Some Geotechnical Aspects of Land-to-Sea Transition Zones

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ABSTRACT

The transition between land and water, whether in lakes, rivers, and ocean shorelines, often presents special challenges by virtue of geological conditions as well as the geotechnical aspects relating to design, construction and operation of facilities located in such zones or activities which may take place in them. The transition zones often contain beaches which can be prominent features, particularly in areas with high tidal ranges. Structures in transition zones may include transportation facilities (such as roads, bridges, causeways, and tunnels), wharves, harbors, pipelines, power stations, sea defence and coastal management works, pumphouses and intakes, and residential areas. In terms of operations, such zones are significant from both civilian and military standpoints. Civilian activities include dredging, mining, reclamation, environmental protection, marine salvage operations, exploration, and specialized construction. From a military standpoint, such zones are obviously important in respect to amphibious landings and shoreline defense installations. The paper will review the special geotechnical issues associated with land-to-sea transition zones and present several case histories from the Authors' experience, pertinent to such zones.

ABSTRAIT

La transition entre terre et eau, que ce soit dans les lacs, les rivières ou les rivages des océans, présente souvent des défis particuliers en raison des conditions géologiques et des aspects géotechniques relatifs à la conception, la construction et l'exploitation d'installations situées dans de telles zones ou activités pouvant prendre place en eux. Les zones de transition contiennent souvent des plages qui peuvent être des éléments importants, en particulier dans les zones à marée haute. Les structures dans les zones de transition peuvent comprendre des installations de transport (telles que des routes, des ponts, des chaussées et des tunnels), des quais, des ports, des pipelines, des centrales électriques, des ouvrages de défense maritime et de gestion côtière, des stations de pompages, des prises d'eau et des zones résidentielles. En termes d'opérations, ces zones sont importantes tant du point de vue civil que militaire. Les activités civiles comprennent le dragage, l'exploitation minière, la remise en état, la protection de l'environnement, les opérations de récupération en mer, l'exploration et la construction spécialisée. D'un point de vue militaire, ces zones sont évidemment importantes pour les atterrissages amphibies et les installations de défense du littoral. Le document passera en revue les problèmes géotechniques spéciaux associés aux zones de transition terre-mer et présentera plusieurs cas d'expérience tirés de l'expérience des auteurs et pertinents pour ces zones.

1 INTRODUCTION

The transition zone between land and water is an area in which much construction and other activity takes place. It often presents special challenges by virtue of geological conditions, as well as the geotechnical aspects relating to design, construction and operation of facilities located in such areas, or activities which may take place in them. Challenges are also presented by varying natural conditions, e.g. climatic factors; tidal variations; sea states, and man-made activities such as marine facilities; land-based installations; dredging; and reclamation works.

Site investigations in such zones can also present challenges not normally encountered at land or overwater sites. Investigations in the breaking wave part of a shoreline, for example, or drilling from the ice at a site in a Northern climate with a high tidal range.

Two examples are discussed in Section 4. The clandestine investigations carried out on the Normandy beaches in preparation for the amphibious landings on June 6, 1944 were particularly challenging as noted later.

2 TYPES OF TRANSITION ZONES

There are, of course, also a variety of transition zones which have to be contended with in engineering practice. They include ocean shorelines; shores of lakes; islands; river banks; margins of harbours and other man-made works such as canals, reservoirs and reclamation works. Within such zones there may be features such as beaches, bars, reefs, spits, and cliffs.

Loading conditions also vary depending on origin, e.g. man-made structures; seismic; tidal (including tsunamis); action of waves and currents; flooding (including rapid rise and drawdown of river levels due to ice jams); ice action in Northern climates; and unusual effects such as impacts from ships. The loading from the explosion caused by the collision of two ships in Halifax Harbour in 1917 represents an extreme case. (Cuthbertson 2017).

Several examples from the published technical literature and the Authors' experience are discussed in summary in Sections which follow.

3 CONSTRUCTION IN TRANSITION ZONES

Many types of structures are, of course, also located in such zones. To name some: causeways; bridges; canals; tunnels; wharves; jetties; nuclear and thermal power plants; canals; highways and railways; shipping facilities; sea defence and erosion control works; ocean outfalls; pipelines, dams; buildings and storage facilities. An example of the diverse geotechnical design and construction challenges that may be associated with such projects is described for the Canadian section of the St. Lawrence Seaway by Peckover and Tustin (1958).

By the same token, there are a variety of expedients used to enable construction of the facilities in or through transition zones. These may include cofferdams; reclamation works; and use of geotechnical processes such as groundwater lowering, blasting, or the displacement technique for embankment construction in soft ground areas.

