The Challenge of the Beaufort Sea – Sand, Clay and Ice. A Record of Geotechnical Work by Golder Calgary in the 1980s

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1.0 INTRODUCTION

The purpose of this note is to provide a brief record of the soil mechanics work carried out by Golder in Calgary in the 1980s. As a result of contract research and consulting projects related to oil and gas exploration in Arctic offshore in the Beaufort Sea (Fig. 1), we established a comprehensive approach to describe soil behavior in terms of the "state" of the material. This approach integrated many of the soil behavior theories that had existed previously (e.g. Critical State Soil Mechanics, SHANSEP and others) albeit with some significant changes. We published our work extensively (Appendix 1) and used our approach on many of our consulting projects. Our approach has had a significant influence on how soil behavior is now understood in our profession not least because it is simple to understand and apply in practice. Evidence of the influence of our work can be seen in the number of citations related to our publications. For example, the state parameter paper (Been and Jefferies, 1985) is #5 of Geotechnique's most cited publications for the past 30 years. Mike Jefferies and Ken Been have also published a well referenced book on sand liquefaction based on the 1980s work (Jefferies and Been, 2006).

As the author of this document, I have leaned towards a personal account of our work in the 1980s. I also received considerable input and advice from Mike Jefferies (e.g. the "math" section), Dennis Becker (e.g. the "geotechnical circle" section) and Ken Been (e.g. the "liquefaction" section) as well as editing as required. Mike, Dennis and Ken were the drivers behind the work in the 1980s – they were (and still are) wonderful colleagues and friends and I thank them for their leadership and assistance. However, let me make it clear that these gentlemen are not responsible for my ramblings nor any errors and omissions (or offences given) in this document. These flaws are my responsibility alone.

Figure 1: Location of the Beaufort Sea (Google Search)

2.0 BACKGROUND

2.1 Calgary

Calgary in the 1980s was a very interesting city to live in. It is located on the prairies in Alberta just east of the Rockies and at that time, had a population of about half a million. It has grown enormously over the past 30 years and the population now is in the order of 1.2 million. Young people are attracted to the city because of job opportunities as well as access to the magnificent skiing and winter sports facilities in the Rockies which are within 1.5 hours drive from the city. Despite its growth, Calgary has remained a very friendly city and an easy place to do business. The old "handshake" approach of the 1980s has gone but business today is still very workable.

Calgary is a "city of villages" – by that I mean that the communities that make up the majority of the city are very well defined and the spirit that one would expect in small towns is ever-present. For example when our community teams (Lake Bonavista in my case) played lacrosse or hockey in another community, feelings of pride and representation were very strong.

Calgary was not an international city until 1988 when we hosted the Winter Olympics – then the world knew who we were. Calgary is a party city and what a party that was!! I remember well during the Olympics watching a TV interview with a Nordic winter sports guru. He thought he was "off the air and said that he was astonished how much fun people were having – I guess that describes Calgary pretty well.

Calgary boasts a full complement of academic institutions as well as arts and sports facilities. The Calgary Philharmonic Orchestra is widely known as are our major professional sports teams – the Calgary Flames hockey team won the Stanley cup in 1991 and the Calgary Stampeders football team wins more than its share of Grey cups. It is a volunteer city – people give readily. There was a time when Calgary's culture was defined as the "yoghurt" we bought in the local grocery store. Not any more – the arts, music and so many other scenes have developed so rapidly that in 2012 Calgary was named the cultural capital of Canada.

There is a general view of Alberta (typically held by those who have never visited the province) that it is a "redneck" society, very right wing and of course that element does exist as it does anywhere. However, the reality is that it is a very consultative – Ralph Klein (Canada's favorite provincial Premier?) always said – "what do Martha and Henry think about this?" Martha and Henry were his "acronym" for the "common folk". Alberta is actually a very consultative and open-minded place. This year, Albertans removed the Conservative party that had ruled the province for 44 years and replaced it with a majority NDP government – how radical is that!

Calgary is also the only city in North America to elect a mayor who is a practicing Muslim. Mayor Nenshi has provided excellent leadership for the city for two terms. So forget the "redneck" thing – Calgary is a very progressive city on all fronts and by any measure.

2.2 The Economy

Alberta's economy is based on resource industries, traditionally agriculture, forestry and the oil and gas industry although the basis of the economy has been broadening over the years (e.g. the IT business). Also coal mining has always been a factor in the province's economy. Canada is ranked tenth in the world in total proven coal reserves and Alberta's coal represents 70% of Canada's total reserves. I guess the question is – "Can we have clean coal?"

Calgary is the oil and gas capital of Canada with the head offices of most companies in the industry based here. Until the 1990s, oil and gas was produced based on conventional technology. Since the late 1990s, there has been massive development of the oilsands resource in the north-east area of the province which has been a major driver of provincial and Canadian economies until the recent collapse in oil prices. The Alberta oilsands reserves are second only in the world to the reserves in Saudi Arabia.

However, there was limited oilsands mining in the 1980s and it had little impact on the provincial economy. In fact, the 1980s was a very tough time because of the world-wide recession in the early-mid stages of that decade. Inflation rates were in the low teens and mortgage rates were as high as 19%. An interesting point – the provincial government stepped in to mitigate the high mortgage rates and we received a cheque from the government each month to reduce the mortgage rate to the equivalent of 14% - another example of the nature of a "caring" society in Alberta.

The soil mechanics work that Golder did in Calgary in the 1980s was based on oil and gas exploration in the Beaufort Sea (Fig.1) which begs the question – "why would anyone want to explore for hydrocarbons in the Beaufort Sea in the 1980s?" The answer is – The National Energy Program (NEP) – the brainchild of the then Liberal Government under Prime Minister, Pierre Trudeau. This program was much hated in Alberta as it prevented producers in the province from benefitting from higher oil prices world-wide (i.e. the price of Alberta oil sold in Canada was deliberately kept low). This was viewed as stealing from the west (Alberta) to coddle the eastern provinces where all of the Liberal's support was located. Thus the expression which appeared on many bumper stickers in Alberta at the time – "let the eastern bastards freeze in the dark". The purpose of the NEP was to ensure that Canada was self-sufficient in oil and gas and there were significant inducements (i.e. tax breaks) for companies who were exploring for oil and gas across the country including offshore exploration in the Beaufort Sea. Of course, while it was proven that there are massive hydrocarbon reserves under the Beaufort Sea, there was no way to bring the oil and gas south. The McKenzie Valley pipeline, proposed in the 1970s was put on hold as a result of the Berger Commission in the late 1970s which concluded that the population in the north was not ready for the social change that would accompany such a development. The MacKenzie Valley pipeline has still not been built and the hydrocarbon reserves in the Beaufort Sea area remain undeveloped. Global climate change may open other avenues for transporting oil and gas (as well as other recoverable resources) from the Arctic. However this will spark a whole spectrum of other issues which society will have to address.

2.3 Golder Calgary in the 1980s

This quote captures Golder Calgary in the 1980s perfectly – "It was the best of times, it was the worst of times" (Charles Dickens' opening line in his novel "A Tale of Two Cities"). When I was asked (not too politely) by my colleagues in Mississauga to leave Eastern Canada, I visited Calgary in March 1982 and bought a house. The place was "humming", the office was around 70 staff mainly based on work on a new surface oilsands project aptly named Alsands and the AOSTRA Surmount project (the first "underground" oilsands project). Our permanent move took place in July 1982 when our kids had finished school and would you believe it, by the time we got to Calgary the entire situation had changed as a result of the world economic recession – doom and gloom everywhere – "the worst of times".

The value of our house had declined 30% in 3 months and we hadn't even lived in the place. But while I had an excellent technical career in Mississauga, the work we did in Calgary was incredible – "the best of times". And we had fun – perhaps we were too young to appreciate the maelstrom we had entered and survived.

We certainly were young and in desperate need of personal security, but we were always reaching – so we tried harder. We were very committed to learning and advancing the state of the art in geotechnique. What also comes with youth is arrogance which led to us to the belief that we could do anything better than any of our competitors or anyone else for that matter. Spirit by itself always takes care of at least half the battle!

Camaradie in the office and with our clients was the order of the day. Since this was well before the current regime of health and safety, lunches were often long and liquid with much debate over high level technical concepts and ideas (it was the way of the industry at the time). On one occasion, I left my car parked too long over lunch (street parking was over at 3 pm) and my car was gone (towed) when I eventually emerged from our lunch venue. I took a cab home which was probably the right thing to do!!

Technical literature is great when two (or more) schools of thought are having a "bun-fight" over differences in philosophy or approach to a particular problem. This has happened in geotechnique at times in the past and such controversy has invigorated (even galvanized) our technical community on each occasion. I am proud that we generated such controversy in the 1980s and we had excellent adversaries from whom we learned a lot. Unfortunately, today's technical "discussions" are much tamer – we often achieve more when we disagree than when we agree!!!

A short description of the nature of our business in the 1980s is necessary as background to this memoir. Golder's office in Calgary was founded by Glen Gilchrist in 1972. Jack Clark joined Golder in Calgary in the late 1970s – Jack had been one of the "big fellows" in Hardy Associates (the class company on the Prairies in the 1970s) and became the president of Golder Associates Western Canada. Jack left his "have done, can do, will do!!" footprint on Golder Calgary and in fact on Golder worldwide. He left Golder in the early/mid-1980s to lead the development of C-Core in Newfoundland.

The 1980s was a time when Golder's business was, with some notable exceptions, still largely based on individual practices. An example of an exception to the individual practice syndrome was Glen's work on canal rehabilitation in southern Alberta. Glen employed many staff in a prime consulting role (not as a sub-consultant) and was basically the person who saved the Calgary office in the dirty 1980s. This was well before the days of "big" business (i.e. big projects, big management, big company systems, etc.).

As described below, our oil and gas business was built around acquiring and developing expensive laboratory equipment but as dictated by the economic conditions at the time, clients would not pay the upfront cost of this development until they knew we had what they wanted. So, we used our own money to build the laboratory equipment they wanted and then recovered the cost on a per test basis. We were not concerned about being "out on a limb" financially because we had trust-worthy clients and we were confident that we were delivering a world class product or better.

The non- technical staff (admin., accounting, drafting) were infected by the enthusiasm of their professional colleagues and believed in what we were doing, at least through our attitude – not necessarily because of technical understanding.

On the same note – an observation on the absolute importance of having a committed and intelligent support staff… my example is Kathy Koch. Kathy did all the heavy duty typing for the office and operated our first ever word processor – the infamous AES!! This equipment was expensive at the time and used 8 inch disks. The incorporated printer was a "daisy wheel" which sometimes lost all the "e"s in the text……IT was not easy in those days!

So it was tough times in the 1980s but believe it or not, we had fun. The staff was simply excellent. But I should not forget Elsie Hazen who was Jack Clark's secretary and when times were really bad – no money to buy anything, Elsie hosted the 1983 Christmas party in her basement – pot luck and BYOB. It was the best party in Golder I remember – bar none!!! Well maybe there were another few parties that I remember well – like the one when Ken Been and Dennis Becker dressed in grass skirts and did an amazing hula dance for the assembled masses.

