Archives in Geotechnical Engineering Practice

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ABSTRACT
Archives are important to geotechnical engineering undertakings, beginning with design, construction, post-construction performance and as-built records. Also included may be technical literature on geology, hydrogeology, seismicity, climate, environment, scientific research and relevant case histories. Data to be consolidated into reports often originates with a diverse group of consultants. Reports may be required by the owner, designer, contractor, regulatory authorities, insurers, financial organizations and review boards. Effective cataloguing and storage of archival data for ready access in usable form are now significant concerns. There is an increasing reliance on digital techniques. The merits of maintaining good archives are discussed together with some case examples.

RÉSUMÉ
Les archives sont importantes pour les entreprises d'ingénierie géotechnique, en commençant par la conception, la construction, la performance post-construction et des dossiers tels que construits. Elles peuvent également inclure la documentation technique sur la géologie, l'hydrogéologie, la sismicité, le climat, l'environnement, la recherche scientifique et études de cas pertinents. Les données qui doivent être consolidées dans les rapports proviennent souvent d'un groupe diversifié de consultants. Les rapports peuvent être exigés par le propriétaire, concepteur, l'entrepreneur, les autorités règlementaires, les assureurs, les organismes financiers et les commissions d'examen. Le catalogage efficace et le stockage des données d'archives pour les rendre rapidement accessibles et utilisables soulèvent un intérêt nouveau et significatif. Il y a un recours croissant aux techniques numériques. L'importance de maintenir de bonnes archives est discutée de pair avec des exemples de cas.

1 INTRODUCTION

In engineering endeavours, the most important deliverable is generally the finished project. Supporting documentation relating to phases such as design, construction, operation, monitoring and closure (as applicable) forms part of the project and warrants preservation in archives for ready reference. As discussed later, this is particularly the case for many larger, technically complex projects with a long service life. The challenge of maintaining good geotechnical archives for such projects is increasingly more critical because of the inability to rely on institutional memory.

Although project archives in general may be historical, business or technical in nature, the main emphasis in this paper is on archives of geotechnical engineering relevance. The term archive is used interchangeably for the retained documents and their repository.

The document "Save Engineering Records – a guide for civil engineers" was prepared by the Institution of Civil Engineers (ICE) Archives Panel established in 1975 to concern itself with the ICE's own records and also those of the profession and industry. The document defines archives as "records adjudged worthy of permanent preservation for reference or research" and notes that "today's records are tomorrow's archives". As noted by the ICE Archives Panel, most large organizations have protocols for the selection, preservation and access of key records; the Panel correctly points out that responsibility for sound archive practise falls to all members of the engineering organization, principal and junior alike. Preservation of key engineering records is also recognized by the Canadian Geotechnical Society (CGS) and this paper may thus serve as a reminder. The ICE Archives Panel also provides comment on suitable repositories for what are believed to be valuable engineering records, and emphasizes the need to protect such documents from becoming useless through physical decay and disaster as well as through lack of reliable identification and retrieval.

From a geotechnical standpoint, archives can be classified in a variety of categories and have many end uses in practice, recognizing that geotechnical engineering is often applied in conjunction with other disciplines. Of particular significance in this regard are (i) the many organizations, both private and regulatory, to which such archives are important, and (ii) the need to be able to access and use archives as required, both during the service life of a project, as well as over the long term. The comments given below are made by reference to data in the published technical literature and also from the authors' combined experience gained while employed (or engaged as consultants) variously with firms specializing in geotechnical engineering; multi-disciplinary design organizations; general contractors; and project owners. Some thoughts are also presented on the archiving of geotechnical engineering data in the future.

