Liquefaction at Kaiapoi in the 1901 Cheviot, New Zealand Earthquake

J B Berrill, P C Mulqueen, E T C Ooi, J-L Pautre, Department of Civil Engineering, University of Canterbury

ISSN 0110-3326

LIQUEFACTION AT KAIAPOI IN THE 1901 CHEVIOT, NEW ZEALAND EARTHQUAKE

by

J B BERRILL, P C MULQUEEN, E OOI,
J-L PAUTRE

March 1994 Research Report No. 94-3

Department of Civil Engineering
University of Canterbury
Christchurch, New Zealand

ABSTRACT

A clear case of seismic liquefaction occurred in northeast Kaiapoi during the 1901 Cheviot earthquake. A contemporary newspaper report describes the ejection of sand and lateral spreading in Waites' market garden at the east end of Sewell Street, Kaiapoi and also south of the Waimakariri River near Belfast.

Soil conditions at Waites' property in Sewell Street and at three other sites in northeast Kaiapoi were investigated by piezocone probing and rotary drilling. Loose, fine sands and silty sands, with a cone resistance q_c as low as 2 to 3 MPa, were found. These soils would be quite susceptible to liquefaction, and it is not surprising that they liquefied in 1901.

Lack of precise seismological parameters for the 1901 earthquake precludes any definite conclusions about the performance of liquefaction potential models.

A comparison of Dutch cone penetrometer resistances and standard penetration test N-values supports the old q_c (bars)/N = 4 rule, but the data are quite scattered. In view of the large amount of scatter, use of the more refined rule of Robertson of Campanella, where q_c/N is a function of D_{50}, does not seem warranted.

Although the field results cannot be used with any precision to verify or recalibrate liquefaction models, they do confirm that there is a significant risk of liquefaction at Kaiapoi. Furthermore, we now have four reference sites, each with slightly different soil conditions, whose performance can be monitored following future earthquakes in the region.

ACKNOWLEDGEMENTS

This work forms part of a larger project to document liquefaction sites and to study the behaviour of the piezocone in liquefiable soils, which has been supported by the NZ National Roads Board, the EQC, the NZ Ministry of Energy, the University Grants Committee and by the French Ministry of Science and Technology. Their support is gratefully acknowledged.

Canterbury newspaper archives and the Christchurch Drainage Board records were searched by Mr Anthony Cuttriss, and his historian's skills are warmly acknowledged. The co-operation of Kaiapoi landowners and of Mr Max Trumper of the former Kaiapoi Borough Council is also gratefully acknowledged. Mr John Weeber and Dr Jarg Pettinga are thanked for their critical reading of the manuscript and their helpful suggestions.

The permission of the Department of Survey and Land Information to reproduce the aerial photograph and map used in Figures 1-3 is acknowledged.

TABLE OF CONTENTS

INTRODUCTION

The 1901 Cheviot earthquake is one of the strongest earthquakes to occur in the Canterbury province of the South Island of New Zealand since European settlement. Its magnitude has been estimated at around 6.5 to 7 by Dibble et al (1980) and as $M_s = 6.9 \pm 0.2$ by Dowrick and Smith (1990). McKay (1902) records reports of ejected sand and water, and he himself observed fissures, in the epicentral region that were almost certainly sand boils and the results of lateral spreading due to liquefaction. Sand boils and other liquefaction phenomena were observed also at a number of other locations to the south of the epicentre (Fairless and Berrill, 1984). The most widely reported cases of liquefaction occurred in the town of Kaiapoi, about 90 km south of the estimated epicentre. There is also a rather vague newspaper reference to liquefaction near Belfast, some 6 km further from the epicentre to the south of Kaiapoi, which is the most distant report we have been able to find.

The aim of this article is to document the historical reports of liquefaction at Kaiapoi in 1901 and to describe soil conditions at the site, determined by rotary boring and penetrometer tests.

Very loose, cohesionless soils were found near the ground surface, and it is not surprising that they liquefied in 1901. The cone penetrometer (CPT) results were used to examine the success of various empirical liquefaction models in predicting the 1901 observations. However, without a precise magnitude and epicentre it is difficult to say that any model performs better than others. The test results do, however, confirm that the liquefaction hazard in northeast Kaiapoi is significant.

Kaiapoi, with a population of about 7000, is situated on the Kaiapoi River, near the north eastern end of the Canterbury Plains, about 20 km north of the city of Christchurch (Figure 1). The plains themselves are formed by large coalescing alluvial fans extending some 50 km from the Southern Alps to the west. At Kaiapoi, 300-400 m of late Pleistocene sand and gravel overlies early Pleistocene, Tertiary and Cretaceous rock, that in turn overlies greywacke basement rock at a depth of more than 2 km. Sea level fluctuations during glacial periods have led to interbedded marine and terrestrial sediments in the upper one hundred metres or so (Brown & Weeber, 1992).

As seen from Figures 1 and 2, the dominant, present-day feature of the Kaiapoi area is the Waimakariri River. Before 1868, the Waimakariri River comprised two principal branches: a north branch flowing in the channel of the present Kaiapoi River, and a south branch flowing in the now abandoned channel seen in Figure 2 running northeast from the lower left hand side of the photograph, to meet the north branch at the bend in the Kaiapoi River near the centre of the photograph at the foot of Charles Street (Reid et al, 1982). From 1868, the Waimakariri River near Kaiapoi has followed its present course in a cut channel constrained by stopbanks. Prior to 1868, the Waimakariri was free to meander, and several old meander loops are seen in Figure 2. In particular, the semicircular feature to the north of the Kaiapoi River near the centre of the photograph marks a large, recent meander in which loose silt and sands would have been deposited. Furthermore, the site is behind the present dune system, and the very loose, silty nature of the surficial soils found in the investigation suggests that they may be esturine in origin.

In the 150 years since the beginning of European settlement, eight earthquakes, listed in Table 1, have reached intensities of MM 7 or greater in Christchurch (Dibble et al, 1980). Newspapers and City Council records from around the time of these earthquakes were searched for reports of liquefaction in the North Canterbury region, especially in Christchurch itself. Apart from damage to sewers in two locations (the East Belt sewer of St Asaph St and the Ferry Road sewer at its outlet) in the 1888 Amuri earthquake, no report of liquefaction damage in the Christchurch urban area could be found.

The clearest report of liquefaction in the historical earthquakes comes from Kaiapoi in the 1901 Cheviot earthquake. There are also reports of apparently minor occurrences of liquefaction at Waikuku and Leithfield beaches in the 1922 earthquake (Dibble et al, 1980).

OBSERVATIONS IN 1901

From newspaper reports, it is clear that liquefaction occurred over an area of about two or three, town blocks at the eastern end of Sewell and Charles Streets on the north bank of the Kaiapoi River (Figures 2, 4). The area affected probably extended east to the Waimakariri River. A vivid report of ground effects observed here is found on page 6 of the Christchurch newspaper, "The Press", of November 18, 1901. Ejection of sand, lateral spreading and ground settlement are described. The passage reads:

"REMARKABLE FISSURES IN THE EARTH"

"At Kaiapoi, when the shock had passed, Mr W. Waites, who owns an orchard and garden at the end of Charles and Sewell Streets, noticed that his land was apparently flooding from springs having been opened. It was then discovered that across his land, and part of Mr Dunn's section, and over the surface of a paddock of several acres held by Mr J. Sims, fissures from 1in to 3in in width, and several chains in length, had opened. These extended across Sewell Street, and affected an embankment. From these earthquake openings the water was freely issuing in such volume as to cause apprehensions of a probable inundation. Fortunately the rapid exudation of water seemed to be checked by a liberal supply of sand from a grey quicksand layer below the level of the river, and this was deposited in the orchard and elsewhere in the shape of round and oval porridge pots and little hills. The water, which had risen about six inches in an hour or two, disappeared by percolation, leaving the sand deposits in fantastic forms.

The fissures remained open, and could be probed to a depth of six feet. On Mr Waites' section the artesian well pipe had been raised a foot out of the ground, and the elevation of part of his land he maintains has been raised to a higher level. The flow of an artesian well, 200ft in depth, was increased, while the flows of three other tube wells to the first strata were entirely suspended. Wells in other parts of Kaiapoi also went dry. Upon Mr W.J. Dunn's land an upheaval was also noticed; and Mr Dunn's pump and tube well in the wash-house was raised bodily 4 inches.

Similar openings were subsequently found further to the eastward. The direction of the fissures was S.W. and N.E., and some of them in two hours were observed to visibly close. The widest was in Mr Waites' garden, and as it intercepted a water-race the water disappeared into the ground.

On the opposite side of the Waimakariri to Mr Waites' land a crack is traceable out of the river 2ft in width on to the river bed at the end of Mr James Holland's farm, where one of the fissures is 9in wide, and has, like many smaller cracks of the earth, been filled with quicksand blowing up, as in the other cases referred to. Mr J. Holland. jun., followed up the fissures on the south side of the river for several chains, until they disappeared with the loose earth and sand. In continuation of the cracks referred to, a similar one was traced across the North road near Belfast. The rents referred to seemed to be within a comparatively narrow strip, about half a chain wide. But for the quicksand from several feet below the surface blowing up into the *rents they would have remained open. A rod several feet long was inserted in the sand, but was not long enough to test the exact depth of the ooze, though it is surmised to have come up from 20ft to 25ft. Some persons were inclined to believe the springs might be of a thermal character, but they had only a smell of swamp gas, and not the least trace of sodium to give them any virtue. Crowds visited the places indicated on Saturday (16/11/01) and yesterday, but the neatly formed mounds of sand thrown up had been disfigured by children on Saturday. Numbers of samples of the sand were taken away."*

This is ample evidence that liquefaction had occurred in the Charles Street, Sewell street area.

An aerial photograph (Figure 2) taken in 1941 shows Charles St ending at Jollie St, but Sewell St continuing east to the present-day Commercial St (see Street Map in Figure 4). Mr Waites himself and his market garden are well remembered by elderly Kaiapoi residents. His house, at 14 Beswick St, is marked on the photo in Figure 3. It is thought that in 1901 his gardens and orchards occupied the block of his house, bounded by Cass, Sewell, Beswick and Jollie Streets and the block diagonally southeast, running east from Jollie St, between Sewell and Charles Streets. We have been unable to pinpoint the Sims and Dunn properties referred to in the newspaper report.

SOIL INVESTIGATIONS, 1986-1989

Since the aerial photograph shown in Figure 2 was taken in 1941, Kaiapoi has grown to the north east. One of the few vacant blocks of land in the original Waites market garden was found at 125 Sewell St, east of Jollie St. Cone penetrometer probes (CPTU), using both Parez and Fugro piezecones, were carried out at this site and at three other sites east of Williams St and north of the Kaiapoi River (Figure 4).

The first tests were made at the Sewell St site in 1986, using the 45 mm Parez cone, as part of a broad study of South Island liquefaction sites (Ooi, 1987). They showed a layer of loose sand ($q_c \leq 5$ MPa, $R_f \leq 0.5\%$) between 2 to 6 m with a high liquefaction potential. In 1988, a Fugro piezocone was used to investigate three other sites along the north bank of Kaiapoi River to gauge the extent of the liquefiable soils (Mulqueen, 1989). Further CPTU probes with both cones were carried out in 1989 principally to test different filter positions and de-airing techniques for the pore pressure transducer. Rotary borings were made at the two Charles St sites in order to carry out standard penetration tests (SPTs) and to retrieve samples.

Table 2 lists the piezocone tests carried out, together with details of the cone configurations. None of the tests was perfect. In general, the points performed well on both cones, and the q_c plots are reliable. However, the load cell on the sleeve of the Parez cone was faulty, so no friction ratio traces are shown in its results. However, it has a very sensitive pore pressure transducer, and its pore pressure system is easy to saturate. Hence, it yielded good pore pressure traces. On the other hand, while the Fugro cone gave reliable cone and sleeve results, its pore pressure measurement system was more difficult to saturate, and pore pressure measurements taken at Kaiapoi from this cone are unreliable in all but very permeable soils. Logs of the individual probes are presented in Appendix A.

125 Sewell Street

Figure 5 shows the results of the four tests at 125 Sewell St (Figure 4) plotted together. Unreliable friction ratio traces from the Parez cone and some pore pressure traces from the Fugro cone have been omitted. The probes start below the water table in pre-bored holes, to maintain saturation of the pore pressure transducer system.

The composite plot shows three broad strata: a layer of sandy silt to a depth of around 1.8 m; loose silty sand from about 1.8 m to 3.5 m; medium dense silty sand from 3.5 m down to a much denser cohesionless material at around 6.5 to 7 m. In the absence of drillhole samples, the chart of Robertson, Campanella and Wightman (1983) has been used to infer these soil classifications. Within these layers, there are fluctuations in q_c, probably reflecting sublayers; but the fairly uniform and small value of R_f indicates that the material is predominantly cohesionless.

Using the criterion of Zhou (1980), the liquefaction threshold value of q_c has been plotted for the MM 7 intensity of ground shaking observed at Kaiapoi in 1901. We see that according to this criterion, almost the entire profile is expected to liquify, especially the loose layers above 3.5 m. This is consistent with the ground cracking and ejection of sand that was observed in 1901, though, to some extent, this argument may be circular since the occurrence of liquefaction would be one of the main indicators used by Dibble et al. (1980) in assigning the value of MM 7.

Threshold values of q_c from the model of Davis and Berrill (1983) are also plotted in Figure 5 for various combination of magnitude and epicentral distance. The lowest threshold curve (M6.5 at 95 km) corresponds to the revised magnitude and epicentre of Dibble et al. (1980); the next lowest curve (M6.75 at 77 km) corresponds to the original epicentre and mean magnitude assigned by the Seismological Observatory and listed in Table 1.

Under these conditions, the Davis and Berrill model does not predict liquefaction at the site, suggesting that either the model is somewhat unconservative, or that both sets or seismological parameters are incorrect. Taking the upper end of the Observatory's magnitude estimate, M = 7.5, and their epicentre (at 77 km) liquefaction is predicted in the loose cohesionless layer between 1.8 and 2.0 m and, marginally between 2.5 and 3.4 m.

