Regional Report for Australia & New Zealand

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ABSTRACT: CPT and CPTU testing has gained rapid acceptance in Australia and New Zealand, with most population centres being well served by competent well-equipped testing contractors. In many areas, CPT/CPTU is the dominant investigation technique in most site investigations. Some research and development work is undertaken in the region, but testing and interpretation techniques are largely based on international best practice. Applications depend very strongly on local geology, with CPT and CPTU being more useful and applicable in some regions that in others. In some regions, particularly in WA, seismic CPT has become more common, and in many cases is with complementary DMT testing.

1 INTRODUCTION

Cone penetrometer testing (CPT/CPTU) has grown in popularity in Australia and New Zealand over the past 20 years, and is now the dominant means of site characterisation in the areas and stratigraphies where geological/geotechnical conditions are suitable for its use.

There is a long history of cone penetration testing in Australia. At the European Symposium on Penetration Testing (ESOPT) in Stockholm in 1974, Holden (1974) presented a state-of-the-art report on “Penetration Testing in Australia”, which detailed CPT usage both by his own organisation (the Country Roads Board of Victoria, CRB) and other organisations around the country. Holden’s report indicated that CPT testing was common in many areas of Australia at that time. He carried out a detailed survey of all penetrometer testing usage in Australia (including SPT, and dynamic and quasi-static CPT) It is instructive to note that many of the organisations possessing CPT equipment at the time, 10 were Government organisations of some sort (the CRB and other State Highways Departments, Public Works Departments, etc). Most of the cones in use were mechanical cones obtained from Holland (Delft, Barentsen), and one from Sweden (Nilcon) or Germany (Maihak) or manufactured locally (CRB, Fugro). There appears to have been only 2–3 “electric” cones or friction cones in the country at the time, one being a cone with a 10 cm^2 end area and 150 cm^2 friction sleeve from Germany (Maihak), and two being locally produced by the CRB, which had larger-than-standard dimensions (19 cm^2 tip and 465 cm^2 sleeve).

Holden's personal contribution to CPT testing in Australia, and worldwide, warrants special mention, as he really was the champion of CPT testing in Australia, and his work on CPT calibration using a calibration chamber (Holden, 1971, 1992) is widely recognised as being the first attempt at such calibration in the world.

Use of "Dutch" and "electric" CPT grew steadily in Australia, driven to some extent by Government engineering organisations, as well as private consultants. A notable project in this period included the first major use of the CPT in Western Australia (WA), in the construction of the Kwinana Wheat Export Terminal south of Perth in 1972 – 1974, involving some 1500 CPT soundings, to depths of up to 15 m in loose calcareous sand and organic clays, making it the largest individual CPT site investigation project in the country at the time and for many years afterwards. Another major early CPT project was carried out in Brisbane in the early 1980s for Brisbane Airport, located at the mouth of the Brisbane River, which, is dominated by soft alluvial deposits from the river. Figure 1 shows the setup for this project.

However, as pointed out by Holden (1974): "The use of penetration tests in major urban construction areas is somewhat restricted by the large proportion of sound rock at shallow depths underling the three major cities – Sydney, Melbourne and Brisbane. However, the other two large cities are almost entirely located on penetrable soils: Adelaide on Quaternary alluvium; Perth on Quaternary sands. The most dominant soils in the three largest cities are mostly saturated stiff residual soils, which require a large thrust machine for the CPT".

As will be clear from the next section, the site investigation market in Australia is actually quite localised, given the great distances between major cities, such that CPT contractors tend to be based in one or other of the capital cities, and service mainly that city and the surrounding region, though in some cases (WA in particular), servicing the "surrounding region" can mean mobilising equipment over distances of greater than 2,000 km.

Growth of CPT testing in New Zealand has only occurred more recently, but, as will be shown later, the growth has been rapid, with the result that CPT is now also very common in New Zealand.

Figure 1. CPT testing in the 'mangrove swamp' at the mouth of the Brisbane River for the SI for Brisbane Airport, 1980, showing the CPT rig attached to the blade of a Komatsu bulldozer (photograph courtesy of Allan McConnell, IGS, http://www.insitu.com.au/)

2 OVERVIEW OF THE REGION, AND GEOLOGICAL SETTING

Australia and New Zealand are two countries with very different sizes, geology and geotechnical challenges. Australia has an area of approximately 7.9 M km^2 (about 20% smaller than the contiguous United States), with a population of about 22 M. New Zealand, with an area of about 0.27 M km^2 and population of about 4.3 M, lies to the south-east of Australia, separated from Australia by some 1,500 km at the closest point. Some general comments about each country, and a summary of the geology of each country, are given in the following subsections.

2.1 *Australia*

An outline map of Australia is shown in Figure 2a, Figure 2b shows the south-west corner of Western Australia (WA), while Figure 2c shows the south east of the country, including the island of Tasmania (TAS). Most of the population of Australia lives within 100 km of the coast, in the areas shown in these enlargements. Darwin (pop. 123,000), the capital of the Northern Territory (NT) is the only other major population centre outside of these two areas. Within the south-east (Figure 2c), it can be seen that most of the population centres are on the coast – Adelaide in South Australia (SA), the area around Melbourne in Victoria (VIC), and then a coastal strip from south of Wollongong in New South Wales (NSW) through to just north of Brisbane in Queensland (QLD). In WA, with a total population of just over 2 M, over 1.65 M live in the greater Perth area, with most of the rest being in the south-west corner shown in Figure 2b.

The climate of Australia varies from tropical in the north, through arid and semi-arid regions across the centre, to Mediterranean or temperate in the south.

The topography of much of the country is relatively flat, but the coastal strip of the south east is backed the Great Dividing Range, stretching from VIC, through NSW and into Queensland, as can be seen in Figure 1(c).

