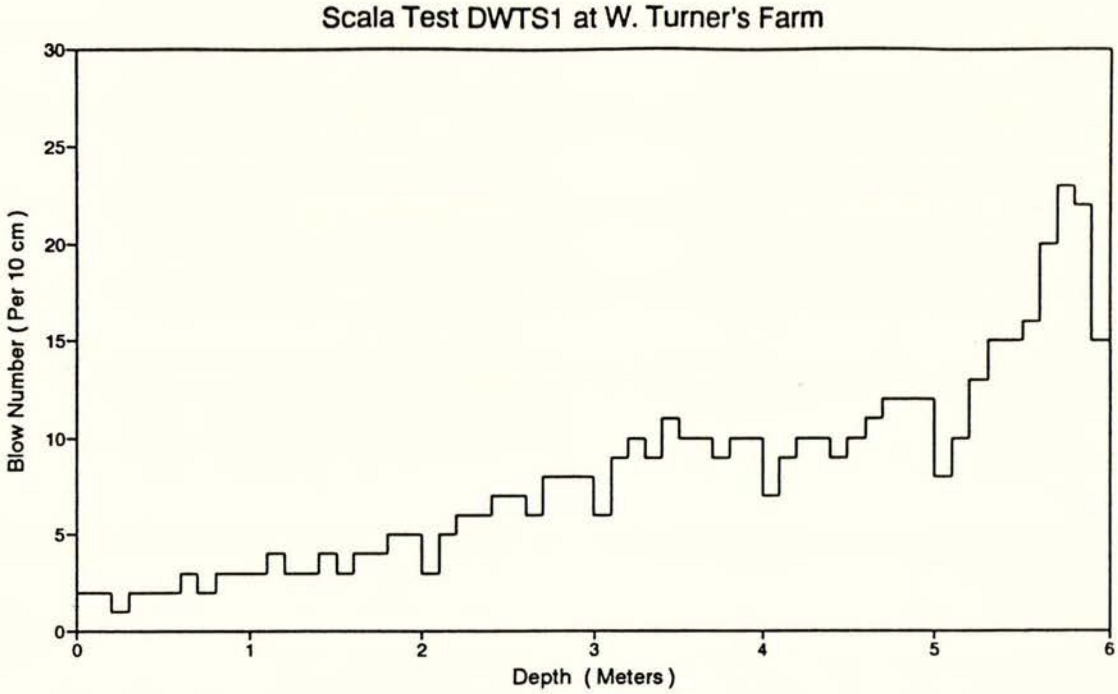


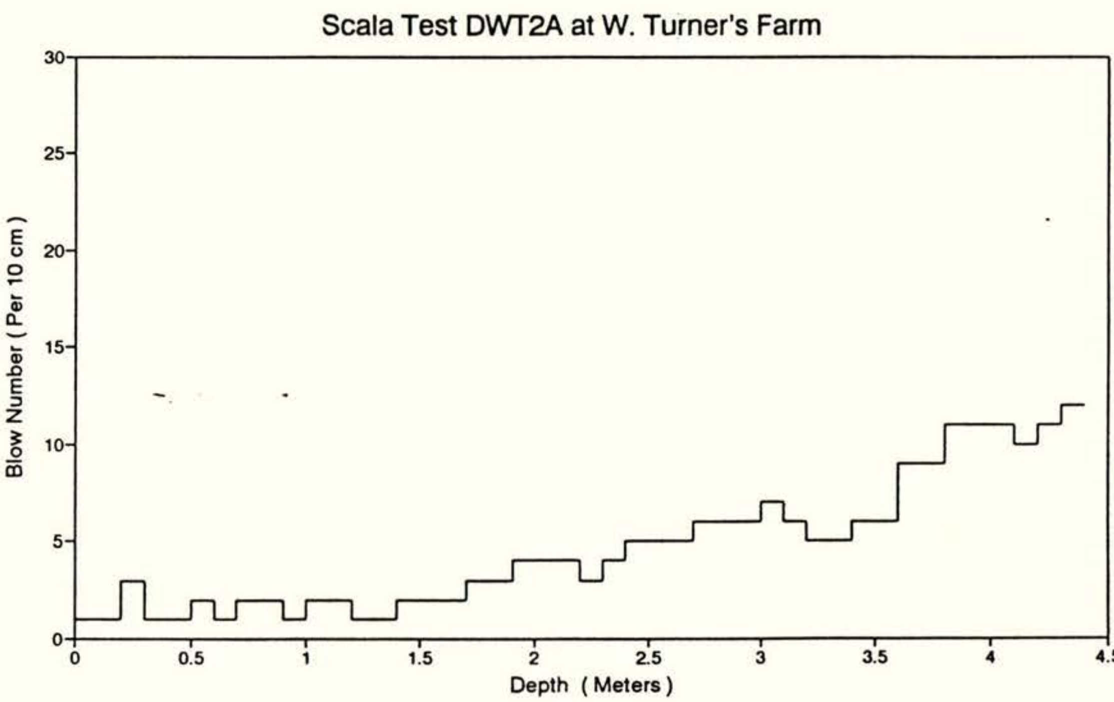
Scala Test DWM3 at Meadows's Farm



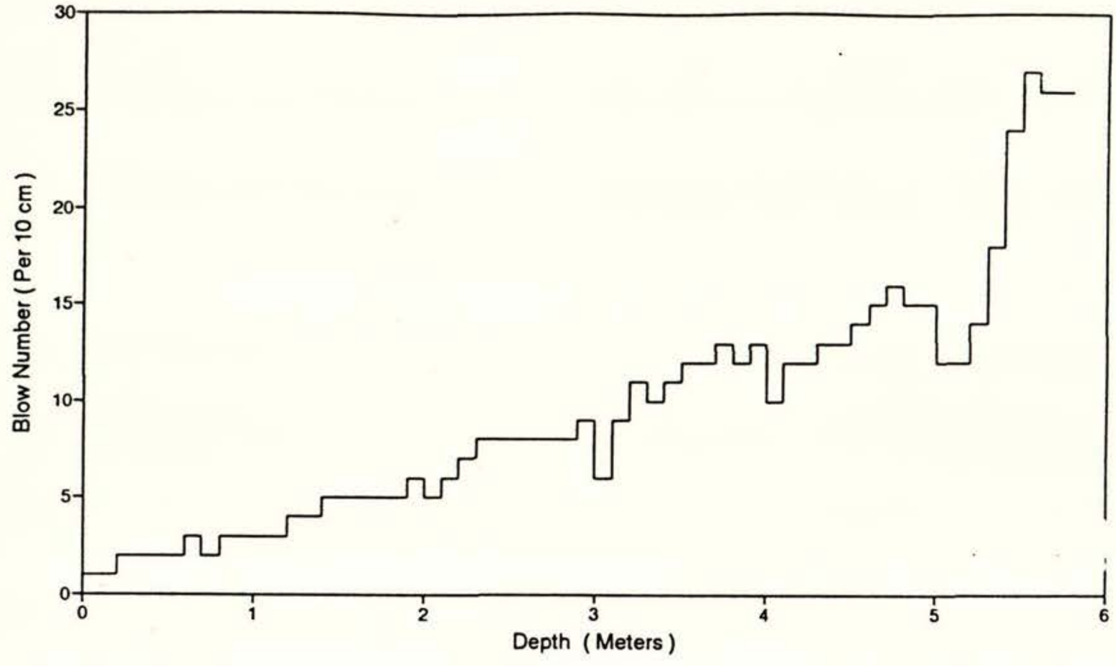

Scala Test DWT2 at W. Turner's Farm
Blow Number (Per 10 cm)
Depth (Meters)
0
5
10
15
20
25
30
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5


Scala Test DWT1 at W. Turner's Farm
Blow Number (Per 10 cm)
Depth (Meters)
0
5
10
15
20
25
30
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5

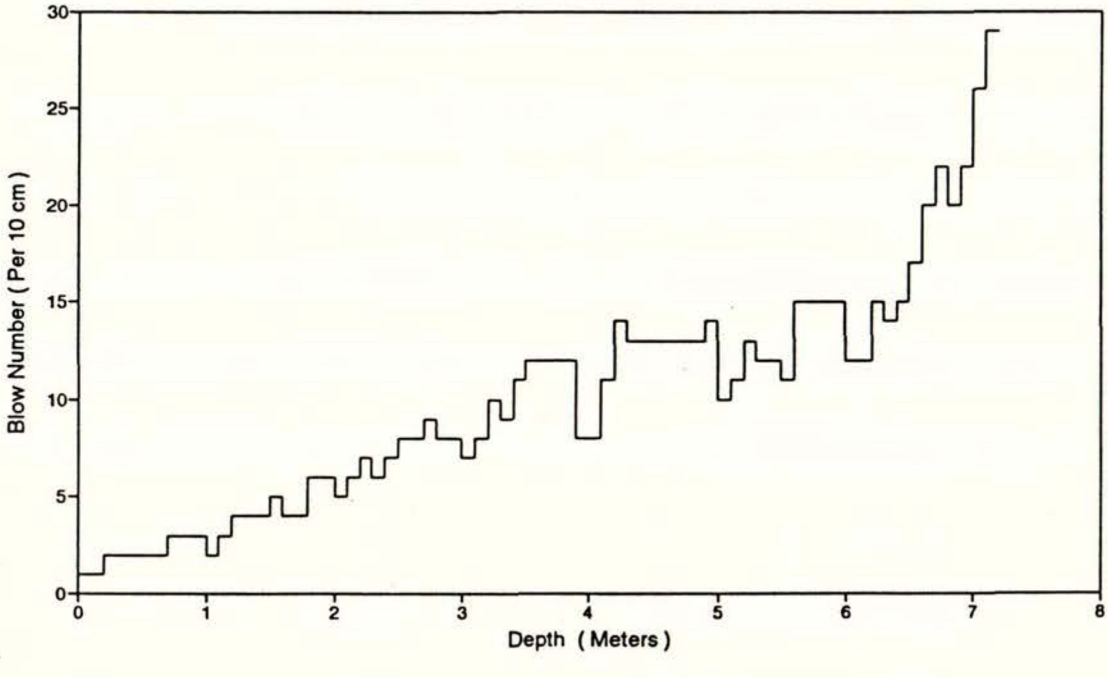

Scala Test DWTS1 at W. Turner's Farm
Blow Number (Per 10 cm)
Depth (Meters)
30
25
20
15
10
5
0
0
1
2
3
4
5
6


Scala Test DWT2A at W. Turner's Farm
Blow Number (Per 10 cm)
Depth (Meters)
30
25
20
15
10
5
0
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5