2 ARCHIVE CATEGORIES

In considering archives from a geotechnical perspective, it is useful to consider the historical development of geotechnical engineering in Canada (which went through several main stages), as well as the end-users of geotechnical data. In the "early days", as pointed out by Legget (1962), "test boring and sampling (of a sort) were a regular feature of construction work long before soil mechanics had been thought of as a separate discipline." There are interesting published case histories illustrating the use of borings to establish ground conditions at important Canadian projects prior to the 1930's. As cases in point, test borings were carried out in the 1860's for a railway bridge over the Miramachi River near Newcastle, New Brunswick (Legget and Peckover, 1973) and for the million-bushel concrete grain elevator at Transcona, Manitoba, which was supported on a raft and experienced a bearing capacity failure during first filling in 1913 (Baracos, 1957). These and other valuable case histories have fortunately been preserved through inclusion in authoritative publications, illustrating the value of such publications as project archives in their own right. The site investigations related to the projects were generally carried out by drillers under the overall supervision of geologists or experienced civil engineers. The field records were probably mostly produced by the drill operators.

By the early 1950's, The Foundation Company of Canada (then a major construction organization) maintained drilling equipment and crews on a full-time basis specially for site exploration services, as well as a team of geotechnical engineers and an experienced multi-disciplinary group of designers and construction engineers. In 1954, this organization formed Geocon Ltd. as specialized geotechnical engineering division. The Montreal consulting engineering firm of Lalonde and Valois, which similarly maintained drill rigs and geotechnical engineers, formed at about the same time a subsidiary called National Borings and Soundings, Inc. (NBS). In western Canada, the consulting firm of R.M. Hardy & Associates specialized in geotechnical engineering. These firms were largely influential in establishing records and documentation procedures including field reports, laboratory testing results, geotechnical analyses and reporting, which then were often adopted by other Canadian geotechnical firms formed at about the same time. By this time, field work was usually conducted under supervision of a soils engineer, although drillers were still generally tasked with record keeping as well as execution. Geotechnical reports were often submitted directly to the owner, or to an architect, consulting engineer designer or contractor as designated by the owner. Field copies of documents were maintained at the consultants' archives, as were soil samples and rock cores. Samples and cores were generally maintained in secure storage until disposal was approved in writing by the client.

With time, geotechnical investigations became increasingly diversified and technologically advanced. In addition to the geologists and geotechnical engineers previously involved in carrying out investigations based on drilling and sampling, other specialized investigative techniques began to be used on an increasing basis. These included geophysical and in situ testing methods (e.g. cone penetration testing) which were offered by specialist firms. Within the overall geotechnical domain, other firms were also formed, including specialist contractors in subsurface water control and ground improvement work (e.g. injection grouting, dewatering, piling, reinforced earth and soil nailing). Each of these organizations generally employed geotechnical engineers and produced reports on their speciality, and had their own policies regarding archives. The "end user" on projects where multiple specialty reports were involved (e.g. the owner, designer, or contractor) had to maintain archives for orderly storage and retrieval of such reports, often at considerable expense for the personnel and office space involved.

As geotechnical engineering became increasingly applied to projects with phased development and long service lives (such as mine tailings dams and heap leach projects), geotechnical reports pertaining to the initial site investigations and design became required by regulators for initial permitting. Regulators and owners in particular also required regular geotechnical reporting during the operating phase, as well as development and updating of operation, maintenance and surveillance (OMS) manuals, closure plans and other geotechnical documents related to long-term care commitments. This added an important burden to the preservation and effective upgrading of documents in archives, particularly for the owner.

The management of archives has special dimensions for large organizations with multiple offices and international operations, where important considerations may include consistency world-wide, technology transfer between offices, staff training, translation into different languages, local regulatory requirements and other responsibilities.

To economize on space, a number of owners first adopted microfilming to conserve storage space. As noted by the ICE Archives Panel, the permanence of film has not yet been sufficiently established to rely on it for information which must be permanently preserved. More recently, archive storage space has increasingly been measured in data bytes, but with parallel concern for long-term, future availability and reliance of the hardware and programs to access and use the digital files. Many geotechnical firms and their clients, as well as regulators and other associated parties, make use of the numerous companies that provide archive storage and management services (including record destruction, as requested), at least for paper-based documents. Increasingly, those services have expanded to include scanning and digitization of such records.

To facilitate access to background data of importance to geotechnical studies, the CGS Foundation Engineering Manual (1985) includes a section titled "Background Information for Site Investigations" which identifies government sources of information on such topics as topographic maps and surveys, hydrographic charts and surveys, aerial photographs, satellite and unusual imagery, geological surveys, soil surveys, climate, hydrology and seismicity.

