GEOTECHNICAL ENGINEERING ASPECTS OF CURRENT RESEARCH INTO TREATMENT OF HYDROCEPHALUS

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ABSTRACT

Hydrocephalus is the accumulation of cerebral spinal fluid (CSF) in the brain with corresponding increase in fluid pressure that can compress the brain against the interior of the skull, enlarge the skull and cause brain damage or death. Hydrocephalus is usually treated with a catheter and valve system (a shunt) that is surgically implanted into the brain to drain excess pressure. In an attempt to minimize the need for surgical revision and reinsertion of failed shunt components, research at the Stollery Children's Hospital (SCH) in Edmonton, Alberta has focused on discharging the excess CSF into the venous system via dissipation in the porous portion of the skull bone. Various aspects of geotechnical engineering are directly applicable to the ongoing research at the SCH. Knowledge gained during diamond drilling, packer testing and pressure grouting projects were used to guide research and testing on cadaver tissue and laboratory animals.

RÉSUMÉ

L'hydrocéphalie est l'accumulation dans le cerveau de fluide rachidien qui entraine l'augmentation de pression qui peut comprimer le cerveau contre les os craniens. Ceci peut entrainer une expansion du crane, causer des liaisons cérébrales et la mort. D'habitude, l'hydrocéphalie est traitée au moyen d'un drain et d'une valve implantée au cerveau lors d'une intervention chirurgicale, afin de réduire la pression excessive dans le cerveau. Dans le but de réduire le besoin d'opération de suivie et de ré-insertion dans le cas d'un drain ne fonctionnant plus, une recherche a été entreprise à l'hopital des enfants Stollery à Edmonton, Alberta. Cette recherche a visé à étudier comment transmettre dans le systéme sanguin l'excess de pression dans le cerveau, par dissipation de cette pression à travers la partie poreuse des os craniens. Différents aspects de la géotechnique sont directement applicables à cette recherche, tels que le forage au rocher, les tests de perméabilité in-situ ou l'injection de produits de scellement. Cette connaissance tirée de la géotechnique a été appliquée à la recherche conduite sur des cadavres et sur des animaux de laboratoire.

1. INTRODUCTION

"The theories of soil mechanics provide us only with working hypotheses, because our knowledge of the average physical properties or the subsoil and of the orientation of the boundaries between the individual strata is always incomplete and often utterly inadequate." From *Theoretical Soil Mechanics*, Karl Terzaghi.

"One of the difficulties on understanding the brain is that it's like nothing so much as a lump of porridge." From *Eye and Brain: The Psychology of Seeing*, by R.L. Gregory, 1966.

Hydrocephalus is the accumulation of fluid in and around the brain with corresponding increase in fluid pressure that can compress the brain against the interior of the skull, enlarge the skull and cause brain damage or death. Surgical procedures for treating hydrocephalus have been researched since approximately 400 BC (Drake and Saint-Rose, 1994) when Hippocrates first recognized that fluid accumulating in the brain caused the skull to enlarge. Since then, research into the treatment of hydrocephalus has been ongoing, resulting in improvement of surgical procedures and treatment success rate in treatment of hydrocephalus.

Research is currently being conducted at the Stollery Children's Hospital (SCH) in Edmonton, Alberta on a proposed new treatment for hydrocephalus. Surprisingly enough, theoretical and practical aspects of geotechnical engineering, in particular, those relating to flow through porous media or through rock fractures, can be used to evaluate collected data and observations as well as provide guidance for future research activities. A brief overview of the current research conducted at the SCH and the geotechnical aspects of this research are presented in this paper. Recommendations for further study or consideration in a neurosurgical context are also presented herein from a geotechnical perspective.

2. NEUROSURGICAL ASPECTS

2.1 General Brain Anatomy

The brain is supported and protected by the following general areas (from outside to inside):

- Skin;
- Skull bones;
- Dura matter, a tough leathery membrane adhered to the inside of the skull; and
- Arachnoid mesh and space containing cerebral spinal fluid (CSF).

These zones are illustrated in Figure 1.

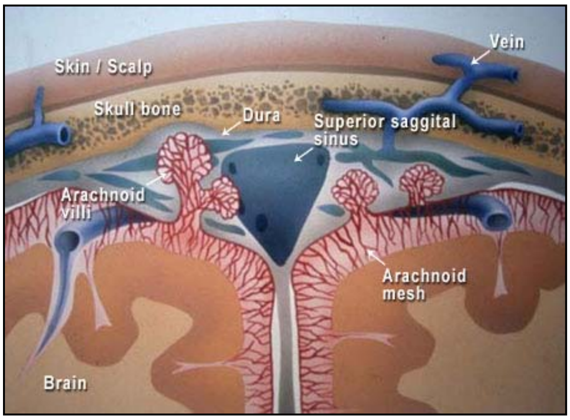

Figure 1: *Brain anatomy in the vicinity of the superior sagittal sinus.*

The CSF acts as a dynamic absorber of pulsations for the brain and spinal cord as well as a medium to transfer hormones and nutrients to the nervous system.