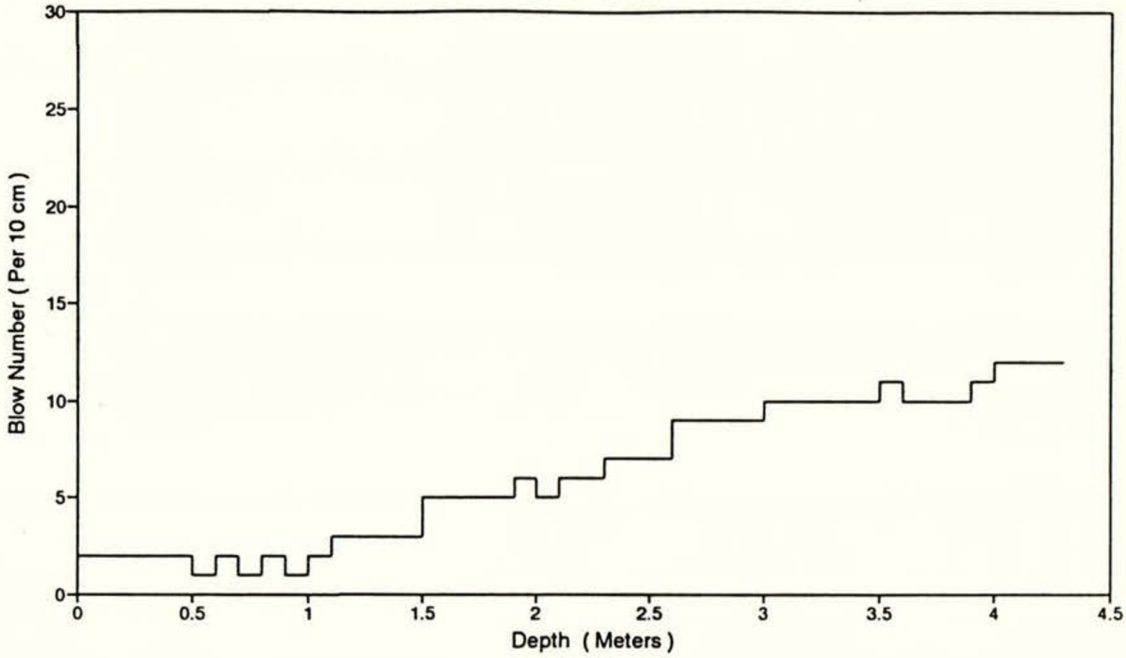
Scala Test DWTS2 at W. Turner's Farm



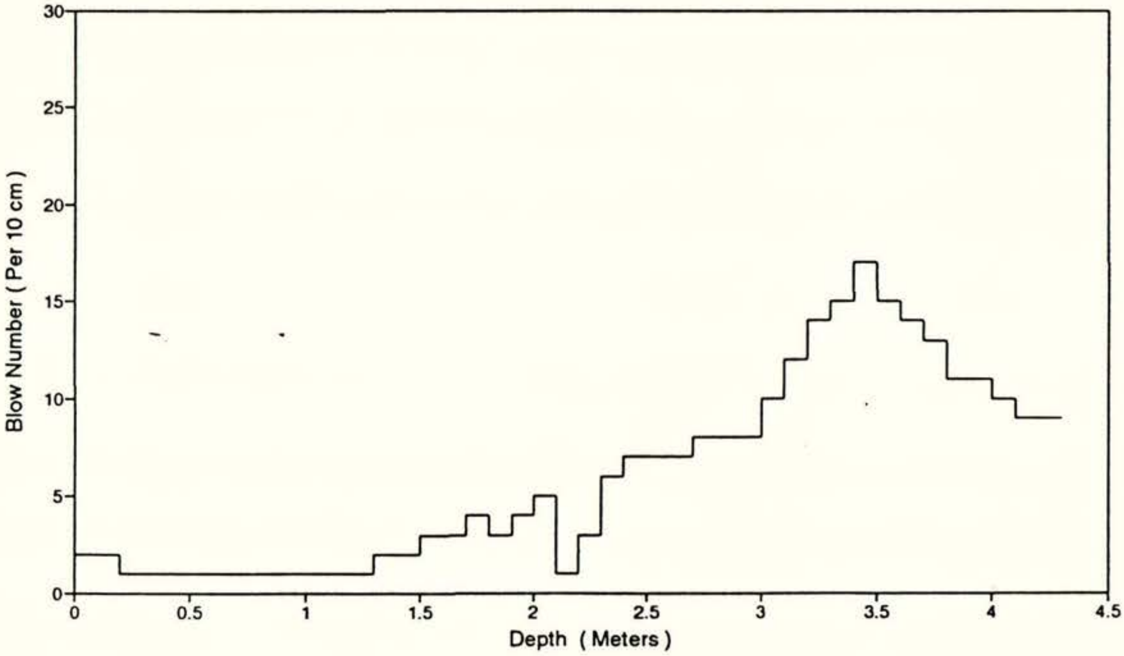
Scala Test DWTS3 at W. Turner's Farm

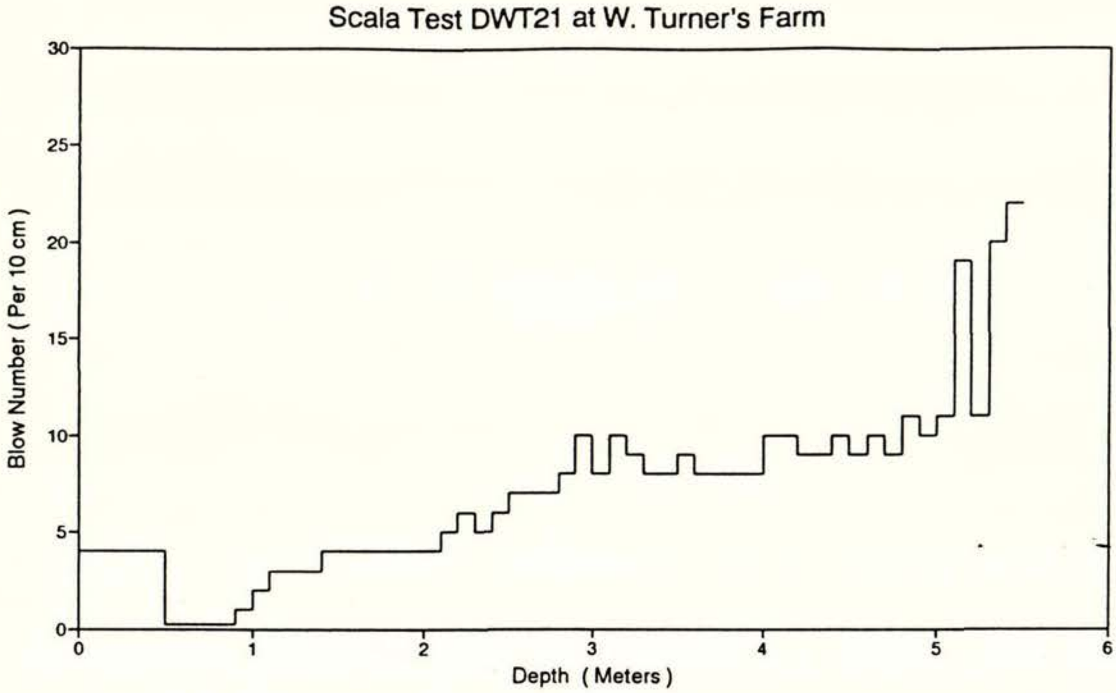


Scala Test DWT4 at W. Turner's Farm

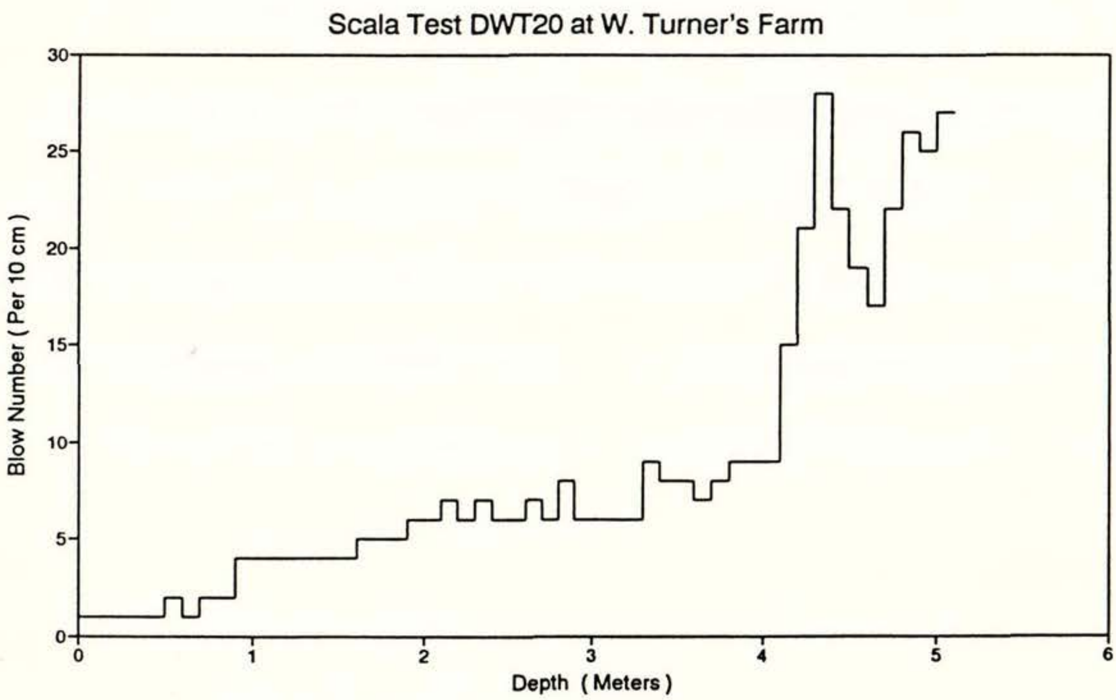


Scala Test DWT3 at W. Turner's Farm





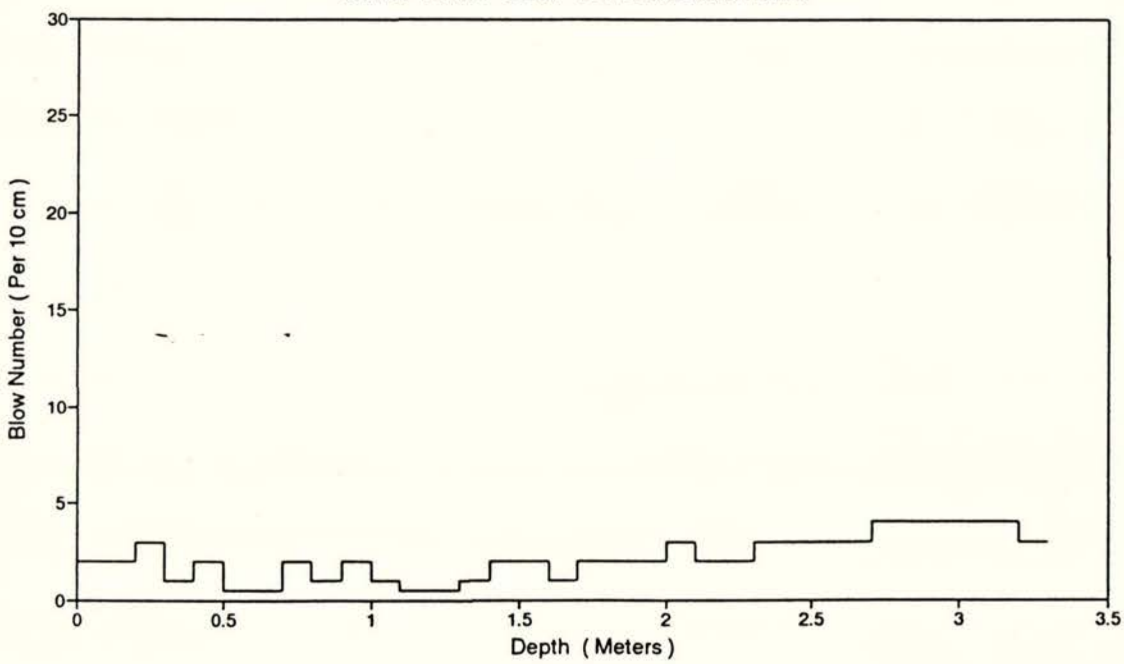
Scala Test DWT21 at W. Turner's Farm
Blow Number (Per 10 cm)
Depth (Meters)
0
5
10
15
20
25
30
1
2
3
4
5
6



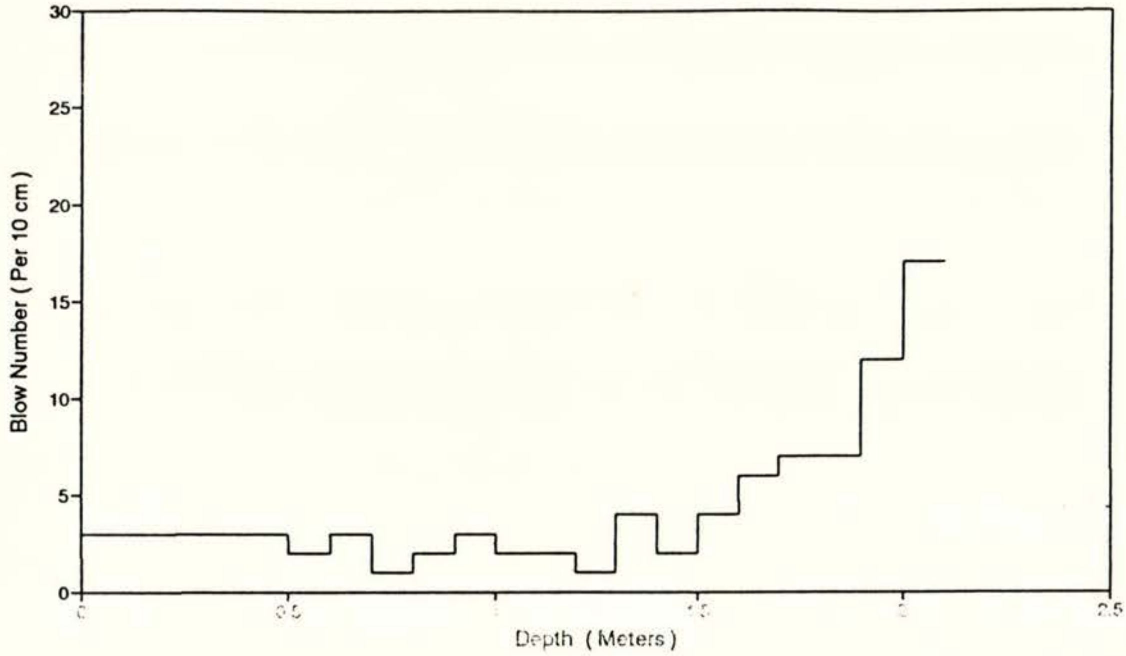
Scala Test DWT20 at W. Turner's Farm
Blow Number (Per 10 cm)
Depth (Meters)
0
5
10
15
20
25
30
1
2
3
4
5
6