2.4 Our Business

For the first 10 years that the Calgary office was in business, we tended to work on mining projects. Glen (the founder of the Calgary office) did not have a high regard for the oil patch and did not like to work for other consultants. Our competition was excellent, probably the best anywhere in Canada (Hardy, EBA, Thurber). The U of A geotechnical group was also very strong and deeply involved in the consulting business in the Arctic as well as the oil sands area. It is interesting to note that unlike our competition, Golder Calgary did not have many UofA or UofC students. Our talent mainly came from other parts of Canada and literally from all corners of the world.

Early in the 1980s we were engaged in a major new oilsands project with 60 – 70 staff in Golder Calgary. Then the oilsands project was put on hold at the same time the world economy collapsed and we retrenched back to 19 people. Our response to the downturn was not to cut rates or salaries; instead we cut overhead costs and staff. We did a lot of hourly hiring which allowed us to keep good people close. Hardy Associates, the best company in the province in the 1970s, cut rates and took on work where they could not possibly make a profit. Also they cut salaries across the board which is not good business – many of their really good productive staff left. Eventually Hardy was bought for $250k (a pittance) in mid 1980s by BBT which was owned by Ben Torchinsky from Saskatoon – our former partner in the Sandisles venture. If innovation is important and I obviously believe this to be true, Sandisles and Pangea – the latter was Golder's solution to disposal of the world's nuclear waste – were absolutely brilliant ideas…. well worth a write up in the company's history. BBT-Hardy went on to become Agra Earth and Environmental who were bought by AMEC and is still our major competitor (and also a major client/partner).

There is an expression that has been used to describe the dirty 1980s in Calgary "The ship had sunk, the lifeboat was leaking and we were slipping bodies over the side before they were dead". But the Golder Calgary core was very strong and extremely resilient. The professional staff was a dream team – can you imagine working with people like these (in no particular order): Becker, Been, Burwash, Clark, Gilchrist, McKeown, Leach, Horsfield, Arnall, Hachey and many others. All went on to make major contributions to the overall Golder organization and to the geotechnical community in general.

For the Arctic soil mechanics work, our main clients were Esso and Gulf Canada. Our main contact in Gulf was Mike Jefferies – a former Golder employee. Mike challenged us to produce our best, gave us his best, got the most out of us and enhanced everything we did. Mike was our leader as far as that was possible. Then of course, we always had access to Leo Rothenburg who was lecturing at Waterloo. Leo had worked for Golder in Mississauga and was another leading thinker in the field of soil mechanics – he was an excellent person to bounce ideas off and to spark other avenues of thought.

To stay in business and remain profitable in the 1980s in Calgary, we focused on three market areas – in business, one always has to focus. Glen Gilchrist, who came from a huge ranch in the Milk River area in S. Alberta, got us into the irrigation canal rehabilitation business. Gilchrist was one of the four big ranching names in Southern Alberta and so Glen was already well connected (he was like a Paw Cartright in the 1960s Bonanza TV show). It was very important in those days to be connected in the community since the provincial government insisted on a high Alberta content. The irrigation canal rehabilitation projects were large prime consulting assignments and were the main reason that we survived the dirty 1980s. We could be as clever as we wanted to be in other areas of work but the canal work was our "bread and butter". But note….with Bryan Leach's vadose zone skills (the vadose zone is the shallow unsaturated zone in the soil), we brought a new level of thinking to canal design – we were all about technical innovation. The second business focus was the foundation design for the 1988 Olympics infrastructure projects – Jack Clark and Shawn McKeown looked after this area. Again, they took geotechnical design to new heights by designing the world's most highly laterally loaded piles to resist the enormous lateral forces associated with the new skating oval. Finally, our third focus was on the Beaufort Sea – the subject of this note.

Our laboratory was really the engine of our Beaufort Sea business and what a high-tech adventure it was (Photo 1 shows some of our equipment including a youthful David Horsfield). We could theorize all we wanted but we had to back up our theories with actual data and initially, a lot of the data was laboratory based. Our first data acquisition system was an Apple 2E – it cost an exorbitant $3000+ but it allowed us to make rapid data collection in the post peak part of static liquefaction tests (i.e. many data points/sec). We had “rescued” the static liquefaction triaxial cell from our Vancouver office. This really got us going on the work that led to the “state” concept for sands. And then of course, we had to spend more $ (driven by our clients). First was a high level, state of the art data collection system called GDS – automated data collection, programmable for a huge range of tests. Excellent systems but remember, data collection is only useful as long as you know what data you want (i.e. you are calibrating your constitutive model – how you think the soil will behave). There is no point in measuring behavior of soils if you don’t anticipate the outcome – you have to think before you test.

Then of course we embarked on our most adventurous development – a cone calibration chamber which turned out to be a magnificent success. At the same time we did prototype testing – for example, ice sheets ploughing into sand islands.

Photo 1: Some of our laboratory testing equipment (Left - early load controlled liquefaction cell; Upper Right – modified triaxial cell to measure dielectric changes during test; Lower Right – GDS computer controlled cell for any stress path or cyclic testing)

When spray ice island construction became of interest for offshore arctic exploration, we built a temperature controlled cold room and carried out testing to determine the properties of spray ice. We were also closely involved with the construction and monitoring of the performance of the in-place spray ice islands (Photo 2 shows Dennis Becker and Ken Been making measurements on a spray ice island – handsome young chaps that they were at the time!!). Spray ice resulted from spraying sea water high into the cold Arctic air using high pressure pumps (Photo 3). High in the air, the sea water formed droplets and salt was exuded from the water droplets to form pure water ice particles with a melting temperature of 0°C. The sea water was at a temperature of -2 to -3°C so the pure ice particles, when they came in contact with the sea water did not melt. Spraying tons of sea water/minute into the frigid air to form pure ice particles which fell onto the ice sheet led to the formation of an ice mass which eventually founded on the sea bottom and then we could build it up to form a drilling platform (Photo 4).

Photo 2: Dennis Becker and Keen Been installing instrumentation on a spray ice island (December 1985)

Nothing was known about the behavior of spray ice but as we determined from cold room testing, it behaved much the same as any granular material except it was pretty “creepy” and had a high cohesion. However spray ice islands would have been recognized with an environmental award in later decades – in the spring when everything had been removed from the drilling platforms, they would drift away during the summer and melt back into the ocean. I believe that the spray ice concept was initially developed in northern Saskatchewan in the early 1950s to produce potable water from brine water on land. The cold room we used for spray ice testing was later used to investigate the effect of cold temperatures on clay properties and for research into pipelines in frozen ground. Good research testing equipment is essential for taking on state of the art work in any area of geotechnique.

Photo 3: Constructing the Mars spray ice island (January 1986)

Photo 4: The first exploration well drilled from a spray ice island was from the Mars spray ice island (Early 1986)

Through Arvid Landva who spent a sabbatical year with us in Calgary in the mid-1980s, we even did fundamental research into the geotechnical behavior of domestic refuse, samples of which Arvid had collected from all across Canada. We had to build a tent-like structure in the parking area behind the office to do this work – the smell was awful!!

In fact, there was nothing we wouldn't take on – and frankly, we felt there was nothing we couldn't do.

3.0 THE BEAUFORT SEA WORK

3.1 Exploration Methodologies

The Beaufort Sea is the extension of the oil and gas rich geological corridor that extends from the Gulf of Mexico northward through Texas, Colorado, Alberta, into the MacKenzie Valley and offshore onto the Beaufort Sea shelf. Millions of years ago this corridor was low-lying land which became inundated and formed a shallow sea. Hugh quantities of organic matter (e.g. including many of the world's population of dinosaurs) as well as all sorts of vegetation was trapped in the seabed and formed the basis of the oil and gas deposits along the corridor as the organic deposits were buried by deposition of soils which were subsequently converted into rock formations.

Since the MacKenzie River drains the largest area in Canada, there has been significant deposition of soft soils on the bottom of the Beaufort Sea. These deposits typically directly overlie relict permafrost soils and soils that had been exposed to the atmosphere during ice age when the global sea level was much lower than it is now.

In the 1980s, the Beaufort Sea was ice covered for about 9 months/year – obviously this is changing due to global warming. The ice sheet was typically about 1 m thick at the end of the winter, but included much thicker rafted first year and multi-year ice ridges. Thus it was not possible to use conventional drill ships for hydrocarbon exploration in the off-shore Arctic which continued across the Canadian/US border into the North Slope of Alaska.

There were 3 major oil companies exploring in the Canadian Arctic in the 1980s. Esso (Imperial) had on-land and near-shore leases in water depths up to about 15 m. Esso had been producing oil from their Norman Wells field in the Mackenzie River since before 1939. Gulf Canada's offshore leases were in the 15 m to 40m water depth range while Dome had the deepest water leases, typically 30 m to perhaps 50 m (Dome's Nerlek island was the then limit for islands in about 42m water depth).

Gulf and Esso were our main clients in the Arctic exploration work. We did little work for Dome. I never really understood why it was Gulf/Esso vs. Dome but that was the environment we operated in. Much to our benefit, there was serious competition between Gulf/Esso and Dome in relation to geotechnical issues. This led Golder to be in conflict with EBA and U of A – the "bun-fight" I referred to earlier. This conflict peaked when an exploration island (Nerlerk) that Dome built in deep water failed. Dome (and its consultants) claimed that the failure was the result of static liquefaction of the sand fill. Gulf/Esso challenged this interpretation since if this was really the case, hydraulic sand fills could not be relied on to provide support for their exploration structures. If they accepted Dome's explanation, that would shut down all exploration in the Beaufort Sea. Gulf and Esso's blistering response was rapid and well documented in our response published in the Canadian Geotechnical Journal (Been, Conlin, Crooks, Jefferies, Rogers, Shinde and Williams-Fitzpatrick, 1987).

Exploration in the Beaufort Sea was carried out from ice resistant islands which took several forms. In their shallow near shore leases, Esso built sacrificial beach islands sometimes using gravel if it was available or more frequently, sand. The term "sacrificial" relates to erosion of the beach during summer storms – the beaches were designed to be sufficiently robust and extensive so that erosion would not encroach on the drilling area. Esso also had a "necklace like" steel structure which they could tow out to a site where it was linked up in a "circle", founded directly on the seabed and filled with sand. This was the first caisson island used in the Beaufort Sea and Hugh Golder worked on this project in the 1970s. Golder did do other work in the Arctic in the 1970s and early 1980s, mainly projects carried out by our Vancouver office.

Gulf could not build sacrificial beach islands in their deeper (10 m to 30 m) water leases. Instead they developed a fixed steel structure (a caisson) called the Molikpaq (the Mobile Arctic Caisson - "MAC") shown on Photo 5.