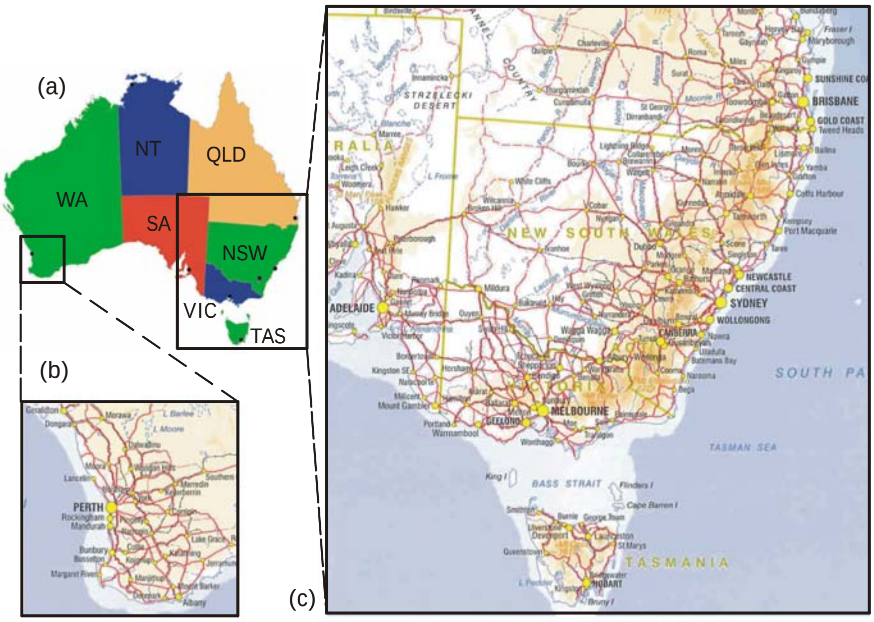


Figure 2. (a) Outline map of Australia, with enlarged sections showing (b) the south-west of WA, and (c) the south-east (© Geosciences Australia www.ga.gov.au/image_cache/GA14986.pdf).

Figure 3 shows an overview geology map of Australia, which also shows locations of currently-operating (2009) mines in the country. The geology is complex, ranging from ancient Archean cratons in WA and SA, to Ordovician mountain ranges in the south east (VIC and NSW), to extensive Cretaceous and Tertiary deposits through much of the centre of the country. However, in the context of this report, the geology of most of the country is irrelevant, since much of normal civil engineering (and hence site investigation) activity occurs in or close to the areas of population concentration shown in Figure 2b and 2c.

As indicated in Figure 3, mining activity occurs throughout Australia, though much of the mineral wealth is in remote areas with low population. This includes gold in WA and elsewhere (see Inset A), iron ore in the north of WA, extensive coal deposits in QLD (inset B) and NSW (inset C), and base metals, uranium, heavy minerals, etc, throughout the country. While there is considerable civil engineering activity involved with these mining activities and the associated infrastructure, very little of this involves CPT testing, though there is considerable application of CPT testing for assessment of tailings deposits throughout the mining regions.

There is also an extensive offshore oil-and-gas industry of the north western coast and in the Bass Strait (the sea between TAS and the mainland), with extensive use being made of CPT/CPTU in offshore foundation investigations, and in onshore developments associated with the offshore industry. These activities are outside the scope of this report.

Thus, in the context of this report, it is more instructive to consider the geology of the populated areas shown in Figure 2, and in particular to discuss the aspects of the geology that influences site investigation practices, including the use (or otherwise) of

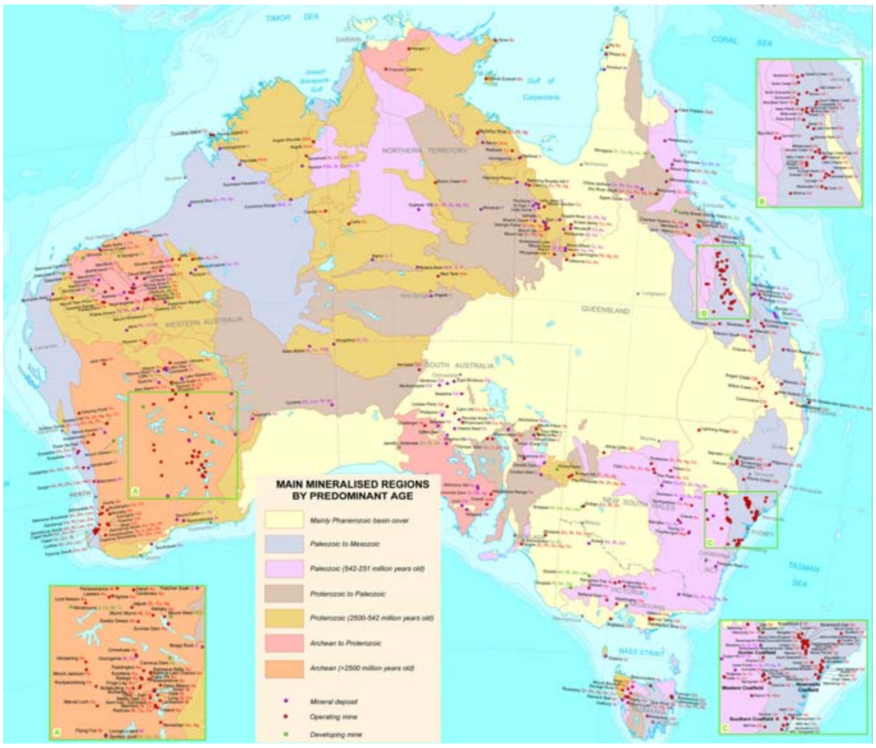


Figure 3. Overview geology of Australia, including sites of mining activity (© Geosciences Australia, http://www.ga.gov.au/image_cache/GA15125.pdf)

the CPT. A brief summary of the relevant geology of the various population concentrations is therefore given below.

2.1.1 *Perth and the SW of WA*

A dominant feature of the geology of the west coast of WA is the more than 1500 km long Darling Fault, which separates the Archean craton of the interior from the sedimentary deposits of the coastal strip, which in the Perth area is only some 30 km wide. This fault occurred during the break-up of the Gondwana super-continent, with the Archean basement rock in this coastal strip being some 10 km below the current ground surface.

The near-surface stratigraphy in the Perth area consists of interbedded sands and clays, underlain by sedimentary deposits (e.g. the King's Park Shale at about 30 m depth in the Perth CBD). Over most of the area, the upper layers consist of dune sand deposits or alluvial sand deposits, with the western-most sands being high in calcium carbonate, resulting in extensive limestone deposits forming along the west coast, typified in many locations by a top layer of high-strength caprock, underlain by much softer limestone or sand-filled cavities.

The current Darling Scarp in the Perth area is some distance east of the original fault, due to erosion of the original scarp; this erosion resulted in alluvial sand and clay deposits along the scarp margin. The Swan River, the main river running through Perth, and its tributary the Canning River, have transported some of these erosion products some distance from the Scarp, such that the soil stratigraphy in the city centre of Perth includes some sands and clays of the so-called Guildford Formation. As the sea level rose during the Holocene, the slowing river also deposited soft clays along the river margin, including two major river meanders within the city – the Maylands Peninsula and the Burswood Peninsula.

East of the Darling Fault, deep weathering of the Archean rocks has produced a strongly lateritised profile, characterised by an upper ferricrete layer, underlain in places by deep kaolin strata.