The importance of cofferdams for construction, particularly in areas of breaking waves, was demonstrated on a project where the pipeline for delivery of fuel to a Thermal Power Plant from a Single Point Mooring terminal located 4.5 km. offshore had to pass through the surf zone of a beach subjected to significant wave action. The pipeline was assembled in long lengths on shore with the plan to pull it across the beach and through the surf zone using winches on a pipe laying barge. Heavy seas were encountered during construction and the pipeline became buried in the sand beach over a length where the frictional resistance was such that the force to move the pipe exceeded the capacity of powerful winches on the barge. It was then necessary to dismantle sections of the pipeline so that they could be installed in the beach and surf zone without pulling.

Other examples of hazards to marine pipelines in the breaking wave zone are given in the published technical literature, e.g. Powers, 1983.

The use of reclamation works that become part of the finished structure is discussed in Section 5 in connection with the sudden failure of a grain elevator. Another example of such works was the approach used for disposal of large quantities of spoil from the Channel Tunnel at both the United Kingdom and France ends. Some of the spoil was used for construction of Terminals and working platforms. However, about 2 million cubic meters was surplus on the U.K. side. This was used as fill at the base of the cliffs to build an environmentally acceptable site suitable for recreational pursuits (G. Anderson and B. Roskrow 1994).

In respect to use of special techniques for construction an example is the Rainy Lake Causeway, a major link between Atikokan and Fort Frances, Ontario (Matich et Al 1963.). The Causeway consists of alternating embankments and bridge structures. Significant physical conditions at the site are water depths of up to 50ft. (15m) underlain by about the same maximum depth of soft to firm clay. A maximum ice thickness of 3 to 4ft (1m to 1.3m). To achieve stable embankments the underlying clay was remolded by dynamite blasting so that total displacement of the clay would occur during embankment construction. Tests to determine the amount of dynamite needed to effect sufficient reduction in shear strength of the clay are described. The application at one of the bridge abutments is shown in Figure 1.

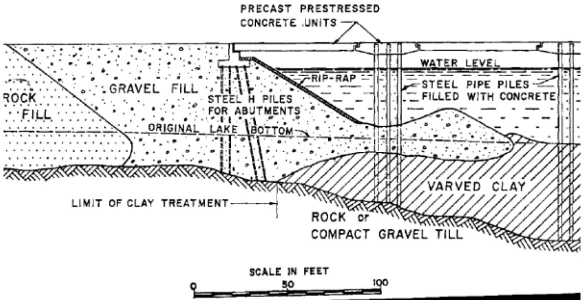

Figure 1. Detail at a Bridge Abutment

4 OPERATIONS IN TRANSITION ZONES

There are a wide variety of operations in transition zones. They include transportation facilities both land-based and shipping. Other examples are site investigations; construction activities; alluvial mining; salvage operations; maintenance of sea defence and erosion control works; management of shipping facilities; and military operations.

4.1 Challenging Site Investigations

As already alluded to, site investigations in transition zones can present significant challenges from logistical standpoints, particularly where difficult marine conditions have to be contended with. One such case, where ocean swells and breaking waves were involved, was encountered in 1996 when the Department of Transport of Canada commissioned an investigation of foundation conditions at a rock outcrop known as Lurcher Shoal located in the Atlantic Ocean about 16 miles (26 kms) west of Yarmouth, N.S. Water depths at the site varied from about 10ft. (3m) at low tide to 33ft. (3 to 11m) at high tide. Except under the most favourable weather conditions, waves broke menacingly over the Shoal and safe access and operation from floating plant was virtually impossible. A team of engineers and drillers therefore designed a self-supporting and levelling drill platform carried on a tripod filled with 3.5 tons (3.6 tonnes) of steel punchings. The platform was handled by a crane-equipped derrick boat attended by an ocean-going tug. Access onto the shoal was made during a brief period of favourable weather and marine conditions in 1967. This in itself was a major accomplishment on the part of the marine crews as described by Matich and German (1979). However, credit for the success of the operation rested with the Drillers who completed four coreholes (each 30ft (9m) into bedrock in a record time of about 4 hours.. The tripod drill rig (40 ft. high and 20 tons total weight) is shown in operation in Figure 2.

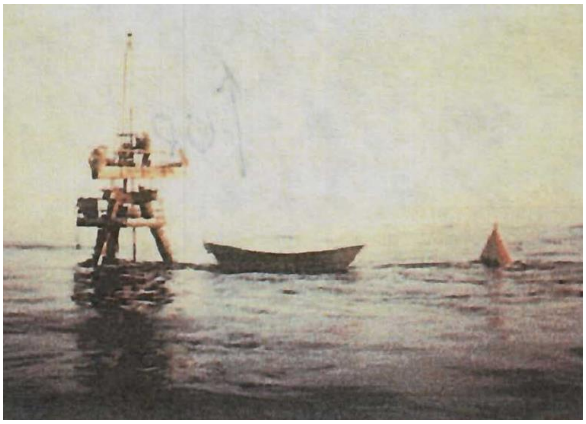

Figure 2. Drillers at Work on Lurcher Shoal, N.S.