As noted above, authoritative publications such as refereed geotechnical journals may serve as project archives, with the distinction of providing access for interested readers outside the common project group of owner, consultant and (where applicable) regulator. Proceedings of geotechnical conferences and case examples provided in geotechnical texts may fulfil a similar role, and increasingly the information in all these publicly-available records may be accessed (and copied) digitally.

3 APPLICATIONS IN PRACTICE

In the authors' experience, there have been many occasions where special attention to archives has been important in geotechnical engineering practice.

The first is the obvious need to record the results of relevant field investigations in adequate and reliable form so that they can be, in turn, checked and reviewed in-house as the findings are processed into formal geotechnical reports. These field records and data, which include material such as rock cores and soil samples, should be kept in appropriate storage, particularly in cases where independent peer review might later be involved. Many geotechnical organizations dispose of rock cores and soil samples only with the written approval of the client, a practice with which the authors agree. Ideally, written records which support geotechnical reports should be kept in a secure repository where they can be accessed readily during construction, the operational life of a project, and over the long term where applicable. This practice is already in place with a number of organizations.

Comprehensive archives are also vital where independent peer review is involved, particularly for major projects with challenging design, operation and closure issues. A case in point is Syncrude Canada Ltd., which retained an independent Geotechnical Review Board (GRB) in the early 1970's and have relied on the GRB since for assistance in its oil sands mining operations in northern Alberta. As noted by McKenna (1998) "As time progresses, the GRB becomes the custodian of knowledge regarding key mining and tailings issues. For a long term operation like Syncrude, this sense of continuity for geotechnical information – especially with staff turnover of the early days – is critical to success. The members become the historians for the site, reminding the engineers of historical successes and failures." Other organizations such as Vale Canada Ltd. (and its predecessor, Inco Ltd.) and Barrick Gold Corporation have similarly relied on the advice of independent GRB's for many years, with the added benefit to preservation of archives.

There are many cases in the published technical literature and within the authors' experience, which attest to the value of having preserved archives where older structures are involved. These occur, for example, during expansions to existing facilities such as industrial plants; upgrading of hydro power and tailings dams to comply with current regulatory requirements; and remediation of environmentally-sensitive projects and long-inactive mine sites. Special examples of the value of long-term archive preservation have included (i) requirements by insurers to know the specifics of structures such as hydroelectric dams, as a condition of continuing insurance coverage, and (ii) valuation of a hydroelectric facility as part of long-standing arrangements relating to a change of ownership. The examples known to the authors were between fifty and one hundred years old at the time of the studies. In some instances, original archives were well preserved in the continually occupied and controlled environment of a powerhouse building. In other cases, where important archives were missing, exploratory investigations had to be carried out at considerable expense.

Historic archives in particular can be of considerable value in forensic studies. Their importance was highlighted by Morgenstern (2000) in relation to the Kwung Lung Lau Landslide which occurred in July 1994, notwithstanding that Hong Kong probably had, at the time, the most advanced landslide reduction program of any major city in the world. The landslide was triggered by failure of a masonry retaining wall built in 1901 and was not representative of local experience. Intensive investigations showed that subsurface infiltration from defective buried drainage systems behind the wall caused the failure. However, the underlying problem was inaccurate data in the archives concerning the thickness of the retaining wall. Had a report of the actual wall thickness been prepared and maintained in the project archive, which was referred to when the landslide evaluation program was conducted, the wall would likely have been found to be unsafe and upgraded proactively.

Archives are of obvious importance to cases where disputes relating to geotechnical issues arise. Archives are of course also a source of data for publication of case histories of value to the geotechnical profession as a whole. Their use in this manner is to be commended.