Photo 5: Gulf's Mobile Arctic Caisson (MAC) deployed in the Beaufort Sea

The MAC was floated from site to site and founded on undersea sand berms. The corners of the MAC were cut off so it was really like an octagon with 4 long sides and 4 short sides. The MAC was "hollow" inside and when it had been set down on the undersea berm, it was filled with sand to provide resistance to lateral ice loading. Since this structure had a fixed height 8 m above water and 21 m below water, the different water depths at the exploration sites was accommodated by varying the height of the undersea berm.

Dome used a structure similar to the Mac called the SSDC (lovingly referred to as the Single Season Detoxification Centre – the arctic was "dry", no rum rations). The SSDC was a fully developed structure without a hollow center – like a ship (it was a converted oil tanker) which was floated to a site and set down on a previously prepared undersea berm.

With a drilling area about the size of a football stadium, it is clear that the construction of islands and undersea berms required the dredging and transport of millions of cubic meters of sand from the ocean floor – the volume of sand for berm construction depended on the water depth. It is very important to note that the side-slopes on islands were very flat, in the order of 15 to 20H:1V. The island construction work was carried out by Volker Stevin, a Dutch dredging firm using a fleet of dredges and split bottom barges. Material was either dumped through the water column from the split bottom barges or pumped hydraulically into the water to form the required structure. Beaver Dredging (Boskalis/Westminster) were also involved in island construction.

The arctic exploration work was all carried out before the age of a rigorous environmental assessment process. Given the nature of the cutter suction dredges that were used, I can't imagine how many fish were sacrificed to build an island. Also, when the islands or berms were abandoned, they were not excavated back to the sea bed; instead they were simply left to erode. Given the wave regime in the Beaufort, erosion likely only removed the upper 5 m of the island/berm. So there are quite a few subsea islands right across the region which will lead to interesting navigation issues in the future.

A company from Vancouver, Foundex, provided the majority of geotechnical site investigation services from a rig mounted on the MV Frank Broderick (Photo 6).

Photo 6: The Frank Broderick (Summer 1981)

The development of the site investigation techniques used in the Beaufort Sea deserves a paper of its own. This is particularly true of the CPT set- up which as described below, became the main source of information for design and understanding of the in-situ state of hydraulically placed sands. As is the case in every aspect of this endeavor in the Arctic, the irrepressible entrepreneurism, unbounded enthusiasm and ability of Foundex's president, Dennis Diggle played a large part in the development of a world class site investigation capability in the Canadian Arctic. If ever there was an unsung hero of the arctic work, it is Dennis. Dennis was ably supported by a cast of enthusiastic drillers and a "wacky" Englishman, Mike Rowlat, an ex-paratrooper who had certain military values that were quite helpful in carrying out work in remote areas. Mind, some Foundex employees gained first-hand knowledge of this when en-route to the offshore, failed to realize that Edmonton was not in the same time zone as Vancouver and missed their flight to Tuktoyuktuk leaving their fellow drillers on the Broderick for yet another week.

3.2 The Geotechnical Challenges

Obviously, the construction of major structures in such an extreme environment as that which exists offshore in the Arctic brought many major engineering challenges. Largely these problems were not part of our mandate. Our role related only to the geotechnical aspects of offshore projects but it should be appreciated that in most cases, the geotechnical aspects of island construction were front and center issues on which the success (and defensibility) of the overall exploration approach depended.

A major consideration in the construction of exploration islands using hydraulically placed sands was that not much was known about the behavior of these materials. Dams had been constructed in this way previously with some well documented failures mainly as the result of seismic activity (for example the Lower San Fernando Dam). The main issue with sand island construction was the state of the material when placed. If the sand was in a dilatant state, static liquefaction would not occur. On the other hand, if the sand was in a contractive state, static liquefaction could occur.

Conventional thinking at the time was to represent the state of a cohesionless material (sand) in terms of its relative density. The problem is that relative density is a notoriously imprecise way to define the state of a material such as sand and it is impossible to measure the relative density in-situ in an undersea berm. Further relative density does not capture stress level and therefore cannot fully describe the state of sand. Correlations such as that shown on Fig. 2 are next to useless.

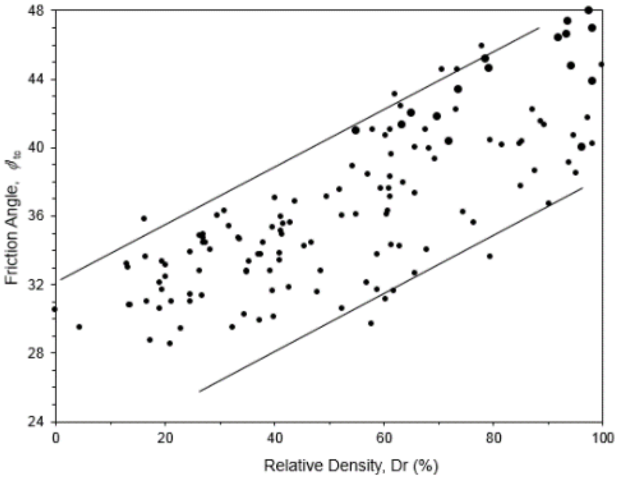


Figure 2: Relative Density vs. Angle of Friction (Crooks, 1990)

There were two schools of thought in terms of representing sand behavior in the 1980s. The western US school was largely based on the response of sand to cyclic (seismic) loading while the eastern approach was based on liquefaction under static loading. While static liquefaction was clearly important in Beaufort Sea structures, repetitive ice loading even at low cyclic stress levels over a long period was a real issue; there is no seismic activity to speak of in the Beaufort Sea area. In fact the Molikpaq almost succumbed to repetitive ice loading at the Amauligak site when a stubborn multi–year ice ridge pounded the structure. By the time the ice ridge fractured and passed by the caisson, about 15% of the sand core had liquefied. Another 15 min. of dynamic loading would have seen the MAC pushed off the berm and onto the seabed. The monitoring record related to this event has been made public and represents a very importance contribution to both the soil and ice mechanics fields. An overview of this event can be found in Jefferies, M.G. and Wright, W.E. (1988) – Appendix 1. For those interested, a few of the relevant papers and the data itself can be found on the Golder Foundation website in the Molikpaq Case History folder under Jefferies and Been (2015) and in Jefferies and Wright (1988) in Appendix 1.

A “Joint Industry Project” was set up to understand how such ice loads could develop. The ice loads were viewed as unprecedented although, as often the case, there was ample but dismissed comparable behaviour from twenty years earlier in the Alaskan Cook Inlet experience.

Another aspect that caused concern regarding sand island performance related to the criteria to be used to control the placement of the material. The sands used from different sea floor borrow areas had different gradations and mineralogy. Also the results achieved (i.e. the in place state of the sand) using different methods of placement were not known.

The second issue related to the weak, unfrozen cohesive deposits that formed the seabed across much of the Beaufort Sea. Island construction directly on these recent, unfrozen MacKenzie River deposits meant including a weak layer into the foundation of the structure which could pose a threat to its stability as happened at Nerlerk. While there was fierce discussion, it was thought by the Gulf/Esso faction that the failure of the Nerlerk berm was the result of failure through the sea-bottom clay layer. Pre-excavation of these weak materials at the surface of the sea-bed, was an expensive proposition. The state of the art in terms of understanding clay behavior was much more advanced than was the case with sand. However, the Beaufort Sea clays were difficult to characterize because they exhibited a very rounded “e-log p” curve in consolidation tests. When a clay exhibits a sharp “e-log p” curve, it is simple to determine pre-consolidation pressure and OCR, but this is not the case for rounded curves.

Monitoring of the porewater pressures in the soft unfrozen soils below some of the early caisson structures also indicated some unusual behavior that required investigation. For example, porewater pressures would continue to rise for long periods after loading was complete. This required explanation – were we dealing with a very unusual soil?

3.3 State Concept for Soils

The “state” of a soil refers to the physical conditions under which it exists – for soils, the important physical conditions which control its behavior are void ratio and stress conditions. Since different soils have different mineralogical and geochemical characteristics as well as having been deposited by different mechanisms in different environments, two soils at the same state will not likely exhibit the same behavior. For example, highly structured soft clays which exhibit extreme strain softening behavior will exhibit different behavior than non-strain softening clays.

Knowing the void ratio and stress level is not enough to quantify state…..these must be related a reference line in a “void ratio – stress” space. This is relatively straightforward for clays – traditionally, the virgin consolidation line (VCL) has been used for this purpose and the state of clays has been described in terms of over-consolidation ratio (OCR) as shown on Fig. 3.

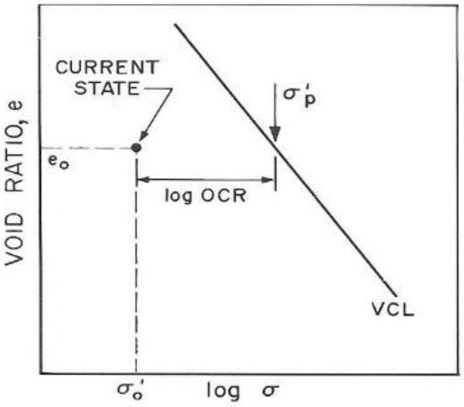


Figure 3: Definition of the state of clays (Becker, Crooks, Been and Jefferies, 1987)

The MIT SHANSEP concept (*Ladd*, C. C, and *Foott*, R. (*1974).* "New design procedure for stability of soft clays." J. Geotech. Engrg. Div., ASCE, 100(7), 763-786) is based on this approach and uses OCR as a normalizing parameter to describe the behavior of clays. An alternate reference for clays is the critical state line which is defined by the void ratio and stress condition at which critical state is achieved during shear. This approach was embodied in the critical state concept put forward by Casagrande in 1935 for the construction of Franklin Falls Dam (NH) and which eventually resulted, after various other contributions, in what we know today as the complete framework for soil behavior as "critical state soil mechanics". It is noted that the VCL and CSL are parallel. For clays, we chose the VCL to quantify the state of clays and defined the state of clays in terms of OCR.

The situation was not as simple for sands. The concept of a single virgin consolidation line does not apply to sands. However, the steady state line (SSL) is a repeatable and measurable behavior. Steady state is defined by the void ratio – stress condition at large strains following static liquefaction. We used the SSL to quantify the state of sands and referred to the state of sands in terms of state parameter, ψ (Fig. 4). This was a very fundamental contribution to the state of the art in soil mechanics. If the sand lies below the SSL, the sand is in a dilatant state; if it lies above the line, it is in a contractive state and subject to static liquefaction.

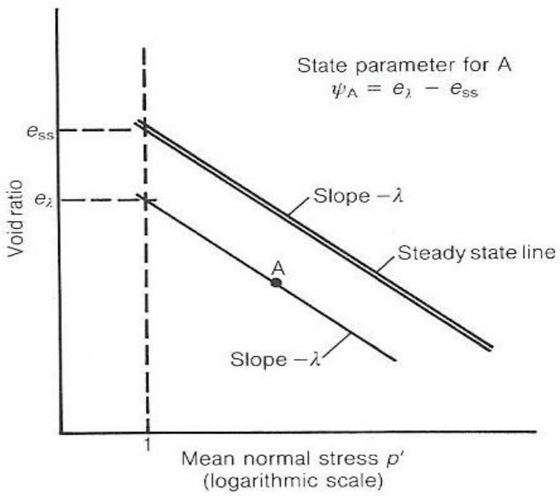


Figure 4: Definition of the state of sands (Been, Jefferies, Crooks and Rothenburg, 1987)

The determination of the SSL for a typical Beaufort Sea sand (Ersak sand) used to construct islands is shown on Fig. 5. The results are from static liquefaction triaxial tests on "loose/contractive" samples and from normal strain controlled triaxial tests on "dense" samples. The SSL was well defined for all sands we tested.