This contrasts with the Zhou model, which for the MM intensity of VII, assigned by Dibble et al. (1980), predicts liquefaction throughout most of the profile. However, if we take the Seismological Observatory's estimate of MM intensity at Kaiapoi, MM 6, then no liquefaction is predicted. Indeed, the principal evidence used by Dibble et al. in assigning an intensity of VII at Kaiapoi was the occurrence of liquefaction. Furthermore, this illustrates the coarse nature of the intensity scale, and emphasises the danger of placing to much credence in individual values. The strength of the MM intensity scale is in bringing out regional trends.

A further piece of information can be obtained from the criterion of Kuribayashi and Tatsuoka (1975) for distance to the farthest site of liquefaction. This criterion requires magnitudes 7.1 and 7.25 for liquefaction at the loosest of sites at distances of 77 and 95 km respectively. This result suggests that the magnitude was greater than 7 and casts doubt on the revised epicentre estimate of Dibble et al. but lends support to the more recent revision of $M_s = 6.9 \pm 0.2$ of Dowrick and Smith (1990).

With this in mind, the "M7.5 at 77 km" curve is probably the most appropriate one from amongst the Davis and Berrill set plotted in Figure 5. Thus we can conclude that the results of this model are consistent with liquefaction at Sewell St; but given the uncertainties as to magnitude and epicentre, it is impossible to say more. Similar remarks can be made about the Zhou model. Furthermore, the sensitivity of the models to changes in seismological parameters emphasises the need for a large set of case histories to check or calibrate such models, and highlights the limitations of case studies where adequate seismological data is lacking.

19 Cass Street

A second set of piezocone probes was carried out at 19 Cass St, near the intersection of Cass and Williams Streets, about 800 m northwest of the Sewell St site. This site was chosen to have a better geographical coverage of soil conditions in NE Kaiapoi rather than because of any report of liquefaction at the site. We could find no report, to confirm or deny liquefaction at this site in 1901. The probes were made in two clusters on this section, about 20 m apart, as shown in Figure 6. We will focus on the southern group of 7 probes, numbers 9 to 15. Results from these tests are plotted together in Figure 7; the individual logs are given in Appendix A.

The seven probes of the southern group cover an area of ground roughly 10 m in diameter and represent trials with the two different cones, with different filter positions for the pore pressure transducer and different de-airing techniques in the case of the Fugro cone.

The marked differences between the various pore pressure traces indicate the importance of good de-airing and of a standard filter position, as well as reflecting inhomogeneities in the soil itself. The q_c traces are generally similar, and variations between probes are most probably due to variations in soil properties. A similar remark applies to the R_f traces.

The low friction ratio, R_f, indicates a cohesionless material throughout, again with three broad strata: a silty sand of variable density to about 3.5 m; a more uniform loose silty sand from 3.5 to near 6 m; a more dense, cleaner sand below about 5.5 to 6 m.

The cone resistance of the silty sand stratum between 3.5 and 6 m falls below the critical value of Zhou for the 1901 MM 7 intensity of shaking, and it is probable that liquefaction occurred beneath this site, too, though because of its greater distance from the river, marked lateral spreading cracks may not have appeared. Figure 7 shows the threshold values of q_c according to the Davis and Berrill model. Again, liquefaction in the 3.5 to 5.5 m stratum appears possible.

River Bank Reserve, Charles Street No 1 Site

Results from a set of three probes carried out on the River Bank Reserve opposite 114 Charles St are shown in Figure 8. A detailed location plan is given in Figure 9. Both Charles St sites have been filled and regraded from their original condition. This should have increased their liquefaction resistance from their 1901 state, through an increase in overburden stress, and through consolidation.

A rotary boring with standard penetration tests (SPT) was carried out at this site. The log, BH 1, is reproduced in Figure 10. The piezocone results are generally consistent with those from the boring. For example, the transition at about 2.6 m from *loose silty fine sand* to *grey fine sand* occurs within the range of the first SPT starting at 2.4 m. This recorded 400 mm of set for a seating blow, followed respectively by 2 and 4 blows per 150 mm. This corresponds to the marked reduction in friction ratio that we see at 2.5 m in the piezocone probe plots, together with a steady increase in q_c.

At this site, the most likely candidate for liquefaction is the layer of loose fine sand from 2.5 to about 3.3 m. Its q_c value falls well below Zhou's criteria shown by the dotted line in Figure 8. The Davis and Berrill criteria shown in Figure 8 also favour liquefaction in this layer, and perhaps also around 4.0 m.

River Bank Reserve, Charles Street No 2 Site

One Fugro piezocone probe, Figure 11, and one rotary boring, Figure 12, were carried out on the river bank reserve to the south of the road, opposite number 126 Charles Street.

Here, the loose fine sand layer between about 3 and 4.5 m is a candidate for liquefaction in MM 7 shaking, together with thinner layers around 5.5 m, 7.5 m and 9.0 m. The Davis and Berrill model, with M7.5 at 77 km, indicates that the present profile would be just on the brink of liquefying at 3.5 to 4.0 m and no more. With less overburden, the likelihood of liquefaction would be greater.

CPT-SPT RELATIONSHIP

Since the CPT test is becoming more common, yet many design procedures in geotechnical engineering are based on SPT N values, the relationship between CPT cone resistance q_c and SPT N is of great interest. An old rule of thumb states that q_c in bars equals 4N, in blows per 300 mm (1 bar ≈ 100 kPa). This relationship was refined by Robertson and Campanella (1985) who found that it depended on grain size. They proposed the relationship shown in Figure 13, where q_c/N is plotted as a function of mean grain size, D_{50}.

To check this relationship, we have plotted two results from Kaiapoi on Figure 13, together with several results obtained by Bienvenu (1988) at Buller sites. Only two points could be plotted for the Kaiapoi tests since it was only in two cases that sufficient material was recovered in the split-spoon sampler of the SPT for sieve analysis. The points plot around Robertson and Campanella's mean curve, but show somewhat more scatter than did their data points. Yet all the SPT tests were carried out very carefully, with Gemco trip hammers, by experienced drillers, in carefully advanced holes. At Kaiapoi, cased holes with bentonite drilling mud were employed, while in the Buller, hollow-stemmed augers were used. The augers were drilled in with the bottom plug removed. A head of water at or above ground level was maintained in the augers and the central tube cleared by bailing before each SPT test. Both techniques are common in New Zealand.

The results shown in Figure 13 generally support the Robertson and Campanella (and the $q_c/N = 4$) rule. But the large amount of scatter indicates that the relationship is not very precise, at least in the very loose, fine sand found at all of these sites. From these results there seems to be little advantage in using the Robertson and Campanella relationship rather than simpler $q_c/N = 4$ rule.

CONCLUSIONS

There is clear historical evidence for the occurrence of liquefaction in the north east section of Kaiapoi during the 1901 Cheviot earthquake. Piezocone probing and rotary boring was carried out at four sites east of Williams Street and adjacent to the north bank of the Kaiapoi river. Loose, silty fine sands with cone resistances ranging from 2 to 5 MPa were found at all four sites. While it was not possible to pinpoint the 1901 sites precisely, the Sewell Street test site was almost certainly very close to, if not within, the Waites Market garden referred to in the 1901 newspaper reports and which was the principal site of liquefaction. The Sewell Street site was indeed the loosest of the four test sites, with cone resistances of about 2 to 3 MPa throughout a layer extending from about 2 m down to a depth of about 6 m, where denser coarse sands and fine gravels were encountered.

It is difficult to test liquefaction models against these results because precise seismological parameters for the earthquake are lacking. However, all four sites would liquefy according to the model of Zhou (1980) under the Modified Mercalli intensity of MM7 assigned by Dibble et al. (1980). This does not provide unequivocal support for the Zhou model, however, since the reports of liquefaction were themselves used in assigning the intensity value. Dibble et al. estimated a magnitude of 6.5 at an epicentre about 95 km north of Kaiapoi. This epicentre is inconsistent with the formula of Kuribayashi and Tatsuoka (1975) for distance to the farthest site of liquefaction. Furthermore, with the Dibble et al. earthquake parameters the model of Davis and Berrill predicts that none of the test sites should liquefy under these conditions. The earlier estimates by the Seismological Observatory, however, give a magnitude in the range 6 to 7.5 with a closer epicentre, at about 77 km. With M7.5 at 77 km, the Davis and Berrill model predicts liquefaction through most of the 2 to 6 m layer at Sewell Street; at the other three sites, it predicts that thin isolated layers may liquefy. These observations lend some weight to the Seismological Observatory's epicentre, with a magnitude near the upper end of the 6-7.5 range.

Even though it is not possible to make precise checks on prediction models with test, on these results, they do establish that there is a significant liquefaction hazard in this part of Kaiapoi. They also give us a set of sites with potentially liquefiable soils, of known properties spanning a range of densities, that can be checked following future earthquakes. At the two Charles Street sites at least, retesting to look for any modification of soil properties should be possible.

Finally, the scatter in the detailed features of the several tests made at three of the sites should be of interest to geotechnical engineers, and warn against assuming that results from one or two probes or borings are exactly representative of even quite small sites.

REFERENCES

Bienvenu, V C (1988). "Studies of Liquefaction in the 1929 Murchison and 1968 Inangahua, New Zealand Earthquakes", *ME Thesis*, University of Canterbury. 161 pp.

Brown, L J and J H Webber (1992). *Geology of the Christchurch Urban Area*, Institute of Geological and Nuclear Sciences, Lower Hutt, NZ. 104 pp.

Davis, R O and J B Berrill (1982). "Energy Dissipation and Seismic Liquefaction in Sands", *Intl. J. Earthq. Eng. and Struct. Dyn.*, Vol. 10, pp 59-68.

Dibble, R R, J H Ansell, J B Berrill, (1980). "Report on a study of seismic risk for BP (NZ) Ltd sites at Woolston and Heathcote". *Unpublished report to BP (NZ) Ltd.*

Dowrick, D J and EGC Smith (1990). "Surface Wave Magnitudes of Some New Zealand Earthquakes 1901-1988". *Bull. NZ. Nat. Soc. Earthq. Eng.*, Vol. 23, pp 198-210.

Fairless, G J and J B Berrill (1984). "Liquefaction during Historic Earthquakes in New Zealand", *Bull. NZ. Nat. Soc. Earthq. Eng.*, Vol. 17, pp 280-291.

Kuribayashi, E and F Tatsuoka (1975). "Brief Review of Liquefaction during Earthquakes in Japan", *Soils and Found.*, Vol. 15, pp 81-92.

McKay, A (1902). *Report on the recent seismic disturbances within Cheviot County in North Canterbury and the Amuri district of Nelson, New Zealand (November and December 1901)*. Wellington, Government Printer. 88 pp.

Mulqueen, P C (1988). "Studies of Earthquake Induced Liquefaction at Kaiapoi New Zealand"), *Master of Engineering Report*, University of Canterbury, Christchurch NZ.

Ooi Edmund (1987). "Investigation of Liquefaction in the Buller Region", *Master of Engineering Report*, University of Canterbury, Christchurch NZ.

Robertson, P K and R G Campanella (1985) "Liquefaction potential of sands using the CPT", *J. Geotech. Eng., ASCE*, Vol. 111, pp 384-403.

Robertson, P K, R G Campanella and A Wightman (1983). "SPT-CPT Correlations", *Journal of the Geotechnical Engineering Division, ASCE*, Vol. 109, GT11, pp 1449-1459.

Reid, R E and R H Poynter (1982). "The Waimakariri River Improvement Scheme : 1982 Review", *Unpublished report*, North Canterbury Catchment Board, Christchurch, NZ.

Zhou, S (1980) "Evaluation of the liquefaction of sand by static cone penetration test", *Proc. 7th World Conf. Earthq. Eng.*, Istanbul, Vol. 3, pp 156-162.

TABLES

Table 1. Historial earthquakes producing an MM intensity of seven or more at Christchurch (from Dibble et al. 1980). Two sets of values are shown: those from the Seismological Observatory files, Wellington and those reassessed by Dibble et al. in 1980.