4 FORENSIC STUDIES

A study of background archival material is an essential part of forensic studies on projects of geotechnical relevance. In the authors' experience, such studies have included, among others, condition and stability evaluations of old mine tailings facilities; landslides at urban and industrial sites; distress to highway and rail embankments; differential settlements of structures, and sudden collapse of a major grain elevator. Some of the projects had major adverse implications from financial and other standpoints. Several became the subjects of litigation before they were resolved. Archives from a variety of sources both within and beyond project site boundaries, including institutional memory, were utilized. Their value is illustrated by reference to two projects in the discussion which follows. The projects are presented herein, in brief, primarily to illustrate the importance to geotechnical studies of off-site data and events which may occur in the site environs after the original investigation is carried out.

4.1 Hockey Arena in Russell Township, Ontario

The forensic studies are described by Matich et al. (2007). In this case, a recently-constructed hockey arena experienced unanticipated differential settlement, and litigation had been initiated by the owner. The second author of this paper was involved in an expert review capacity. The arena was of conventional design and located in an area characterized by soft, lightly-preconsolidated sensitive clay, granular till and limestone bedrock. Based on geotechnical studies in 1974, foundations selected were end-bearing piles for the building with concrete floor slabs carried on a thin lift of engineered fill (used to raise grade) and were structurally separated from the pile-supported elements. Construction was carried out in 1975. Between 1975 and about 1979 the grade-supported elements of the arena experienced settlements which were acceptable. However, by 1984, differential settlements of floors relative to the pile-supported elements had significantly exceeded design expectations. Attention by independent investigators then focussed on the clay because of its reputation for dramatic consolidation and resultant settlement when loaded above its preconsolidation pressure. This behaviour is well documented in the published technical literature (e.g. Burn and Hamilton, 1968).

At this stage, precise settlement surveys, additional geotechnical investigations and analyses, safety and structural assessments, and identification of potential remedial measures were initiated. On the assumption that the problem was due to excessive surface loading on the clay, complete pile support was originally considered necessary by one investigator even though the concrete slab had settled uniformly without any cracking. Fortunately this drastic measure was not carried out, as the estimated cost was three to four times the initial cost of the arena. The perceived problem and its potential consequences produced serious contention among the parties involved and resulted in initiation of litigation.

During the preparatory stages for litigation, settlements continued. However, the settlement pattern with time was not consistent with precedent for single or staged surface loadings on Leda clay. An in-depth review of records showed that design and construction of the hockey arena was conventional and supported by successful experience elsewhere. The settlement experienced by the arena was not explainable on the basis of design and construction-related factors.

Two detailed geotechnical investigations were carried out at the site, one in 1990 and the second in 1994. They involved undisturbed sampling of the clay and installation of piezometers (details are given in Matich et al., 2007). These initial studies, undertaken by an independent investigator, focussed on the arena site and did not follow the advice in authoritative publications such as Terzaghi et al. (1996) to the effect that “every subsurface exploration should be preceded by a review of all available information concerning the geological and subsurface conditions at or near the site” and that “whenever information can be obtained by inspection of existing structures in the vicinity, this opportunity should not be overlooked”.

During the subsequent forensic studies and overview process (by the second author), in which many documents were examined, valuable information was also gained from observations of the performance of other nearby structures having similar foundation conditions and discussions locally relating to the original site and construction of the arena. Accessing this institutional memory, which had not been documented (i.e. formally archived), assisted greatly in resolving the underlying cause of the arena settlement. Critically, the forensic study also extended beyond the arena site. Careful review of piezometer data revealed that the clay was being consolidated from the bottom up and that this was attributed to lowering of groundwater levels in the till and bedrock. A study of hydrogeological data for the site and surrounding area, including water well records, showed that a regional drawdown had occurred beginning in the mid 1970’s. By this time, Russell Township was being studied from the standpoint of depletion of groundwater resources and structural distress which appeared to be attributable to increased pumping from wells due to rapid residential developments. Reference to the problem was made in the press (e.g. The Ottawa Citizen, 1993). Large scale discontinuation of pumping from wells in Russell Township had already begun around 1989, when a municipal water system was installed. Settlement of the arena stopped after pumping was discontinued and only minor remedial work was required. The cause was attributed to the groundwater lowering and the matter was resolved at a mini-trial in November, 1994. Significantly, a contractor and a consulting engineer (both with local experience) suspected groundwater lowering as a contributory cause as early as 1985.