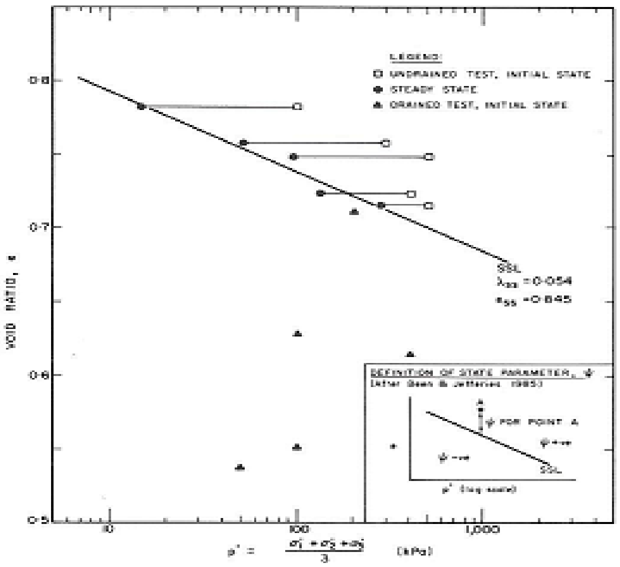


Figure 5: Steady State Line for Ersak sand (Been, Lignau, Crooks and Leach, 1987)

Fig. 6 shows the SSLs for a variety of sands. The difference in the SSLs is quite remarkable and is the result of different mineralogy, compressibility etc. of the different materials.

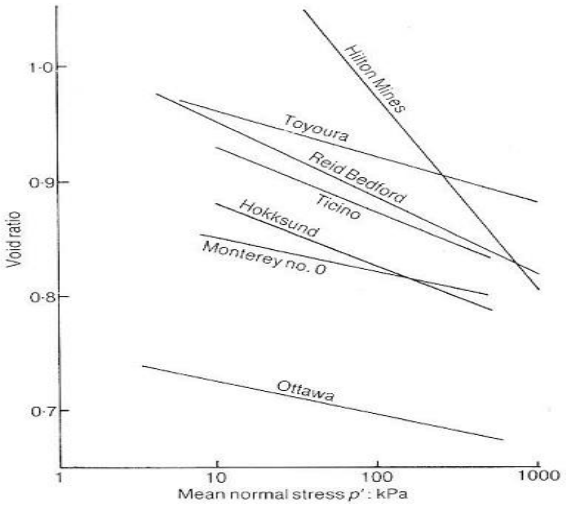


Figure 6: Steady state lines for various sands (Been, Jefferies, Crooks and Rothenburg, 1987)

It is noted that the use of the SSL to quantify the state of sands required very sophisticated laboratory testing. Also, determining the OCR for clays such as those found in the Beaufort Sea which exhibit a rounded void ratio – stress curve, was equally difficult. So laboratory testing and interpretation of results was a major aspect of the work we carried out and this is discussed in more detail below.

From an early stage we adopted the integration of all three geostatic stress directions in the interpretation of our laboratory and field data. As demonstrated in a later section, this proved to be important.

3.4 Soil Behaviour in terms of State

As noted above, OCR has been used to describe clay behavior for a long time and there is no need to repeat this basic information. A more refined description of clay behavior incorporating a better definition of pre-consolidation and lateral stress is provided in a later section.

Fig. 7 shows the relationship between ψ and the effective angle of friction (Φ') for a wide variety of sands. While there is some scatter, it is relatively modest and a very significant improvement over the relationship between relative density and the effective angle of friction (Φ').

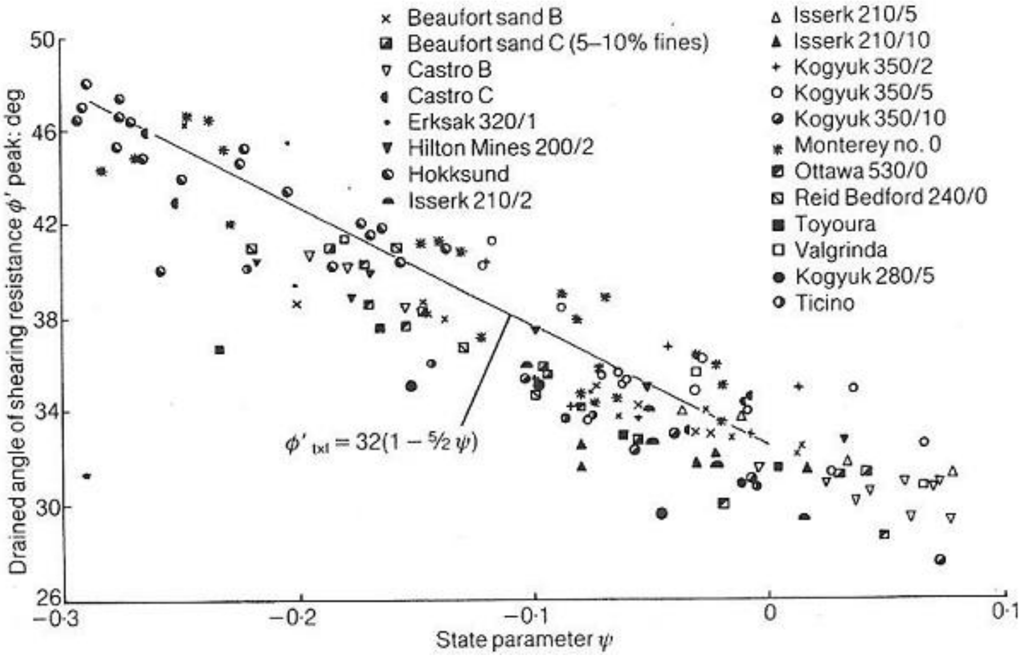


Figure 7: Effective friction angle vs. state parameter for a variety of sands (Been, Jefferies, Crooks and Rothenburg, 1987)

Further, as shown on Fig. 8, the dilation rate for the same sands is well described by state parameter.

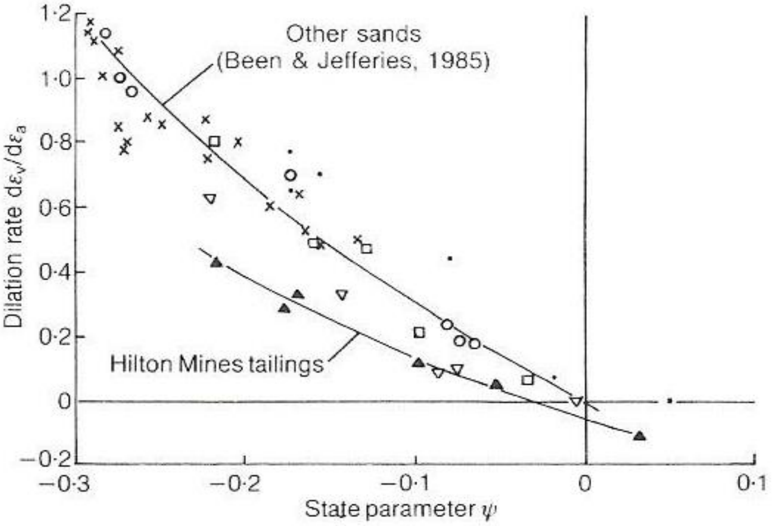


Figure 8: Dilation rate vs. state parameter for various sands (Been, Jefferies, Crooks and Rothenburg, 1987)

The usefulness of state parameter in describing the behaviour of sands in undrained triaxial tests is also shown on Fig. 9

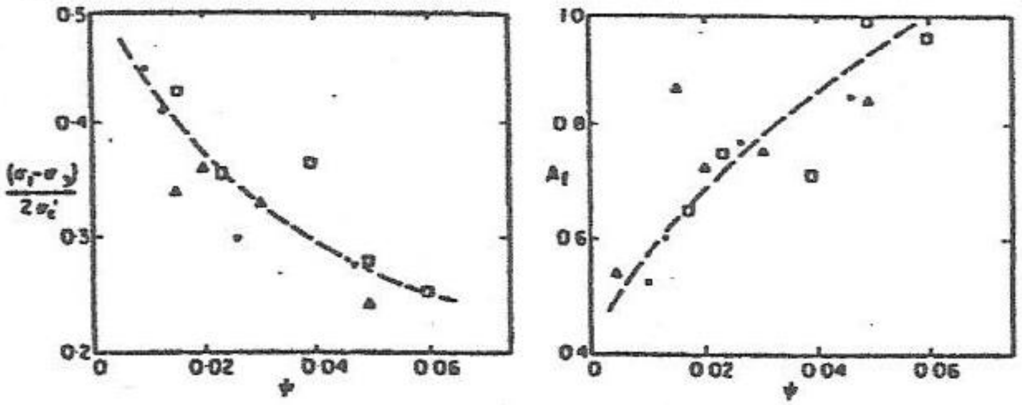


Figure 9: Undrained behavior of sands in terms of state parameter (Crooks, 1990)

Testing programs on a wide variety of cohesionless soils has demonstrated clearly that state parameter is a very reliable indicator of sand behavior. The range of materials investigated included a wide variety of natural sands (including published data by other researchers), oil sand tailings, coal tailings and many other tailings materials.

3.5 In-Situ State of Sands

By the time we understood that we had the right approach to characterizing sand behavior, we realized that this was insufficient. We could use state concepts to predict the behavior of sand if we knew the state of the sand. The problem was – how do we measure the state of the sand in place? It is virtually impossible (or ridiculously expensive) to retrieve acceptably undisturbed samples of cohesionless soils. The answer obviously lay in the direction of in-situ testing….if we could make an in-situ measurement that could be related directly to the in-situ state (ψ) of the sand, we were done.

The common approach to defining the state of materials in-situ at the time was the Standard Penetration Test (SPT) with its various correction methodologies. The SPT is a very imprecise measurement tool and is only really useful as a "gross" level of characterization albeit one does recover a disturbed sample. The SPT is also a very challenging test to attempt from the moving deck of a drillship. The Cone Penetration Test (CPT), on the other hand, provides measurements with much greater precision and repeatability. Further, the CPT is a "doable" test in the offshore – indeed the CPT is the offshore standard.

The problem was - how to interpret CPT results on different soils in terms of state? The answer was – build a calibration chamber and get at it – a very Calgary attitude at the time!! Only a few (6) CPT calibration chambers existed world-wide at the time and they were in university laboratories. So we did what we had to do – we built our own calibration chamber (Photo 7). This was a remarkable achievement but we had staff who were eager and sufficiently capable at research work to do it. The problem was….we didn't have the money to support such a venture. However, we had trustworthy clients who said – "build it and we will use it" – they were already committed to the state concept and were major contributors to the science.