CSF is a colourless liquid, low in cells and proteins but similar to plasma in its ionic composition. It is, for the most part, formed in the choroid plexus by filtration of the blood through osmotic transfer across membranes in the interior of the brain. The rate of CSF production is, on average, 350 µl/minute (6 x 10^{-3} cm^3/sec) at a relatively constant rate independent of blood pressure or existing CSF pressure (Nolte, 1988). At this rate, the total volume of CSF is renewed approximately three times a day. The points of discharge are the arachnoid villi which can be generally described as "one way valves" that allow CSF to be discharged into the venous system via the superior saggital sinus. The points of discharge are illustrated in Figure 1. The blood pressure within the superior saggital sinus is practically 0 kPa.

CSF will continue to be produced if circulation and/or absorption becomes impeded or ceases. In either event, the volume and pressure of the CSF increases, expanding the ventricles with corresponding compression of the brain and eventual enlargement of the skull with headaches, loss of consciousness and, in some cases, death. This condition is the most common form of hydrocephalus and is the focus of the research currently underway at the SCH.

2.2 The Use Of Shunts To Treat Hydrocephalus

Shunts are devices designed to transport CSF from the generation or accumulation site to a reabsorption site. Shunts have been in use for approximately 50 years. A shunt consists of the following components:

- A catheter extending into the brain to act as a drain in the ventricles;
- A shunt valve attached to the catheter outside of the skull to regulate CSF flow from the brain; and
- A flexible tube that extends from the shunt valve to an absorptive site such as the abdomen (peritoneum) or pleural space.

Attempts to dissipate excess CSF into the superior sagittal sinus have not gained widespread support as most still prefer the peritoneum, pleural space or the right atrium of the heart.

Theoretically, shunt systems should last a lifetime. However, they frequently fail and require subsequent surgical revision or re-insertion. Shunt systems frequently malfunction for the following reasons:

- Blockage at valves and/or discharge catheter; and
- Breakdown of the tubing in the neck area due to over-stressing caused by normal neck motion.

2.3 Focus Of Current Research At SCH

The research being conducted at SCH is directed at dissipating CSF from the shunt into the superior saggital sinus via the skull bones. The skull bones are living tissues that require blood flow. Dissipation of CSF into the skull bones in the vicinity of the superior saggital sinus should result in the CSF reaching into skeletal (osseous) venous system that drains into the superior saggital sinus. A hypothetical illustration on how this would be achieved is illustrated in Figure 2.

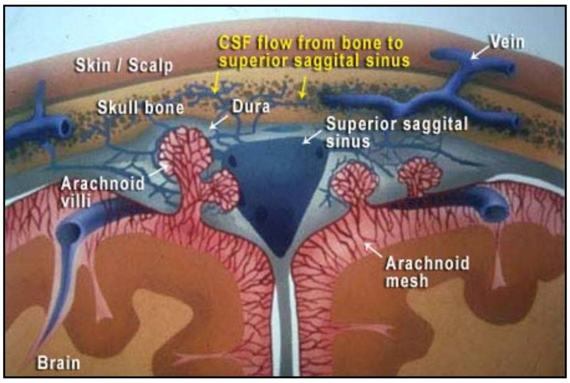

Figure 2: *Conceptualization of proposed treatment method for hydrocephalus.*

3. NEUROSURGICAL CONCEPTS IN A GEOTECHNICAL ENGINEERING CONTEXT

3.1 General

The researchers at the SCH have identified that the mechanism of fluid flow through porous media was critical to the success of the proposed treatment. Subsequent discussions between the authors identified certain geotechnical engineering principles and practices as being applicable in developing the proposed treatment of hydrocephalus. These aspects are discussed in the following sections.

The questions faced by the neurosurgeon at the SCH regarding the dissipation of CSF in skull bone fall into the following general categories in a geotechnical context:

- Site characterization;
- Characterization of permeability;
- Design and construction of drainage measures; and
- Monitoring pore pressures.

3.2 Site Characterization

3.2.1 Geotechnical Perspective

Site characterization is one of the first tasks a geotechnical engineer would undertake in the design of a dam or embankment. Site characterization activities would include, but not be limited to, review of background information (topography, geology, land use, etc), intrusive methods such as drilling boreholes, excavating test pits or trenches and indirect methods such as ground penetrating radar and other surface based geophysical methods. The results of the site characterization activities would be modeled in a two or three dimensional computer assisted drafting (CAD) model to permit assessment of surface topography, the inferred soil and rock conditions below the subject embankment of dam as a digital terrain and stratigraphy plan.

3.2.2 Neurosurgical Applications

Intrusive and non-intrusive methods could be could be used by the neurosurgeon to evaluate the thickness of skull bones and the thickness and location of the porous centre of the bone. Computerized tomography (CT) scans taken along various orientations could be interpreted by the neurosurgeon and the results be input into a three dimensional CAD model.

Bone porosity of a preferential orientation could result in anisotropic permeability. The skull bone structure should be investigated for anisotropic bone structure bearing in mind the process involved in skull bone genesis. An investigation for anisotropic bone porosity could involve the use of a scanning electron microscope survey of thin sections of cadaver skull bone cut along different planar orientations with a high quality cutting device such as a fine diamond saw or high pressure water jet.