Scala Test FULs2 at Fulsham's Farm

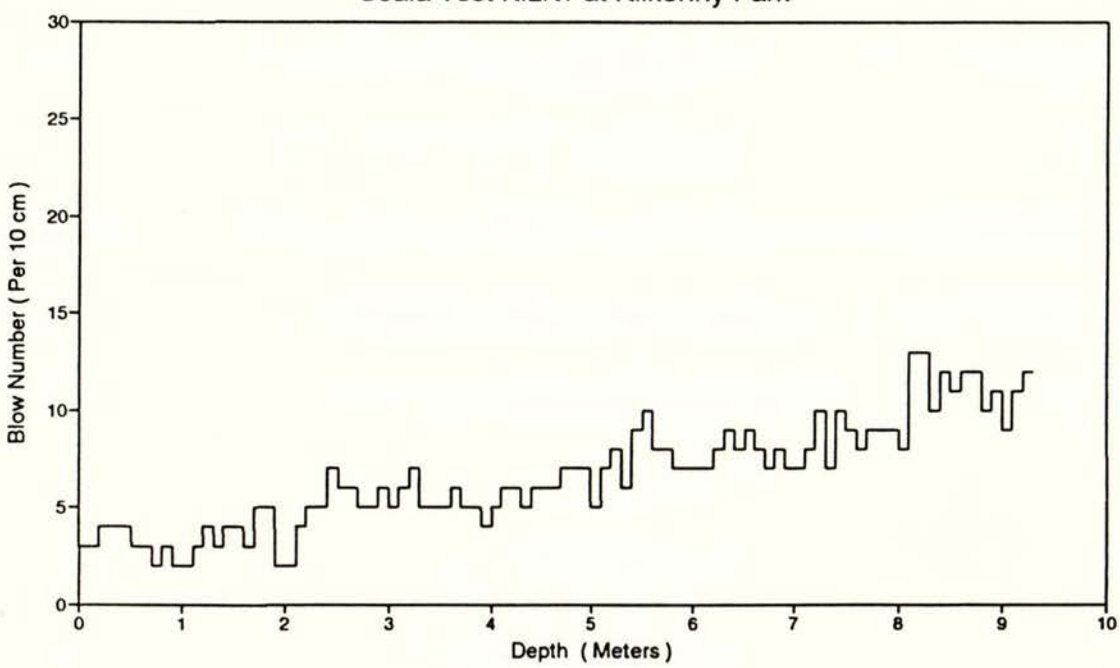
Scala Test FULs1 at Fulsham's Farm

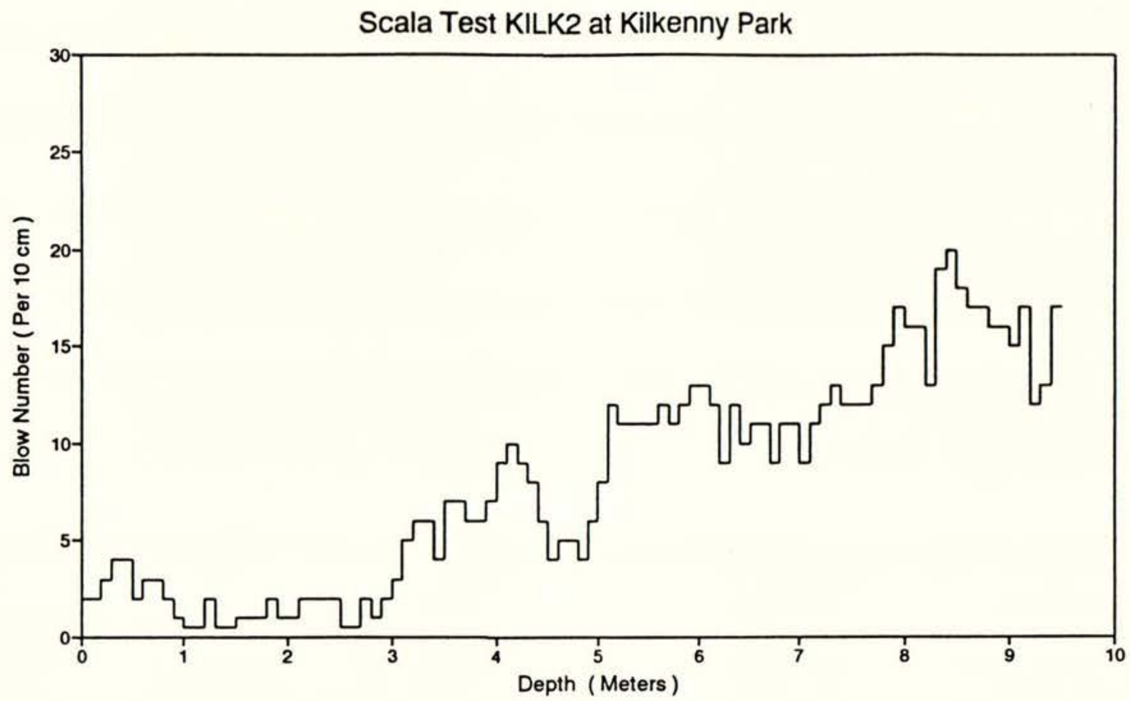


Scala Test FULs3 at Fulsham's Farm

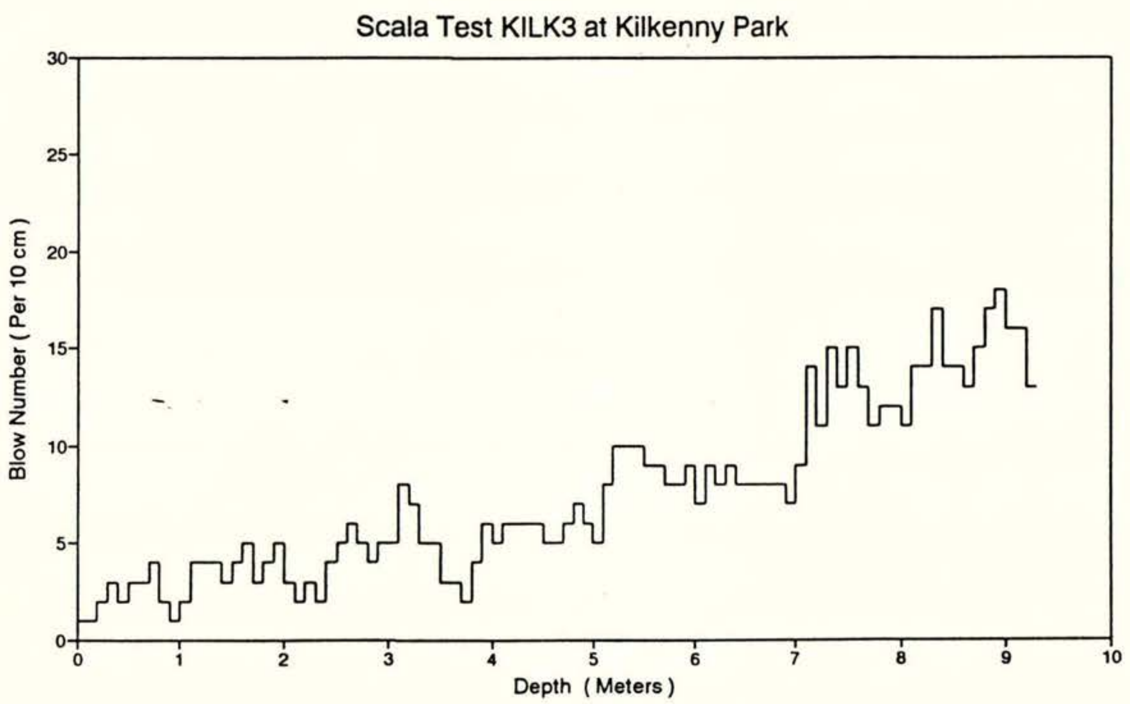


Scala Test KILK1 at Kilkenny Park



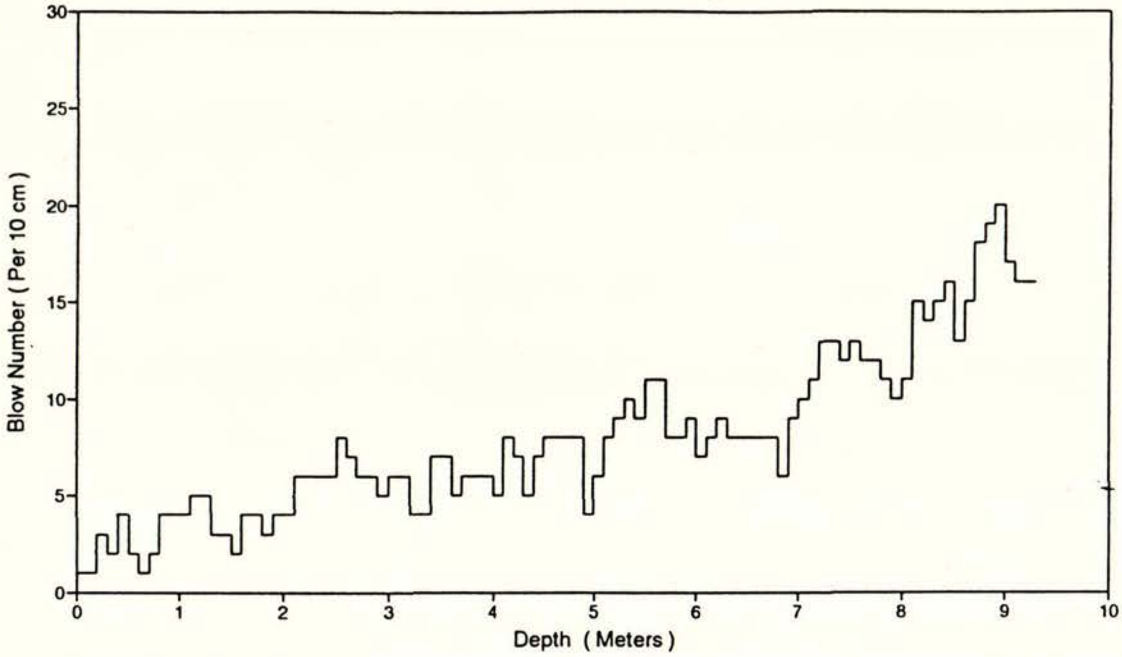


Scala Test KILK2 at Kilkenny Park
Blow Number (Per 10 cm)
Depth (Meters)

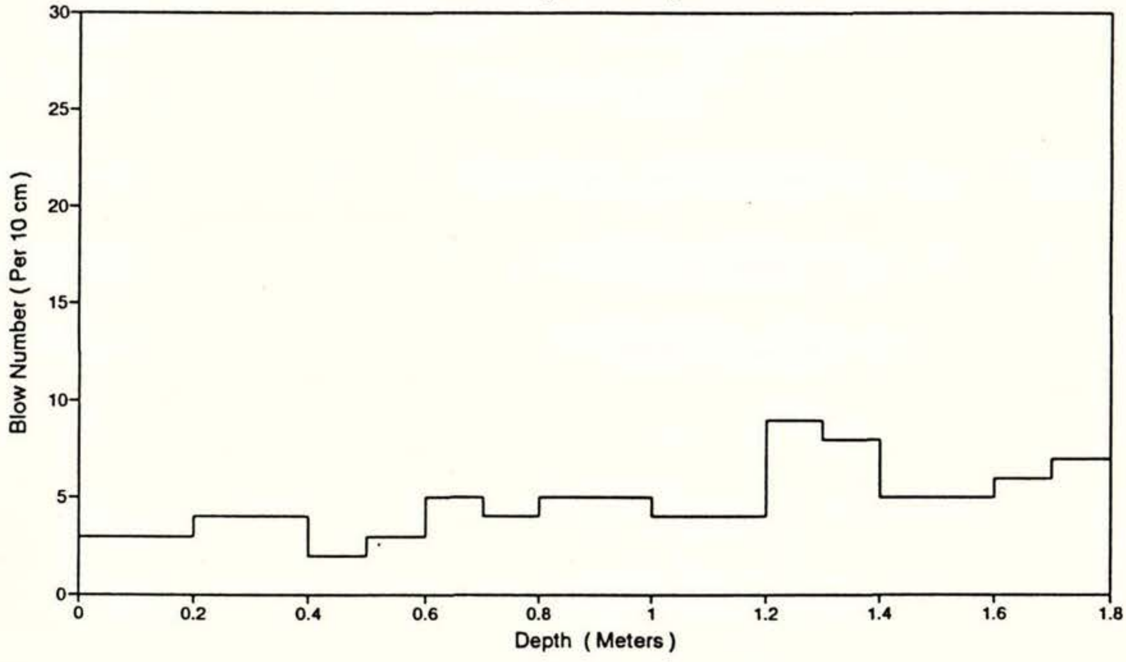


Scala Test KILK3 at Kilkenny Park
Blow Number (Per 10 cm)
Depth (Meters)