The design of our chamber was based on the published accounts of other similar chambers taking into account size vs. practical constraints, stress levels that could match field stresses and most important, the capability to manage the placement of a couple of tons of sand at a very specific void ratio. Our chamber was 1.4 m in diameter and 1 m high, and could be operated at about 300 kPa. The pressure was applied through a membrane, much like in a triaxial cell. We had to learn how to make our own latex membranes big enough, thick enough and strong enough for this work.

It worked with the capable support of such notables as Al Gosselin – don't forget that we were already well experienced in the laboratory testing area – this was just a bigger test!!

Photo 7: Golder's CPT calibration chamber

Within a year or two, we had substantially added to the CPT calibration information available to the world at that time and of course we established the fundamental relationship between CPT tip resistance and state parameter. We demonstrated this using a wide variety of sands and mine tailings including Erksak sand from the Beaufort Sea, Syncrude tailings sand and Ticino sand. We also developed SSLs for sands on which others had carried out CPT calibration tests so we could develop state parameter – CPT tip resistance relationships for these materials (Fig 10). Also included in in the following figures are the correlations that we developed between CPT tip resistance and the state of silt and clay materials. Since we knew the in-situ state of clays based on laboratory tests, we could construct the CPT vs. state correlations for silts and clays without the use of the calibration chamber. The result is an integrated approach to determining the in-situ state of soil of any type using the CPT – a truly remarkable achievement.

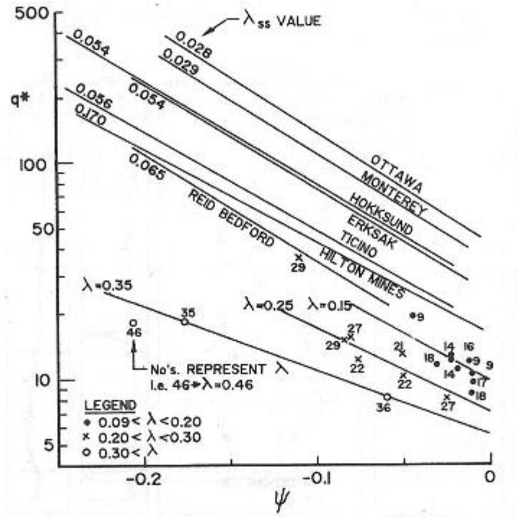


Figure 10: Normalised CPT tip resistance vs. state parameter for sands, silts and clays (Been, Crooks and Jefferies, 1989)

As noted previously, our interpretation of soil behavior in terms of state included adopting a stress description which included both vertical and horizontal stresses (i.e. σ'_m as opposed to vertical stress only). As described in the next section, this was particularly important for clays.

Based on the available data set, we were able to develop a normalized relationship which captured essentially all of the CPT calibration data as well as relationships for silts and clays:

$$(q_c-p)/p' = k^*\exp(-m^*.\psi)$$

where m is the slope of the normalized $q_c - \psi$ relationship and k is the normalized value at $\psi = 0$.

The parameters k and m were related to Λ_{ss} which is the slope of the steady state line (Figs. 11 and 12) and led to a $q_c - \psi$ relationship based on I' and Λ_{ss} Thus, knowing the CPT tip resistance, the overall stress state and the SSL we could define the in-situ state of the sand. For silts and clays, we used the VCL slope in lieu of the slope of the SSL – after all, they are all parallel.

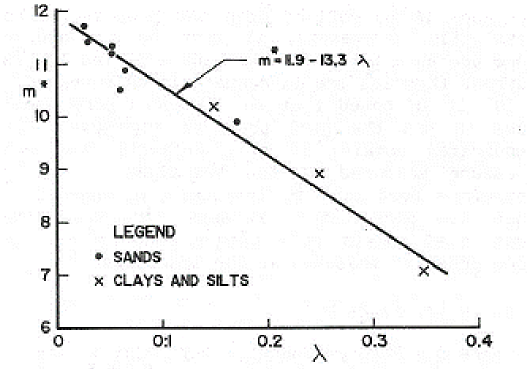


Figure 11: m* vs. state parameter for sands, silts and clays (Crooks, 1990)

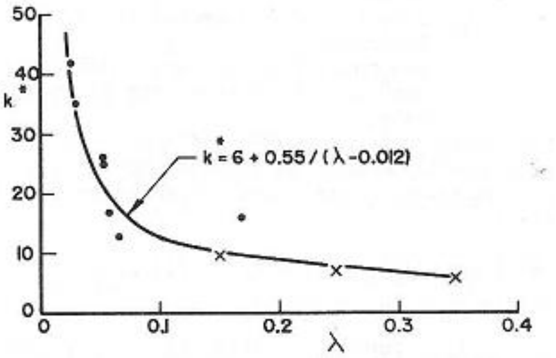


Figure 12: k* vs. state parameter for sand, silts and clays (Crooks, 1990)

Now we had the ability to reliably measure in situ state of any material and together with Foundex who actually had to push the cones from a ship-based platform, we established the ability to determine the in situ state of the sands which were used to construct the islands in the Beaufort Sea.....this was a unique achievement. We now had the basis for a defensible design of hydraulic sand islands.

3.6 Formalizing the Ideas (the Math behind the state concept)

Our advances in understanding the behavior of clays largely fell within existing frameworks. For example, SHANSEP was well accepted but we added detail such as the importance of including Ko in the interpretation of both laboratory and field tests. Creep was also a well-known aspect, albeit with less in the way of standard approaches – we didn't contribute much in this area. Stress-path dependence as well as using the Effective Stress Path/Yield Envelope (ESP/YE) approach (Folkes and Crooks,

1985) approach to interpret the field behaviour of foundation clays under loading was also widely accepted. The same cannot be said of our framework for sands.

In the 1950-60s there were two significant ideas in soil mechanics: the Cambridge idealization we know today as Cam Clay and the Manchester work related to stress-dilatancy. One was derived from the ideas of thermodynamics while the other was derived from micromechanics. Each group viewed their approach as more fundamental and much "throwing of buns" resulted (have a look at the Roscoe Memorial Symposium – "robust" discussion does not do the exchanges justice!). Anyway, it was common parlance in the UK during the 1970s that 'dilation should scale with distance from the critical state', in essence linking the two competing fundamental approaches. Parry (one of Bishop's PhD students) even provided an explicit figure showing such data for clays, but it all got ignored. Our insight was simply to apply what others were loosely discussing.

Strictly speaking though, even well-established empirical trends do not prove basic understanding. One needs to dig deeper and have some basis in applied mechanics, however idealized, to explain why the trends should develop in the first place. In the vernacular, one needs to "do the math". And here we ran into a bit of an impediment with the collapse in oil price of 1986 – much of our testing work evaporated as did budget sources for "thinking"…. but, that was not the end of the story.

In terms of the Golder part of the continuing story, action moved from Calgary to GAUK with three of us winding up there in the 1990s (Crooks, Been and Jefferies). There was also a push from the US National Science Foundation who funded our participation at various workshops and conferences and kept us in the game when otherwise we might have been forced to move on to other things. In reality, when the Arctic work came to a halt in 1990, the triaxial version of 'the math' existed although it took a few years for it to see the light of day in Geotechnique. That development paved the way for our contribution to cyclic liquefaction for the NSF funded VELACS study (multi $million, multi organization) of which Golder (our team) was the only Canadian group. We then went further and anchored our CPT method in soil mechanics. Thus within a decade of the Arctic work going on ice we had put the mechanics behind the observed trends and that led to the invitation to Jefferies and Been to write "the book" (Jefferies and Been ,2006,) see Appendix 1 for full reference.

But, the ideas of the state parameter were indeed fundamental and it was not just us who pushed the mathematics behind the idea forward. While our version of the mathematics made it into the literature first (just), the idea that the state parameter could unite theoretical plasticity and soil micro-mechanics was recognized by many groups – perhaps Yannis Dafalias and his co-workers at UCal Davis being the most influential with their incorporation of the ideas into Bounding Surface plasticity. Today, there are about ten state-parameter based models and the approach has become the dominant methodology for representing soil behaviour (the various models really only differ in the details – after all, they are all trying to predict the same stress-strain behaviour).

Why the attraction for the state parameter? Simply put, years ago there would be a different set of soil properties for each density (and sometimes each stress level) of a sand – and that is before we even mention silt content. The state parameter concept enormously simplified the situation with just a few properties being sufficient to represent sand behavior, drained or undrained, triaxial compression through to plane strain (indeed any loading path): we now predict the effect of void ratio and stress level on that behaviour using just a few properties. And that is why the state parameter paper is one of the most referenced papers of the past thirty five years in Geotechnique.

3.7 Liquefaction

Perhaps the biggest contribution to the soil mechanics world that came from this work was in terms of sand liquefaction. The subject was relatively new at the time, and was dominated by two schools of thought. The first was what we can think of as the Berkeley School, applied to liquefaction during earthquakes, under the leadership of Prof H. Bolton Seed. They were interested in the phenomenon related to earthquake loading, and because of the complexities involved developed a largely empirical approach based on SPT N values. The second approach was the Steady State School, led by Prof A. Casagrande and Dr. G. Castro, and Dr. S. Poulos on the east coast of North America (Harvard and MIT). The Steady State School was more interested in static liquefaction, as observed for example in Fort Peck Dam in the 1930s. In the late 1960s Castro had succeeded in reproducing liquefaction in laboratory triaxial tests and was able to measure the steady state (or critical state) line talked about earlier. Their thought was the steady state provided an assured minimum strength of liquefied sand (regardless of whether it was caused by static or cyclic loading.) The problem was that the two Schools could not agree on some case histories, especially the Lower San Fernando Dam. There was another bun-fight going on south of the border over liquefaction, which really needed our critical state method based on the mechanics (or maths) insight we had initially with the state parameter concept.

The US bun-fight was actually not that different from our own Canadian one - both could be boiled down to two related questions. What is the in-situ state of the sand? What is the post-liquefaction strength? The strength issue was not too controversial, but the strength had to be related to the in-situ state which in turn was determined by the SPT (Berkeley School), laboratory testing of "undisturbed" samples (Steady State School) or the CPT (Canadians). We had the solution!

Our work started largely empirically with recognizing the state parameter as a reference condition, and then concluding that the CPT must also be measuring state more so than it measures anything else. But the theory took a lot longer than the 1980s, although we certainly knew we were on the right track. Leo Rothenburg's particle mechanics (or "peanut mechanics" as we called it in reference to the shape of the particle contact distributions) was confirmation of this, although the theoretical developments were naturally in the line of critical state soil mechanics and stress-dilatancy - partly because of CSSM becoming mainstream and partly because the maths and numerical implementation was more tractable with the computing power available at the time.