2.1.2 *Adelaide and surrounding areas of SA*

Adelaide is founded on deep Quaternary alluvium deposited by the Torrens River, and colluvium from the Adelaide Hills. Most of the city area, and a significant portion of the metropolitan area of Adelaide, is underlain by very expansive clays know as the Keswick and Hindmarsh Clays. The overall formation consists of an upper (Keswick) clay layer of high plasticity (CH) and extreme reactivity, which can be described as a heavily fissured, very stiff to hard, grey-green mottled clay; a middle sand member; and a lower (Hindmarsh) clay member similar in appearance and behaviour to the more recent upper clay layer. The overall formation is thought to have been deposited in the Pleistocene, and is typically 10 to 25 m thick. Within the Adelaide city area, the groundwater table generally occurs between 20 to 30 m below the ground surface in the Hellett Cove Sandstone, a permeable formation that immediately underlies the Hindmarsh formation (Jaksa and Kaggwa, 1992).

The upper Keswick clay is thought to be essentially saturated, but with high suctions being recorded to considerable depths – suctions that vary substantially from the end of the (wet) winter to the end of the (long, dry, hot) summer.

2.1.3 *Melbourne and southern VIC*

Most of Victoria is underlain by Paleozoic-age bedrock. The bedrock is folded, faulted and intruded by granite. Various materials unconformably overlie the bedrock including Tertiary fluvial and marine sediments, Tertiary and Quaternary lava flows (basalt) and Quaternary fluvial and estuarine sediments.

Ice age related sea level changes throughout the Quaternary have influenced the composition and distribution of colluvial, alluvial and estuarine sediments within southern VIC. River valleys have formed, been subsequently infilled with sediment or basalt and altered their course repeatedly throughout the Quaternary. South-central Melbourne is underlain by a complex sedimentary sequence comprised of basal marine sediments, overlain by fluvial sand and gravel, overlain by further marine sediment and upper normally consolidated estuarine sediment. Periods of erosion and lava flows in the periods between the deposition of each of these sedimentary units formed hills and valleys. As a consequence, the subsurface conditions in the Yarra Delta are characterised by a series of infilled valleys.

In drainage courses further upstream from the Delta, Quaternary sea level changes induced similar periods of erosion and deposition. Alluvial terraces with variable sedimentary composition are associated with most VIC drainage courses. During times of erosion and valley formation, landslides, some covering several hectares in plan area, formed on the sides of the valleys. Remnant colluvial fans can be found along drainage courses in the Yarra Valley and other drainage courses flowing from out of the highlands.

2.1.4 *Wollongong – Sydney – Newcastle (NSW)*

About two-thirds of the Sydney area consists of the variably-weathered Triassic Wianamatta shales, though in many areas, these shales form only a thin capping over the harder Triassic Hawkesbury Sandstone, which outcrops to the north, to the south, and in the eastern suburbs. To the west, the thick shale beds are weathered to considerable depths, producing extensive areas of stiff residual soils, some of which are expansive. The only other significant foundation materials are the Tertiary sands of the Richmond area, and the Pleistocene and Holocene alluvium and dune (aeolian) sand deposits, especially in the Botany Bay area (Holden, 1974).

According to Fityus et al. (2005), the geology of much of the region around Newcastle and the Hunter Valley is dominated by the gently dipping sedimentary rocks of the Permian-Triassic Sydney Basin to the south, and the more structurally complex sediments and volcanics of the Devonian-Carboniferous New England Fold Belt. In addition, it is capped to the north and west by Tertiary Flood Basalts, and in many areas is concealed by poorly consolidated sediment sequences that have accumulated in incised valleys during glacial periods during the Quaternary. In the context of this report, the main areas of interest are the Quaternary sediments, most notably in three estuaries adjacent to the Hunter region (Lake Macquarie, Newcastle Harbour and Port Stephens) and many more along the extended coastline. The Quaternary deposits of engineering interest in the Newcastle area include alluvial and aeolian sands, and soft clays in the estuary areas.

2.1.5 *Brisbane and coastal strip north and south of Brisbane (QLD)*

Approximately two-thirds of the Brisbane area consists mainly of highly to medium weathered Lower Palaeozoic phyllites and schists that occur at shallow depths. Triassic soft sandstones and shales are present in the southern suburbs, comprising about one quarter of the Brisbane area. The remainder consists of deep (to 50 m) Quaternary alluvium deposited by the Brisbane River (Holden, 1974). Very thick

Holocene and Pleistocene alluvial deposits occur throughout the Brisbane CBD, but are mainly concentrated in old creek channels and the floodplain of the Brisbane River. The Silurian Neranleigh-Fernvale strata outcrop at the surface or underlie much of the CBD at a relatively shallow depth. Many high-rise buildings and significant sections of recently-constructed tunnels in the city are founded on those rocks (Baczynski, 2001).

2.1.6 *Tasmania (TAS)*

The geology of TAS is dominated by pre-Carboniferous folded rocks in western TAS, and younger middle Palaeozoic granitoids in eastern TAS, juxtaposed at a NNW trending dislocation known as the Tamar Fracture system. During the Jurassic, large volumes of dolerite were emplaced, and dolerite surface exposure covers about half the area of Tasmania.

All of Tasmania's large rivers have buried rock channels in their lower courses. The sediments date from the Last Interglacial and the Holocene. These sediments are generally normally consolidated and "compressible". The nature of the basement rocks has dictated that the estuarine sediments are often associated with tributary creeks and the width of the estuarine flood plain is seldom more than 200m. Exceptions are highlighted below.

The 3 main population centres in Tasmania are Hobart, Launceston and Davenport, located near the mouths of the Derwent, Tamar and Mersey Rivers, respectively. In the context of this report, the sediments associated with these rivers are the main deposits in which CPT testing is or can be carried out. In Hobart, the estuarine sediments are generally associated with the flood plain (up to 50 m wide) or tributary creeks. Launceston is located about 50 km from the sea, at the head of the Tamar Estuary, and at the confluence of the North Esk and South Esk rivers. The estuarine flood plain is particularly wide: up to 3 km wide in one area. Approximately 10 km of flood levee is maintained by the Launceston City Council. While there is no flood plain at the port of Davenport, a 1 km wide flood plain exists several km up-river of the city.