Earthquakes	**Seismological Observatory Files**			**Dibble et al.**		
	Epicent. dist. km	**MM at Christchurch**	**M_L**	**Epicent. dist. km**	**MM at Christchurch**	**M_L**
1869, 5 Jan	60	7-8	4.5-6	10	7-8	5.75
1870, 31 Aug	60	6	4.5-6	50	6-7	6.5
1881, 5 Dec	78	7-8	6-7.5	80	6-7	6.25
1888, 1 Sept	78	7-8	7	105	7	6.75
1901 16 Nov	**92**	**6**	**6-7.5**	**110**	**7**	**6.5**
1922, 25 Dec	66	6	6-7.5	66	7	6.75
1929, 9 Mar	125	6	6.9	125	6-7	6.9
1929, 17 Jun	195	6	7.7	195	7	7.7

Table 2. Piezocone Tests at Kaiapoi, 1986-1989

Site	Test No	Code	Date	Cone	Filter Position	WT (m)
125 Sewell St	1	KAI004	12 Nov 86	P	S	
	2	KAI010	12 Nov 86	P	S	0.89
	3	KAI005	15 Nov 88	F	S	1.2
	4	KAI005	16 Nov 88	F	S	1.12
Charles St, No 1 Site	5	KAI001	10 Nov 88	F	S	2.05
(Approx 30 m from	6	KAP005	8 Feb 89	P	S	2.02
kerb opposite 114 Charles Street)	7	KAP016	8 Feb 89	P	C	2.10
Charles St No 2 Site (opposite 126 Charles Street)	8	KAI002	10 Nov 88	F	S	2.0
19 Cass Street (near	9	KAI003	15 Nov 88	F	S	2.0
Williams Street)	10	KAP002	26 Jan 89	P	S	1.97
	11	KAP003	26 Jan 89	F	S	2.0
	12	KAP004	26 Jan 89	P	C	1.94
	13	KAI301	31 May 89	F	S	1.46
	14	KAI302	31 May 89	P	S	1.55
	15	KAI303	31 May 89	F	S**	1.45
	16	KAI004A	15 Nov 88	F	S	1.6
	17	KAP001	17 Jan 89	P	S?	1.65

* P = Parez cone S = filter on shoulder between cone and sleeve
F = Fugro cone C = filter on cone

** Coarse plastic filter

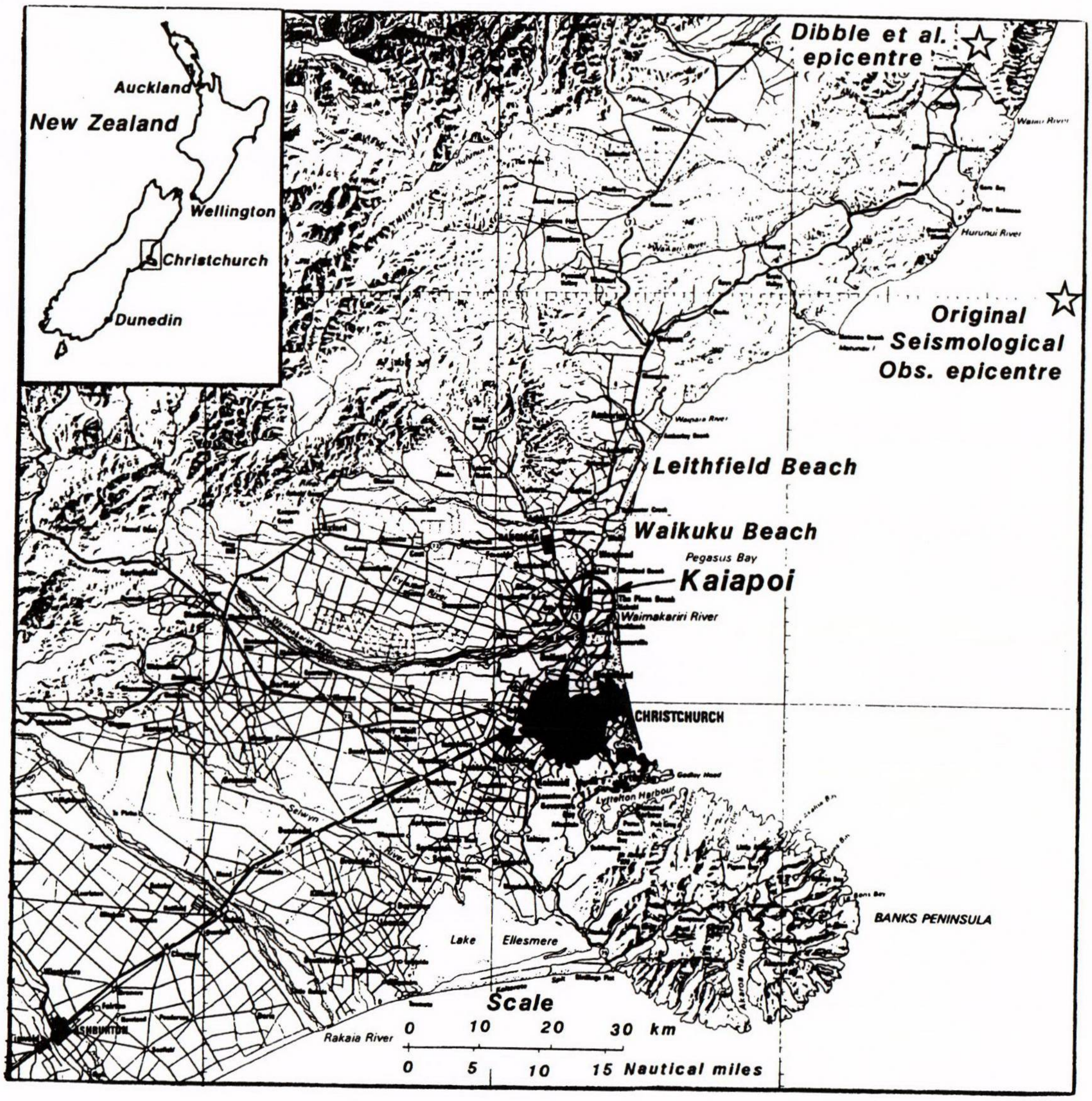


Figure 1 **The North Canterbury region of the South Island of New Zealand, showing the location of Kaiapoi and the 1901 earthquake epicentres.**

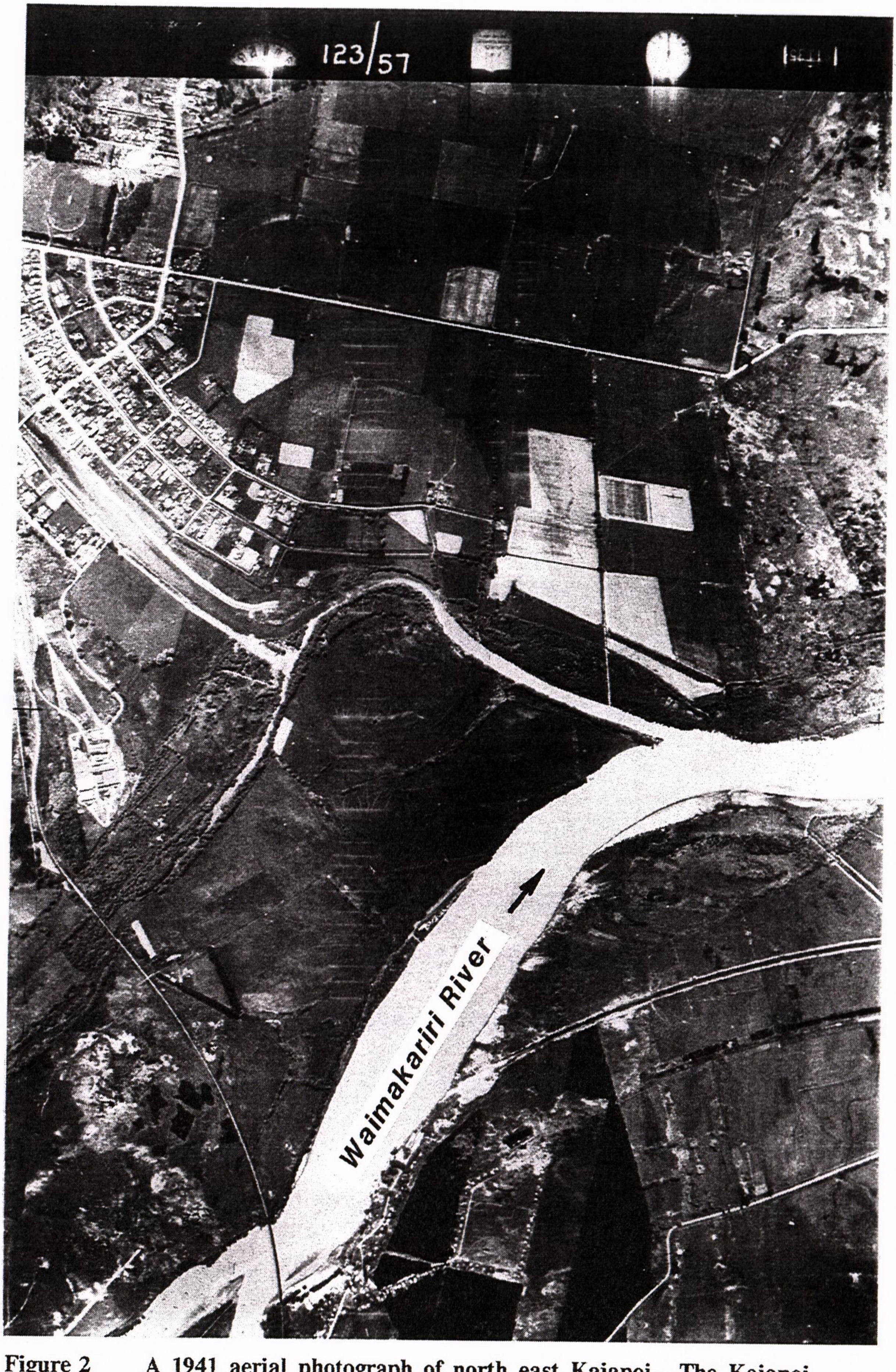


Figure 2 A 1941 aerial photograph of north east Kaiapoi. The Kaiapoi River flows into the Waimakariri River, seen in the lower right of the photograph. Note the semi-circular feature north of Cass Street near the centre of the photo, denoting a former meander loop of the Waimakariri. Several other, less prominent, meanders are seen in this photograph. (Photo: NZ Aerial Mapping)

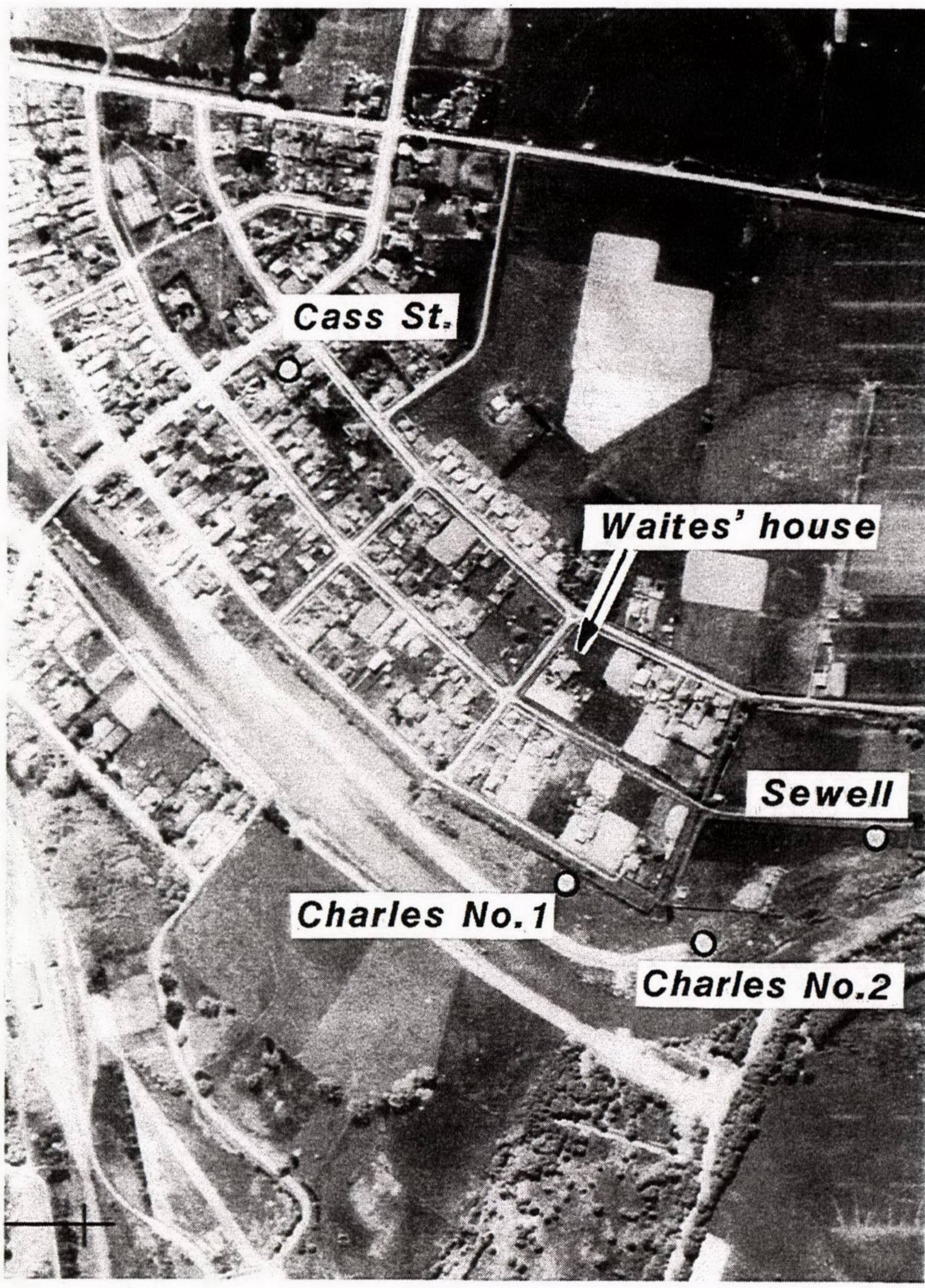


Figure 3 An enlargement of the area studied, from the 1941 photograph, showing Waites' house surrounded by part of his market garden, and the test sites.