By about 1995 (long after the team in Calgary had moved on to other parts of Canada, UK, USA and Germany) we had the main pieces of theory together. We had NorSand (Jefferies, 1993), and we had sorted out the CPT testing (Shuttle and Jefferies, 1998) and we had contributed cyclic modeling of liquefaction to the VELACS project. In addition, we had published widely on the state parameter, critical state line of sands, CPT interpretation and the Beaufort case histories. So when Mike was asked about writing a book about some of it, we were rather enthusiastic. This was partly to document our ideas in one location, and capture the unique data set we had accumulated. But it would also be good PR for Golder and what we had achieved in Calgary in the 1980s. Maybe "ego" came into it as well. It was a long path to final publication, but "Soil Liquefaction: a critical state approach" (Jefferies and Been, 2006) was finally published by Taylor and Francis. Yes, it was about 10 years from concept to reality!

Soil Liquefaction is now (2015) a widely cited textbook, confirming our thought that getting it all in one place was a good idea. So much so, that in 2011 Taylor and Francis asked if we would consider a second edition. "It won't be so much work this time." It turned out to be almost as much work, as we updated a lot with data from tailings projects we had worked on in the interim period, the whole cyclic liquefaction chapter was rewritten with new material and added the numerical implementation with the help of Dawn Shuttle. The 2nd Edition will hit the streets in October 2015.

We have used the state parameter, NorSand, and all that goes with them to address liquefaction problems in our consulting practice since the 1980s. Perhaps the first application outside the Beaufort Sea was when we were commissioned by ZCCM to look at inflow of surface tailings into the underground at Mufilira (there had been a major disaster there about 12 years earlier, and clearly that could not be repeated.) We also managed to convince the Hong Kong Government Geotechnical Engineering Office (formerly GCO, now GEO) that they could use our advice and participated in a large study of hydraulic fills they sponsored at the local university. This resulted in several consulting assignments for the infrastructure that was being built before the 1997 handover, all of which involved hydraulic fills and reclaimed land. We worked on mass transit railway lines (cut and cover tunnels in reclamation), stations (deep excavations in the same fills), a hangar at the new airport, amongst other projects.

But the application to tailings is perhaps more important, because tailings tend to be silts. And the empirical methods of liquefaction assessment and CPT interpretation are for sands with "a little bit" of silt. A "fines correction" is applied to take silt content into account. But when more than about 30% of the material is silt, this all breaks down (and many fine tailings are almost pure silts). So "state parameter" has been applied to tailings projects across Canada (BC, Alberta, Ontario), Portugal, Chile, Peru, Argentina, the USA, Kyrgyztan, South Africa, Australia, and likely many more countries.

Carbonate sands have a reputation for being different and "difficult". We always thought state parameter should work for carbonate sand just as well as it does for mainly quartzitic sands. Finally, in 2013/14 we were able to prove it very nicely when Ken was asked to be on a 3 person review panel for the Upper Zakum artificial islands offshore Abu Dhabi. The review panel essentially used lots of testing and the state parameter to resolve the contractual disputes (revolving largely around the fact that relative density couldn't be measured).

4.0 CLAY BEHAVIOUR

4.1 "Rounded" behaviour of Beaufort Sea clays

Clays that exhibit defined distinct yield behaviour (e.g. a pronounced break in a void ratio – stress consolidation curve or a clear peak in a stress strain shear test) are easy to interpret in terms of values to use in design. However, many clays exhibit less distinct behaviour (i.e. rounded void ratio – stress consolidation curve) as is the case with Beaufort Sea clays and definition of the strength and yield stresses in these materials is difficult.

To solve the problem of defining yield stresses in Beaufort Sea clays, we adopted the strain energy approach (a.k.a. work/unit volume) in the interpretation of oedometer consolidation tests. Crooks and Graham (1976) had introduced this approach for the interpretation of triaxial tests. In this approach the strain energy accumulated during primary consolidation for each load step is cumulated and plotted against the loading stress. Both quantities were plotted on arithmetic scales which removed the imprecision which accompanies the use of the traditional log stress approach. This was the first time this approach had been used to interpret oedometer test results and was very successful. For normally consolidated clay, a singular value of "pre-consolidation pressure" could be clearly identified by the intersection of the strain energy – stress line at low stress levels and the line following the pre-consolidation stress (Fig. 13).

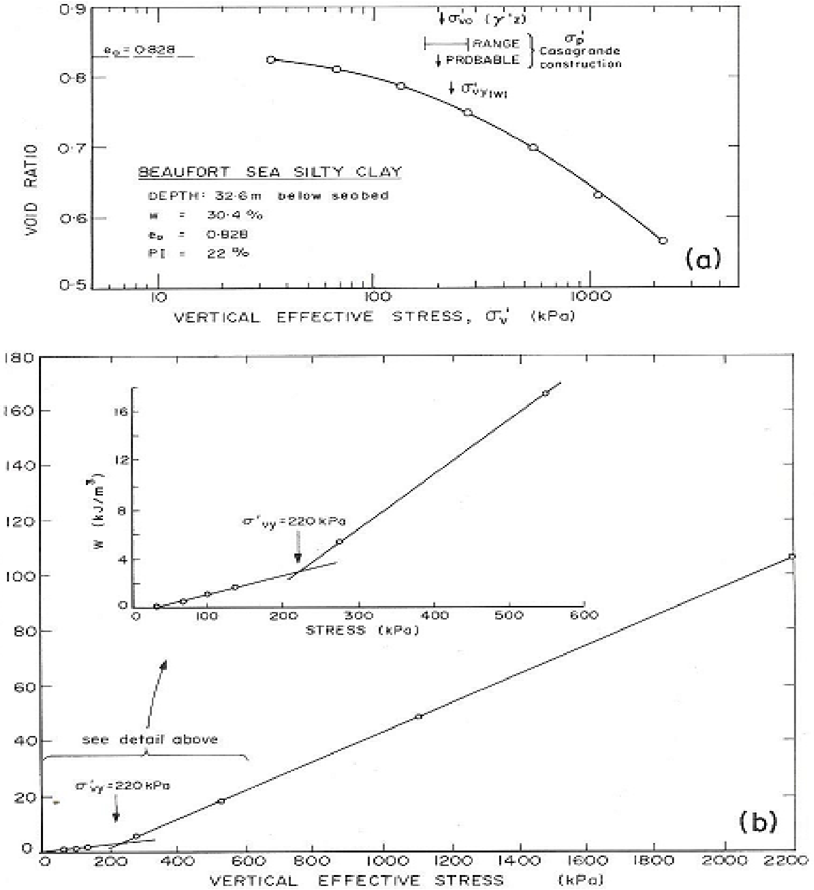


Figure 13: Work/unit volume interpretation of an oedometer test on normally-consolidated Beaufort Sea clay (Becker, Crooks, Been and Jefferies, 1987)

Together with undrained strength data from triaxial tests, we now had a clear definition of the yield envelope for Beaufort Sea clays (Fig 14).

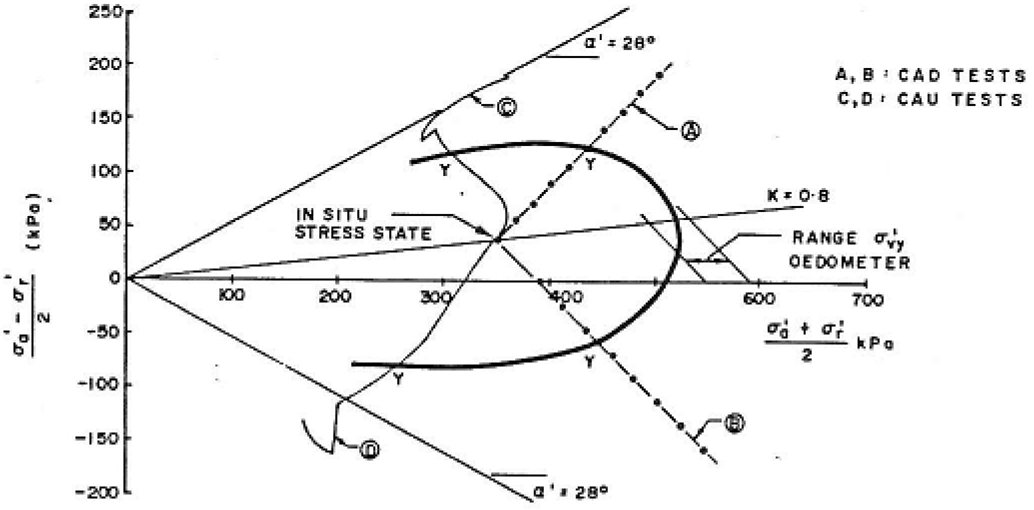


Figure 14: Yield envelope for Amauligak clay (Crooks, Becker, Jefferies and Been, 1986)

However, strain-energy interpretation of oedometer tests on over-consolidated samples (Fig. 15) indicated the existence of a third line which met the line at low stress levels at the in-situ stress. This was confirmed by comparing the in situ stress interpreted from the oedometer tests with the known value based on simple unit weight and depth calculations. Fig. 16 shows this comparison for one set of tests on samples from the Tarsiut Island site.

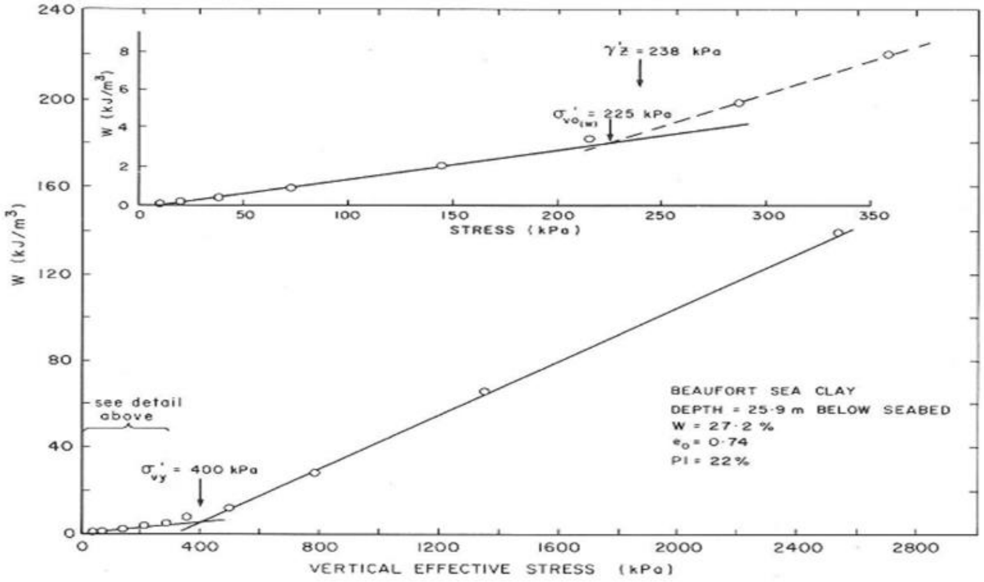


Figure 15: Work/unit volume interpretation on over-consolidated Beaufort Sea clay (Becker, Crooks, Been and Jefferies, 1987)