Another example is the geotechnical investigation carried out preparatory to removal of Ripple Rock by blasting. This rock was a submarine knoll tapering to a ridge about 300 feet (90m) high which projected up into Seymour Narrows located between the east coast of Vancouver Island and the west coast of Maud Island, near Campbell River, B.C. As described in an article by the Campbell River Museum, marine conditions were a tidal range of about 12 feet (3.5m); currents up to 17mph (7.5m/s); a water depth of 10 feet (3m) at low tide, and very rough and turbulent water except at high and low water slack. Navigation was only possible during such periods. The Rock represented an extreme hazard. Prior to its removal in 1958, it was responsible for the loss of numerous ships and up to 114 lives. After much study of options to increase water depths over the Rock, it was decided to achieve this by blasting. Initial attempts to drill holes for blasting using a large barge floated over the Rock were unsuccessful because of difficulties in holding the barge on station. Attention was then given to tunnelling under the Narrows and loading explosives into the Rock from below. A study by the National Research Council of Canada (NRC) showed that this was feasible (Porter, 1955). The design task was assigned to Dolmage and Mason, a consulting firm well known in geological studies for tunnelling purposes. The drilling to obtain cores for evaluation by geologists at NRC and Dolmage and Mason, was assigned to Boyles Brothers Drilling Company who did a highly commendable job of using directional drilling methods to drill about 2300 feet (700m) in rock from Maud Island under the Narrows and up into the Rock. The Rock was successfully accessed by tunnelling from Maud Island and blown up in April 29, 1958. A more detailed description of the project, and particularly the planning for and results of the blasting operation, is given in Rutley, 1959. As noted later herein, the massive blast was one of the biggest non-atomic man-made explosions in history.

4.2 Dredging Applications

Dredging is used in transition zones in a number of different ways, including maintenance work, alluvial mining, and special projects. Its use for alluvial mining is described, for example, for ironsand mining of beaches in New Zealand (McConnell et Al., 1974). The use of dredging in the construction of a Dam to isolate an open pit mine from a lake is described in Section 6. A non-routine example of dredging in a transition zone is the burial of the wreck of the S.S. Union Faith, a cargo ship which sank next to one bank of the Mississippi River in New Orleans Harbour in 1969. The burial scheme utilized dredging alongside the wreck together with soil cutting by wire cable to induce a landslide of the wreck and underlying soil into a trench and below navigation depth. (Matich et. Al, 1998)

5 CASE EXAMPLES (HARBOURS)

5.1 Harbour Modernization

St. John's Harbour, Newfoundland, is formed of a bay 7000 ft. (2100 m) long and 1000 ft. (300 m) to 2000 ft. (600 m) wide with a narrow exit leading to the Atlantic Ocean. High surrounding terrain together with its land-locked configuration, make it one of the finest harbours in the world. It is North America’s oldest port, with a history of activity of well over 200 years. In the 1960s a major modernization program was initiated by The Department of Public Works Canada to produce a new general cargo handling marine terminal. This included a new general cargo pier at the west end of the Harbour; a new wharf on the south shore; and a four lane road and marginal wharf for medium and large ships along the north shore for a distance of about 3000 ft. (900 m) (Chmielenski, 1956). An air photo of the Port taken after completion of the modernization is given in Figure 3.

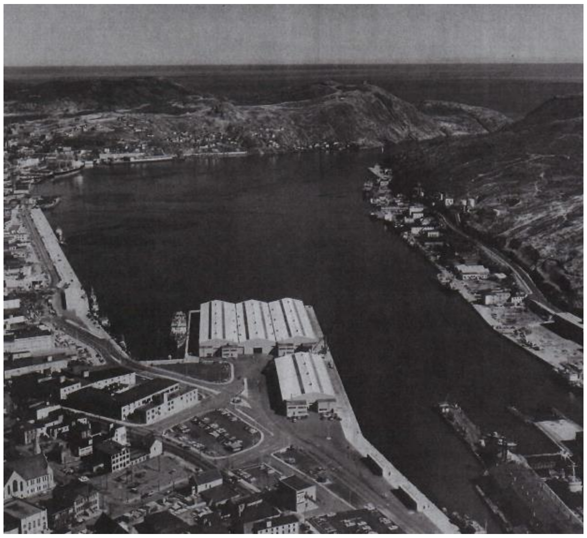

Figure 3. Air Photo of St. John’s Harbour. Looking East. Courtesy: Canadian Foundation Company Ltd.

The north shore is of particular interest to this paper because of the type of land to water transition zone that it presented. This consisted, on the land side, of a variety of old buildings, the foundations of which could not be established with certainty. Generally speaking, they appear to have been built on fill dumped on soft organic silt and carried on timber piles of unknown condition. For a considerable length on the water side, timber bulkheads in various stages of disintegration, retained fill and thus acted to stabilize adjoining structures. The wharves along the north shore were 50 to 100 years old. They consisted of timber decks supported on untreated timber piles. The majority were found to be decayed and badly in need of repair. They were beyond economical replacement.