2.1.7 *Darwin (NT)*

According to Nott (2003), the most remarkable aspect of the geology of Darwin is the angular unconformity that extends beneath most of the urban area separating lower Proterozoic rocks from near horizontal Cretaceous strata. The city of Darwin sits upon the Cretaceous strata and the Proterozoic strata are principally exposed in road cuts and sea cliffs along Darwin's foreshore. The labile nature of the marine Cretaceous rocks together with the tropical monsoonal climate has resulted in extensive deep weathering of these strata, producing a lateritised profile of piezolitic laterite, lateritised siltstone, kaolinised siltstone, and a silicified pallid zone known locally as porcellanite (Nyland and Gerner, 1984). Because the city of Darwin is situated on a slightly elevated plain of largely deeply weathered Cretaceous strata, the Quaternary sediments are restricted in area to coastal beach and dune sands and minor amounts of alluvium in creek valleys and colluvium on shallow slopes. This is in contrast to the Alligator Rivers region to the east where extensive marine and alluvial deposits record the Holocene sea-level rise and stabilisation and changing estuarine environments throughout the late Holocene.

2.2 *New Zealand*

Figure 4 shows a map of New Zealand, indicating the 7 largest cities, which collectively account for almost 60% of the population. Some 75% of the population lives in the North Island, where the topography is generally much flatter than in the South Island. The climate is temperate, with rainfall varying from greater than 6 m on the western flanks of the Southern Alps (which run along most of the western coast of the South Island), to less than 600 mm in eastern parts of the South Island (a rain-shadow effect from the Southern Alps).

New Zealand broke away from the Gondwana super-continent some 65 M years ago. Precambrian rocks form the basement of New Zealand, and some Precambrian rocks outcrop to the west of the Alpine Fault in the South Island. The geology and topography is largely determined by the fact that New Zealand lies on the boundary of the Australian Plate and the Pacific Plate. The latter is subducted under the former under the North Island, leading to significant volcanic activity and volcanic peaks, hot springs, etc., but the relative motion consists more of lateral shear along the Alpine Fault in the Southern Island. The North Island and western fringe of the South Island sit on the Australian Plate, while the rest of the South Island sits on the Pacific Plate. The central North Island is dominated by the Volcanic Plateau, an active volcanic and thermal area. The Southern Alps and the axial ranges of the North Island form the "backbone" of New Zealand. To the east of the Southern Alps lies the rolling farmland of Otago and Southland, and the vast, flat Canterbury Plains.

These mountains are mainly composed of hard sandstone and mudstone, collectively known as "greywacke", of Mesozoic age, but the southern and western parts of the Southern Alps are formed of schist. The uplift of these ranges began about 15 million years ago and has accelerated in the last few million years. The total amount of uplift in that period has been estimated to be in the order of 20,000 m, but continuing erosion is responsible for the present height (up to 4,000 m) as well as the dissected nature of the country.

A feature of the Central Otago area (NE of Dunedin in the South Island) is the flat, even-topped, rather subdued, schist topography, commonly with rocky outcrops (tors). About 70 million years ago this part of New Zealand was reduced by

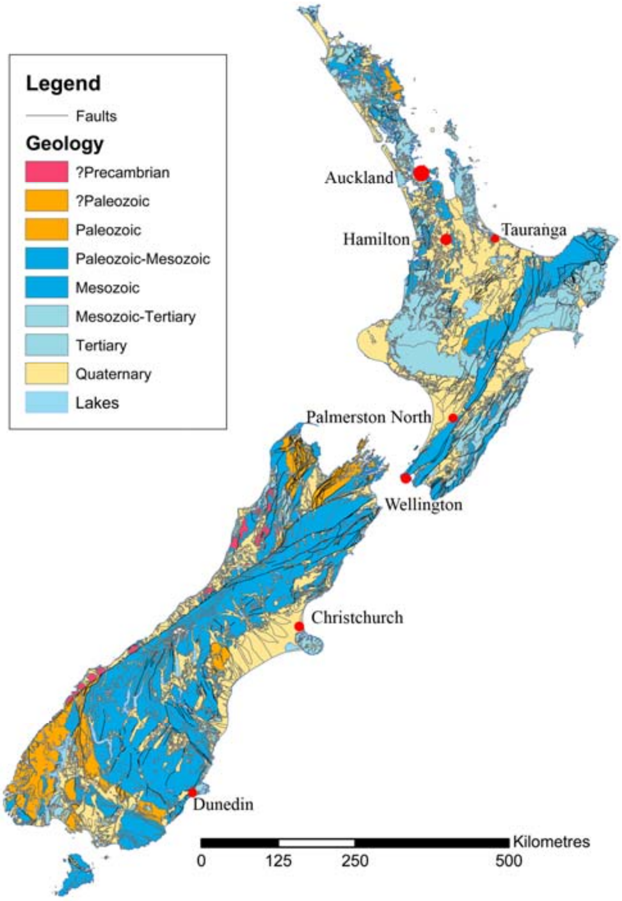


Figure 4. New Zealand: geology and principal cities. www.sci.waikato.ac.nz/evolution/geologicalHistory.shtml

erosion to a nearly level peneplain close to sea level. This level surface has been particularly well preserved as it has been only gently uplifted and tilted rather than complexly deformed.

A great proportion of the southern part of the North Island is formed of rather soft Tertiary rocks. The rocks are very similar in character throughout the area: blue-grey sandstone or mudstone. They form a very characteristic topography of steep slopes and sharp ridges, reflecting the easily erodible nature of the rock. Harder rock types, such as limestone, stand out prominently, particularly in Hawkes Bay and the Wairarapa.

The limestone commonly forms steep bare bluffs, and erosion resulting in karst landforms. The best examples of limestone formations are near Te Kuiti in the North Island, and in northwest Nelson and south Canterbury in the South Island.

The cone-like silhouettes of volcanoes in Taranaki and Tongariro National Park dominate the topography, while further north, flat-topped plateau areas are formed by ignimbrite flows. Volcanic cones are also prominent in the Auckland region, Bay of Plenty, and in some areas of Northland. Much of the topography in the northern half of the North Island has been modified by deposits of ash from repeated volcanic activity in the past million years. Many lakes in the central volcanic region are in the craters of previously active volcanic centres.

The climate of the last two million years (a time of successive cooling and warming) has had a major effect on present-day topography. Glaciers carved out U-shaped valleys in the mountains, and fans of alluvial detritus eroded from the bare mountain slopes built up during the colder times. The Canterbury Plains, for example, were built from glacial outwash. During warmer periods, sea levels rose and cut coastal terraces into rocks and alluvial debris; successive rises and falls of the sea to different levels formed the flights of terraces seen in the river valleys and around the coast. When sea level was low, wide areas of sand exposed to the wind were blown into dunes. They form the extensive dune country of the west coast of the North Island and Northland.