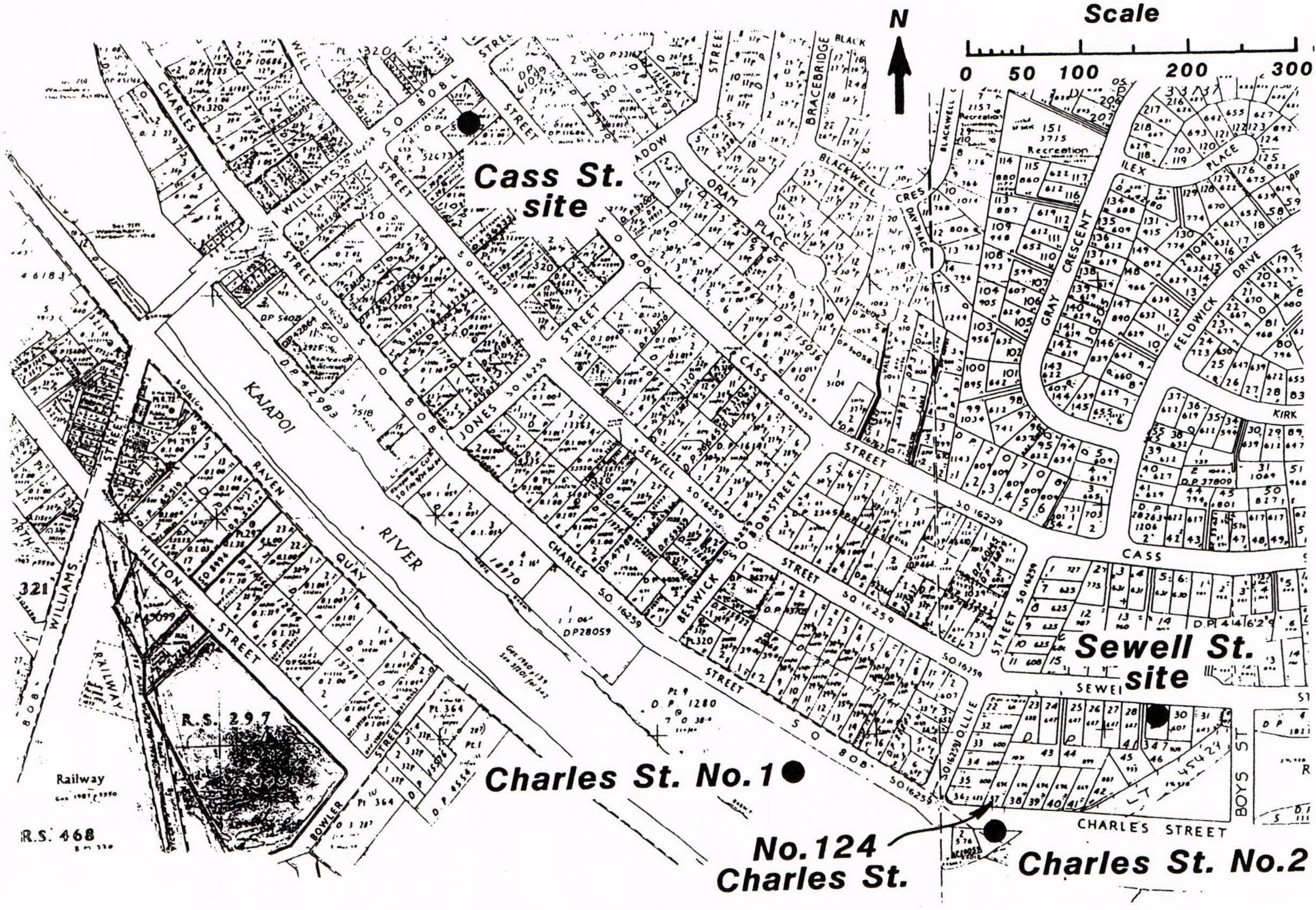


Figure 4 Street plan of Kaiapoi, showing the test sites.

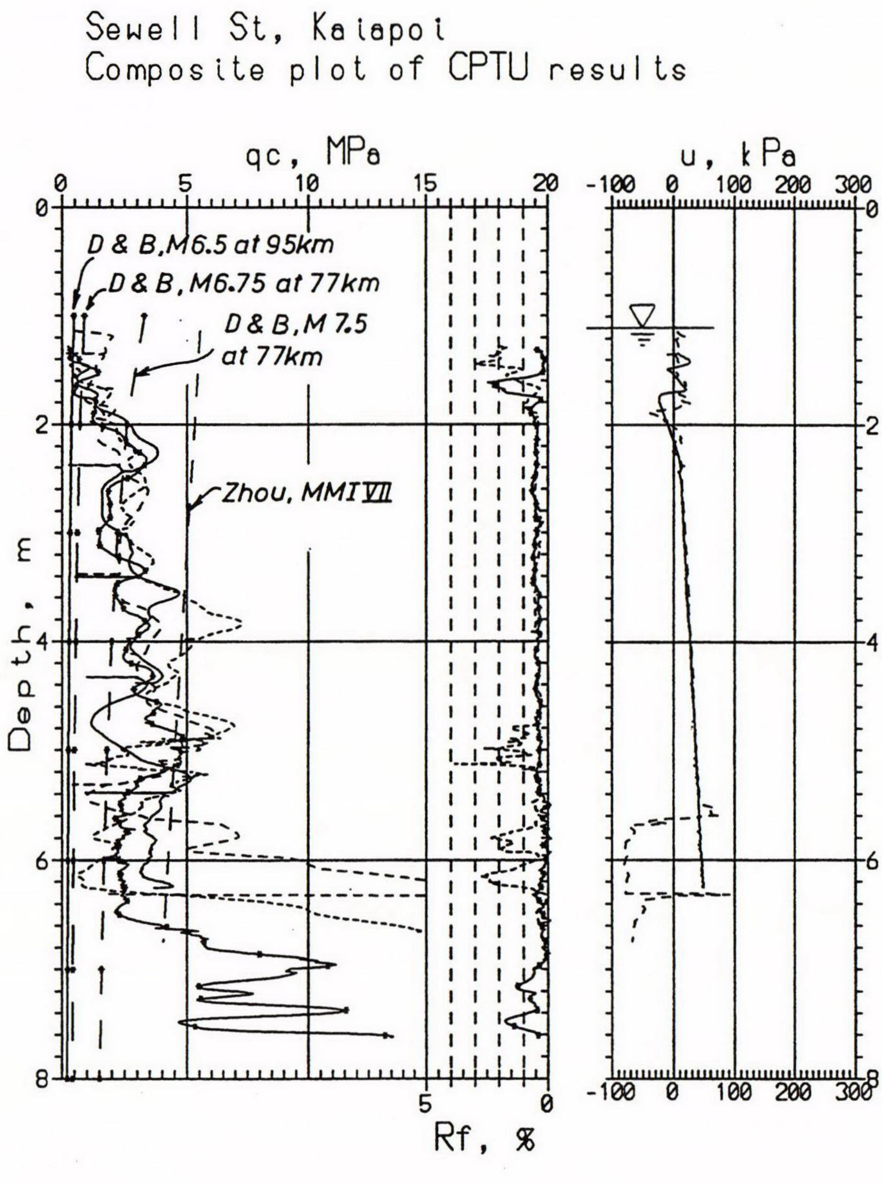


Figure 5 **Combined piezocone results for 125 Sewell St. together with threshold values of q_c from the Zhou (1980) and the Davis and Berrill (1983) model for various seismic parameters. The water table is assumed to be at 1.0 m in plotting the threshold curves.**

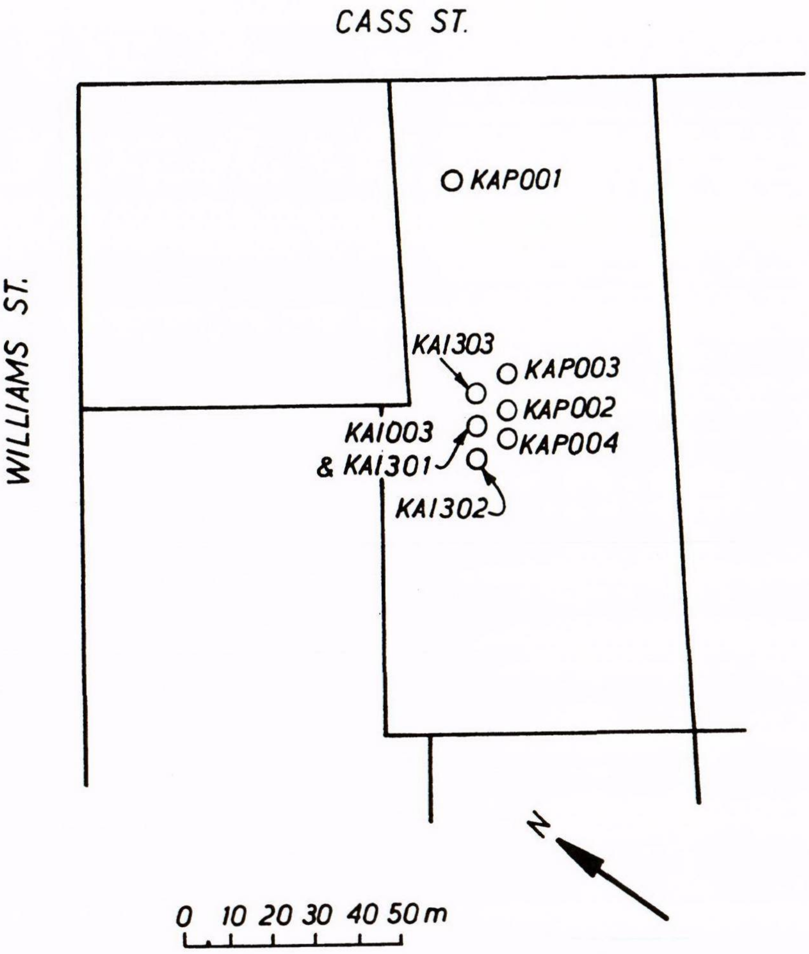


Figure 6 Probe positions, 19 Cass St.

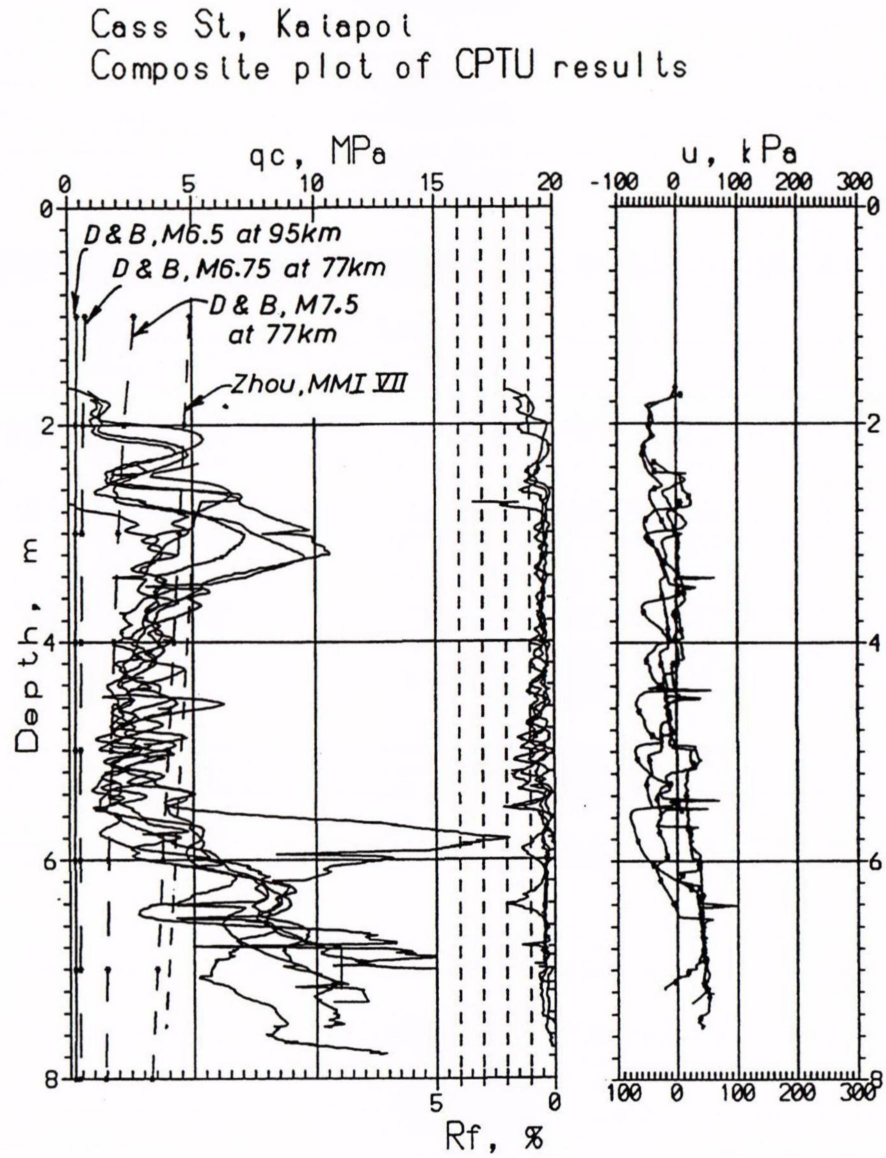


Figure 7 **Combined piezocone results for 19 Cass St. together with predicted threshold values. Water table assumed at 2.0 m.**

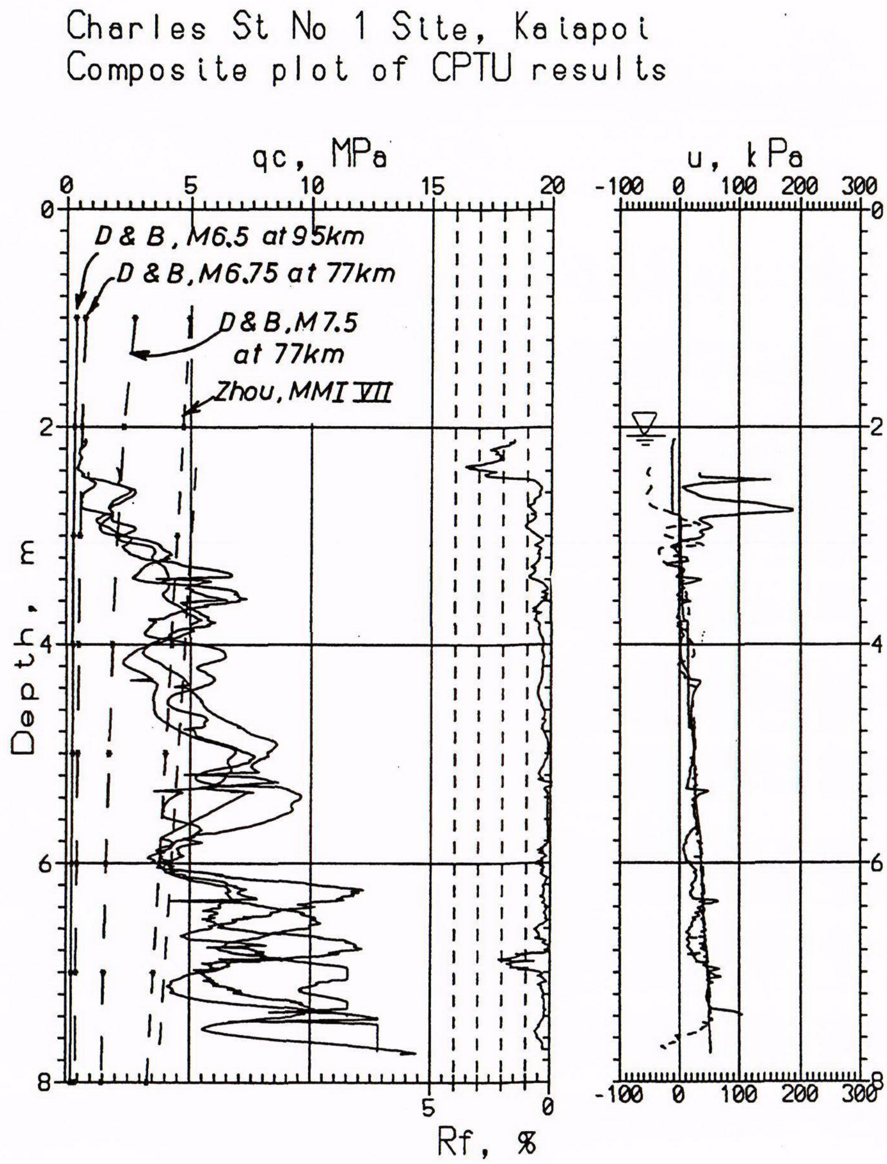


Figure 8 **Combined piezocone results for the Charles St No 1 site, opposite 114 Charles St. Watertable assumed at 2.0 m.**