Several constructive lessons with respect to archives resulted from this forensic study. Much has been published on research and practical case histories of settlements and slope stability in Leda clay which was the main soil formation at this site. The initial detailed investigations studies should thus have considered the clay as being a possible contributor to the settlement that occurred, but not to the exclusion of geology and hydrogeology of the area around the site, changes to the site area since the original investigation, and evidence for settlement-related distress being experienced by other structures in the vicinity. This aspect was highlighted by the subsequent forensic study, the results of which underscored the importance of keeping good records of all aspects of geotechnical relevance on a project, as well as authoritative construction records. Lastly, a timely examination of possible causative factors outside the arena property would have eliminated a significant amount of effort and cost involved in the forensic study as well as the undesirable aspects of proceeding to litigation.

4.2 Grain Elevator Collapse in Thunder Bay, Ontario

On 23 September 1959, one of the offshore storage annexes (Annex 2) at the United Grain Growers Limited Current River Elevator Terminal (referred to as the UGG Elevator Terminal) located on the waterfront in Port Arthur (now known as Thunder Bay), Ontario suddenly collapsed into the Lake Superior harbour and broke into small pieces. The collapse of the large reinforced concrete structure spilled some 2.5 million bushels of grain into the adjacent slip creating a tidal wave 5 m high, wreaking havoc in the harbour.

The disaster was without precedent and was completely unexpected as the elevator had operated without incident for over 30 years since its construction in late 1927. A review of the causes of this unprecedented collapse will be detailed in a forthcoming paper (Peck et al., in press), being prepared by the second author of this document. As part of the review, a detailed forensic study was carried out. Of particular note to the importance of sound archive practice was the fact that many records had been preserved by the owner and the designer. These records, along with performance data for other grain elevators in the Thunder Bay area, were of vital importance in arriving at the most likely cause of the failure.

The UGG Elevator Terminal consisted of two storage annexes (Annex 1 and Annex 2), each 115 m long, 30 m wide and 38 m high. Along with ancillary structures, the annexes were arranged in a line on a dock some 365 m long; the dock was formed originally by Wakefield timber sheet piling. Soil conditions at the site consisted of silty clay, clayey/silt and hydraulic (dredged) fill overlying natural soft varved clay and firm to stiff stratified clay. The varved and stratified clay units had a combined thickness of about 10 m, and were underlain by compact to very dense silty till and shale bedrock. Each storage annex was supported on 5,052 piles driven to refusal in underlying till. A six track, 24 m wide timber railway trestle 6 m high was located on the land side of the terminal. The area under the tracks was backfilled with granular soil in the early 1930's to mitigate possible fire risk; this fill exerted lateral pressure against the terminal structure.

The slip was deepened by dredging in 1939, and some remedial maintenance was carried out on the dock. Periodic surveys showed that cumulative lateral movements since construction as measured at various locations in the UGG Elevator Terminal had been small (less than 50 mm). Approximately one month before the collapse, an inbound ship struck the outer end of the wharf. Six days before the collapse, another ship collided head-on with the wharf, the first time this had occurred in the service life of the facility. The small lateral movements recorded at the UGG Elevator Terminal were in marked contrast to the considerable lateral movements (as much as 400 mm cumulative) at several other pile-supported, nearby operating grain elevator facilities with reasonably similar subsoil conditions, and where several of the elevators were also subjected to lateral pressures from adjacent fill. At these other elevators, individual movements generally were small immediately after construction, but increased with time; in most cases, remedial measures consisting of secure anchorage were successfully completed.

The UGG Elevator Terminal site was subjected to a detailed geotechnical investigation as well as a comprehensive forensic study during removal of the collapse debris and reconstruction of the facility. In the interpretive analyses, which required concurrent consideration of a variety of potential failure scenarios, a number of prominent Canadian geotechnical organizations and experts were involved, in addition to the owner's representative and the designer. The historical site investigation, design, construction and operation records for the elevator (as well as data for other elevators locally, as mentioned earlier) were of fundamental importance to the analyses, and to establishing the cause of the collapse. Of particular relevance to this paper is that fifty years ago, before today's increasing emphasis on preserving geotechnical archives, a decision was made to do so by the owner's representative. Although the authors (Peck et al., in press) were involved in the original studies, the files were complete and fortunately no reliance on institutional memory was required.