On the Harbour side, subsurface conditions included about 10 ft. (3 m) of heterogeneous fill at surface along the shoreline. Beneath the harbour bottom and underlying the fill for varying distances from shore, there was a stratum of loose organic silt whose depth varied from 5 to 30 ft. (1.5 to 10 m) and was generally about 15 ft. (4.5 m). The silt is a harbour bottom muck with an undrained shear strength of about 100 pounds/sq.ft (5 kPa). It is underlain by glacial drift or till.

The new berths along the north shore were designed as open type structures consisting of a concrete deck on prestressed concrete beams supported at one end on piles and at the other by a retaining wall seated on a rockfill embankment which also formed part of the north shore road. The design cross-section is given in Figure 4.

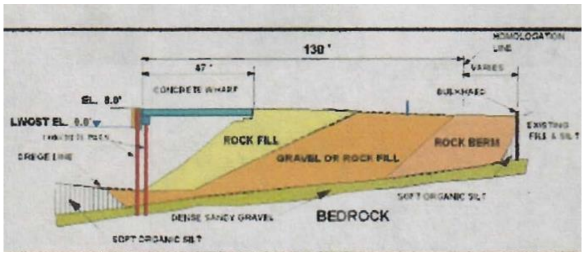

Figure 4. Typical Section of Completed Wharf

From considerations of stability of the fill and satisfactory performance of the road, it was necessary to remove the silt by dredging. In view if the manner in which the existing structures were founded, it was evident that special precautions would have to be taken during dredging to avoid endangering existing buildings by undermining them and/or existing bulkheads. It was concluded that the cost of underpinning the buildings and strengthening the bulkheads in advance of complete removal of the silt by dredging would have been prohibitive.

The approach adopted was to use the displacement technique to replace the loose organic silt adjacent to the offshore side of the old buildings and retaining structures such as timber bulkheads and piles, while simultaneously maintaining support to the toe of such structures. The displacement technique has a history of successful use in the construction of highway and railway embankments through soft ground areas in Canada and elsewhere. A classic reference in this field is a 1922 Report of The Swedish State Railways. Practical factors which are known from experience to be important in its use are described by Matich and Wang (2006).There was little published however for projects other than for road or rail embankments and causeways.

A test section was therefore built to confirm construction details. At the same time, at several locations where buildings were in particularly close proximity to the shoreline, additional measures, such as short steel sheet pile bulkheads were applied as deemed necessary based on the results of the test fill and experience in the early stages of construction. It was also recommended that the fill should be placed as a “rolling surcharge” to assist in the displacement of the silt. Careful monitoring of all of the construction operations was considered essential and was carried out in practice.

The operation of placing the initial rock berm for the road was successful. Once completed, the remainder of the organic silt within limits of the wharf structure was removed by dredging and fill consisting of sand and gravel and rock placed as required to complete construction of the wharf.

5.2 Collapse of Terminal Grain Elevators

The transition zone in this case is in the Port of Thunder Bay, Ontario which is the western Canadian terminus of the St. Lawrence Seaway. It has served an important role in the export of western Canadian Grain since the 1880‘s and thus contains a variety of grain elevators which may be located on rivers entering Lake Superior in the Port area or on lake frontage. Ground conditions in the Port area typically consist of clays and silt over glacial till. Grain elevators have generally been provided with a wharf and were carried on end-bearing timber piles penetrating natural ground or reclamation fill. Batter piles were generally not included in the foundations of the Elevators. The land-to-water transition at each Elevator would thus typically include a wharf facility.

The Ogilvie Grain Elevator described variously by Theimer (1969); Vervoort (1990) and The Thunder Bay Museum; was built on the Kaministikwia River in 1904. It was a 26 bin structure, 90 feet (27m) high, of steel construction carried on a pile-supported concrete mat. On May 26, 1906, it suddenly started to move towards the river. As noted in an article in the Thunder Bay Museum, within 24 hours it had moved about 50 ft. (15m) and had come to rest in the river at a 15 degree angle. The wharf was wrecked. The Elevator was damaged. However it did not break up. Much of its contents of 380,000 bushels of wheat were lost. The cause was attributed to deepening of the river at the Wharf by dredging which was aggravated by scour during flooding. The Elevator was replaced with one twice its size, but built further from the river. The replacement performed well from a foundations standpoint, during a long service life. A photo of the Elevator in its failed position is given in Figure 5.