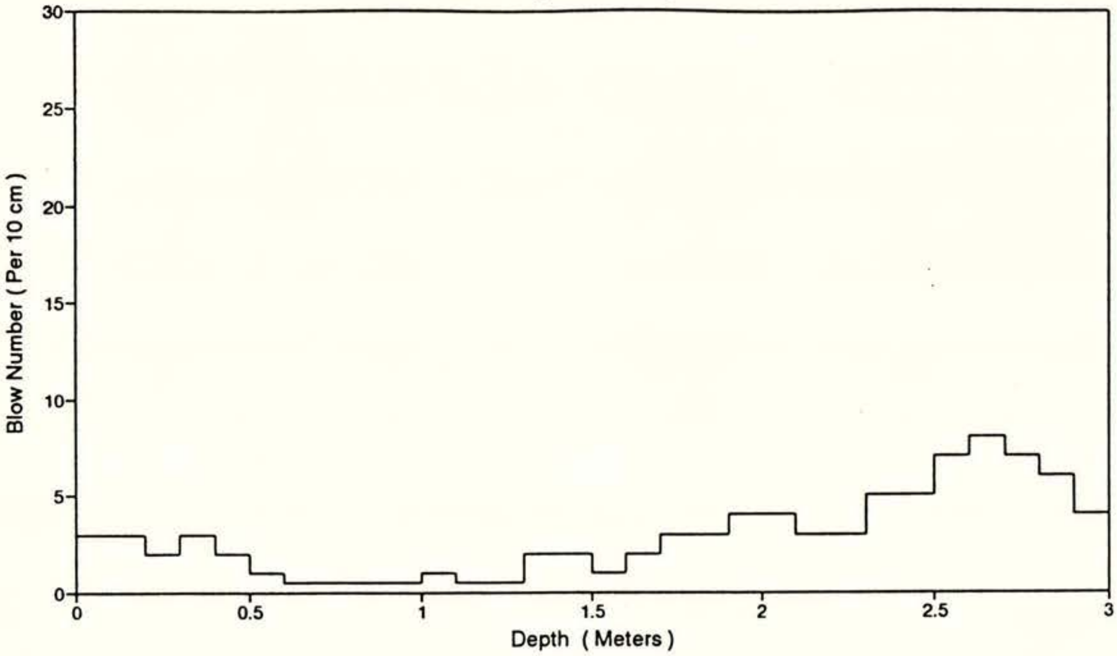
Scala Test KILK4 at Kilkenny Park



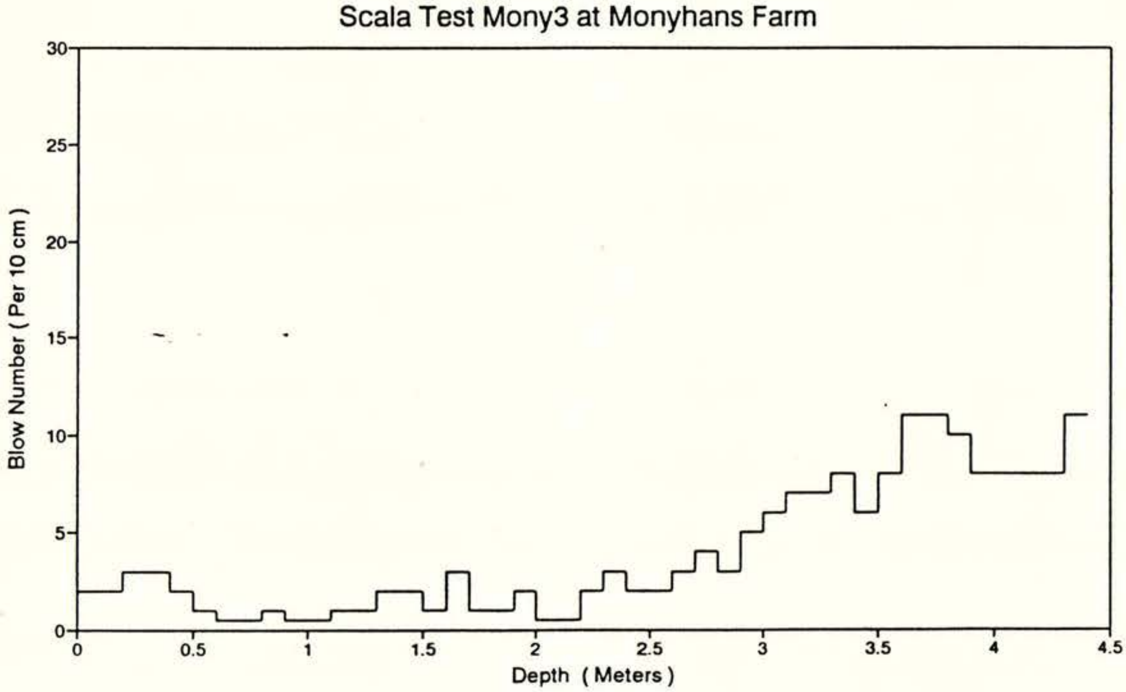
Scala Test Mony1 at Monyhans Farm



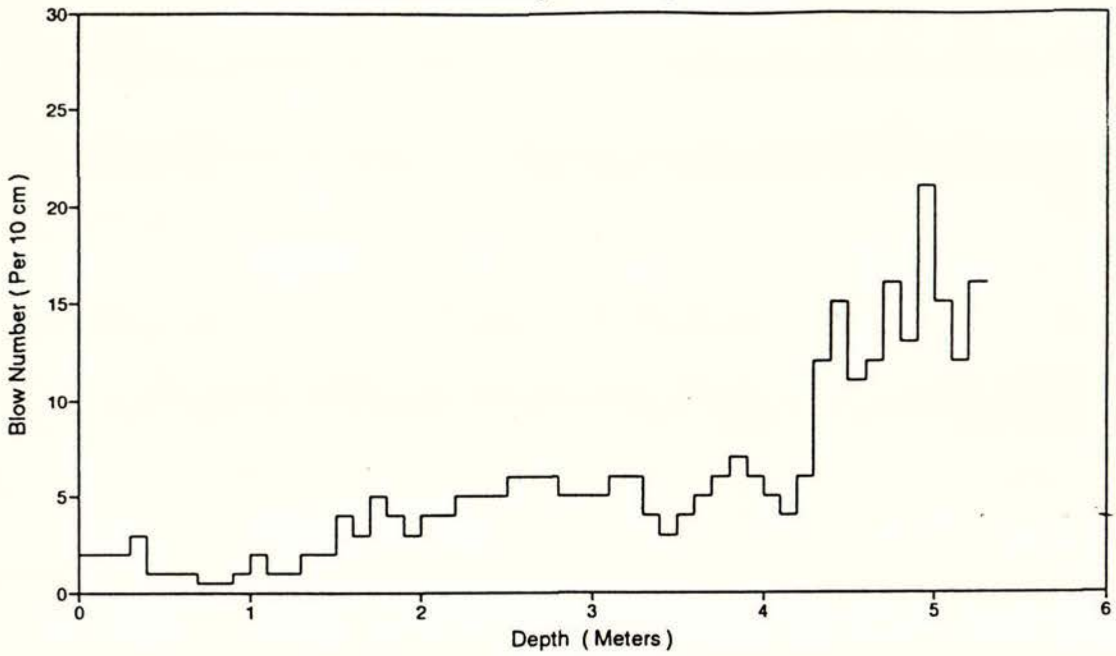
Scala Test Mony2 at Monyhans Farm



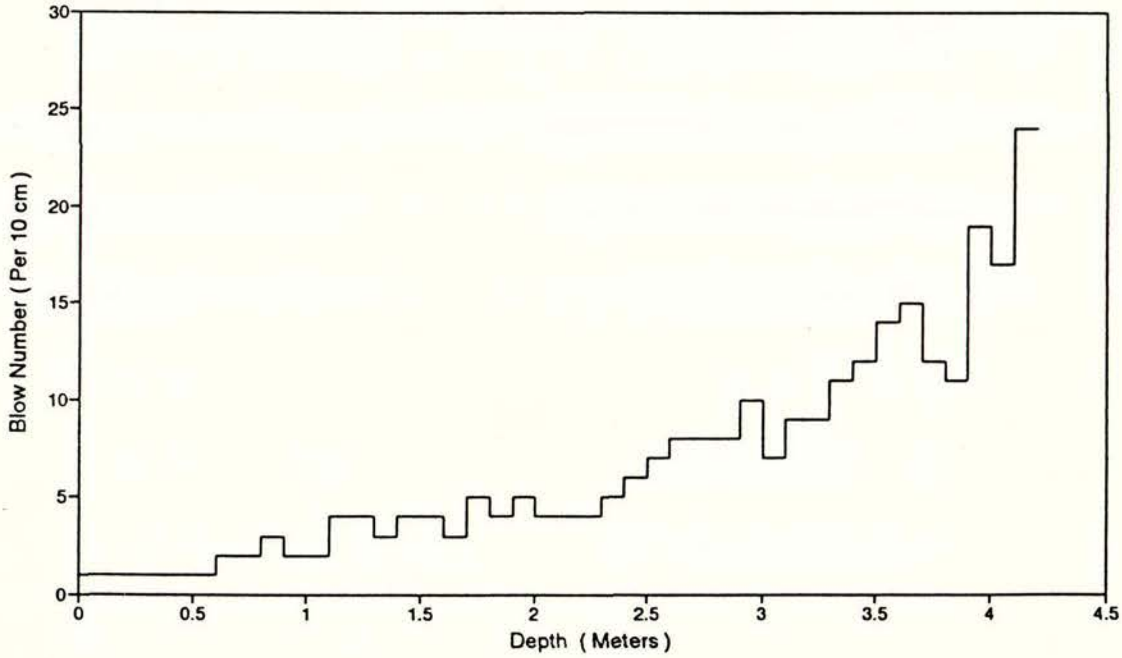
Scala Test Mony3 at Monyhans Farm



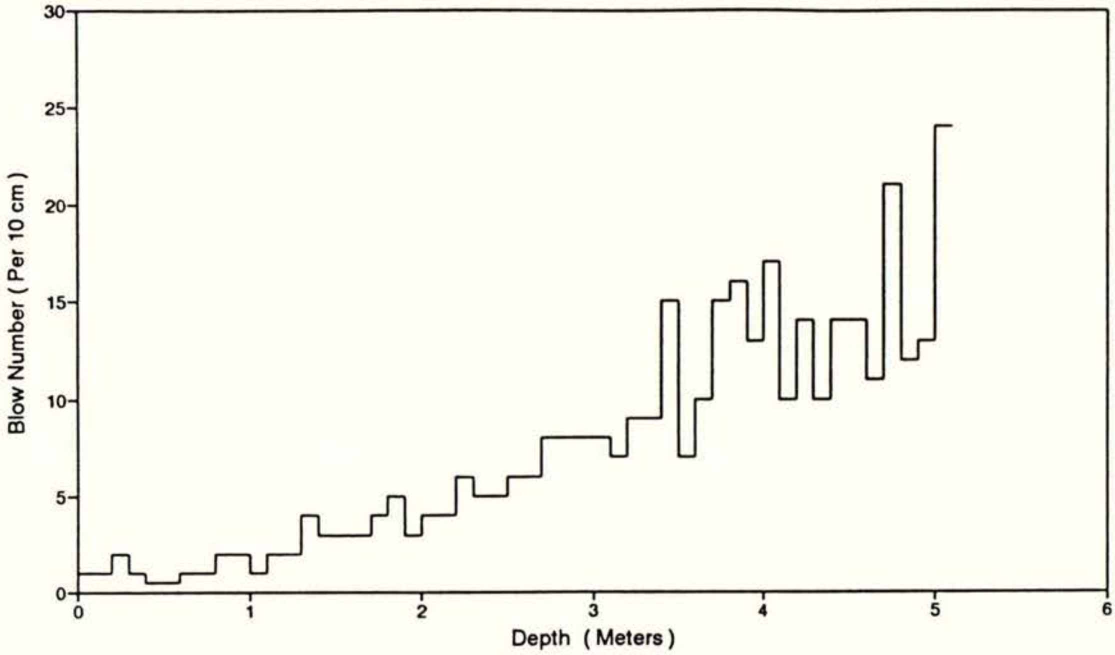
Scala Test Mony4 at Monyhans Farm



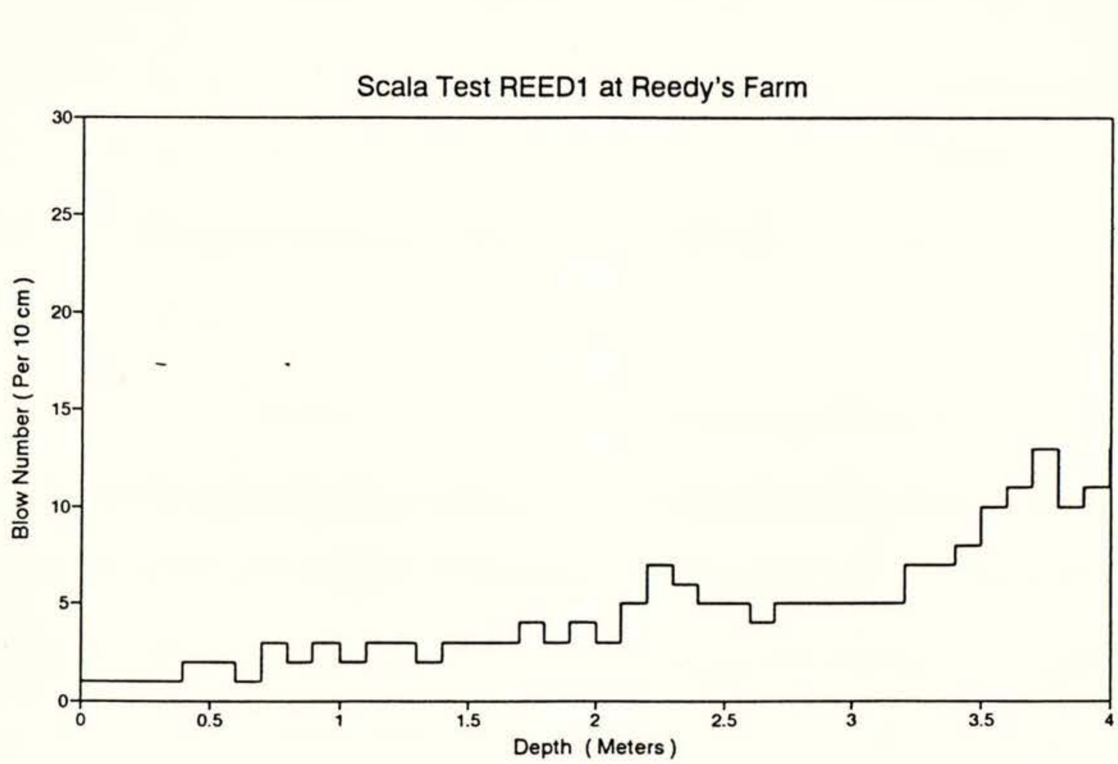
Scala Test OCON1 at O.Connor's Farm

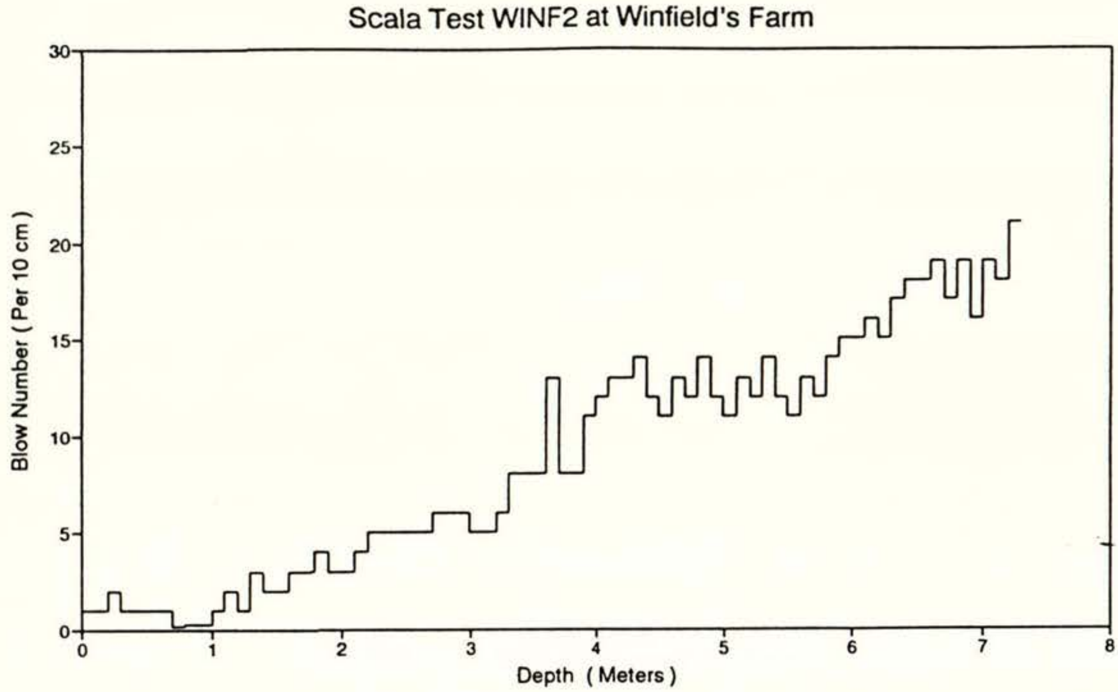


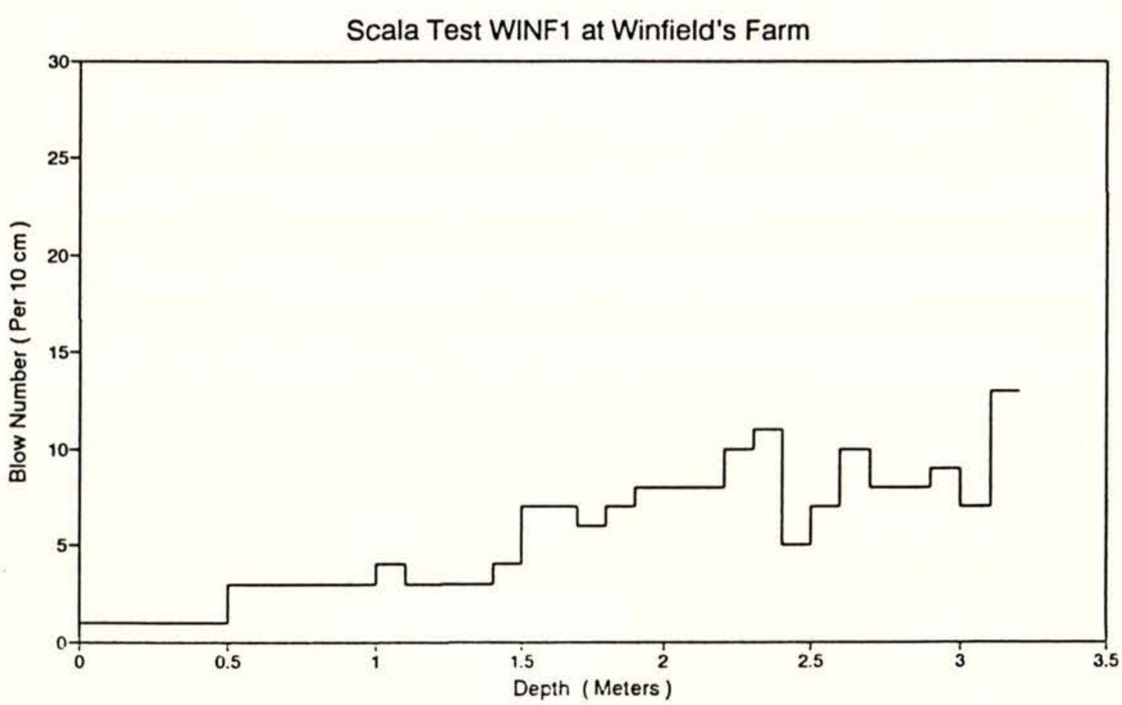
Scala Test OCON2 at O.Connor's Farm



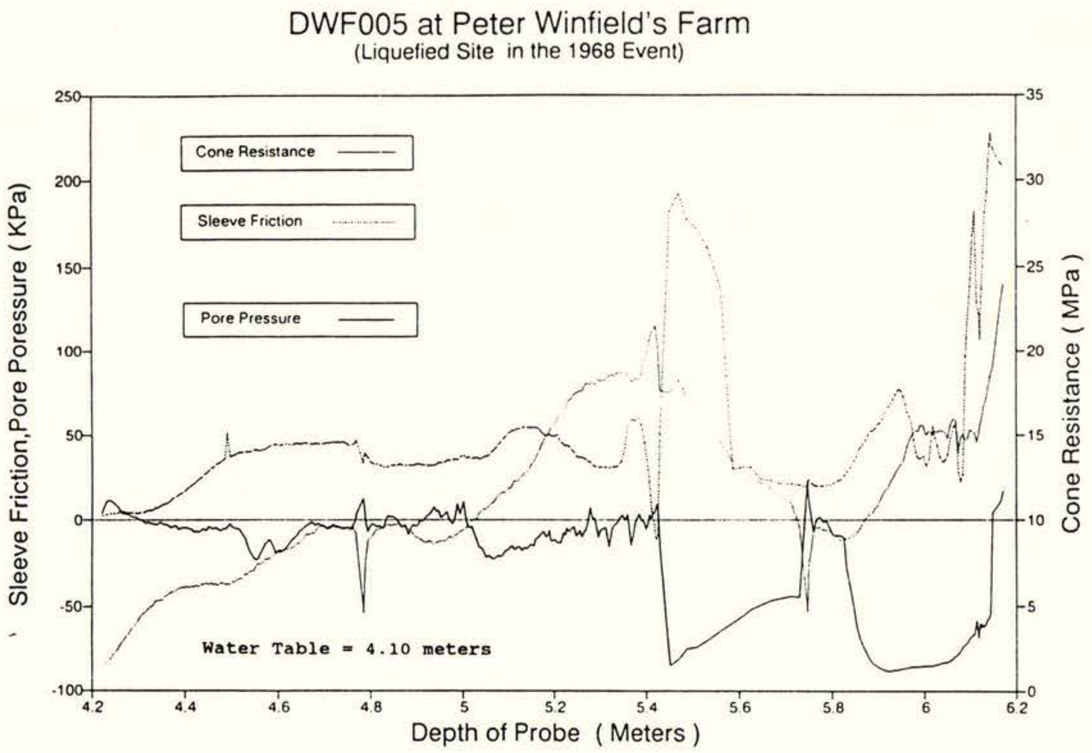
Scala Test REED1 at Reedy's Farm



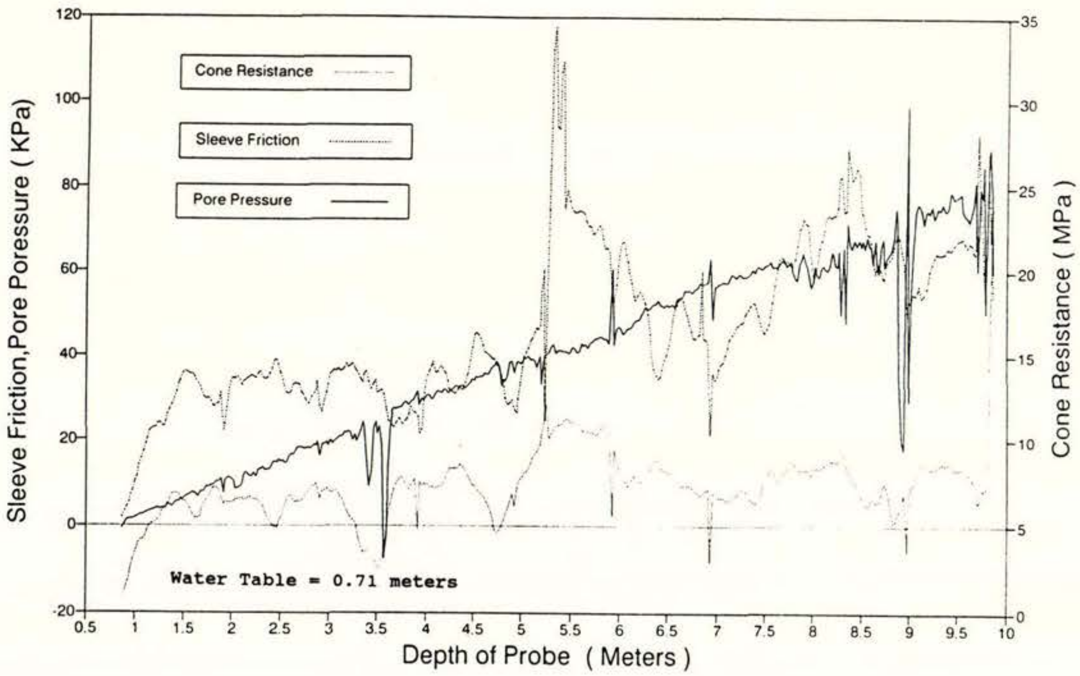

Scala Test WINF2 at Winfield's Farm
Blow Number (Per 10 cm)
Depth (Meters)
0
5
10
15
20
25
30
0
1
2
3
4
5
6
7
8