Figure 5. Mobilising two CPT trucks: a 20t 6×4 rig set up to haul a trailer with a 10-20t all-terrain rig (Courtesy Allan McConnell, IGS, http://www.insitu.com.au/)

3 GEOTECHNICAL CHALLENGES

3.1 *Site Investigation Practices*

Site investigation in Australia and New Zealand is generally undertaken by geotechnical consulting companies, who subcontract the drilling, sampling and penetration testing activities to specialist geotechnical contractors. On-site supervision by a geotechnical engineer or geologist from the geotechnical consulting firm is frequently provided.

The scope of work is generally determined by the geotechnical consultant, in accordance with the aims of the site investigation and the allocated budget. Naturally, the scope of the work, the types of testing carried out, depend on the local ground conditions and the nature of the project. CPT/CPTU testing is employed almost universally where ground conditions are suitable, though this is commonly in conjunction with some drilled-and-sampled boreholes, involving pushed-tube sampling in clayey soils and SPT testing/sampling in sandy soils. There are specialty CPT contractors in most major centres in Australia and New Zealand, generally with standard CPT trucks. Many contractors have also smaller specialty CPT rigs for easier mobilisation to remote sites, or for access onto very soft ground (or mine tailings storages), or for use in confined spaces. Figures 5 to 11 illustrate the range of CPT equipment used.

3.2 *Major geotechnical issues*

Many of the major geotechnical issues in the region of relevance to CPT/CPTU testing are common across the region, but some are specific to particular areas.

One of the most common applications of CPT/CPTU testing in the region is for characterisation of the soft clay deposits that are common in river-mouth and estuary areas throughout the region, and this is the dominant application right along the east coast of Australia, in the main population centres in Tasmania, and in some of the coastal cities in New Zealand. The most noteworthy of these are the eastern part of Brisbane and the adjacent coastal regions north and south of the Brisbane River, the harbour areas of Newcastle and Sydney (Botany Bay), and the South Central part of Melbourne.

In Perth and the WA coastal strip (Figure 2b), design of foundations (spread footings, raft foundations, pile foundations) and prediction of foundation settlements on the aeolian and alluvial sands and interbedded stiff clays is a major activity of geotechnical engineers, probably more so than in any other part of the region. Similar sand deposits are rather uncommon in most of the other major urban centres in Australia, apart from areas of Newcastle, and coastal areas of Queensland.

Much of the Adelaide region is dominated by deep stiff saturated expansive clays, with high suctions, which pose particular challenges for CPTU testing in particular. In Melbourne, significant structures in much of the city require piles founded in sedimentary rocks, though determining the properties of the overlying soft sedimentary deposits is also required. Much of the Sydney and the regions north and south of the city are underlain by strong sedimentary rock, such that the major geotechnical challenges for foundations, excavations, slope stability, etc, are “rock mechanics” challenges.

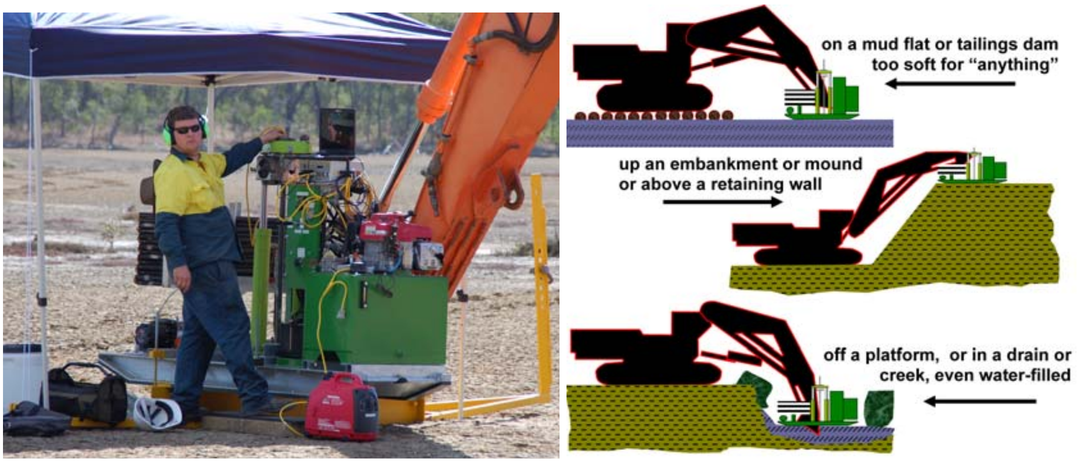
In New Zealand, apart from the characterisation of soft alluvial deposits associated

Figure 6. CPT rig mounted permanently in a sea container (2.2 m L×2.4 m W×2.6 m H), for ease of mobilisation. Handled on site by 20t excavator, which also provides the reaction (right), enabling a 12t pushing capacity (Courtesy Probedrill: www.probedrill.com.au).

with rivers and estuaries (as mentioned above), the other major issue of relevance to this report is characterisation of the liquefaction potential for extensive sand deposits throughout the country, and in particular in the South Island. Unlike most of the populated areas of Australia, New Zealand is a very high seismic hazard zone, such that liquefaction is a major concern. For example, the city of Christchurch (Figure 4), which lies only 125 km or so from the Alpine Fault at its nearest point, is underlain by Quaternary deposits of loose cohesionless soils of considerable depth (up to 1 km). Furthermore, according to Elder et al. (1992), the Alpine Fault, which has been quiescent during the past 150 years, is estimated to have experienced at least four large earthquakes ($M \geq 8$) at intervals of about 500 – 550 years, and the last such event was about 550 years ago.

In Australia, seismic liquefaction is a relatively minor issue, though it is still of some importance in the Perth and Newcastle areas.

As mentioned earlier (and illustrated in Figure 3), there is very significant mining



(a) (b)

Figure 7. (a) Light-weight penetration rig mounted on the arm of a Daewoo 225 LCV excavator, carrying out CPT testing on the surface of a tailings storage; and (b) capabilities of this setup. (Courtesy Allan McConnell, IGS, http://www.insitu.com.au/)

activity throughout Australia (and New Zealand). The geotechnical issues associated with this activity – wall stability for open cut mines, and stability of underground works – are not relevant to this report. However, of major relevance to this report are issues involving tailings dam stability, and the geotechnical condition of the tailings deposits, and CPT testing is commonly employed in this area.

Issues related to slope stability, foundation behaviour, and pipeline behaviour in the offshore oil and gas industries (off the WA coast and in the Bass Strait between VIC and TAS) are outside the scope of this report (see Randolph, 2004, for a coverage of this aspect).