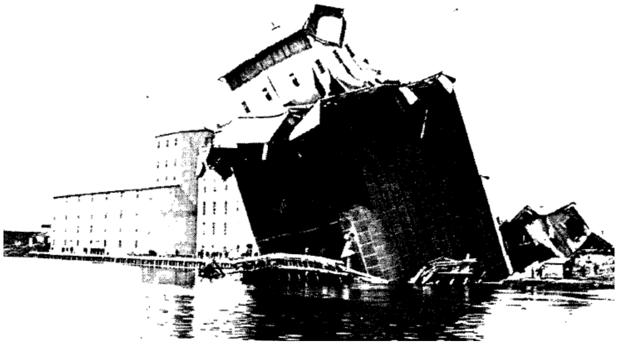

Figure 5. Ogilvie Elevator in its Failed Position (Courtesy: The Thunder Bay Museum)

The United Grain Growers Terminal was built on the Current River in 1927-28. A major component (Storage Annex No. 2) collapsed suddenly into the harbour on September 23rd, 1959 spilling 2.5 million bushels of grain into the adjacent slip. It also created a wave 16 feet (5m) high which wreaked havoc in the harbour. The Elevator Terminal is composed of two Storage Annexes (Nos. 1 and 2) together with a number of associated structures arranged in line along a dock. The dock area was reclaimed using Wakefield timber sheet piling for containment, and silt dredged from the adjacent Lake bottom. Each Storage Annex is 375ft. (115m) long, 100ft (30m) wide, and 124ft. (38m) high. The base of the Elevator Structure rests on a concrete mattress-type raft 3.3ft. (1m) thick supported on timber piles driven through the hydraulic fill and natural lake-bottom clay to refusal in glacial till. Each Annex was composed of 56 circular concrete compartments arranged in four rows of 14 and supported on 5052 vertical piles. The Wakefield sheet piling was anchored at the top by a series of tie rods which were anchored at their inshore ends to timber A-frames each consisting of vertical and batter piles the heads of which were embedded firmly in the concrete mat foundation. A 6 track 60ft (24m) wide, 30 ft (8m) high railway timber trestle was located on the land side of Terminal. It was buried in granular fill in the late 1930's and the tracks transferred to the fill.

In 1958, some loss of reclamation of fill occurred through a damaged section of Wakefield sheet piling. This was repaired. In the month before the failure, the Wharf was hit on two occasions by a ship coming in to the Elevator. Lateral movements of the Elevator prior to the failure were only about 1 inch (25mm). this contrasted sharply with known larger lateral movements of other grain Elevators in the Harbour area which were also carried on timber piles but without batter piles. Movements in the other cases occurred without distress and were stopped by application of restraining measures. A description of this failure and discussion of the most likely causes is included in Peck et Al. (in preparation). It is believed that there were a number of contributory factors among which were the failure of the inclined piles of the A-frames acting as batter piles to the Elevator. A photo of Annex No. 2 taken after the collapse is given as Figure 6.

Figure 6. The United Grain Growers Limited Current River Terminal After Failure. (Courtesy: Viterra Inc.)

6 CASE EXAMPLES – LAKES

Construction on the shorelines of lakes is common in Canada. This includes mining developments where open pits are located at or close to shore and require dams or dikes to isolate the open pit from the lake. Such structures have to cope with a variety of ground conditions in the land-to-water transition zone. They may represent significant challenges in design to ensure both the safety of personnel working in-pit, and control of seepage to acceptable limits. The Steep Rock Iron Mines development at Atikokan in northwestern Ontario which was begun in 1944 is an extraordinary example which required not only diversion of the Seine River and draining of Steep Rock Lake, but also a major dredging operation and construction of various dams and other works. (Legget, 1989).

A modern example is the Diavik Lac de Gras Project in Northwest Territories (Diavik, 2003) where diamond-bearing kimberlite “pipes” are located close to the shore of an island in Lac de Gras and a system of dikes has been built to isolate open pit mines from the lake. Ground conditions consist of granite typical of the Canadian Shield. This is largely exposed on land but covered below lake bottom by generally shallow soft sediments then hard glacial till. The land-to-water transition zone is characterized by permafrost in exposed bedrock areas but not under the water. This requires that special measures be incorporated in the design. The only natural construction material in the site area is the granite. All of the gravel and sand sized material needed for dike construction was therefore produced by blasting and crushing. The design cross-section developed for the Dikes after extensive studies and testing included a central cut-off composed of plastic concrete built within a core of fine crushed rock contained by shoulders of rock fill. The cut-off extends to the bedrock where the juncture was made using jet grouting. The alignment of the Dike system crosses several islands. Beneath the islands and the abutments of the Dikes the permafrost provided water tightness. Thermo-syphons provide the transition between the permafrost on land and the adjoining section of the cut-off wall.