Scala Test WINF1 at Winfield's Farm
Blow Number (Per 10 cm)
Depth (Meters)
0
5
10
15
20
25
30
0
0.5
1
1.5
2
2.5
3
3.5

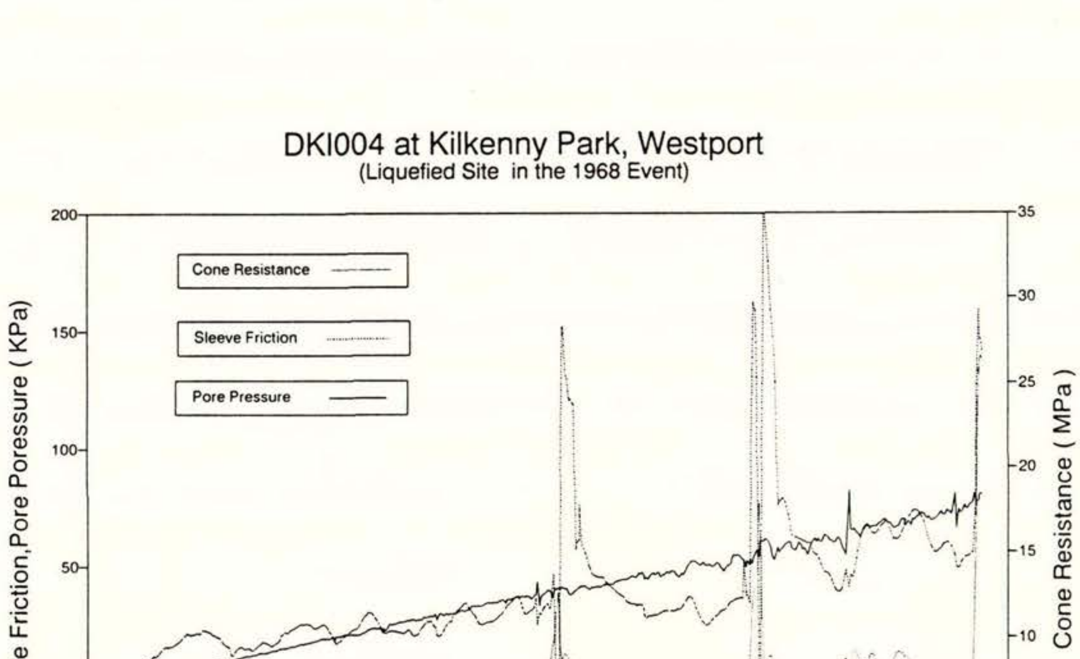
APPENDIX III

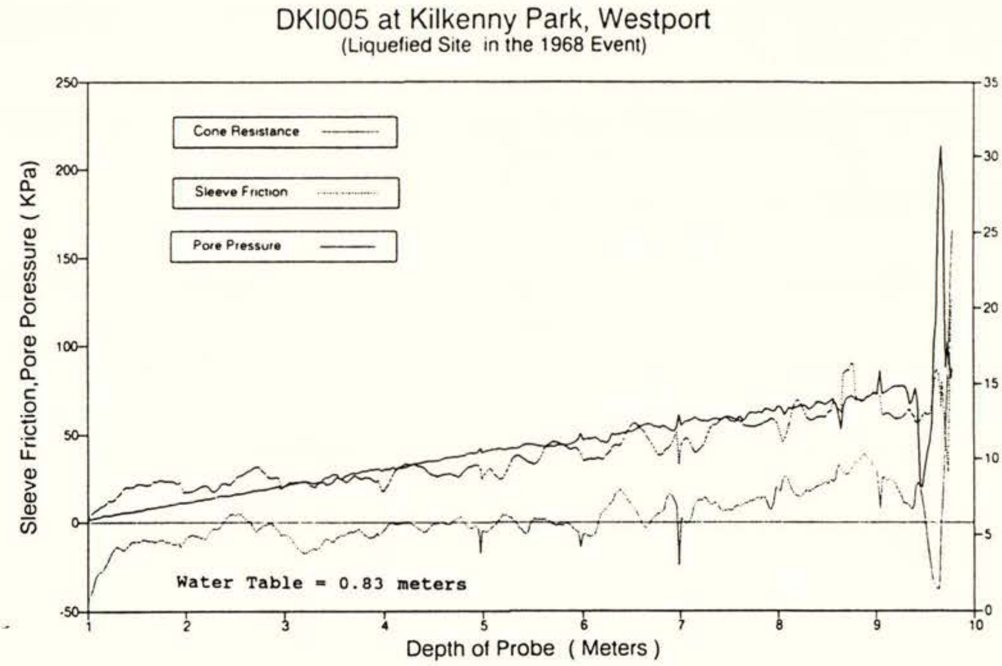

DWF005 at Peter Winfield's Farm
(Liquefied Site in the 1968 Event)
Cone Resistance
Sleeve Friction
Pore Pressure
Water Table = 4.10 meters
Sleeve Friction,Pore Poressure (KPa)
Cone Resistance (MPa)
Depth of Probe (Meters)
250
200
150
100
50
0
-50
-100
35
30
25
20
15
10
5
0
4.2
4.4
4.6
4.8
5
5.2
5.4
5.6
5.8
6
6.2

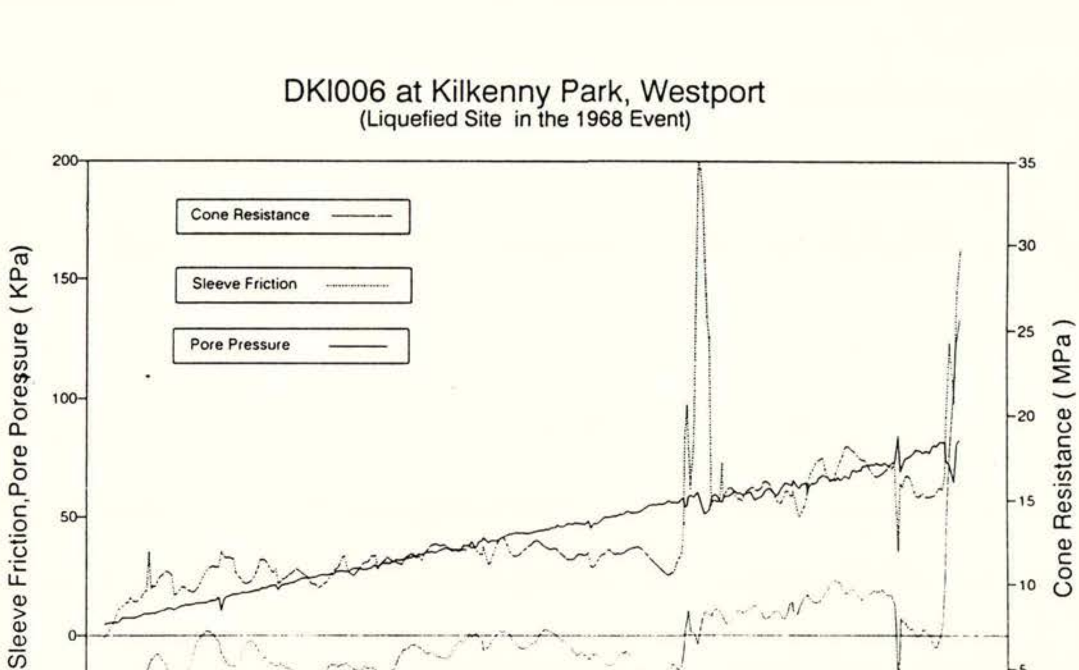
DKI002 at Kilkenny Park, Westport
(Liquefied Site in the 1968 Event)



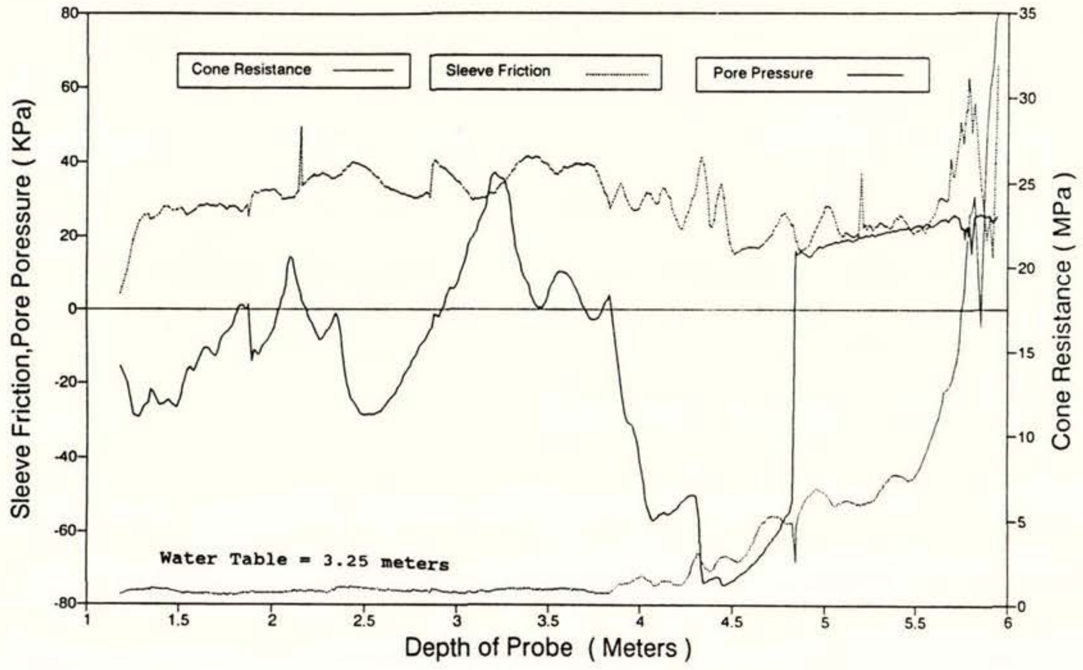
DKI004 at Kilkenny Park, Westport
(Liquefied Site in the 1968 Event)



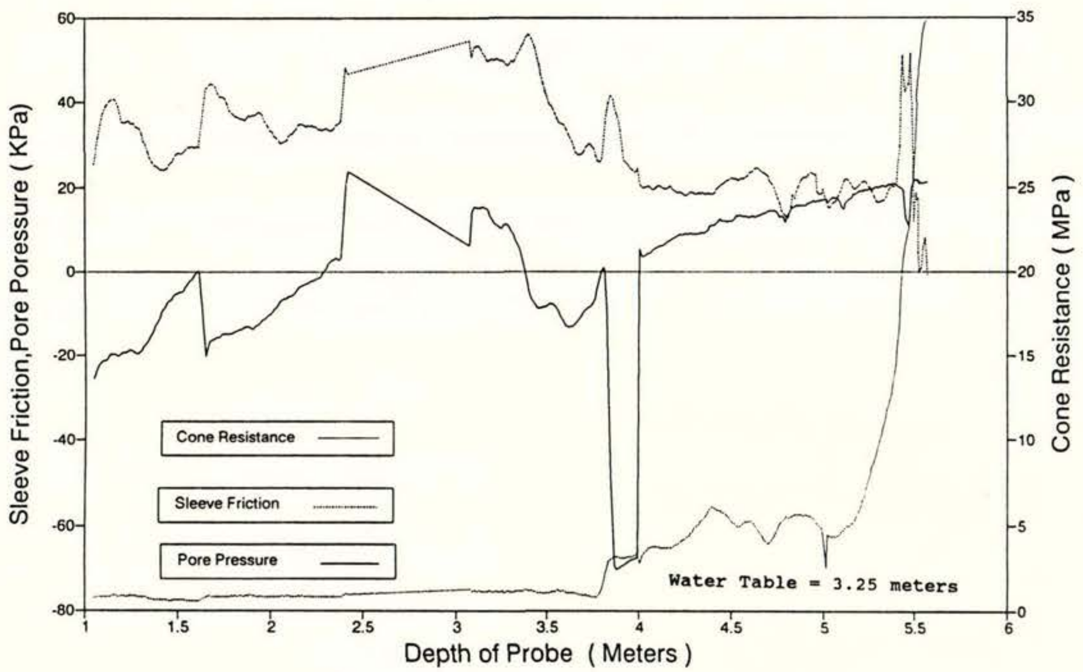

DKI005 at Kilkenny Park, Westport
(Liquefied Site in the 1968 Event)
Cone Resistance
Sleeve Friction
Pore Pressure
Water Table = 0.83 meters
Sleeve Friction,Pore Poressure (KPa)
Cone Resistance (MPa)
Depth of Probe (Meters)


DKI006 at Kilkenny Park, Westport
(Liquefied Site in the 1968 Event)
Cone Resistance
Sleeve Friction
Pore Pressure
Water Table = 0.78 meters
Sleeve Friction,Pore Poressure (KPa)
Cone Resistance (MPa)
Depth of Probe (Meters)

DWT002 at Wallace Turner's Farm
(Liquefied Site B in the 1968 Event)

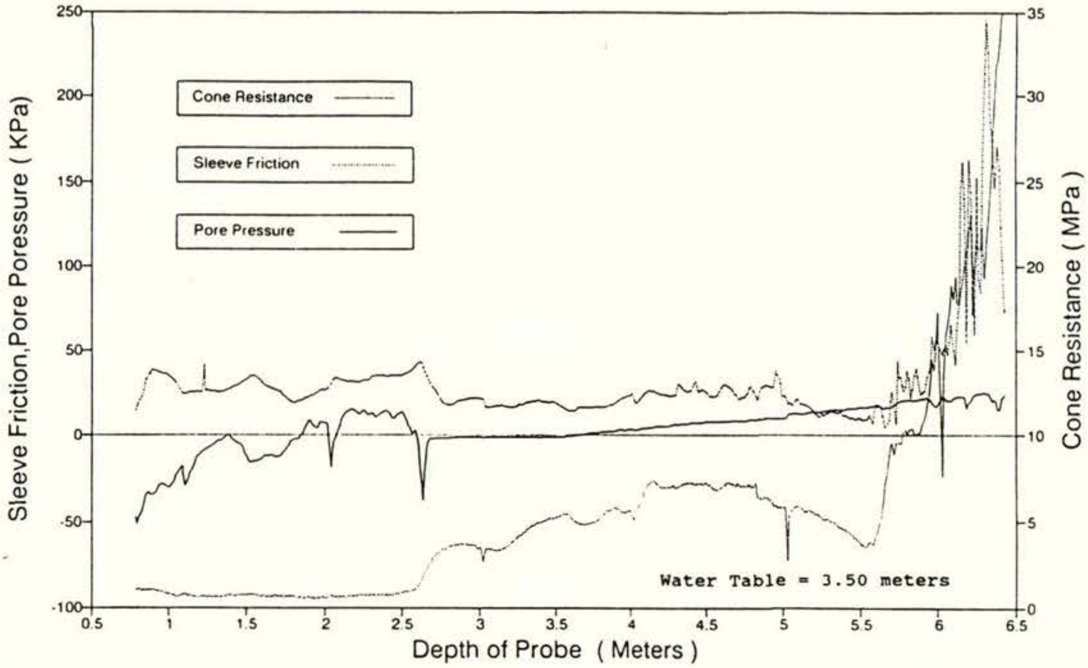


DWT003 at Wallace Turner's Farm
(Liquefied Site B in the 1968 Event)