Of further interest is that performance reviews of the other elevators during the original geotechnical investigations brought to light that an experienced surveyor had diligently maintained, but never reported, movement records for one facility in a field book for sixteen years. The data were only analyzed and acted upon after the UGG Elevator Terminal collapse, which is an illustration of not only the importance of maintaining an effective means of storing and accessing monitoring data within a project's archive, but also analysing it periodically and acting on it as required.

5 DISPUTE RESOLUTION

As noted by Fielding et al. (2012), the geotechnical profession is faced from time to time with situations arising from soil conditions encountered during construction that could not reasonably been foreseen at time of tendering for the work. Defensive actions aimed at minimizing such situations if possible, should obviously include carrying out pertinent geotechnical studies in accordance with current recognized good practice.

A policy of internal review and checking also has considerable merit in the authors' view. On larger and/or technically challenging projects, comprehensive geotechnical baseline reports may be produced to minimize the possibility of disputes, and peer review by independent geotechnical boards is becoming more common, as noted earlier. Despite precautions that might be taken in carrying out geotechnical studies, situations occur which lead to disputes and unfortunately, sometimes to litigation. Where they cannot be resolved by direct negotiation between the parties, resolution by other methods is available.

Within the collective experience of the authors, alternate dispute resolution (ADR) methods have been offered variously by organizations such as the ADR Institute of Ontario, the Contract Disputes Advisory Board (Public Works Canada), and the International Dispute Adjudication Board. Irrespective of the resolution method used, sound archive practice is clearly important to each party in support of its case. Disputes concerning geotechnical investigation and design issues may occur not only during construction, but also years later and related to structure performance. In the discussion which follows, documentation generated during construction provided an unusual basis for dispute resolution.

The dispute concerned geotechnical matters related overburden stripping at an open pit and construction of earth dams and other infrastructure at a phosphate rock mine near Kapuskasing, Ontario (Fielding et al., 2011). The contractor had claimed that changed conditions occurred for a variety of reasons, particularly the fact that limited geotechnical data were available during the tendering process. The changed conditions as claimed by the contractor included significant differences in the characteristics of the soil and rock materials to be handled; a considerable difference in the volume of such materials; major modifications to the planned construction methodology; and lengthening of the construction schedule which resulted work being unexpectedly programmed for severe climatic conditions. The project had been characterized by an apparent reliance on the experience of prospective contractors to assess relevant geotechnical conditions primarily through a site visit and briefing. The contract placed an onus on the contractor to cope with any problems encountered during construction. However, it also included a provision for resolution of disputes in good faith, failing which each party could resort to such remedies as may be available to it at law or in equity.

Not long after construction began, it became evident that a claim from the contractor was going to be submitted. All historic data were made available to the contractor, and good records were also maintained by the contractor and independently by the owner. By the time construction was completed, geotechnical factors were known, relevant design matters had been resolved, material quantities had been established, as were considerations such as schedule and climatic influences. The data was thus available to support the assumption, in simplistic terms, of design during construction (reverse engineering) and thus preparing a hypothetical re-tendering of the project. The approach of basing a claim on a hypothetical revised tender was presented to the owner and construction manager, and the methodology was accepted with the proviso that it was acceptably-structured and justified. The claim was settled to the satisfaction of the parties. The key to the success of the revised tender was the development and maintenance of a good construction archive.

6 HERITAGE TRIBUTES

The importance of providing a permanent record of engineering projects from a heritage standpoint has long been recognized, for example by the Engineering Institute of Canada (Duguay, 1976), through Engineering Heritage Conferences held jointly by Engineers Australia and Engineers New Zealand, and by the ICE Archives Panel. Like the ICE Archives Panel, the CGS Heritage Committee also recognizes past projects of particular interest, such as the early days of development of the Athabasca Oil Sands in northern Alberta, and the failure (and subsequent righting and underpinning) of the Transcona Grain Elevator.