Another project which contrasts significantly with the Diavik Dike system in terms of the geotechnical factors involved, is a dike which formed part of the Steel Company of Canada Limited's Griffith Mine near Red Lake, Ontario built in the 1970's. (Morawski et Al., 1970). The iron ore mine complex included two orebodies which extended partly under Bruce Lake and required construction of a retention dike to isolate the open pits from the Lake. The land-to-water transition in this case was between overburden strata of stiff clay and clay till on land and sensitive, soft to firm clay underlain by strata of compact to dense sand and glacial drift (sand, gravel and boulders) below the Lake. The lake-deposited clay stratum was up to about 100ft. (30m) thick along the dike alignment where water depths were about 10ft. (3m) and seasonal ice thickness 3 to 4ft. (1 to 1.3m). Geotechnical investigations and design studies established that it would be necessary, from design considerations, to remove the clay by dredging and found the dike on the basal sand and glacial drift. In terms of material for use in dike construction, the economics of the entire Mine project were dependent upon the utilization of mine waste material for this purpose. Based on comprehensive design studies and construction planning, the basic dike configuration selected involved a zoned structure founded on the basal sand or glacial drift as shown on Figure 7. As designed, the main structural zone consisted of mine waste rock produced to the necessary size specification of 50 percent minus 6 inches (15mm) by the Mining Department from initial operations in higher portions of the ore deposit. The main section was faced with a transitional slope filter of processed clay till borrowed locally. A low permeability seal of clay stripped during normal pit development was placed on the outside. A sand and gravel filter mat was placed on the basal sands before advancing the rockfill embankment over them. The sloping filter (transition) and seal zones were placed by side dumping from the main embankment, while the base filter was placed by a barge-mounted crane equipped with a clamshell. During construction soundings indicated that the till zone was assuming an overall slope of 4H:IV rather than the 2H:IV design slope. This was attributed to the high percentage of minus 200 mesh material in the till being used in the sloping filter zone, while still meeting specifications. It was considered acceptable to adjust the dike section design and use the clay till for the zones previously requiring till and clay. A 50ft (16m) wide stabilizing buttress of rockfill was placed on the land side of the Dike 40ft. (12m) below crest elevation, after the water was drawn down (not shown on Figure 7). The Dike performed well from both stability and seepage standpoints when put into service. It has completed its service life, successfully.

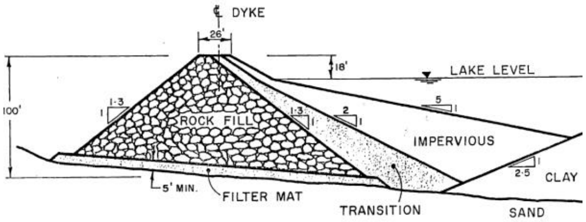

Figure 7. Griffith Mine Dyke. Typical Design Section

7 MILITARY AMPHIBIOUS OPERATIONS

Geological and geotechnical conditions and associated terrain factors have historically had a major influence on the outcome of military operations, and in some cases, a decisive influence. (Rose and Nathanail, 2000). Of vital importance to amphibious warfare have been soil conditions within the landing beaches and immediate environs both onshore and offshore. Four examples, representing a range of site conditions, are discussed in summary below with particular reference to the geotechnical factors involved. Among other examples which could be given special mention, space permitting, are the challenges posed by coral reefs immediately offshore at Tarawa Atoll of the Pacific's Gilbert Islands, one of the most difficult assaults in amphibious history. (Polmar and Merskey, 1988). A feature generally associated with planning of amphibious landings, as might be expected, is the challenge of obtaining geotechnical data directly because of the presence of hostile forces.

Figure 8 from Bird (2007) illustrates the various zones along coasts. The shore is the zone between the water's edge at low tide and the upper limit of effective wave action, usually extending to the cliff base. It includes the foreshore, exposed at low tide and submerged at high tide, and the backshore, extending landward from the normal high tide limit, but inundated by exceptionally high tides or by large waves during storms. The shoreline is strictly the water's edge, migrating to and fro as the tide rises and falls.

A beach is an accumulation of loose sediment, such as sand, gravel or boulders, sometimes confined to the backshore but often extending across the foreshore as well. Some beaches extend down to, and below, low tide level. Shingle is beach gravel, especially where the stones are well rounded.

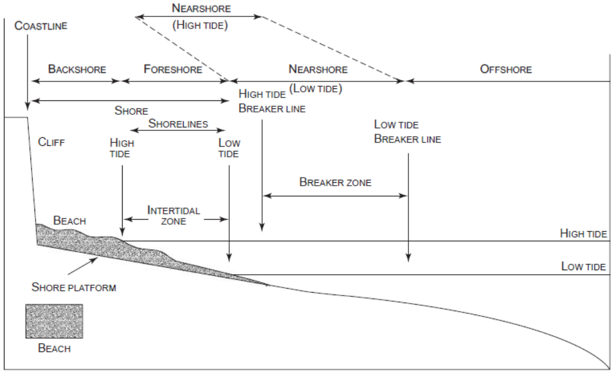

Figure 8. Coastal terminology (After Bird, 2007)

7.1 The Dieppe Raid

The Dieppe Raid in France in 1942 has been the subject of much controversy from a number of standpoints. However, there is acknowledgement that the lessons learned from this Raid were extremely valuable with respect to the geotechnical factors involved and would help preparations for later, greater actions, specifically during subsequent World War II invasions of the European Continent.