4 CPT EQUIPMENT & PROCEDURES

4.1 *Standards & Procedures*

CPT testing in the region is generally carried out in accordance with the relevant national standards – i.e. AS1289.6.5.1-1999 in Australia, and NZS 4402.6.5.3:1988 in New Zealand. In addition, most contractors, and those who specify the testing, adhere to international practice, as expounded for example in ISOPT-1 (De Beer et al. 1988). The book of Lunne *et al* (1997) is used almost universally as a reference, both for conduct of the tests and for test interpretation. In general, contractors strive to keep abreast of the latest developments in international practice in most aspects of testing procedure.

4.2 *CPT Equipment*

Most centres where CPT testing is appropriate for local conditions are well served by specialist CPT contractors, or general SI contractors offering CPT services. Most contractors are equipped with purpose built cone trucks, either imported from one of the European or North American manufacturers, or manufactured locally, or track-mounted rigs for difficult-to-access sites, soft ground, or steep-sloping ground. Similarly, most operators have acquired CPT equipment (cones, loggers, etc) from one of the European or North American manufacturers.


(a) (b)

Figure 8. (a) Marooka 12t tracked CPT rig operating on tailings storage with desiccated crust, Kalgoorlie, WA; and (b) portable CPT rig set up on an "Amphiroll" vehicle on a bauxite residue ('red mud') tailings storage area, Kwinana, WA (Courtesy of Probedrill: www.probedrill.com.au).

Nearly all contractors offering CPT services also offer piezocone (CPTU) testing, which is routinely carried out when testing in soft alluvial deposits, a common application of CPT testing in most parts of the region. The pore pressure transducer filter is almost always located just behind the shoulder (giving the so-called "u_2" measurement), though there is lack of uniformity with regard to the type of porous element, the saturation fluid, and the saturation procedure.


Figure 9. CPT testing on river levee, Launceston (Courtesy Pitt & Sherry, TAS).

There is also a recent trend towards "wireless" CPT equipment, where the signals are transmitted wirelessly, with this being currently more pronounced in New Zealand than Australia.

Seismic CPT tests (SCPT) are performed relatively widely across Australia, and are typically being used in between 5% to 10% of all CPT contracts. They are also becoming more common in New Zealand. Some trends identified from the survey carried out by the authors for this report are detailed below:

- Clients who know that their project requires seismic design rarely question the need for seismic cone tests (SCPTs). However, the same clients often need to be convinced of the need for (more expensive) SCPTs for less high profile projects in areas of low seismicity. There is clearly a need for better education of clients who perceive that seismic shear wave velocity measurements are only relevant for seismic design.
- Most SCPTs in current use continue to employ a single geophone. There is awareness of the advantages of using dual geophones, although it would appear that Clients have yet to start insisting on the use of dual geophones.
- Seismic sources used include the traditional sledge hammer source, but automatic hammers are now starting to be used – e.g. the AutoSeis source developed by Prof. Paul Mayne at Georgia Tech, and the source supplied by Geomil (www.geomil.com) as used by one NZ contractor (Perry Drilling – see below).
- One CPT operator in Queensland has purchased the only seismic dilatometer (SDMT) currently in the region and envisages that the growth of shear wave velocity measurement will be via the SDMT because this device "provides two measures of stiffness".

4.2.1 *Contractors*

In Australia, the most prominent of the CPT contractors are:

- Probedrill (www.probedrill.com.au) and Probetech (no web site), operating in Perth and throughout WA
- Insitu Geotechnical Services (IGS), Brisbane, QLD and Sydney NSW (www.insitu.com.au)
- Cone Penetration Testing Services (CPTS), Brisbane, Qld (www.cpts.com.au)

- Douglas Partners, Sydney, NSW (www.douglaspartners.com.au)
- EAW Group (Earth, Water, Air), Sydney, NSW
- Black Insitu Testing, Melbourne, VIC (www.blackinsitutesting.com.au)
- Pitt & Sherry, Launceston & Hobart, TAS, (www.pittsh.com.au)

In addition, a CPT truck is operated on a commercial basis by the University of Newcastle, NSW (http://livesite.newcastle.edu.au/cgmm/Consultancy.page?), and the University of Adelaide also offers a light-weight CPT rig for commercial testing in South Australia. To the authors' knowledge, there is no commercial CPT contractor based in the Northern Territory (NT), with contractors mobilising equipment from one of the other centres for any major CPT projects in this area.

New Zealand also has a number of specialty CPT contractors, or general SI contractors offering CPT services. As in Australia, these are located in the main population centres:

- Perry Drilling Ltd, Tauranga (www.perrydrilling.co.nz)
- Resource Development Consultants Ltd (RDCL), Havelock North (www.rdcl.co.nz)
- Griffiths Drilling Ltd, Wellington (www.griffithsdrilling.co.nz)
- Brown Brothers Ltd, Hamilton (www.brownbro.co.nz).
- CW Drill, Nelson (www.cwdrilling.co.nz).
- Geotech Drilling, Taupo (www.geotechdrilling.co.nz).
- McMillan Drilling, Christchurch (www.drilling.co.nz).
- Testdrill NZ Ltd, Auckland (www.testdrill.co.nz) (their "CPT" involves measuring only the total pushing force at the top of the rods using a top load cell).

5 CPT INTERPRETATION

Interpretation of CPT/CPTU can be considered in two categories: interpreting the results to identify the soil types and produce a soil stratigraphy; and interpreting the results to obtain traditional soil engineering parameters for design or for design based directly on the measured CPT/CPTU parameters.

5.1 *Soil stratigraphy interpretation*

Soil type is often interpreted automatically by CPT contractors using software based on the soil behaviour type (SBT) classification charts such as those proposed by Robertson *et al.* (1986). These charts have remained popular for automated assessments, despite the more rational basis of the Robertson (1990) SBT chart, which relates soil type to CPT parameters (q_c, f_s) that are normalised by the in-situ vertical effective stress (σ'_{vo}). The additional level of input required to specify a

Figure 10. Geoprobe Geo7720DT tracked CPT drilling-sampling rig (US), operated with Geotech AB (Sweden) cordless CPT probes (Courtesy Brown Bros Ltd, www.brownbro.co.nz)

σ'_{vo} profile has clearly impacted on the use of normalised SBT charts.

It is generally understood that there are deficiencies/limitations in the various SBT charts and that, as a minimum, some site-specific "calibration" boreholes should be performed.