The importance of preserving a record of the achievements of prominent pioneers in the geotechnical engineering field has similarly been recognized. Through its Heritage Committee, the CGS presently recognizes Canadian pioneers in the geotechnical field, building on past work such as that by Gold (1998) and others. Many other projects and prominent individuals of historic importance to the development of geotechnical engineering in Canada deserve recognition and CGS Members are encouraged to do so through the Heritage Committee.

The authors would like to make special mention of several such pioneers to Canadian geotechnical practise, all of whom contributed significantly to the way that various aspects of geotechnical investigations are recorded and reported: Mr. Richard Chadwick, founder of The Foundation Company of Canada, and Mr. Norman D. Lea, first President of its subsidiary, Geocon Ltd.; the Montreal consulting firm of Lalonde and Valois, who founded NBS; and Dr. R.M. Hardy, former Dean of the School of Engineering at the University of Alberta and founder of R.M. Hardy & Associates.

7 HISTORIC MILITARY OPERATIONS

Two cases from the published technical literature are presented where geotechnical data was obtained by unusual methods and where historic records proved to be of great value.

Geological and geotechnical conditions and associated terrain factors have historically had a major influence on the outcome of military operations. As a general statement, the characteristics of the natural terrain within a few metres of ground surface have often been the determining factor between success and failure of a military operation, with trafficability (a function of bearing capacity) being one of the main influences. Of vital importance to amphibious warfare have been soil conditions in the immediate environs of the landing beaches where the difficult transition from sea to land is made and the amphibious assault (landings in the face of an opposing force) is at its greatest vulnerability. Well-known cases in the Pacific during World War II are the soft volcanic ash beaches on Iwo Jima Island (Mann, 2009); uncharted coral reefs immediately offshore at Tarawa Atoll (Polmar and Mersky, 1989), and soft organic silt mudflats and extreme tidal range, at Inchon Harbour, Korea (Heinl, 1968). In each case, it was vital to obtain as much data as possible on ground conditions in advance of the amphibious assault. The U.S. Corps of Engineers' maxim of “know before you go” is particularly relevant. Such data often had to be obtained by clandestine, dangerous missions.

7.1 Dieppe Raid and Normandy Beaches Invasion

The Anglo-American-Canadian force entering France in the Normandy (the D-Day Landings) in June 1944 was the largest amphibious assault in history. The assault was preceded by a massive hit-and-run amphibious raid on the beaches at the Port of Dieppe in France in August 1942.

There is considerable controversy about the overall benefits of the Dieppe raid in providing invaluable experience for future assaults; it did, however, provide important geotechnical information and illustrated the value of researching beforehand all available archival data for undertakings of great consequence.

The Dieppe raid was not preceded by practice on beaches with similar characteristics, nor, it would appear, by a detailed study of the site geology and geotechnical characteristics of the beaches from archives. The focus of the planners was on steep (angle of repose) narrow beaches which were composed of smooth shingle of extremely hard flint-like rock. Most of the tanks and wheeled vehicles landed on such beaches, and all that did became immobilized due to lack of traction. In the confusion of battle, only five of the twenty-eight tanks landed on the compact sand beaches and these were the only units which moved inland and contributed to the battle (Polmar and Merskey, 1989). Verifying suitable landing conditions beforehand was thus an important lesson from Dieppe which was applied in planning the Normandy Beaches invasion.

During aerial reconnaissance for the Normandy invasion, often at very low level, dark patches were observed on some of the beaches, particularly after storm movement of the lighter-coloured sand. Long after the beaches had been selected, a scientist who had escaped from France warned that there were areas of peat below the sand on Utah Beach (Breuer, 2005). This created considerable concern and urgent measures were taken to confirm soil conditions and thus delineate exclusion areas in which tanks and vehicles could bog down. In addition to air photo interpretation, commandos transported by mini-submarines made night-time landings to obtain samples from selected beaches. Of particular importance was detailed archive searches made secretly. Publications, some in obscure or very specialized journals, were located and studied for information on the position of patches of subsurface peat. Amongst the findings was archaeological evidence that there were old Roman peat workings (peat was used for heating) in the Normandy Beach area. Despite the planning effort and recourse to available historic archives, some of the Normandy Beach invasion vehicles unavoidably landed in the peat exclusion zones and became bogged down (Rose and Pareyn, 1996).