Thompson (1956) describes the beach of Dieppe as a steep shingle (gravel) bank rising from about a 1 in 40 gradient to 1 in 10 under the solid masonry, concrete, and well-fortified sea wall. All the beaches are of shingle with hard, rounded flint and chert stones of 3- to 6-inch diameter, and with sand at low tide. Atan A. Kanik, a geological engineer and former Calgary Tanks trooper noted that “the white cliffs of southern England and northern France are composed of siliceous chalk, interspersed with chert lenses and beds. During erosion, the chalk is dissolved in the water and carried away, while the chart remains on the beach and undergoes constant erosion, forming well-rounded and extremely hard stones”. (Whitaker, 1992). Limited pre-raid information on site and ground conditions was available regarding beach characteristics including the following:

- 22-foot tidal range;
- low well-fortified sea wall along the beach;
- first time in history that tanks were used in an amphibious landing;
- unknown pre-raid performance of other equipment including landing craft, wheeled vehicles, dozers, clearance of obstacles.

During the raid, all assault engineers were killed or wounded. Amongst other duties, the engineers were tasked with laying snow fence type wooden tracks (chespaling) on the beach over which all tanks and other vehicles were to pass. Most vehicles encountered the steep beach composed of extremely hard, smooth, chert/flint cobble-size stones. These resulted in tank tracks coming off over the drive sprockets, particularly when the tanks tried to turn. Some tanks which landed on more sandy beaches were able to get to the esplanade. Exits were blocked by concrete walls which tanks could not pass. (Henry & Pallud. 1992).

Many important lessons of geotechnical relevance were learned and applied later in 1944 at Normandy, including:

- know ground/site conditions in the transition zone;
- practice on beaches similar to the invasion beaches.

7.2 The 1944 Normandy Invasion

Rose et al. (2006) describe the maps used by the British military geologists to assess the natural hazards to cross-beach stability vehicle mobility on the Normandy D-Day landing beaches. Planning in 1943 included “preparation of large scale maps of the beaches including those parts which were unsuitable for passage of assault vehicles.” A large part of the pre-invasion research related to evaluation of suitable invasion areas and assessment of beach conditions was carried out by a team of geologists under Professor Fred Shotton, than a staff-officer Geology in the Royal Engineers. The team worked first with whatever documentation was available, including photographs of beaches taken by the public on holiday, supplemented by air photos taken at low level and observations made by Shotton and others during low altitude flights. An indication of the trafficability of beaches was gauged from evidence developed in this manner (including wheel marks left by German carts transporting defence stores, for example) as well as simulations on beaches in the U.K. Significant interpretations of the evidence were (i) that there were areas of clay at shallow depth on the beaches and (ii) that dark areas which showed up after storm movement of the lighter-coloured sand, consisted of peat. Both areas had questionable trafficability characteristics. It is of interest that historic and archeological studies indicated that there were Roman peat works in the Normandy area. Once the French calvados coast was selected for the invasion, it became important to identify the beach zones of peat and clay so that they could be avoided by mechanized vehicle traffic. Rose and Pareyn (1995) describe the work involved in developing maps which identified such traffic exclusion zones using data of the type indicated above.

The secret ground reconnaissance oftentimes included beach sampling by the Combined Operations Pilotage Parties (COPPs) swimming ashore from midget submarines (X-craft). Their tasks included augering and collecting samples of soft sediments, collecting samples of “stone”, and making observations on obstacles to cross-beach movement and exit. On return beach samples were sent to the Geological Survey of Great Britain for analysis (Rose et al. 2006). Some information on seabottom conditions near the shore was obtained by clandestine hydrographic surveys by geophysical means. They indicated generally sand over bedrock.

By the end of 1943 it was becoming clear to the Allied High Command and invasion planners that ground conditions would have a greater influence on planning than originally thought. New, possibly adverse features were appearing in air photos and it was considered essential to obtain additional data by direct methods including recovery of soil samples. The vehicle mobility predictions, in particular, required some validations and confirmation. (Strutton and Pearson, 1959).

On New Year’s Eve of 1944 two members of the Corps of Royal Engineers 21 Army Group, Major Logan Scott-Bowden and Sergeant Bruce Ogden-Smith, crossed the English Channel in a midget submarine to Luc sur Mer and collected soil samples from what later was given the code name Sword beach. They each carried a bandolier containing sample tubes labeled in phosphorous. The resourceful

Scott-Bowden devised a simple beach auger with which they scooped up the sand, decanting it into one of their rubber sheathes. Considerable care was taken to avoid leaving footprints. Review and analysis of their sachets of sand confirmed the suspected peat bog was actually “good hard rock” and indicated the beach was a suitable landing site. Later reconnaissance missions by Scott-Bowden confirmed similar predictions, leading to the identification of Juno, Gold, and Omaha beaches as acceptable land sites for the Allied invasion (Strutton and Pearson 1959).