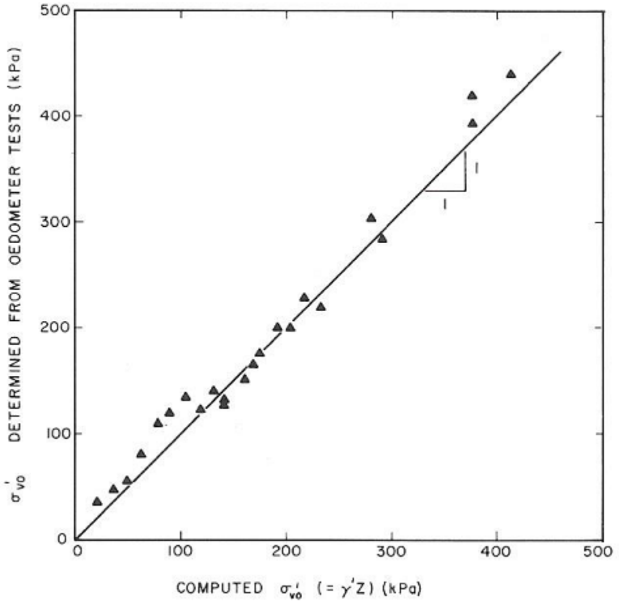


Figure 16: Computed in situ vertical stresses vs: in situ vertical stresses from oedometer tests – Tarsuit Island (Becker, Crooks, Been and Jefferies, 1987)

The intriguing question then arose – if samples were trimmed on a horizontal axis (as opposed to a vertical axis), would we see a similar result and would the "in-situ" stress point we would identify represent the in situ horizontal effective stress (i.e. could we determine Ko from oedometer tests)? The results of oedometer tests on horizontal samples of natural materials were positive in that we could identify 3 distinct lines in the strain energy interpretation on these samples. The problem was to confirm that the value interpreted from oedometer tests was the same as the actual in-situ horizontal stress – we could not calculate the in situ horizontal effective stress as we could the in-situ vertical effective stress (depthxunit weight). We initially made a comparison with the oedometer data and field measurements from in-situ self-bored pressuremeter tests at the Tarsiut site. This comparison showed reasonable agreement between the two approaches which was encouraging. As we said in the paper (Jefferies, Crooks, Becker and Hill, 1987) we wrote on the subject (I always thought this was beautifully stated!!!) ***"….both methods of measurement could be wrong. However, it is considered unlikely that both methods would be wrong by the same magnitude. Further the fact that good agreement is achieved despite the very different natures of the two test types is compelling".***

To examine this issue and also to provide further data to support the overall interpretation approach for both vertical and horizontal stresses, we prepared a slurry of Beaufort Sea clay and consolidated the slurry in flexible moulds (approximately 300 mm high and 150 mm in diameter) in a large triaxial test apparatus. We thus formed soil specimens with known horizontal and vertical effective stresses, from which we could trim oedometer samples in the horizontal and vertical directions. Some specimens were consolidated and not off-loaded (i.e. normally consolidated) while others were off-loaded to create over-consolidated materials. The specimens were allowed to only undergo primary consolidation (no secondary effects) so we knew precisely the vertical and horizontal effective stresses which had been applied to the specimens.

Vertical and horizontal oedometer samples were prepared, tested and the results interpreted using the strain energy approach. Comparison of the interpreted and known imposed "in-situ" and yield stresses shows excellent agreement (Fig. 17) and verifies the approach.

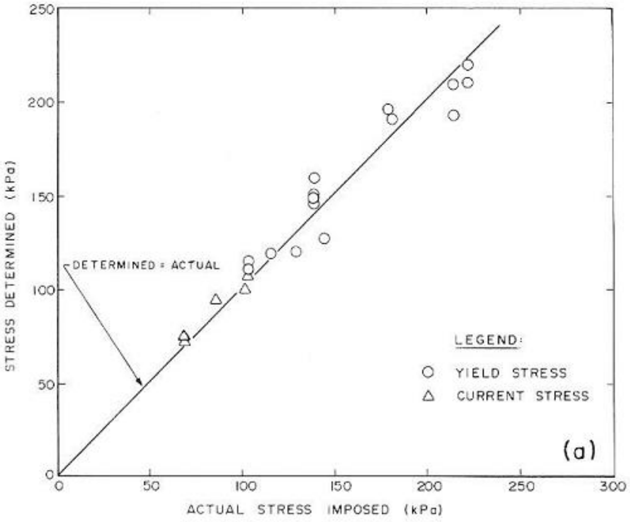
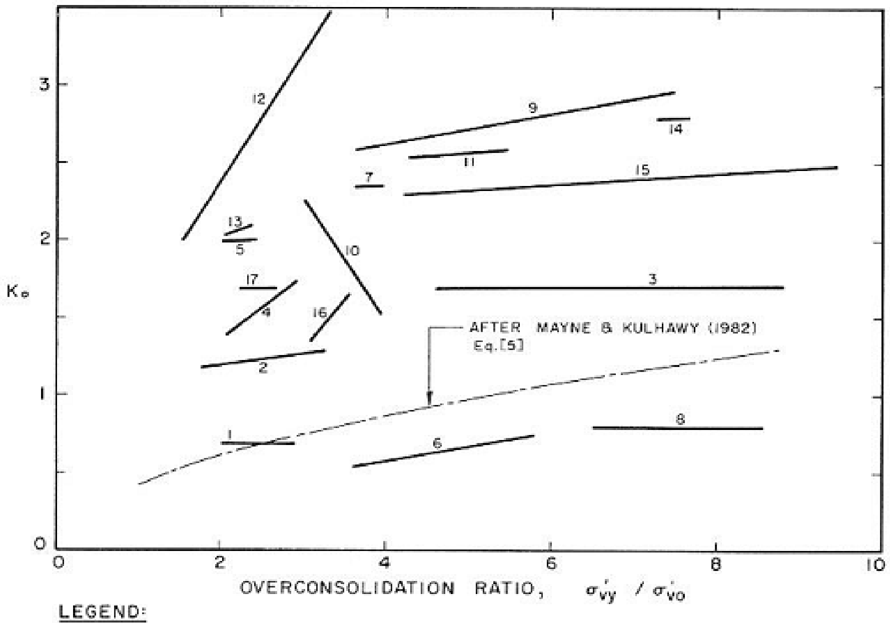


Figure 17: Comparison of known and measured in-situ and yield stresses in oedometer tests (Becker, Crooks, Been and Jefferies, 1987)

So we had provided soil mechanics with a major step forward in terms of our ability to measure and understand clay behavior, particularly in defining in-situ yield stresses and Ko. We went on to explore what we could do with this new found ability starting with an examination of Ko for Beaufort Sea clays. The results were fascinating……traditionally, it is considered that Ko was a function of OCR and Φ'. Thus in-situ horizontal effective stresses were the result of the vertical effective stresses to which the soil was subjected; for a normally consolidated clay Ko was about 0.5 but for higher OCR, the clay "remembered" the effect of the highest vertical stress (i.e. it retained a higher in-situ horizontal effective stress) and thus had a higher Ko value .

Fig. 18 shows the traditional expectation relating Ko to OCR as well as data from various Beaufort Sea sites. Clearly the Beaufort Sea data do not support the expected trend. In most cases, the measured Ko values are much higher than would be expected. The difference was explained in terms of the inadequacy of laboratory measurements (incremental testing) to define Ko and also depositional history effects. With respect to the latter, it should be noted that the Beaufort Sea was a shallow water environment when the seabed clays were laid down. Imagine watching a soil particle being deposited in such an environment. What it would experience would be shaking (sideways movement of the particles) which would build horizontal stress to a greater extent than the vertical stress associated with a shallow overlying deposit.



LEGEND:

CASE	SITE	SOIL UNIT	CASE	SITE	SOIL UNIT	CASE	SITE	SOIL UNIT
1	AMAULIGAK A-23	A2	7	AMAULIGAK I-65	A2	13	SAUVRAK G-55	B3
2	AMAULIGAK F-65	A2	8	SAUVRAK F-45	B1	14	TARSIUT P-45	A
3	AMAULIGAK F-24	A1	9	SAUVRAK F-45	B2	15	TARSIUT P-45	B1
4	AMAULIGAK F-24	A2	10	SAUVRAK F-45	B3	16	TARSIUT P-45	B2
5	AMAULIGAK F-24	D	11	SAUVRAK G-55	B1	17	TARSIUT P-45	B3
6	AMAULIGAK I-65	A1	12	SAUVRAK G-55	B2			

Figure 18: Ko vs. OCR for Beaufort Sea clays (Jefferies, Crooks, Becker and Hill, 1987)

This realization (i.e. the independence of Ko on OCR) had a number of influences on our work:

- In our interpretations of both lab and field data, we learned to use σ'm - the average of all three stresses (as opposed to simply the vertical effective stress) as a normalizing stress to account for Ko. Note that most field tests reflect horizontal stress at least to the same extent as vertical stress. For example, shear strength measured in field vane test is predominantly on a vertical surface and would reflect horizontal stress and we developed a very definitive state – field vane strength for clays with a wide variety of Ko values. The tip resistance in a CPT test is clearly affected by a 3–dimensional stress field. The results obtained from pressuremeter tests are predominantly affected by horizontal stress.
- We would not have had the ability to construct appropriate yield envelopes for Beaufort Sea clays without knowing the Ko value. As shown on Fig. 19, Ko defines the "direction" of the envelope in stress space, in this example, for a Ko =1.4 clay.
- Most importantly, our work allowed us the ability to characterize the properties of soils at any site that provided a meaningful basis for predicting soil behavior under load.

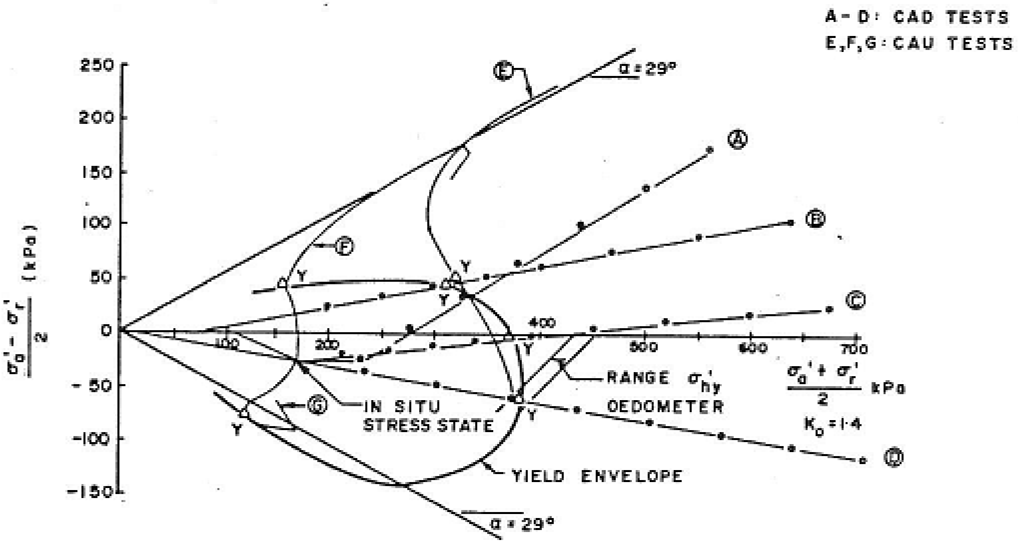


Figure 19: Yield envelope for Tarsuit clay Ko = 1.4 (Crooks, Becker, Jefferies and Been, 1986)

By this point, it should be obvious that laboratory testing is an integral component of a successful design. Figure 20 shows how laboratory testing fits into the process. Testing and design lie at the kernel of the process. There is an important relationship between laboratory and field testing with the linkage between them provided by constitutive relationships for the soil being investigated.