The soil behaviour type index (I_c) proposed by Robertson & Wride (1998) is gaining increased popularity as it provides a single number (rather than a combination of q_c and f_s) to assign to a soil. The I_c values at a given CPT location can be readily plotted alongside borehole logs and the DMT material index (I_D) to assist stratigraphic profiling. Users of I_c will need to continue to be aware of its limitations: for example, there is no I_c value typical of soft sensitive clays or very stiff clays.

Use of SBT charts employing pore pressure (u_2) and cone end resistance (q_c) data are less popular because u_2 data are believed to have a lower level of reliability than friction sleeve measurements. In many areas, there can be a significant thickness of partially saturated soil above the water table, and this impacts on the reliability of the subsequent u_2 measurements in the saturated zone. The reliability of u_2 data could be improved through better sensor saturation procedures. Operators also need to be provided with clear instructions on how to proceed after a sensor cavitates e.g. allow a wait period after a cone has passes through a stiff clay to allow the sensor to recover.

A number of Australian consultants are now making use of the SBT chart proposed by Schneider et al. (2008). This chart, which employs u_2 and q_c data and is reproduced on Figure 12, uses the $\Delta u_2/\sigma'_{vo}$ ratio rather than the traditional B_q ratio because changes in cone water pressure (which are important from a soil type perspective) are usually small relative to the CPT q_c values.

5.2 *Derivation of soil parameters*

Many practitioners do not find time to review CPT research work such as summarised in the various ESOPT, ISOPT and ISC proceedings. The textbook by Lunne et al. (1997) distilled much of this research, and is undoubtedly the major reference used for derivation of parameters in Australia and New Zealand. (Given its popularity, it is hoped that major findings from this conference and a number of others held in recent years are incorporated in a new revision of the book). Australasian consultancies tend to develop their own spreadsheet programs to derive parameters such as relative density, friction angle, undrained strength and soil stiffness from CPT data. Commercial software is also available and is used occasionally.

There is a relatively wide range of correlations in use and particular designers tend to adopt their own favourites, many of which have been superseded by more recent research. Most variability exists in the range of correlations employed for equivalent linear elastic stiffness (E_{eq}). For example, a recent survey

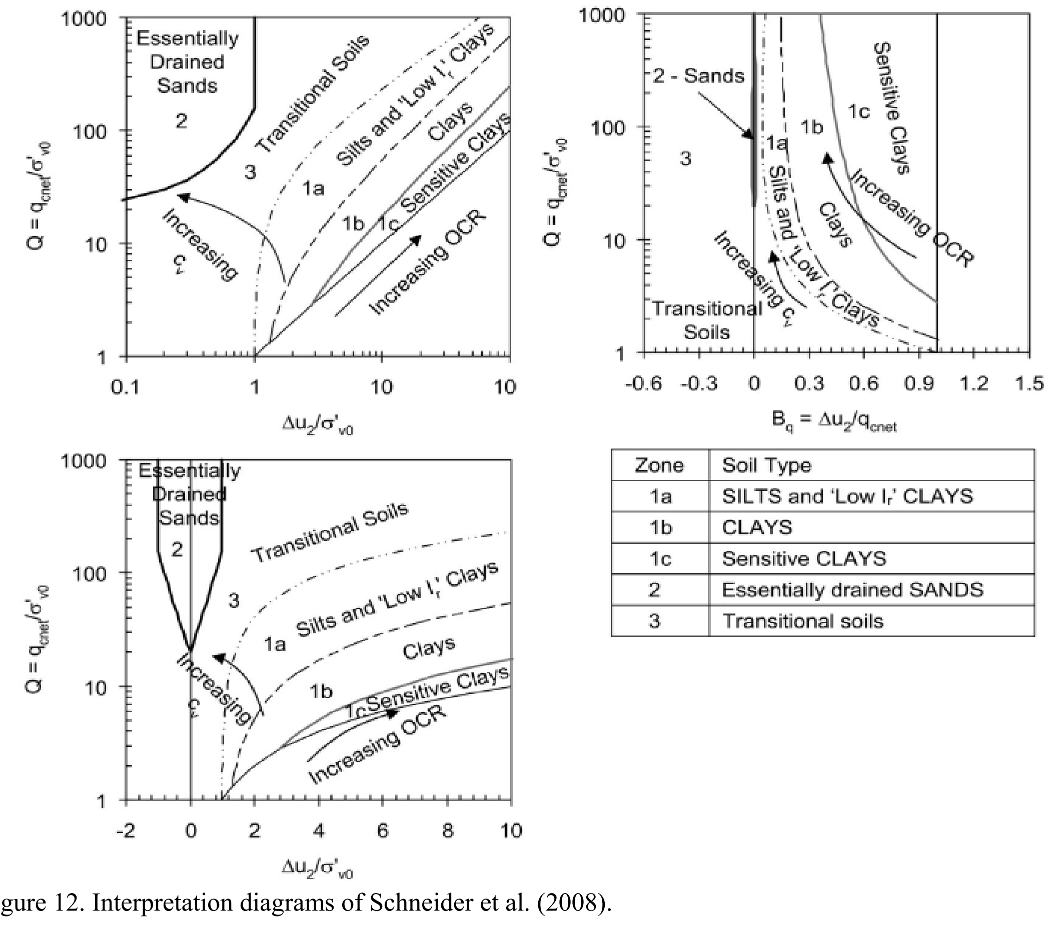
Figure 11. CPT rig on New Holland LS180 Skid Steer; reaction provided by ground anchors (RDCL, NZ, www.rdcl.co.nz)

(which is partly summarised in Lehane et al. 2008) indicated that practitioners' choice of E_{eq} in Perth sand for footing settlement estimation ranged from $2q_c$ to $15q_c$. Such a range may partly reflect the well know tendency for E_{eq}/q_c to reduce as sand relative density increases.

Undrained shear strengths (s_u) are derived directly from end resistance data using cone factors (N_{kt}) which can vary, depending on a particular designer's preference, by a factor of 2 (from 10 to 20) even for the same soil deposit at the same location. The use of such a large range in N_{kt} values reflects the wide variation of factors reported in the literature as well as inconsistency in the s_u value that is calibrated with the end resistance (e.g. vane, or triaxial UU or CIU).

There is confusion amongst some practitioners on how to interpret a piezocone dissipation test, particularly when pore pressures rise to a maximum a few minutes or more after halting penetration. This is partly because this relatively common occurrence is not covered in Lunne et al. (1997). There is also confusion concerning how the coefficient of consolidation inferred from a CPTU dissipation test (c_h) can be applied in design. There is a tendency, for example, to assign particularly high coefficients of consolidation to normally consolidated clays on the basis of the higher (re-loading) coefficient relevant in the dissipation test. Another common trend is to combine the m_v value measured in oedometer tests with the c_h value to deduce in-situ lateral permeability (k_h); this trend generally tends to overestimate actual k_h values.