To facilitate the landings of the troops, vehicles and supplies, the Allies decided to provide two artificial harbours code-named Mulberry A and B in the British and American Sectors, respectively (Hartcup, 1977). The harbours comprised several elements, the main one being a breakwater formed of “blockships” (unserviceable merchant ships) and concrete caissons (“Phoenix”) both sunk in line at the designated site and filled with sand by dredging. The caissons were compartmented box-shaped structures of various sizes to suit the water depths involved, the largest being approximately 200 feet (60m) long, 50 feet (15m) wide and 60 feet (18m) high. In practice, some of the “blockships” and caissons experienced movement under effects of a storm which hit the invasion area on June 12, 1944 six days after the landing. In general, however, they served their intended purpose well.

It is of interest that concrete caissons (known locally as “cribs”) were adapted in Canada for use particularly in construction of wharves. Refinements in design were made and special methods developed for their construction and launching. (e.g. Yan, 1983).

7.3 Iwo Jima

Iwo Jima (Sulfur Island) is the central island of three small islands that make up the Volcano Islands chain in the Pacific. The island is relatively flat with a mean elevation of 110 m except of the southernmost region where Mt. Suribachi (El. 169 m) is located. Natural sandy beaches exist along the southeast and southwest coast lines. The southeast beach, a 3000m strip of coarse, dark gray and black volcanic sand, was designated as the primary assault beach.

In contrast to many other amphibious landings, in this case an amphibious reconnaissance mission, was made in advance of the main operation, to gather intelligence including beach conditions and Japanese defences. This mission was made under fire by swimmers of a Navy and Marine Underwater Demolition Team (UDT) on D-3 and D-2. Samples of beach material were recovered and, on the basis of tactile examination, the Marines agreed that the sand was sufficiently coarse-grained that wheeled vehicles would use it.

At “Yellow Beach”, the designated primary landing beach, the foreshore is about 75ft. (25m) in width and has a 20% slope. Beyond the foreshore, the backshore averages about 45ft. (15m) in width and slopes slightly downward. The forward dune apron extends about 450ft. (140m) inland with an average slope of 12%.

Post-war testing showed that the sands on “Yellow Beach” were poorly graded medium-grained SP sands with zero percent (%) fines. Difficulties during the invasion were associated with the sands being loose and “soft” making walking and running difficult. Their loose condition also created havoc with assault vehicles which bogged down and needed to be towed, pushed or abandoned. Existing terraces were often difficult to traverse.

7.4 Inchon-Seoul. Korea

In the September, 1950 amphibious landing in Inchon Harbour, the particular challenges were a tidal range of about 32ft. (10m) – among the highest in the world being greatly exceeded only by the tidal range in the Bay of Fundy, and a land-to-sea transition zone of wide beaches of soft silt mudflats backed at high water in some cases by seawalls. Tidal currents are as high as 7 to 8 knots. (Heinl JR. 1968). In normal circumstances, such a site would be considered unfavourable for an amphibious landing. A factor in its favour in this case was the element of surprise which made it possible for landing craft to proceed directly to the seawall at high tide and remain there discharging troops and cargo until the next high tide.

7.5 Project “SEAL”

Research during World War 2 involving possible offensive inundation of the sea-to-land transition zone resulted from observations during surveys in the Pacific Theatre that blasting operations on submerged coral formations were occasionally attended by unexpectedly high waves. This gave rise to Project “SEAL”, the investigation of the potential of inundation by means of artificially produced tsunamis for offensive purposes in amphibious warfare. (Bassett 2003). Exploratory trials carried out in New Caledonia by the U.S. Navy were promising and further research was carried out by the New Zealand Army under the direction of Professor T.D.J. Leech of the University of Auckland, with assistance of U.S. scientists (Leech, 1950). The program of testing was well under way when it was overtaken by the development and use of the atomic bomb. In later underwater nuclear tests at Bikini Atoll one of the effects studied was the production of waves. Studies related to “SEAL” were also carried out at the University of Auckland in 1950.

Three other man-made “tsunamis” of note were (i) the December, 1917 Halifax Harbour explosion (Cuthbertson, 2017) where 2600 tons (2350 tonnes) of explosives created a 30 foot (9m) high tsunami wave, (ii) the April, 1958 Ripple Rock explosion near Cambell River, B.C. (Baird, 2017) where 1,375 tons/1250 tonnes of explosives created a 25ft. (7.5m) tsunami wave, and (iii) the collapse of the United Grain Growers Elevator in 1959 16ft. (5m) high tidal wave) (Peck et Al in preparation).

8 COMMENTARY

A number of examples selected collectively from the published technical literature and the Authors' experience are presented in summary. They will highlight the fact that there are many different types of sites which have to be addressed in applied geotechnical practice, which are in the land-to-sea transition zone category. It is believed that they will also illustrate the special nature of such sites from the standpoint of the geological and geotechnical factors involved, including the logistical and other challenges which may have to be contended with in obtaining the necessary information in these areas of expertise.

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