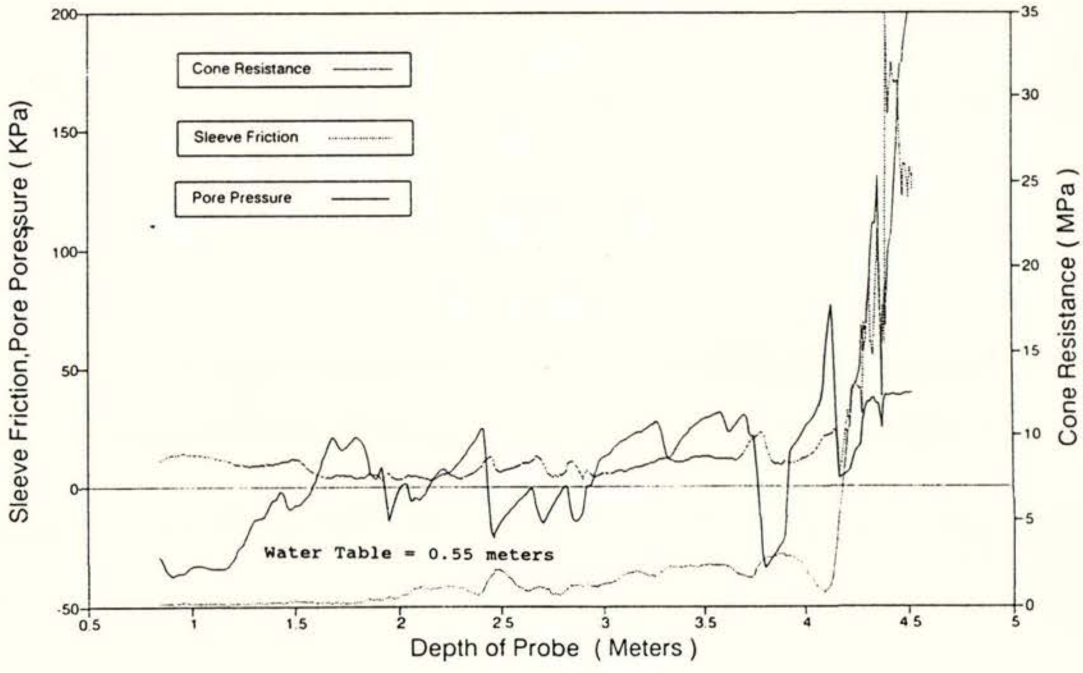
DWT004 at Wallace Turner's Farm

(Unliquefied Site C in the 1968 Event)

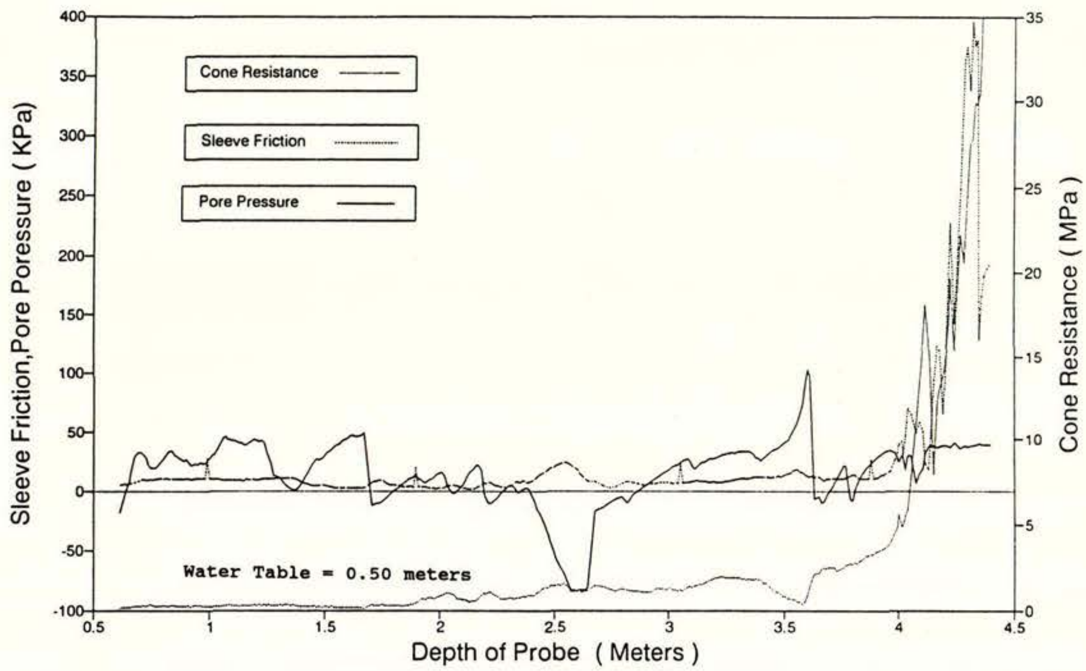


WT5001 at Wallace Turner's Farm

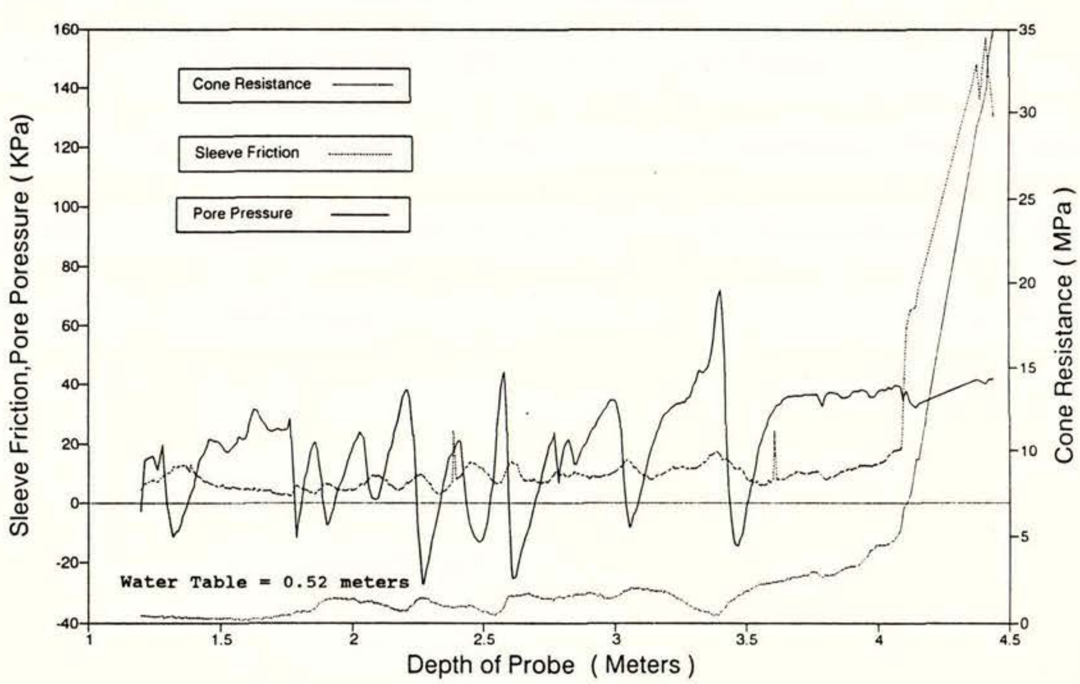
(Liquefied Site A in the Both Event)



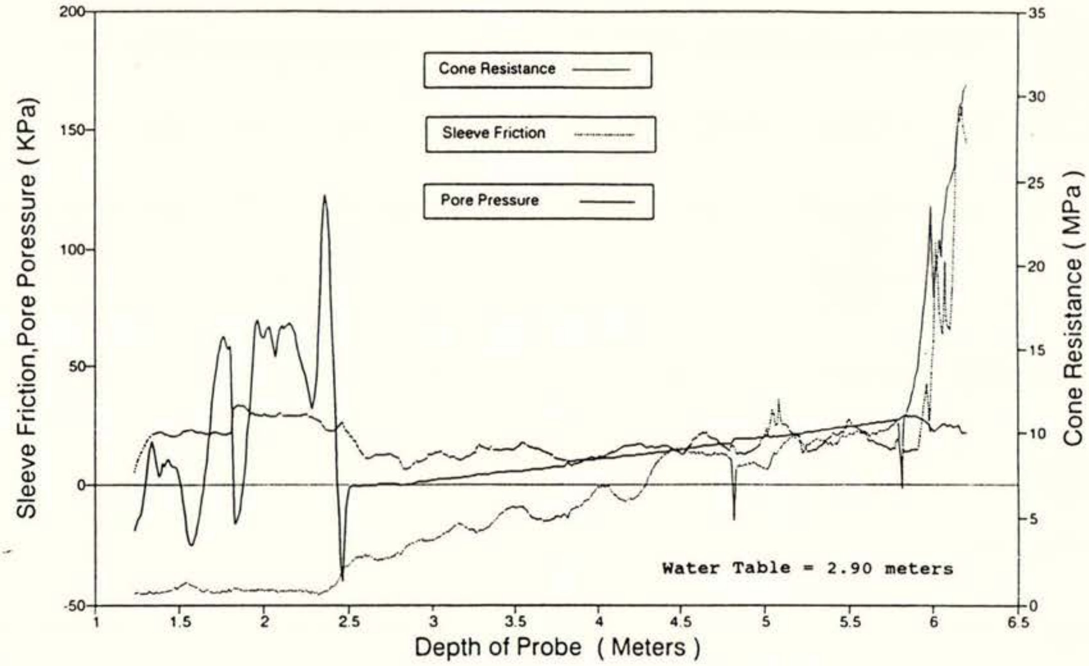
WT5002 at Wallace Turner's Farm
(Liquefied Site A in the Both Event)



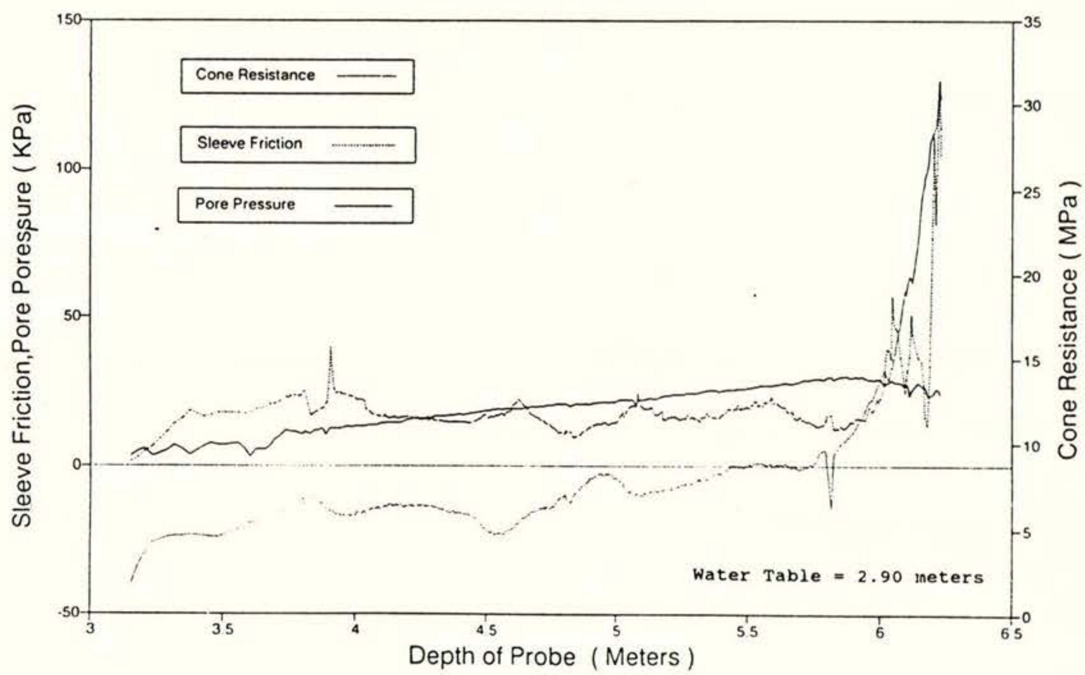
WT5003 at Wallace Turner's Farm
(Liquefied Site A in the Both Event)

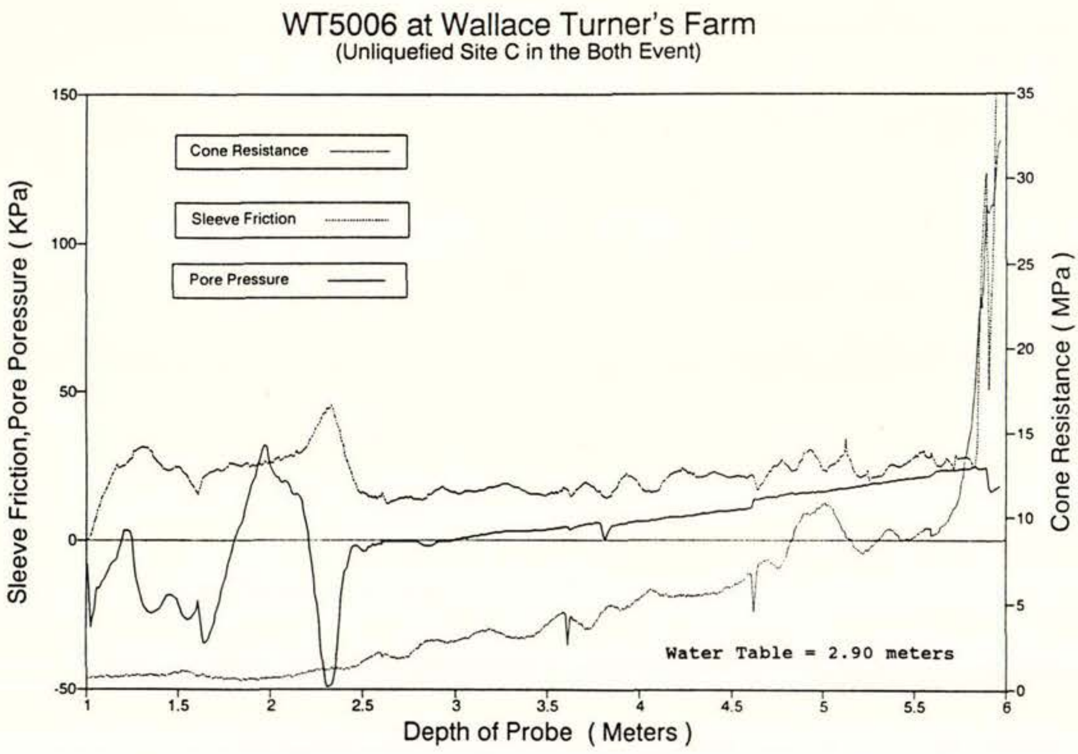


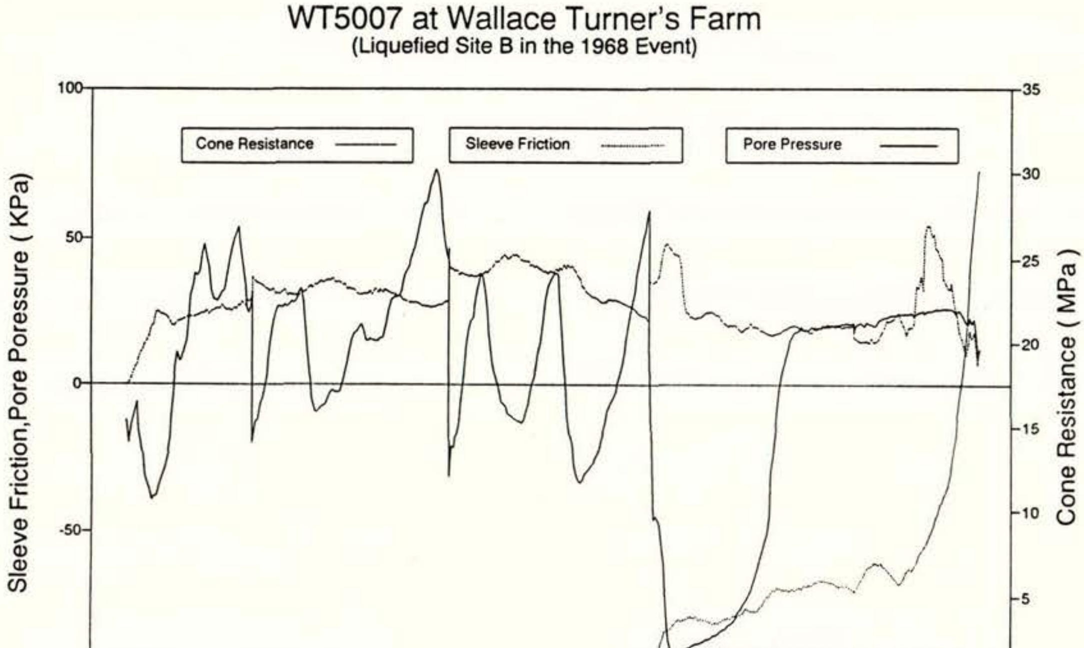
WT5004 at Wallace Turner's Farm
(Unliquefied Site C in the Both Event)