Although there has been some recent research into the influence of partial drainage on the CPT resistance (e.g. Lehane et al. 2009), there is currently insufficient



Zone	Soil Type
1a	SILTS and 'Low I_r' CLAYS
1b	CLAYS
1c	Sensitive CLAYS
2	Essentially drained SANDS
3	Transitional soils

Figure 12. Interpretation diagrams of Schneider et al. (2008).

guidance to practitioners on how best to interpret end resistance values in the extensive deposits of silts present in Perth City centre and elsewhere. As a consequence, many practitioners tend to treat silts for design purposes as either hard clays or loose sands, depending on the assessment of the degree of drainage during cone penetration. CPTs involving rate changes (e.g. a reduction or increase from the standard rate), as advocated by Schneider et al. (2007), and others, would improve the interpretation of the rate dependence of the q_t value in these kinds of materials and thus lead to a more rational basis for design.

6 CPT APPLICATIONS

This section describes some of the applications of cone penetration testing in Australia and New Zealand. Environmental cone testing probes have been largely unused, presumably due to the limited degree of site re-use compared to older more populous parts of the world.

6.1 *Pile Design*

There is extensive use of direct correlations between CPT parameters and pile shaft friction and end bearing. For driven piles, practitioners still make use of the correlations proposed by Bustamante and Gianeselli (1982), rather than employ more recent proposals such as those summarised in American Petroleum Institute recommendations, API (2006). The Australian piling standard (AS2159) promotes the use of CPTs by allowing higher reduction factors on ultimate geotechnical strength (ϕ_g) for a greater coverage of CPTs at a particular site. For example, a ϕ_g value of 0.5 is specified for sites with average CPT site coverage whereas ϕ_g can be 30% higher (=0.65) if CPTs have been performed at all pile locations.

6.2 *Soil Stiffness*

Soil stiffness for movement prediction of deep and shallow foundations and retaining walls are commonly assessed from CPT data. Equivalent linear elastic "operational" moduli are normally derived from q_t data using plots such those of Baldi et al. (1989), but may also be derived from shear wave velocity data. Recommendations for a CPT-based strain dependent soil stiffness (e.g. Lehane and Fahey 2004, Zaremba and Lehane 2007) have been applied in a variety of projects in Perth.

6.3 *Ground Improvement*

CPTs are used to assess the degree of soil improvement achieved on all projects, although they are rarely used in place of nuclear density or sand replacement tests for road pavement assessments. It is felt that research is still required to relate ratios of q_t values before and after ground improvement to corresponding ratios of soil stiffness or strength. This is because effects of age, placement/ground improvement method and degree of consolidation on the properties of the in-situ material differ from those of the improved material. As shown on a number of recent projects in Australia, effects of arching also need to be considered when interpreting q_t data for fill compacted in trenches above pipelines.

6.4 *Soil Liquefaction*

The liquefaction resistance of sands and silty sands is generally determined from CPT q_t and SPT *N* data using the recommendations of Youd et al. (2001). The resistance indicated by q_t data is often preferred to that assessed from shear wave velocities.

Whereas assessment of liquefaction potential is not a major issue in most Australian centres (due to low earthquake risk and absence of significant sand deposits), this is certainly not the case in New Zealand, where assessment of liquefaction potential is one of the major challenges faced by geotechnical engineers, as mentioned earlier. New Zealand consultants generally adopt the approaches described by Zhang et al (2002) and Robertson (2004) for determination of post earthquake settlements.

7 RESEARCH AND FUTURE TRENDS

Ever since the early work of Holden referred to in the Introduction, there has been ongoing research in the region on applications of CPT and CPTU, and more recently on SCPT. Because of the widespread use of CPT/CPTU in the recent alluvial deposits common to many urban areas in the region, as detailed earlier, a common research theme in the region has been determining local interpretation and design parameters for such soils for each area.

Because of the particular relevance of SCPT to foundation design in the dune and alluvial sands and stiff clays of the Perth region, there has been ongoing research at UWA by the authors and their colleagues in these topics, generally in conjunction with DMT or self-boring pressuremeter (SBP) testing (e.g. Lehane and Fahey 2004, Lehane et al. 2008, Lehane et al. 2009).

Perth has a short wet winter and a long dry summer, and seasonal effects on CPT results is an issue. From CPT tests carried out in sand above the water table, Lehane et al. (2004) showed that q_c values were significantly lower at the end of winter than at the end of summer, with this effect being most pronounced near mature trees, indicating the effect of changing suctions on q_c values.

Research on CPT testing in clays has been ongoing at the University of Adelaide (SA) since the early 1980s, and more recently by Jaksa and his colleagues. By carrying out 220 CPTs in a 50 × 50 m grid, as well as a single CPT driven 7.6 m horizontally into the face of an embankment, and acquiring CPT data at 5 mm intervals, Jaksa (1995) was able to measure the vertical and horizontal spatial variability of the Keswick Clay, a stiff, over-consolidated clay whose geotechnical properties are very similar to those the London Clay (Jaksa et al. 1997a, 1999; Jaksa and Fenton 2002). In addition, by further analysing these data, Jaksa et al. (1997b) demonstrated that the CPT incorporates a very low random measurement error of 3%, which is the lowest of any in situ test, and Jaksa et al. (2002) developed a statistically-based method for evaluating the friction sleeve distance which is used in the calculation of friction ratio.

Because of the strong interest in seismically-induced liquefaction in New Zealand, there is ongoing research there on the application of CPT and SCPT for liquefaction assessment, and for determining stiffnesses for site response analysis.

Overall, it appears that CPT/CPTU/SCPT will continue to grow in popularity in the region, probably in conjunction with growing use of DMT and SDMT.

8 SUMMARY

The use of CPT/CPTU is increasing steadily throughout the region in the areas where such testing is appropriate. Well-equipped CPT contractors are based in most of the major urban areas, or can mobilise to centres where no such contractor is located. The popularity of CPT/CPTU obviously depends on the local geological and geotechnical conditions, such that in Perth, for example, this type of testing dominates site investigation activity, while in Sydney, it is relevant only to very select areas.

The main uses of CPT/CPTU in the region are for determination of general soil stratigraphy, for investigations in recent alluvial deposits, for foundation design in stiff clays and sands, and for liquefaction assessment, particularly in New Zealand.

Increasingly, CPT/CPTU is carried out in conjunction with shear wave velocity measurement (seismic CPT), and is often (particularly in Perth, but increasingly elsewhere) complemented by DMT testing.

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