7.2 Destruction of V-Weapon Installations

In the latter part of 1943, the Allies began to assemble evidence of secret, below-ground V-weapon bunkers and launching facilities in northern France directly across the Channel from Dover. These weapons, designated V1, V2 and V3, represented a great threat to London and Southern U.K., as well as the Port of Antwerp which was being used by the Allies for supply purposes after the Normandy landings. The V1 Flying Bomb was a small pilotless jet aircraft launched from a surface ramp that could be countered by Allied fighter aircraft and by saturation bombing of the launch sites using conventional bombs. However, the V2, a large rocket-powered missile, was impossible to stop or intercept once launched. It was assembled in hardened sties deep underground and moved outside just prior to launch. The V3, a multi-barrel, multiple-charge gun was also stored underground and had the potential to hit London with shells that similarly could not be intercepted once fired. The deep underground V2 and V3 sites were considered by the Germans to be impregnable to conventional bombing.

The challenge posed by the need to destroy these underground installations led to the practical development of the “earthquake bomb” a stroke of genius of Dr. Barnes Wallis, inventor of the famed “bouncing bomb” used successfully in low level attacks against the Rhur Dams (Mohne, Eder and Sorpe) in May 1943 (Murray, 2010). Dr. Wallis envisaged using new, single bombs to destroy the V2 and V3 sites, much heavier than the bombs available at the time; the new bombs would also be capable of deep penetration into soil and soft rock as well as man-made materials such as reinforced concrete. Destruction of underground installations would be by both direct explosive action and also by a massive pressure wave.

Comprehensive geotechnical studies were involved in developing the bomb casing design and maximizing bomb penetration. As described by Murray (2010, 2011), the geology of the V-weapon installations was well known from published data (including experience in World War I), and these archives were invaluable in locating proxy testing grounds on the other side of the Channel. Of particular interest from a geotechnical standpoint is that charts were developed showing expected penetration of the three sizes of new large bombs into the target geologic materials (clay; soft chalk or hard clay; hard chalk; and sand), and that post-war investigations revealed reasonable agreement with actual performance.

8 CONSIDERATIONS FOR THE FUTURE

Historically, the preservation of a relatively limited number of critical documents such as field investigation, design and construction reports, has been the challenge (and mandate) of a sound geotechnical project archive. As major projects have expanded in scope and included new sub-disciplines of geotechnical engineering, and the ease and ability to create numerous versions of digital records with an ever-expanding variety of software has increased seemingly exponentially, an increasing challenge to future geotechnical archive practice may be the identification of the critical documents for preservation (and access) in the first place.

The extended durations of the investigation, design, permitting, construction and often operation phases of new, major projects, along with the requirement in many cases of perpetual care (common in the mining industry) has also increased geotechnical data and report preservation requirements. Integral to that is the need to demonstrate clearly the documentation of key approvals, revisions and decisions, as may be required for a corporate, regulatory or independent audit.

Under these considerations, responsibility for the geotechnical engineering archive must be recognized as belonging to the project owner, or more subtly, the owner should not rely on the consultant (or regulator) to become the de facto steward of the geotechnical database. The organization which generates the geotechnical data should, nevertheless, be responsible for its own archives. In the more mobile, modern professional world, reliance should likewise not be placed on institutional memory; regular relocation and career changes are the norm for staff at many operations, and records of the particular geotechnical conditions, performance and lessons-learned may be lost if not attentively and regularly documented.

The ever-increasing diversity, quantity and time of generation of geotechnical information place additional stress on sound document management, which includes efficient and secure long-term storage, reliable identification, and ready retrieval capability. Early development of, and adherence to, a centralized project archive for geotechnical records, with appropriate back-up and other security provisions, must be a priority for major new projects. Clear document control protocols should be established to ensure that current versions of key records are preserved and that additions, removals and modifications to the archive are done only with prior approval and recorded.

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