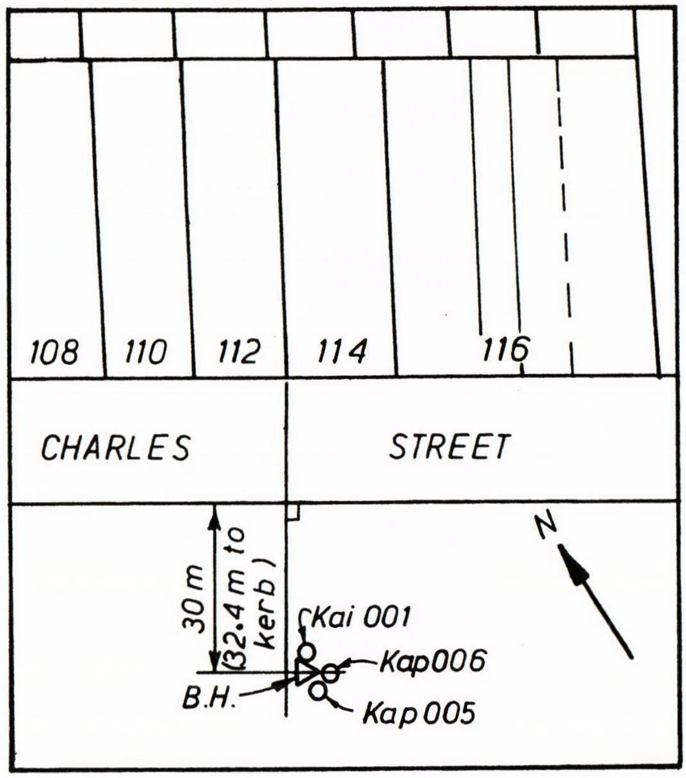


Figure 9 Site plan, Charles St No 1 site.

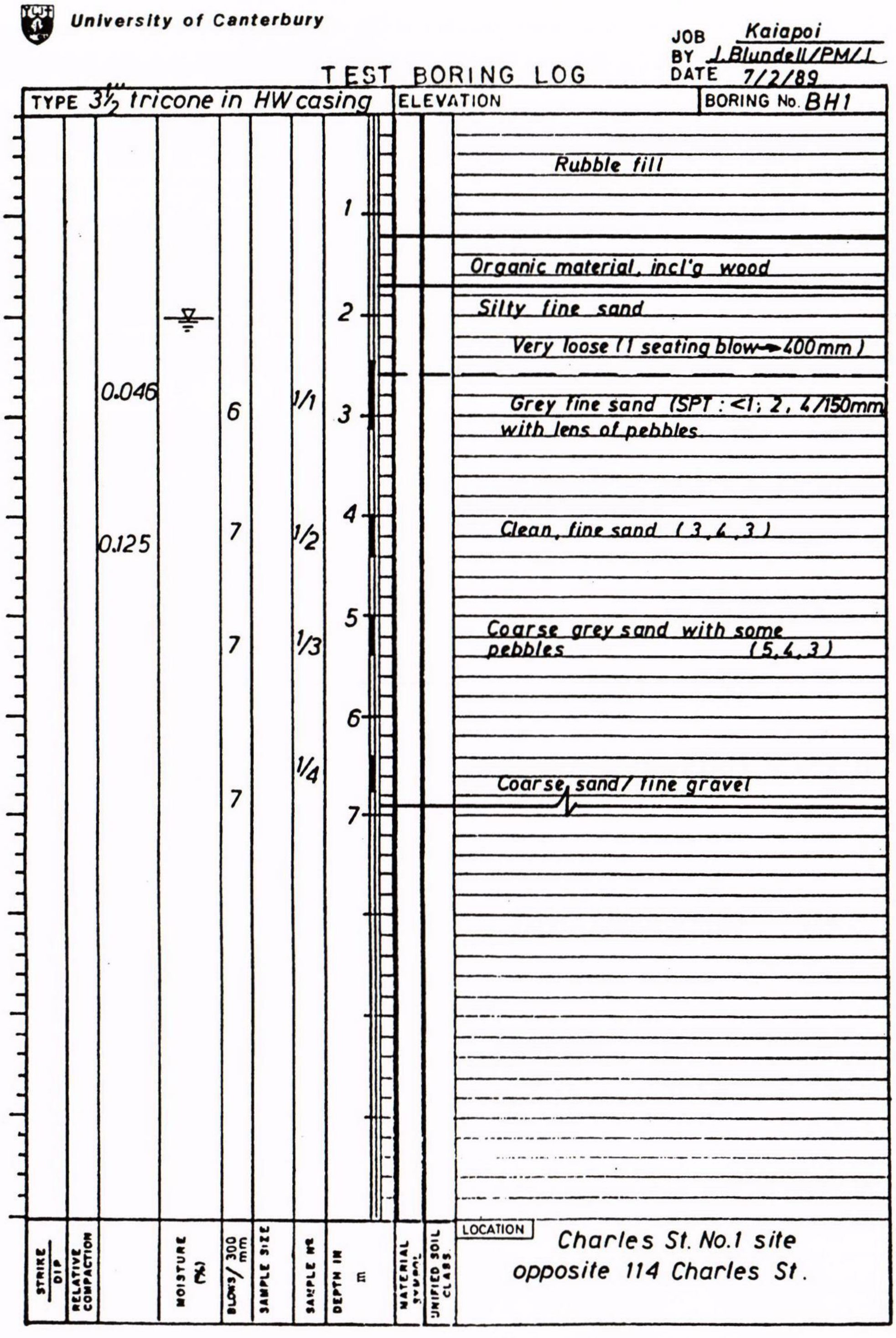


Figure 10 Log from rotary boring at Charles St No 1 site.

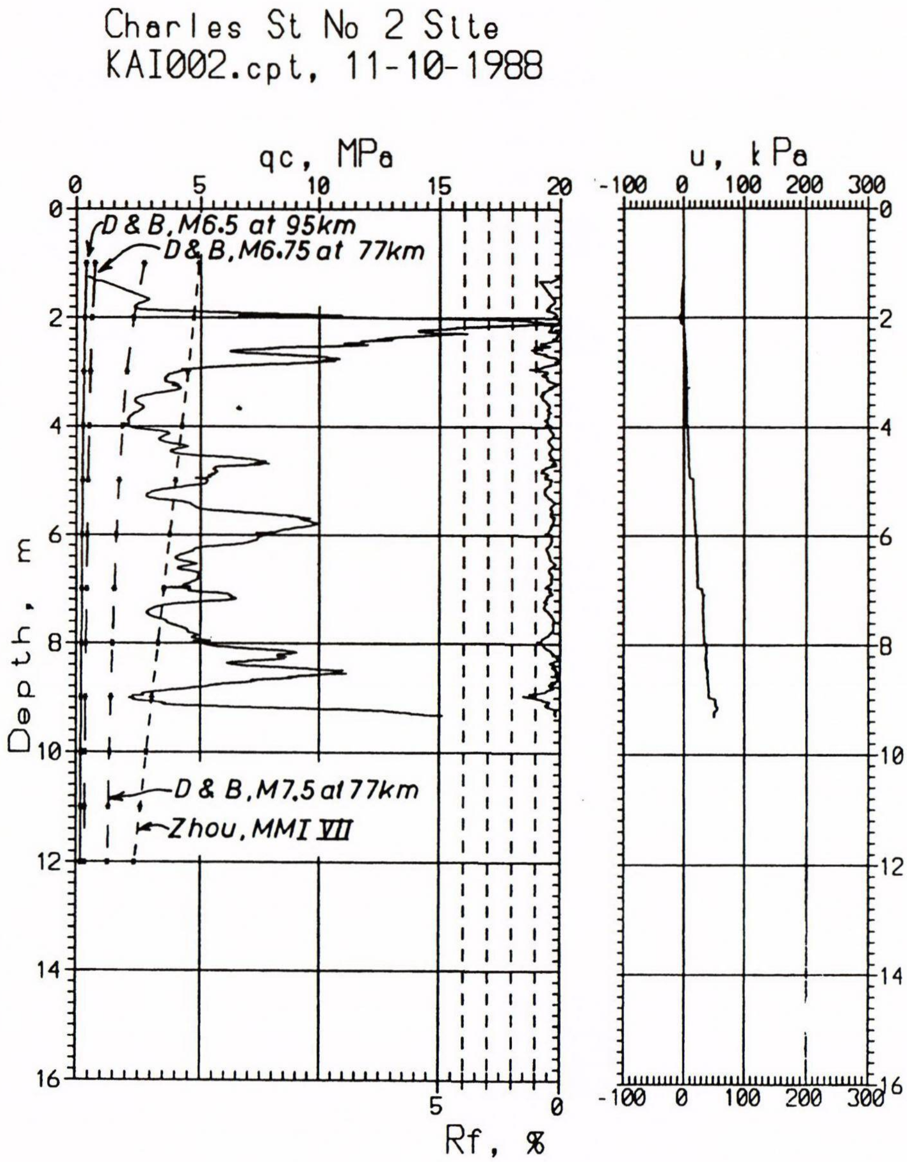


Figure 11 Piezocone results from Charles St No 2 site.