Field investigation and in-situ testing results provide not only direct design information and parameters but also provide the data required to provide to define appropriate test conditions for laboratory testing. An example of this is the measurement of Ko in the field for use in an anistropically consolidated strength – deformation test. Laboratory tests in turn provide data to assist in proper evaluation and interpretation of in-situ test results.

We used the "Geotechnical Circle" concept in our Beaufort Sea work. This is an iterative process – as data are collected and interpreted, it is often necessary to make changes to the constitutive model and additional data may be required.

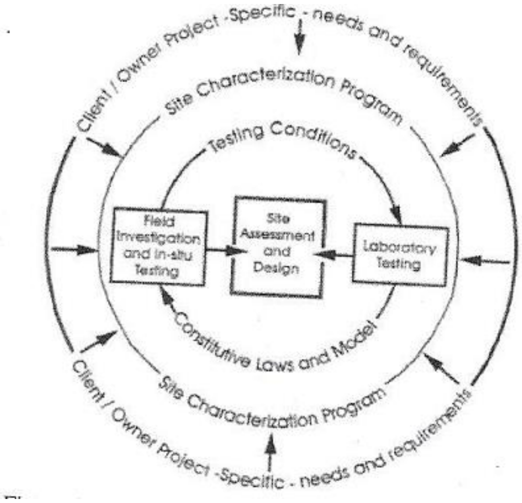


Figure 20: "The Geotechnical Circle"

4.2 "Unusual" porewater pressure behaviour

One of the more puzzling aspects of the behaviour of Beaufort Sea clays below offshore islands was the tendency for porewater pressures in the foundation clay layers to keep rising after island construction (i.e. loading) had stopped (see for example Fig. 21). Normally it would be expected that porewater pressure increases in a clay foundation would stop when the loading process was completed and then porewater pressure dissipation would occur (i.e. consolidation would begin). The concern was that increasing porewater pressure would be associated with strength decrease and reduced stability.

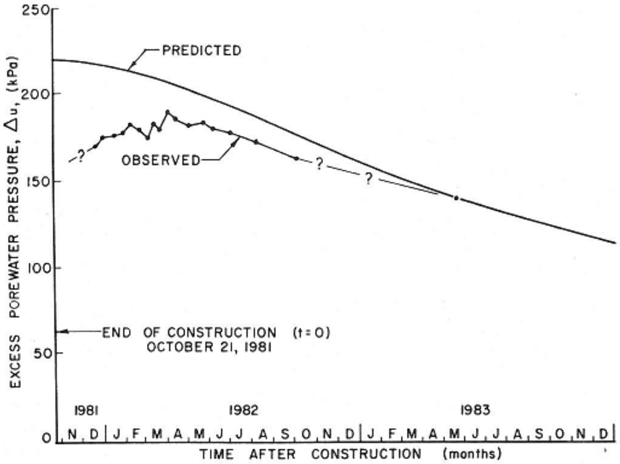


Figure 21: Porewater pressure response in seabed clay below Tarsuit Island (Becker, Jefferies, Shinde and Crooks, 1985)

To examine this phenomenon, we used the Effective Stress Path/Yield Envelope (ESP/YE) approach (Fig. 22). This approach (Folkes and Crooks, 1985) involves determining the effective stress path at a specific (piezometer) location based on computed total stresses and measured porewater pressures. Total stresses are calculated using conventional elastic methods and a Poisson's ratio of 0.5 which is reasonable if the soil is not critically stressed. When the soil is critically stressed and loading continues, the effective stress state remains constant and the horizontal stress increases to maintain the applied shear stress equal to the strength of the soil. It is this increase in horizontal stress which increases the porewater pressure – this may take place after the vertical loading ceases as the stress redistribution takes time to occur. In the situation where the foundation materials comprise sensitive or strain softening soils, the effect of additional loading after critical stressing can be dramatic. High horizontal stress increases are required to match the residual strength of the strain-softened material. The effect of dilation during shear is to reduce the effect – thus when the soil yields, its strength increases until a critical state is achieved. It is only then that horizontal stress increase will occur.

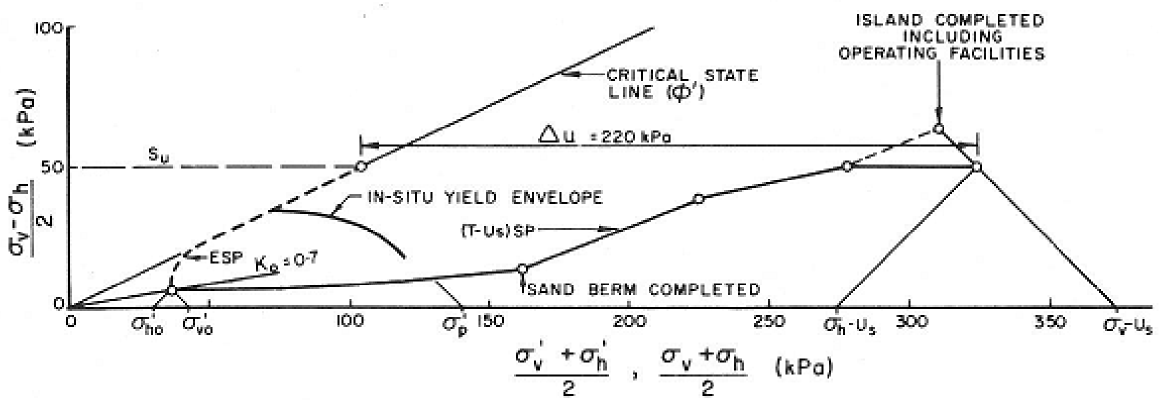


Figure 22: ESP/YE approach for the Tarsuit case record (Becker, Jefferies, Shinde and Crooks, 1985)

The geometry of the problem is also a factor. Artificial islands are extremely wide in relation to the thickness of the soft foundation soils. Thus it is quite possible that the foundation soil could be critically stressed throughout the entire layer but because of the width of the foundation layer, the structure will remain stable. Think of a table set upside down on top of another table with a layer of butter between the tops of the tables – the system will remain stable unless a horizontal force of sufficient magnitude is applied.

Associated with the Beaufort Sea work, we analyzed numerous case records related to embankments on soft clays and were able to explain the observed behaviour in all cases (Becker, Crooks, Jefferies and MacKenzie, 1984; Crooks, Becker, Jefferies and MacKenzie, 1984). Note that since the shape of the yield envelope is determined by Ko, it is important that this value is well known. Similarly the size of the yield envelope is dependent on the pre-consolidation pressure and as a result accurate knowledge of this parameter is very important. Our approach to determining Ko and pre-consolidation pressure are described previously.

4.3 Other aspects of Beaufort Sea work

While the core thinking about the behaviour of sands and clays was obviously the cornerstone to our work in the Beaufort Sea, this was not the only aspect of the Arctic exploration process that we were involved with as described below.

- Investigation: We were present in force during the site investigation programs for some of the sites to be investigated.
- Design: We were the designers of some islands (typically non-caisson islands) and advisors on others.
- Construction control: On many projects, we had a full complement of QA/QC staff on the dredges during the actual construction. Part of "construction control" was the determination of the in-situ state of the hydraulically placed sand.
- Monitoring: We were deeply involved in the installation of monitoring instruments and in particular the interpretation of the monitoring results. This was where the "circle" was closed and theories proven or disproven.
- Spray ice islands: We were involved closely with the design and construction of the 2 spray ice islands that were built in the Arctic – one in the Beaufort Sea and one on the Alaskan North Slope.

There were many other "one-off" projects related to exploration work in the Arctic or which followed on from our work. I won't deal with all of these – too many to try and capture. However, as an example of a "one-off" project – we were asked by an oil company for ideas on how soft offshore foundation soils could be preloaded without using fill. Our idea (similar to the Sandilse concept) was that the water column could be used as the load if a membrane was placed on the sea-bed covering the area to be pre-loaded, followed by pumping of water from beneath the membrane. Depending on its nature, the foundation soil would have to be prepared with wick drains and covered with say 1 m of sand to provide drainage capability. The question was – how to get power to the dewatering pumps? The answer was – there is a strong current across the Arctic oceans, as high as 2 to 3 knots and it should be possible to design underwater current driven power sources which would provide the required pumping capacity.

5.0 CLOSURE

So there it is – a brief history of the soil mechanics work we carried out in Calgary in the 1980s. For my colleagues and I, it was a "purple patch" which we were very fortunate to experience and shows that even under the most difficult of circumstances, good things can happen if one makes the effort. Of course we went on as individual professionals to apply our new found understanding of soil behavior in our subsequent work and it was invariably successful.

We "exported" much of our talent to the UK, USA, Germany and in fact throughout Golder and the world based on our project work. Our lab capabilities led to early lab testing work looking at consolidation and recovery of fine tailings from oil sands, testing failure mechanisms for ice keels scouring the seabed and spray ice. The legacy of pioneering testing still continues in Calgary where the cold room testing facilities are still busy testing various aspects of pipelines in permafrost. We have applied our skills in most of our market sectors and in all sorts of locations: Hong Kong, Taipei, southern Africa, the Confederation Bridge project and mining projects in South America.

I am truly proud to have been part of this work and I know this feeling will resonate with my colleagues.

About the Author

Jack Crooks is a Senior Consultant with Golder Associates based in the Calgary office. He joined Golder in 1973 in the Mississauga office as a geotechnical engineer having completed a Ph.D. in soil mechanics at Queen's University in Belfast, N. Ireland. Throughout his career he has been engaged in consulting engineering projects world-wide. He relocated to Calgary in 1982 where he became President of Golder Associates Western Canada Ltd. from 1983 – 1986. Between 1989 and 1995, Dr. Crooks worked for Golder in Asia and Europe in both technical and management roles. The technical work related to his role as Geotechnical Project Manager on the Taipei Subway project. After leaving Taipei, he was Managing Director of Golder Associates UK and in Europe between 1991 and 1995. Since returning to Calgary in 1995, he has focused on technical projects as well as business development in the oilsands, environmental remediation and management, pipelines, mining and ground engineering areas. He served two terms on the EHL Board of Directors in the 1980s and 1990s and retired from full time employment with Golder in 2012. He is currently employed by Golder on a consulting basis.

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