WT5005 at Wallace Turner's Farm
(Unliquefied Site C in the Both Event)

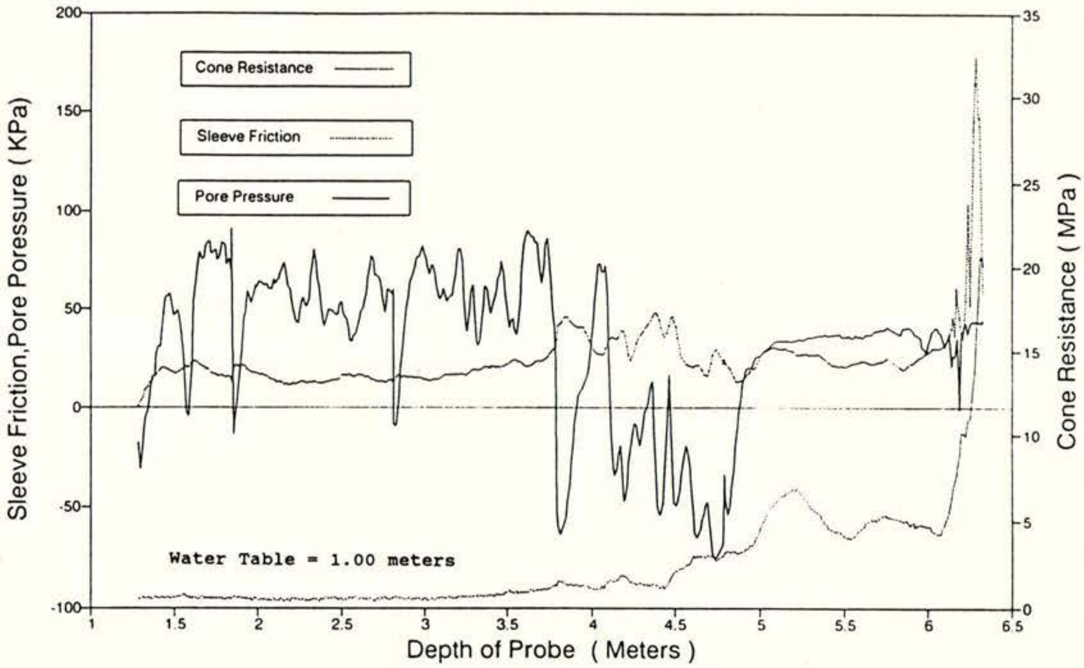



WT5006 at Wallace Turner's Farm
(Unliquefied Site C in the Both Event)
Cone Resistance
Sleeve Friction
Pore Pressure
Water Table = 2.90 meters
Sleeve Friction,Pore Poressure (KPa)
Cone Resistance (MPa)
Depth of Probe (Meters)
150
100
50
0
-50
35
30
25
20
15
10
5
0
1
1.5
2
2.5
3
3.5
4
4.5
5
5.5
6


WT5007 at Wallace Turner's Farm
(Liquefied Site B in the 1968 Event)
Cone Resistance
Sleeve Friction
Pore Pressure
Water Table = 1.00 meters
Sleeve Friction,Pore Poressure (KPa)
Cone Resistance (MPa)
Depth of Probe (Meters)
100
50
0
-50
-100
35
30
25
20
15
10
5
0
1
1.5
2
2.5
3
3.5
4
4.5
5
5.5

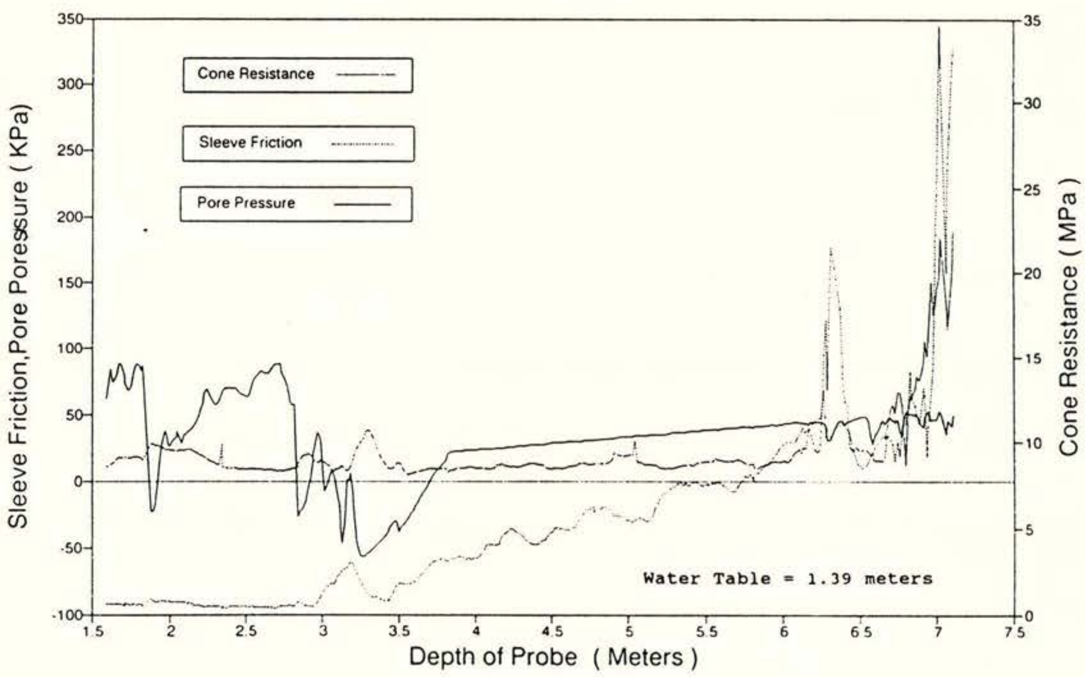
WT5008 at Wallcae Turner's Farm

(Liquefied Site B in the 1968 Event)

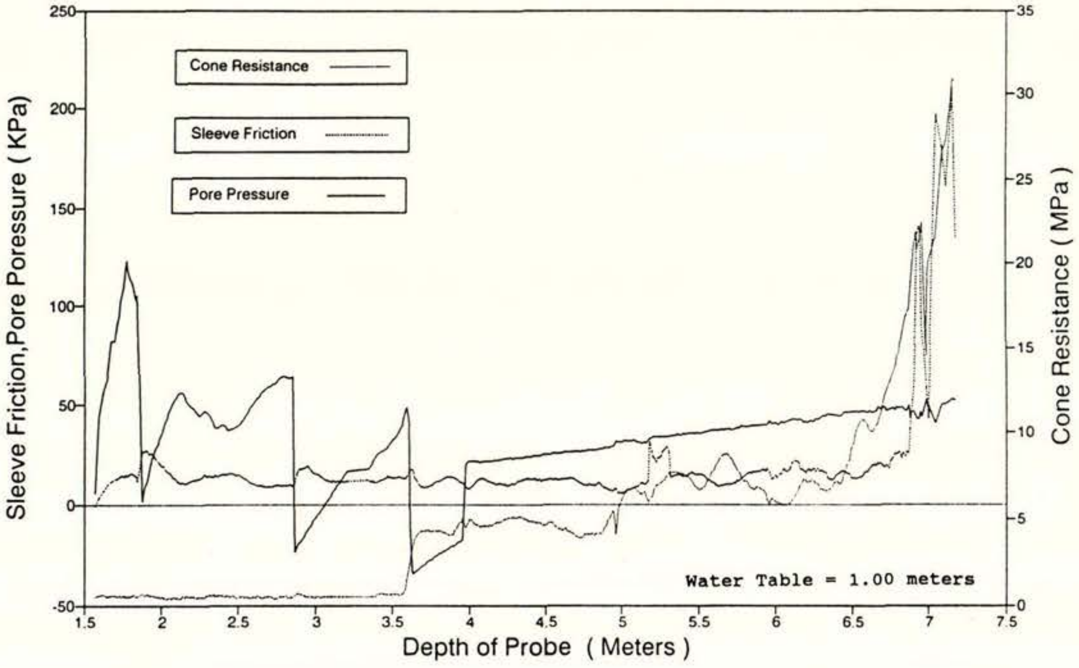


WT5009 at Wallcae Turner's Farm

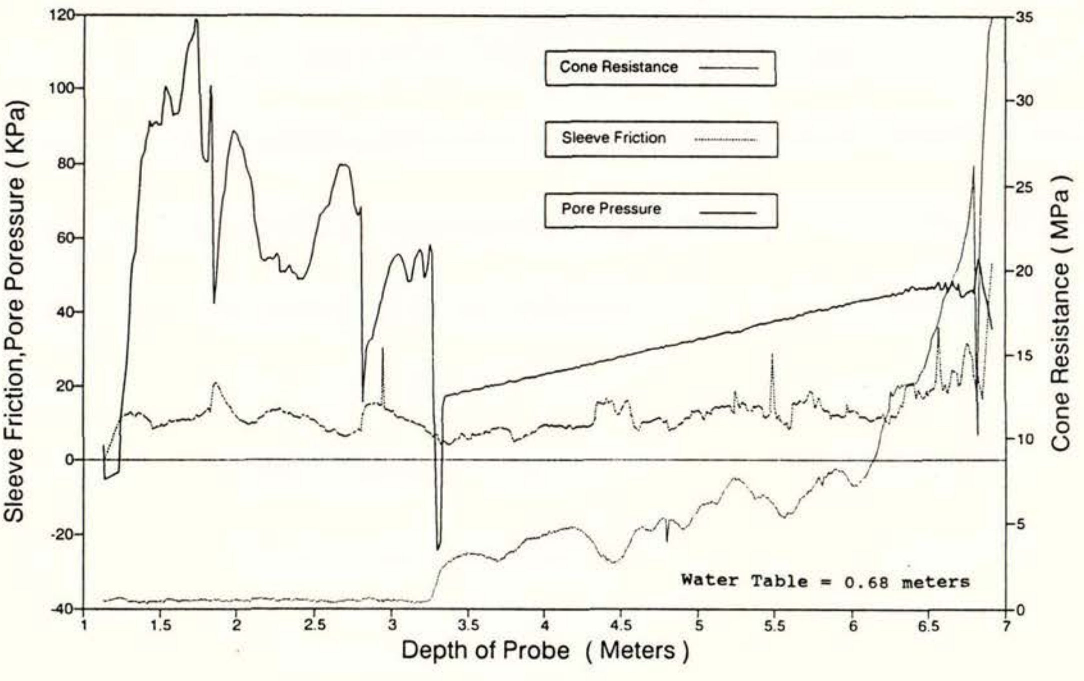
(Liquefied Site B in the 1968 Event)



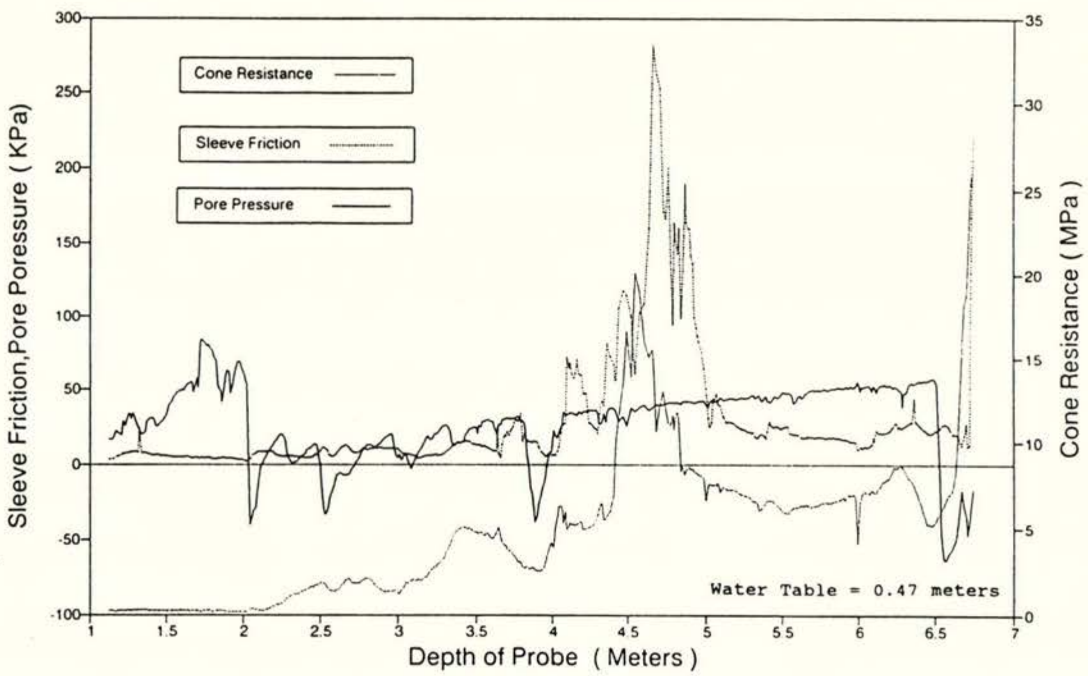
WT5010 at Wallcae Turner's Farm
(Liquefied Site B in the 1968 Event)



WT5011 at Wallcae Turner's Farm
(Liquefied Site B in the 1968 Event)

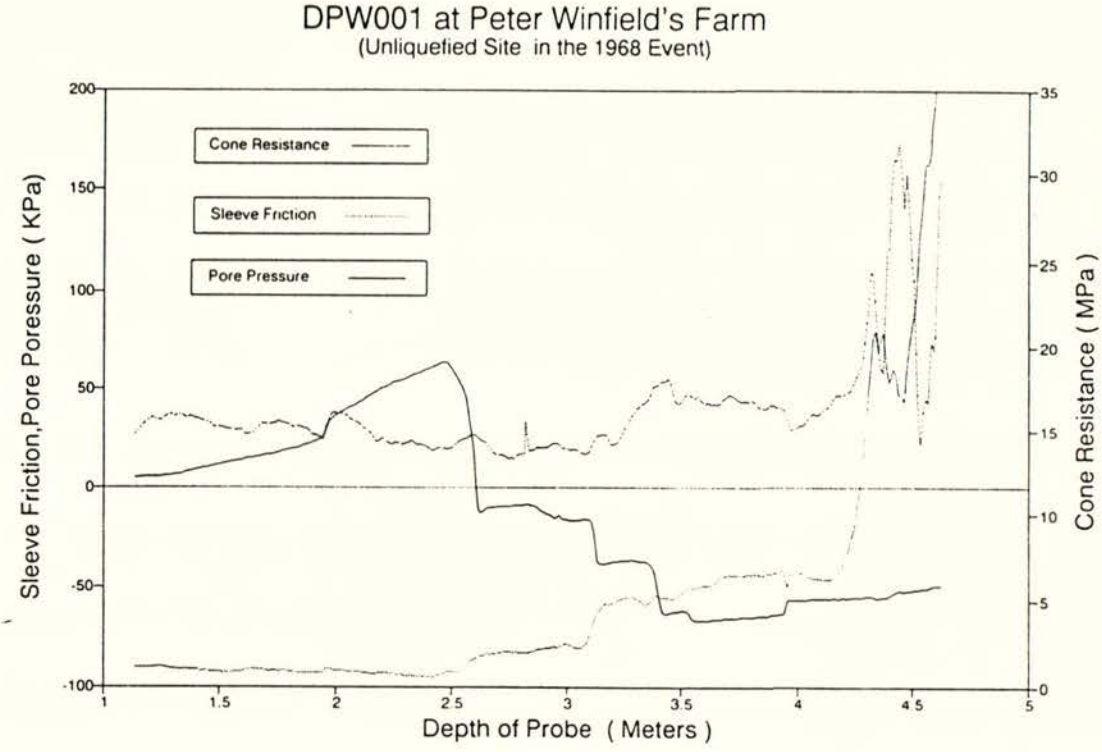


WT5012 at Wallcae Turner's Farm
(Liquefied Site A in the Both Event)