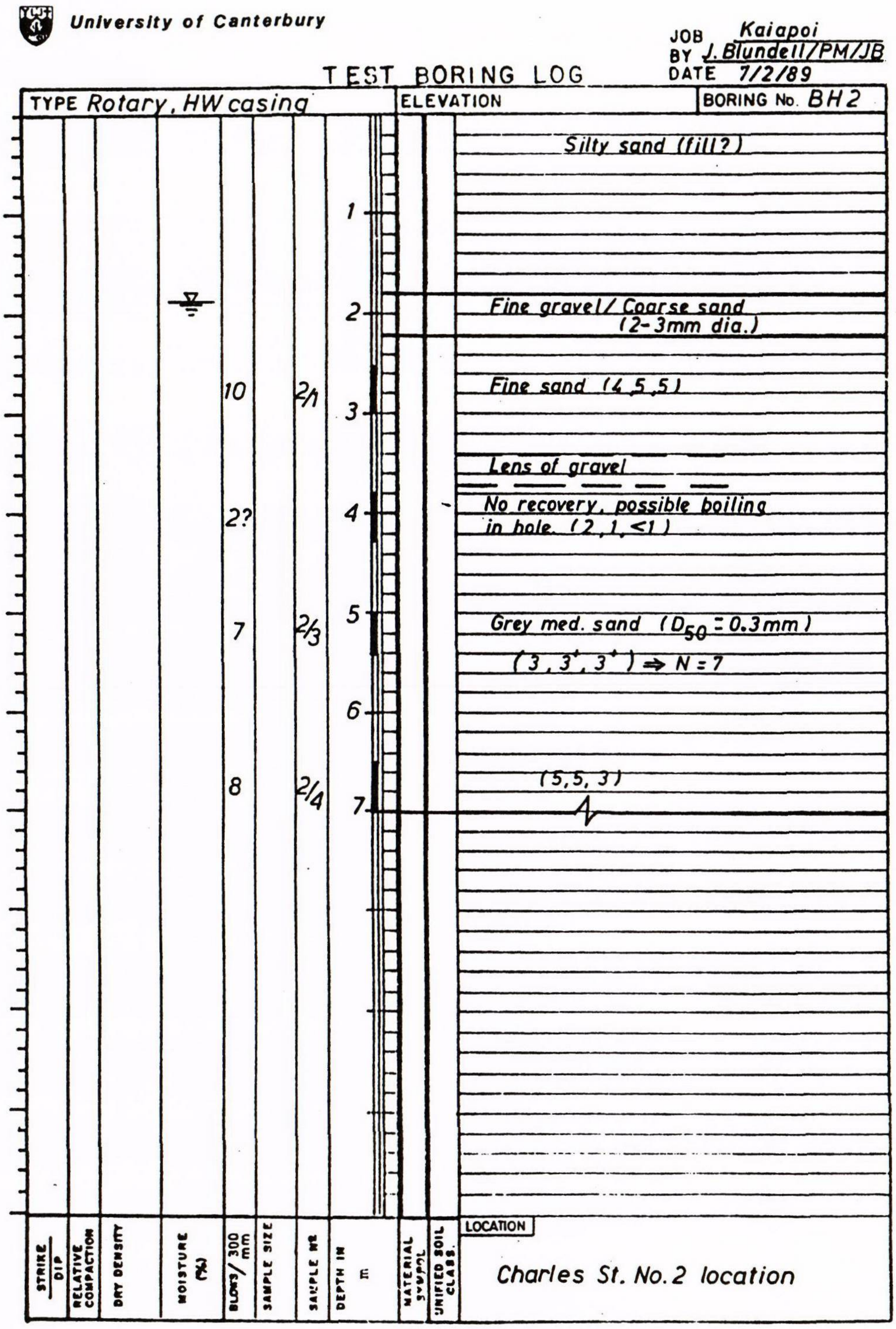


Figure 12 **Log from rotary boring at Charles St No 2 site.**

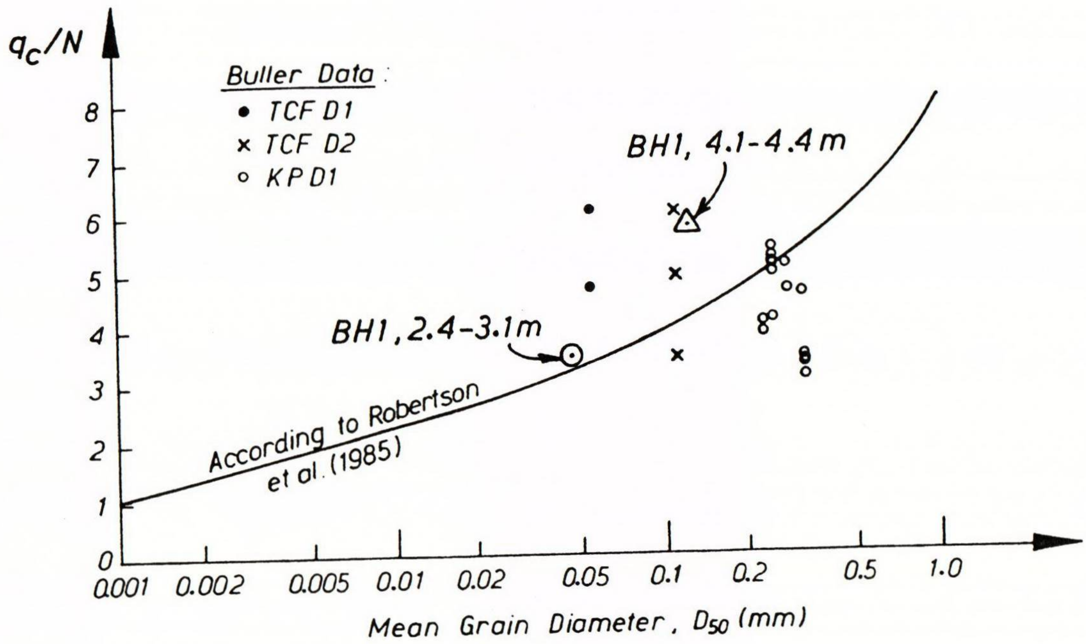
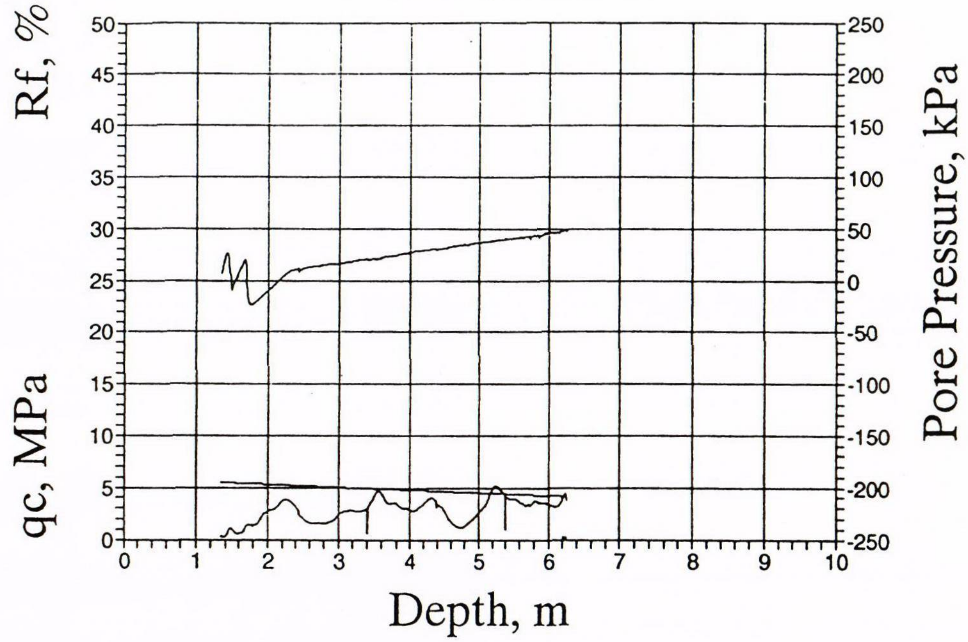


Figure 13 **Ratios q_c/N results from very loose silty sand strata at Kaiapoi and Buller sites, compared with Roberson and Campanella's (1985) curve.**