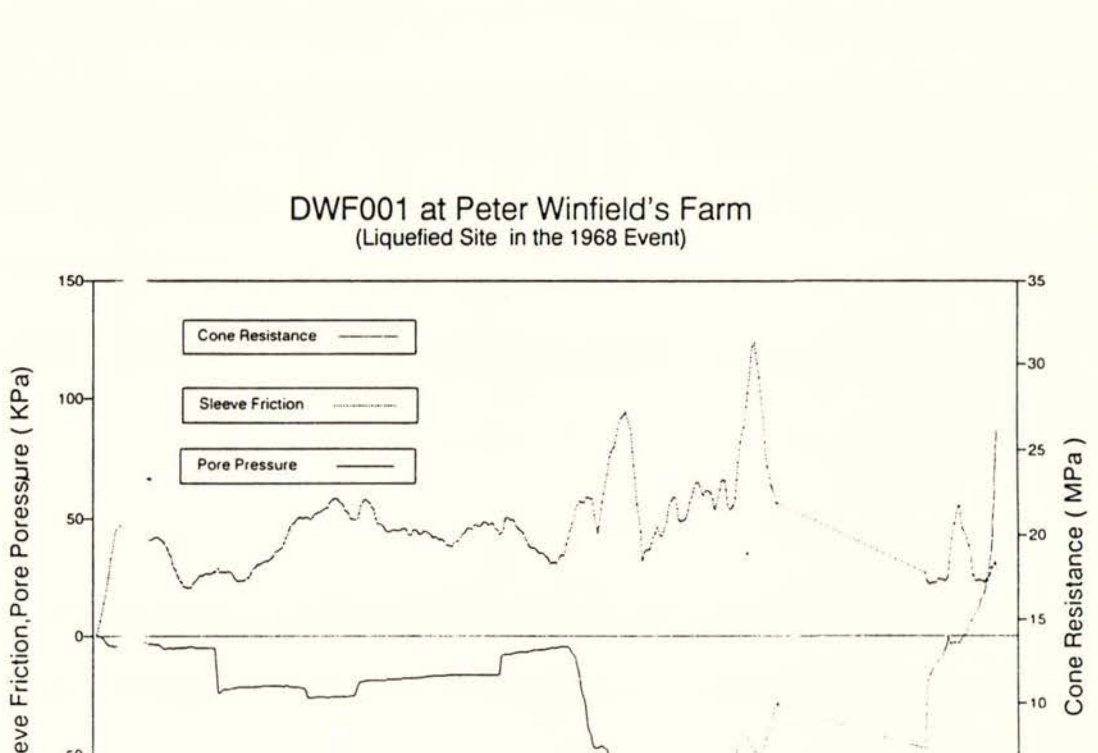


APPENDIX IV

N.B. Porepressure readings are unreliable, since filter not saturated.

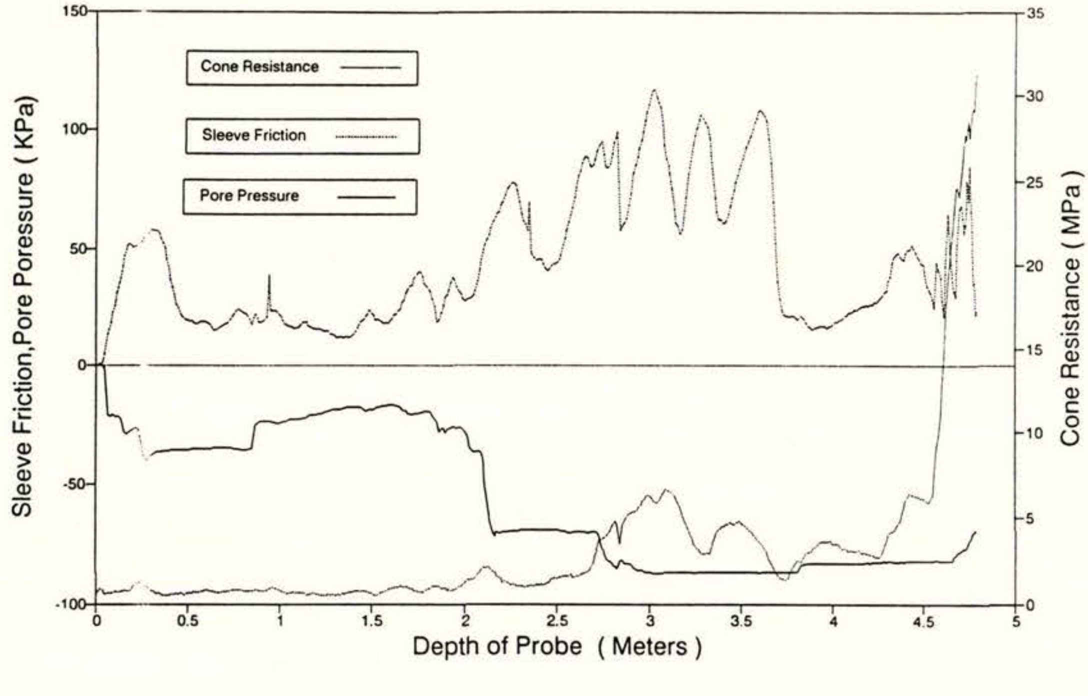


DPW001 at Peter Winfield's Farm
(Unliquefied Site in the 1968 Event)
Cone Resistance
Sleeve Friction
Pore Pressure
Sleeve Friction,Pore Poressure (KPa)
Cone Resistance (MPa)
Depth of Probe (Meters)

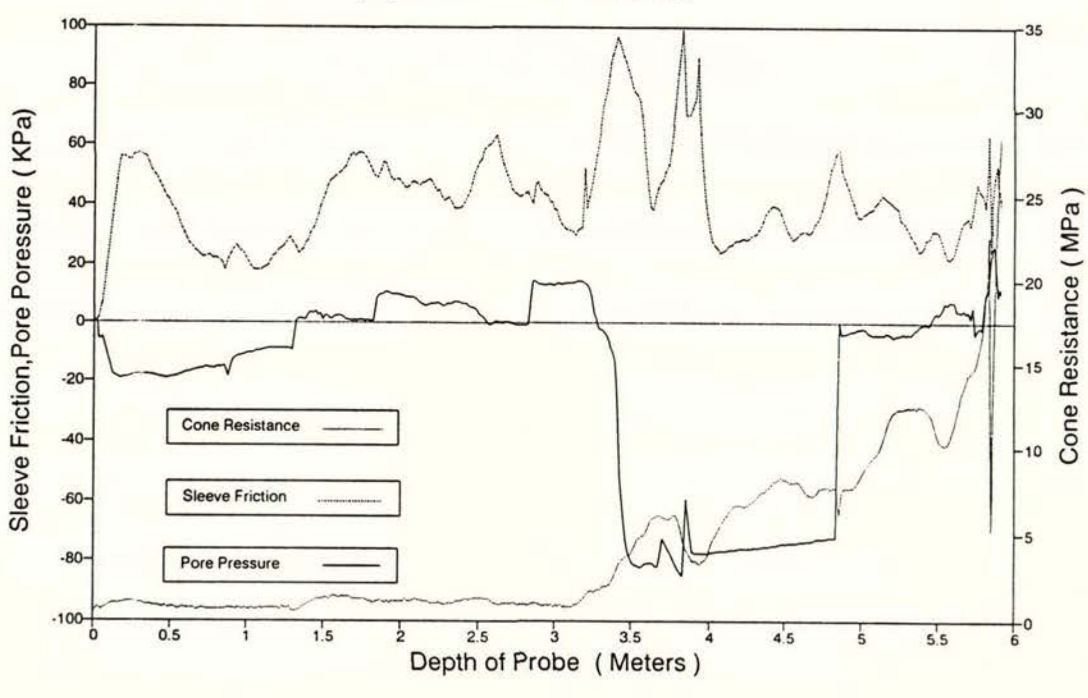


DWF001 at Peter Winfield's Farm
(Liquefied Site in the 1968 Event)
Cone Resistance
Sleeve Friction
Pore Pressure
Sleeve Friction,Pore Poressure (KPa)
Cone Resistance (MPa)
Depth of Probe (Meters)

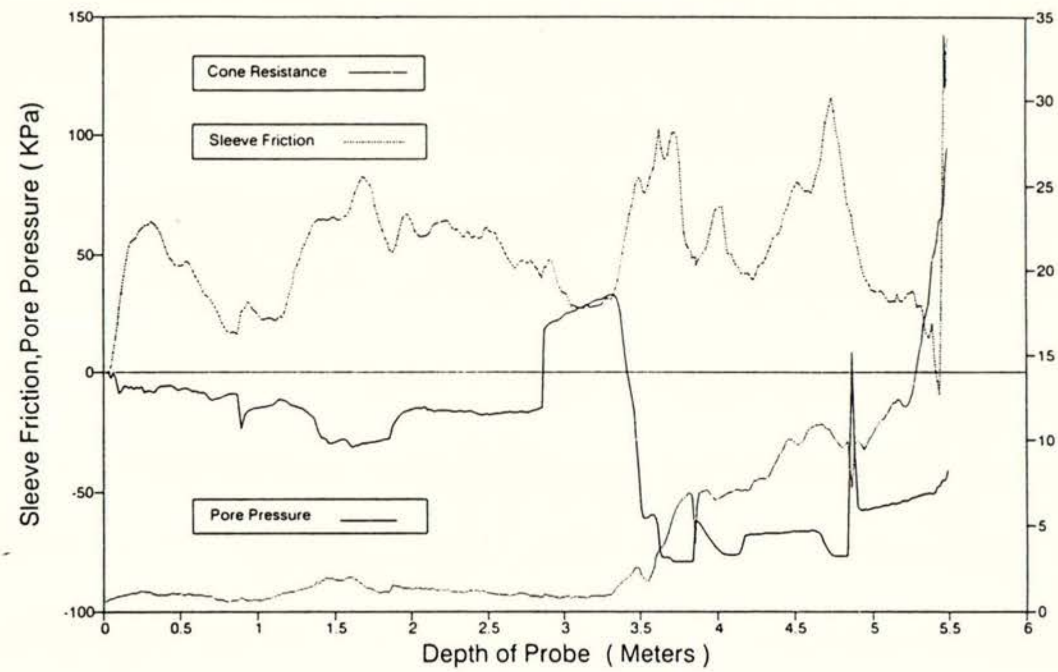
DWF002 at Peter Winfield's Farm
(Unliquefied Site in the 1968 Event)



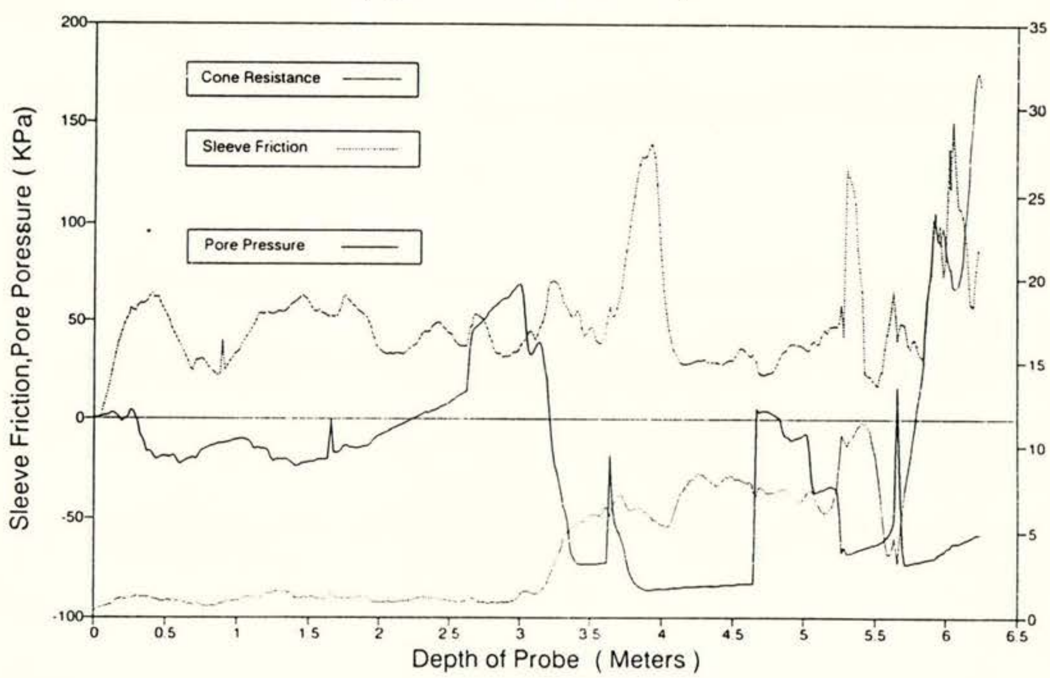
DWF003 at Peter Winfield's Farm
(Liquefied Site in the 1968 Event)



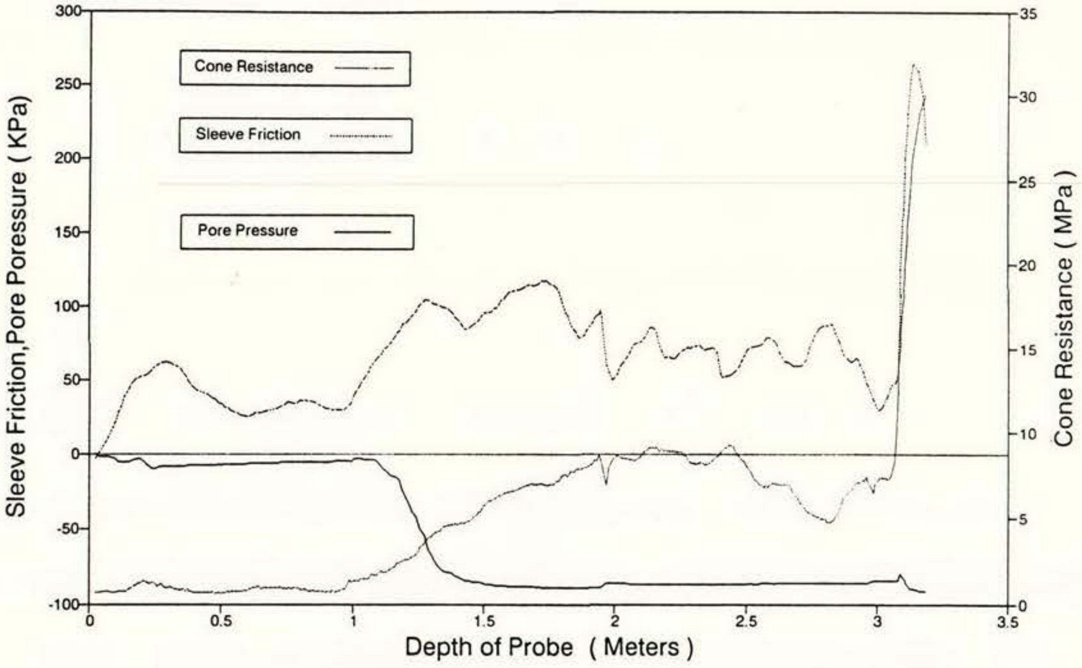
DWF004 at Peter Winfield's Farm
(Liquefied Site in the 1968 Event)



DWF006 at Peter Winfield's Farm
(Liquefied Site in the 1968 Event)



DWF009 at Peter Winfield's Farm
(Unliquefied Site in the 1968 Event)



DKI001 at Kilkenny Park,Westport
(Liquefied Site in the 1968 Event)