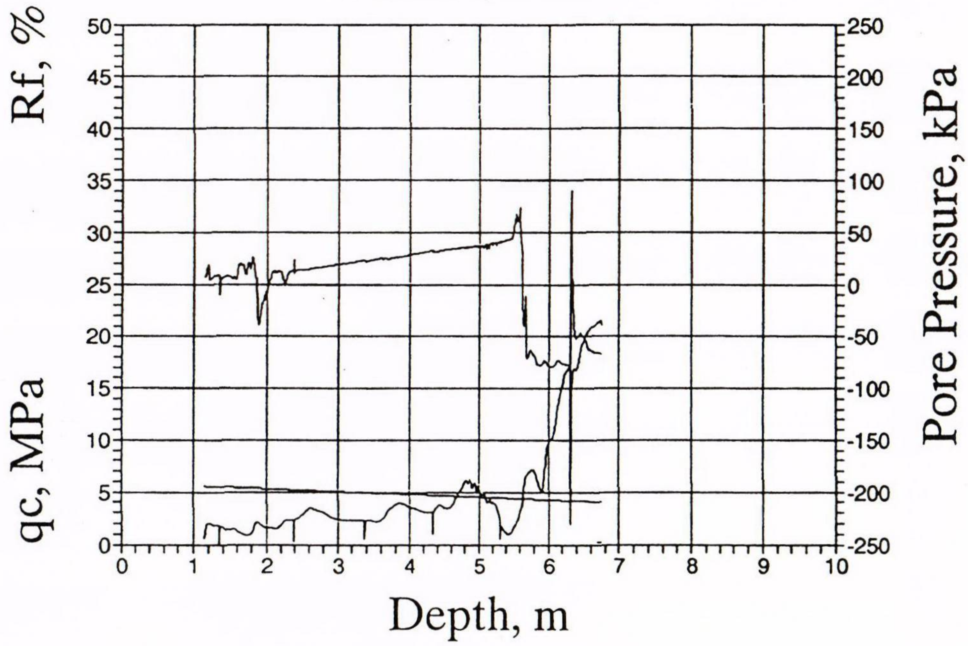
121-127 SEWELL ST, KAIAPOI

KAI004.PPT, 11-12-1986



125 SEWELL ST, KAIAPOI

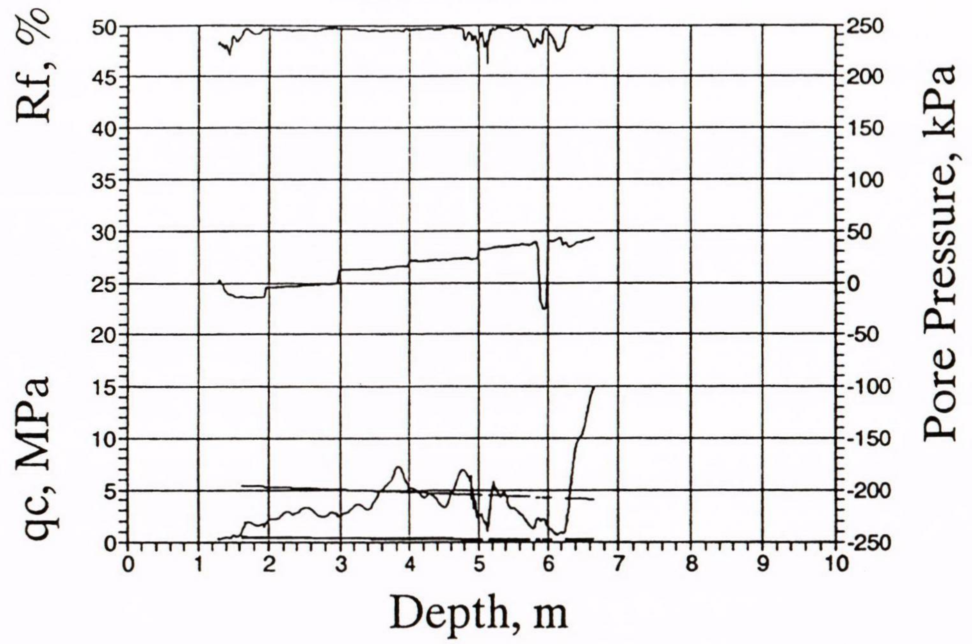
KAI010.PPT, 11-12-1986



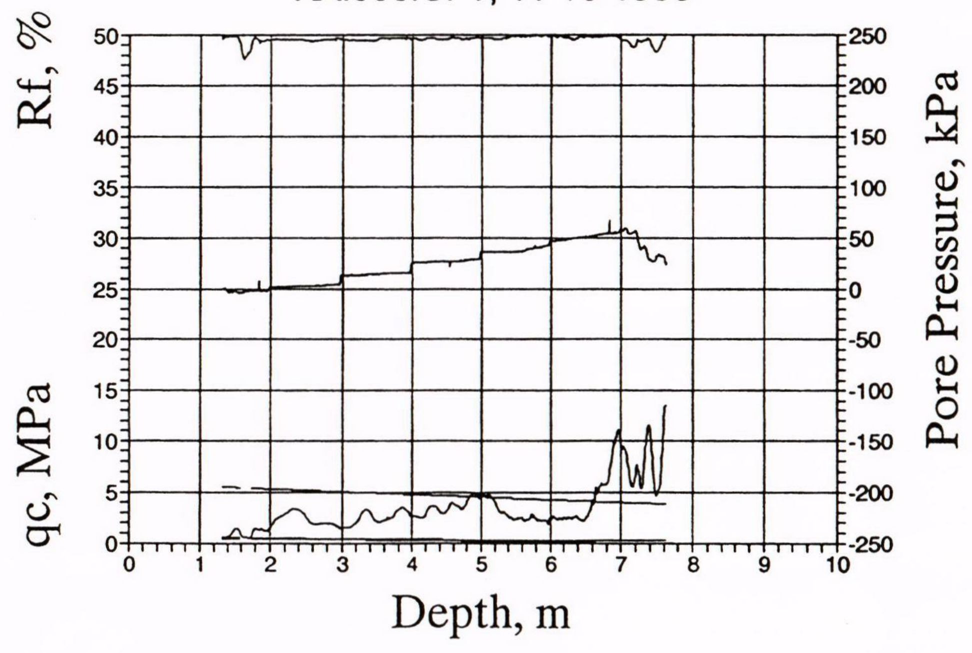
APPENDIX A

PENETROMETER AND PIEZOCONE LOGS

Sewell Street
KAI005.CPT, 11-15-1988

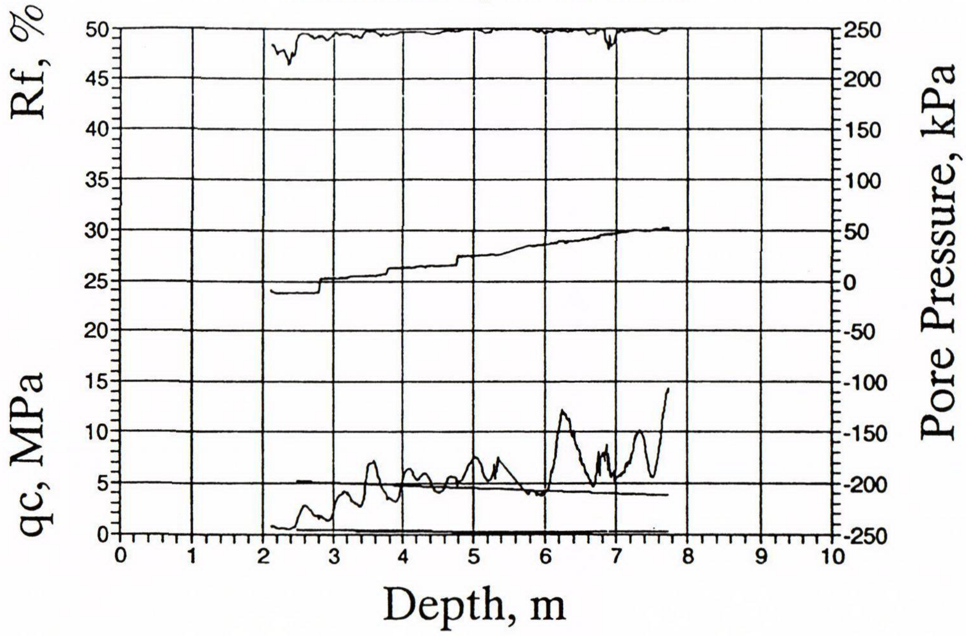


Sewell Street
KAI006.CPT, 11-16-1988



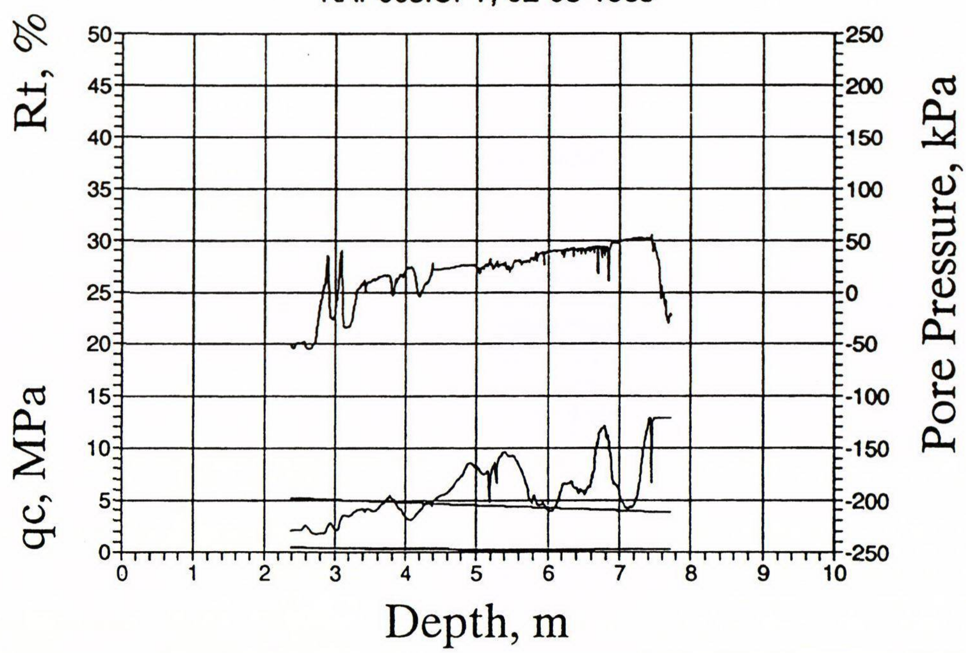
Kaiapoi River Bank Reserve

KAI001.CPT, 11-10-1988



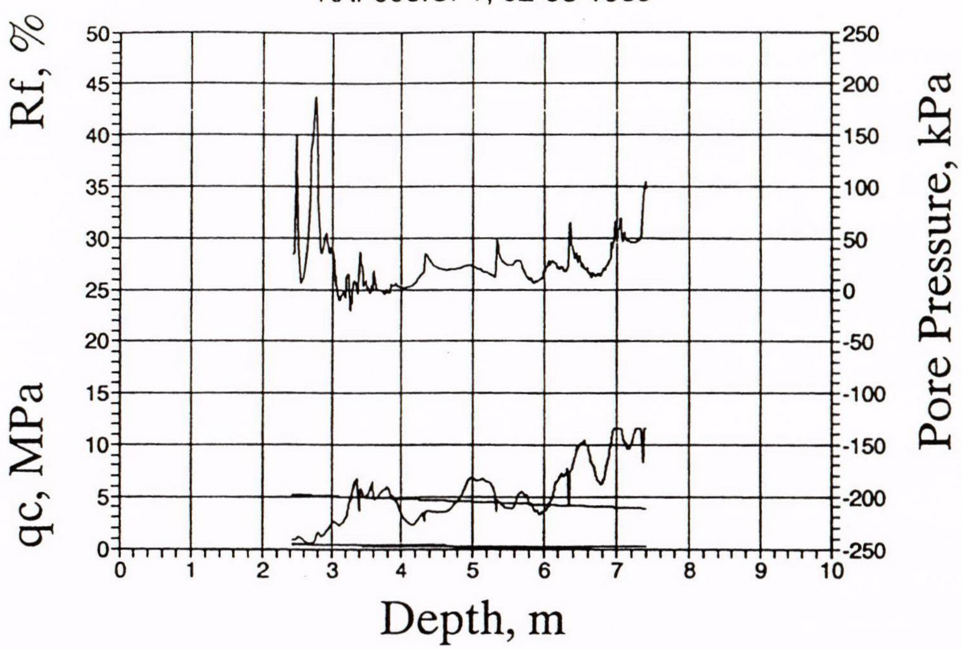
Charles Street, Kaiapoi

KAP005.CPT, 02-08-1989



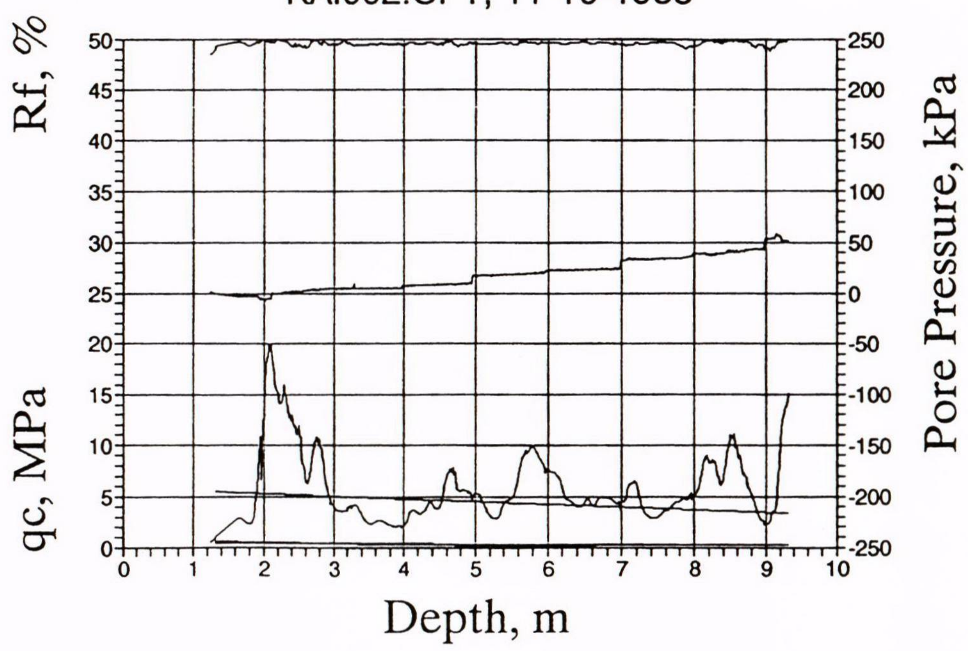
Charles St, Kaiapoi

KAP006.CPT, 02-08-1989



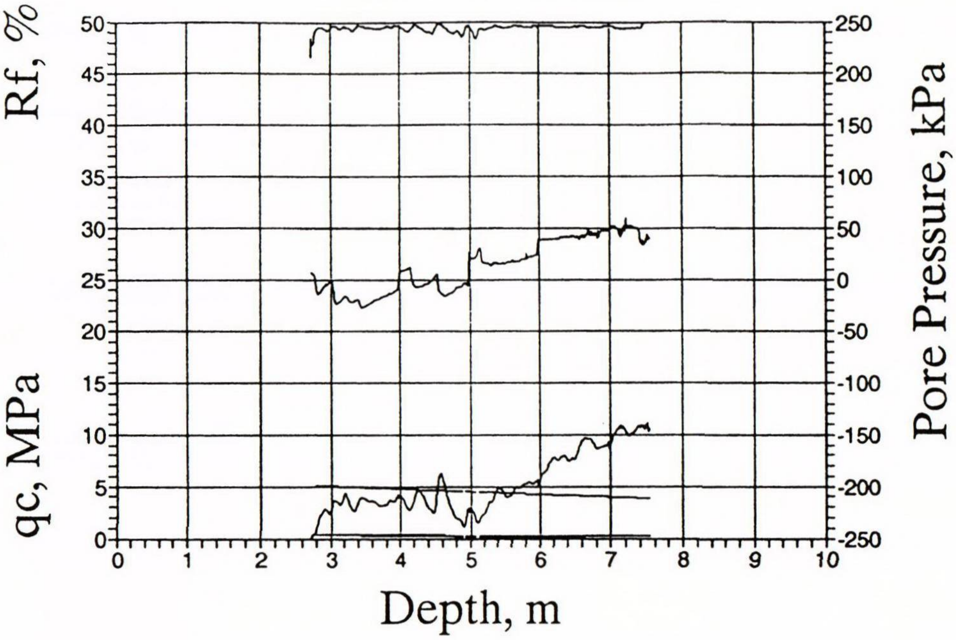
Kaiapoi River Bank Reserve #2

KAI002.CPT, 11-10-1988



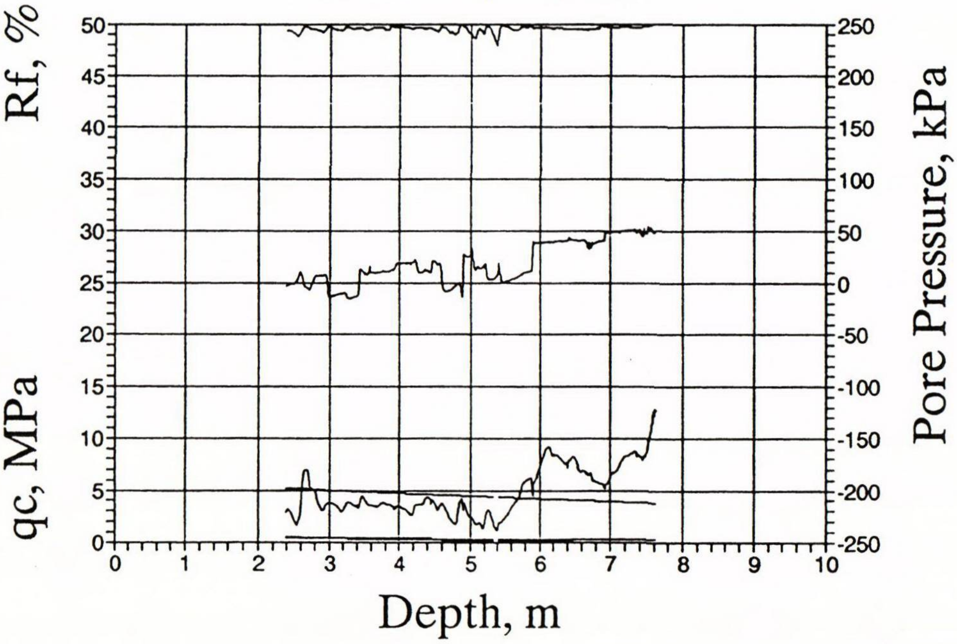
Cass Street

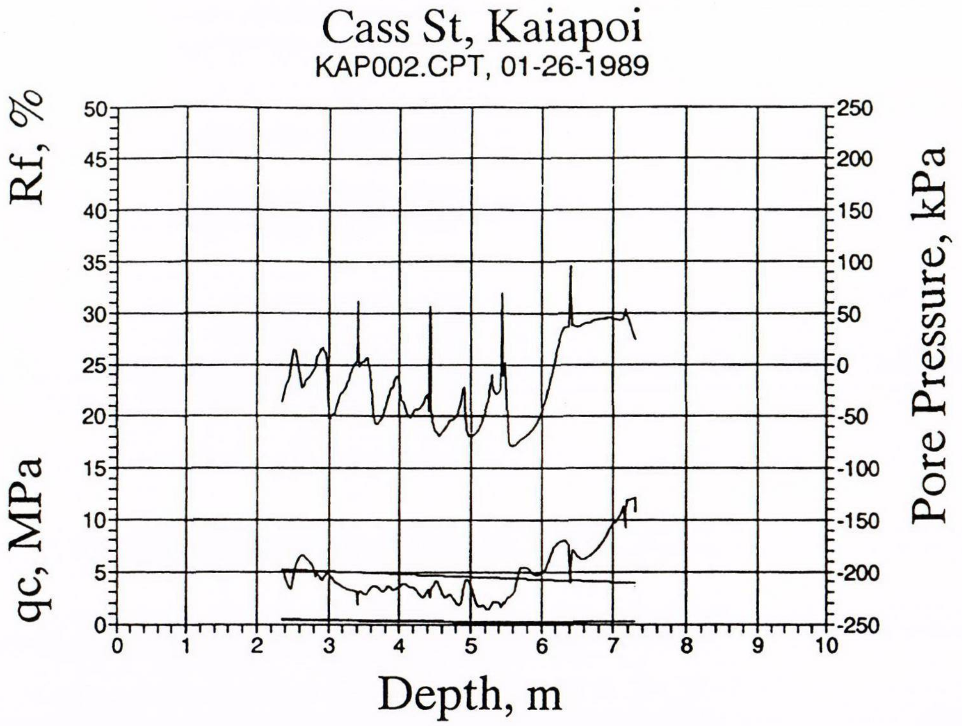
KAI003.CPT, ~~10-09-1986~~ Nov 15th 1989

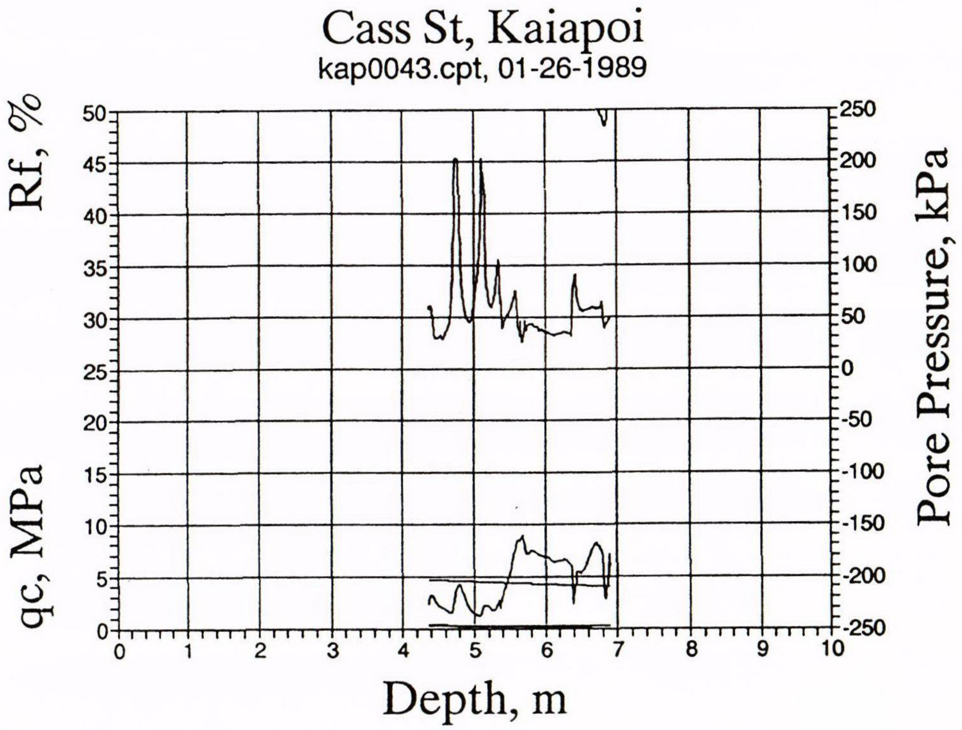


Cass St, Kaiapoi

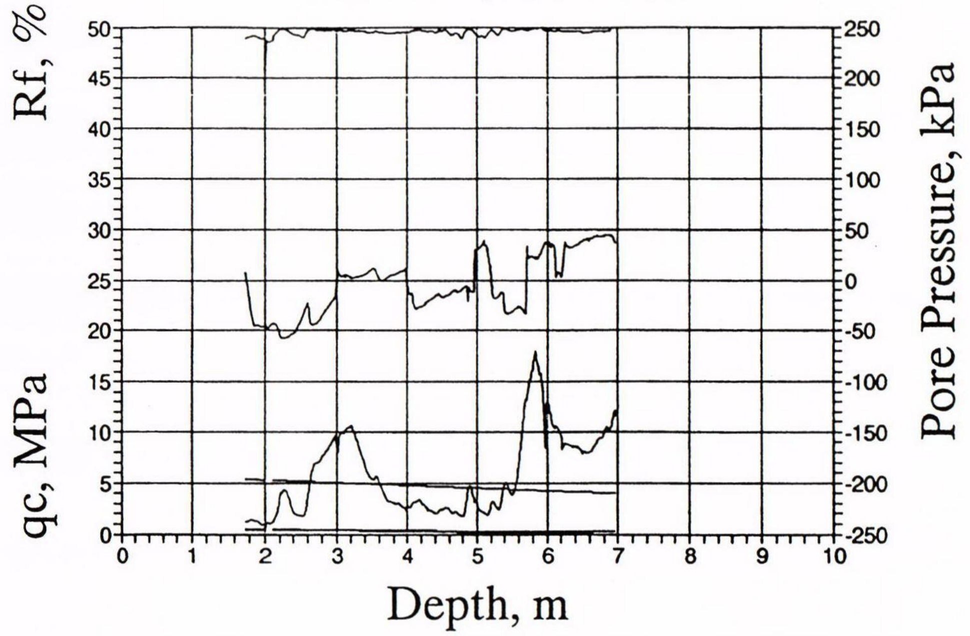
KAP003.CPT, 01-26-1989



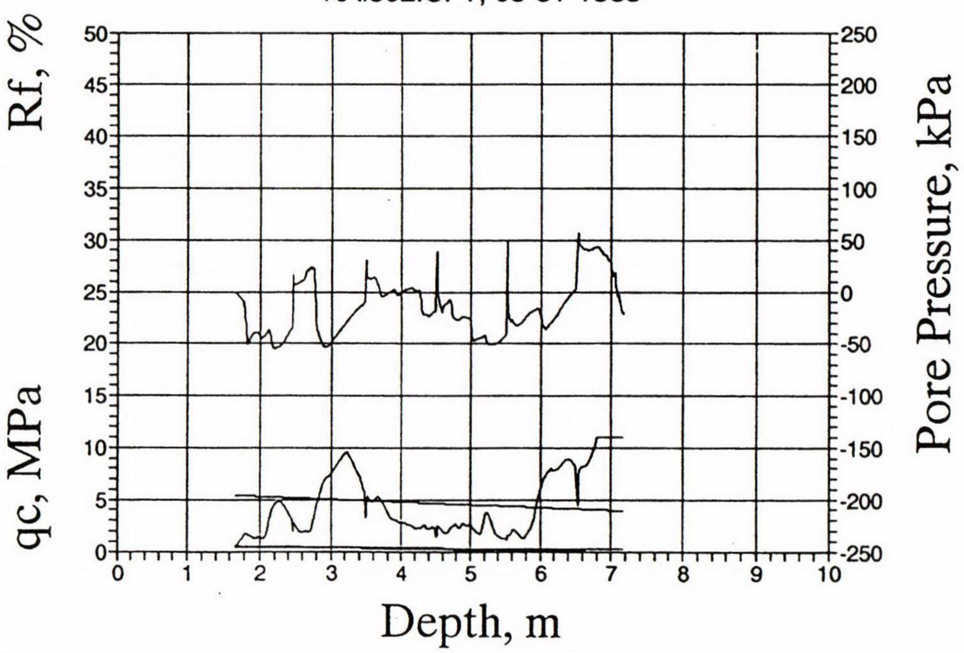

Cass St, Kaiapoi
KAP002.CPT, 01-26-1989
Rf, %
qc, MPa
Pore Pressure, kPa
Depth, m
0
1
2
3
4
5
6
7
8
9
10
0
5
10
15
20
25
30
35
40
45
50
-250
-200
-150
-100
-50
0
50
100
150
200
250


Cass St, Kaiapoi
kap0043.cpt, 01-26-1989
Rf, %
qc, MPa
Pore Pressure, kPa
Depth, m
0
1
2
3
4
5
6
7
8
9
10
0
5
10
15
20
25
30
35
40
45
50
-250
-200
-150
-100
-50
0
50
100
150
200
250

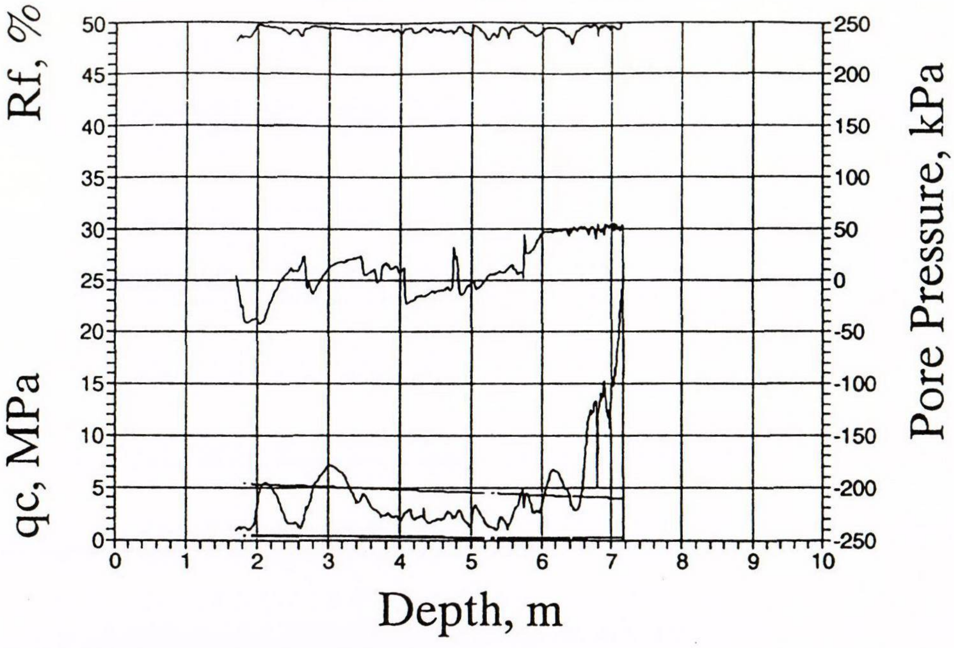
Cass St, Kaiapoi
KAI301.CPT, 05-31-1989

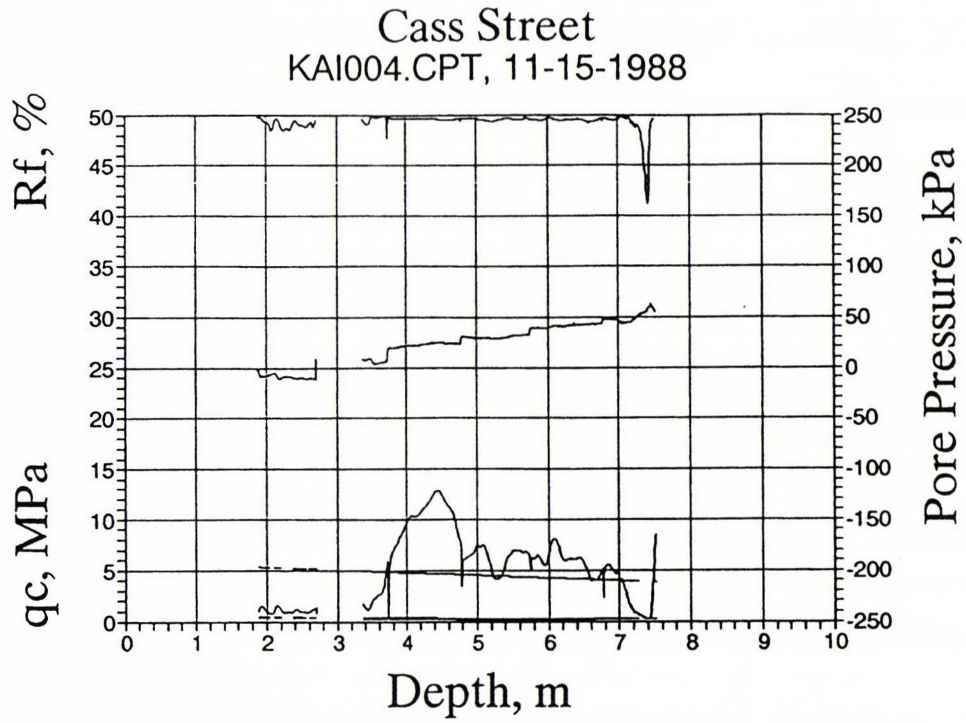


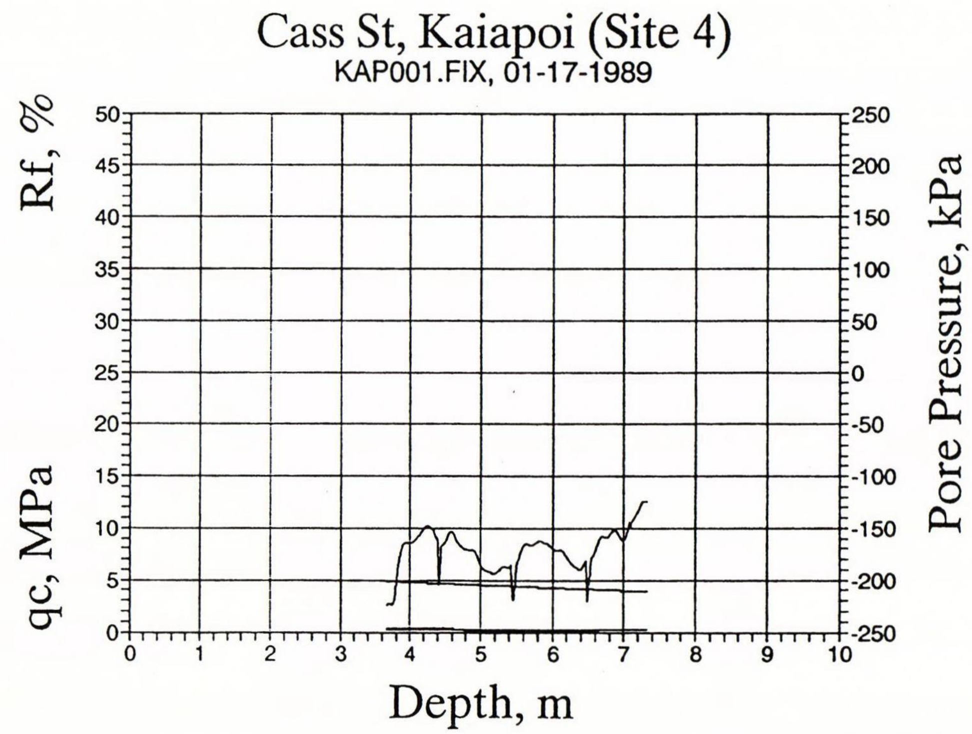
Cass St, Kaiapoi
KAI302.CPT, 05-31-1989



Cass St, Kaiapoi
KAI303.CPT, 05-31-1989




Cass Street
KAI004.CPT, 11-15-1988
Rf, %
qc, MPa
Pore Pressure, kPa
Depth, m
50
45
40
35
30
25
20
15
10
5
0
250
200
150
100
50
0
-50
-100
-150
-200
-250
0 1 2 3 4 5 6 7 8 9 10


Cass St, Kaiapoi (Site 4)
KAP001.FIX, 01-17-1989
Rf, %
qc, MPa
Pore Pressure, kPa
Depth, m
50
45
40
35
30
25
20
15
10
5
0
250
200
150
100
50
0
-50
-100
-150
-200
-250
0 1 2 3 4 5 6 7 8 9 10

Classn:

LIQUEFACTION AT KAIAPOI IN THE 1901 CHEVIOT, NEW ZEALAND EARTHQUAKE

J B Berrill, P C Mulqueen, E Ooi and J-L Pautre

ABSTRACT: Liquefaction occurred in northeast Kaiapoi during the 1901 Cheviot earthquake. A contemporary newspaper report describes the ejection of sand and lateral spreading in Waites' market garden at the east end of Sewell Street, Kaiapoi and also south of the Waimakariri River near Belfast. Soil conditions at Waites' property and at three other sites in northeast Kaiapoi were investigated by piezocone probing and rotary drilling. Loose, fine sands and silty sands, with a cone resistance q_c as low as 2 to 3 MPa, were found, which would be susceptible to liquefaction. In these very loose sands, q_c/N ratios were quite scattered about a mean value of 0.4 MPa.

Dept of Civil Eng. Research Report No. 94-3, 1994