3.3 Characterization of Permeability

3.3.1 Geotechnical Perspective

D'Arcy's Law is the relationship that relates flow of water through porous media under hydraulic gradient to the permeability of the soil and the pressure head of the fluid flowing through the soil. D'Arcy's Law is presented in Equation 1.

$$Q = kiA \qquad [1]$$

where:
Q is the flow rate of CSF transport through the porous media
k is the permeability of the porous media, assumed to be saturated; and
i is the hydraulic gradient.
A is the cross-sectional area of the flow path area.

The following conditions have to exist for D'Arcy's Law to be valid:

- Laminar flow;
- Linear relationship between velocity of flow and hydraulic gradient; and
- 100% saturation of pore spaces.

Soil permeability is usually obtained through lab testing of soils taken during the site characterization or through in-situ testing conducted during the site characterization. Lab testing is conducted under controlled conditions whereas in-situ testing is conducted under field conditions. As such, in-situ testing is subject to many uncertainties that could drastically affect the test results. One of these uncertainties is related to smearing of fine grained soils on the borehole walls during drilling. Borehole wall smear can reduce recorded permeability by several orders of magnitude.

3.3.2 Neurosurgical Applications

The testing conducted to date at SCH has not included permeability testing. However, several tests have been conducted on cadaver skull bone tissue and live animals to prove that the proposed method of treatment is feasible. These tests are similar to in-situ permeability testing methods employed in geotechnical engineering practice and could be modified with minimal effort to permit permeability testing of the porous bone structure.

The feasibility of injection of CSF into the skull bones was tested by the researchers at the SCH fall into the following categories:

- Cadaver tissue testing; and/or
- Live animal testing.

Each of these general methods are described in the following paragraphs.

Cadaver Tissue Testing

Various experiments have been conducted at the SCH to prove that the porous zone of the skull bone is an interconnected series of voids that are connected to veins and capillaries within the bone. Boreholes were drilled into cadaver bone tissue and an acid resistant polymer resin was injected into the bone. The test apparatus and cadaver tissue is shown in Figure 3. After a sufficient time to allow the resin to set, bone and soft tissue were corroded away with strong molar base solutions, leaving the injected resin structure behind. The results of this testing are shown in Figure 4. This experiment proved that the pores within the skull bone were interconnected. However, in initial tests, the presence of a thin smear of bone cuttings and other tissue on the walls of the hole drilled into the cadaver bone effectively prevented resin injection into the bone. Subsequent testing procedures were modified to include rigorous flushing of the drilled hole to remove any materials that could clog the porous bone structure. At the time of submission of this paper, scanning electron microscope data shows that clogging of pores is still occurring, necessitating further review of drilling methods.

It is reasonable to expect that the following occurred in the cadaver skull bone tissue shortly after death;

- Desaturation of bone due to production of gases from decomposing tissue of fluids; and/or
- Congealing and drying of fluids causing residue to build up in the pores of the bones.

As such, permeability testing of cadaver skull bone permeability is anticipated to yield lower bone permeability due to clogging of the fluid flow paths with gases and solids. The presence of air or gas in the soil pores results in unsaturated soil conditions. The air or gas within the water hinder epoxy (or water if permeability testing was conducted) flow, reducing the effective permeability of the sample. It is for this reason that a soil has to be 100% saturated for D'Arcy's Law to be valid. Therefore, permeability testing of the cadaver skull bone tissue could provide a lower bound value of bone permeability, due to the potential influence of gas and congealed fluids, that could be used to predict the minimum level of effectiveness of the proposed drainage measures.

Figure 3: *Epoxy injection apparatus and cadaver bone tissue.*

Figure 4: *Hardened epoxy exposed upon digestion of bone with acid.*

Live Animal Testing

The researchers at the SCH have conducted live animal testing to evaluate the effectiveness of the proposed treatment. The testing consisted of installing dissipation ports into the skull bones of live anaesthetized animals with subsequent injection of aqueous solutions through them into the skull bone. The results of this experiment are currently being evaluated and the results are encouraging.

In-situ testing of the permeability of live animal skull bone could be conducted if the test procedure was modified to include measurement of injection pressure and fluid flow rate. This method of testing would not be subject to the uncertainties associated with conducting permeability testing on cadaver skull bone as the bone would be saturated and would likely not have the gases or dried fluids that are likely present in the pores of cadaver skull bone tissue. However, the potential clogging of the pores during drilling would need to be addressed prior to this juncture.

The effect of desaturation of cadaver skull bone tissue could be evaluated by conducting dog cadaver skull bone tissue permeability testing and comparing the resulting permeability to that obtained during live animal testing. Furthermore, the applicability of live animal skull bone permeability test results to human conditions could be assessed by comparing the laboratory test animal bone structure to cadaver skull bone structure. Through this comparison the researchers could evaluate whether or not the bone structure of the animal species selected for live testing has similar bone foliation and structure as human skull bone.

3.4 Design and Construction of Drainage Measures

3.4.1 Geotechnical Engineering Perspective

Frequently analysis, judgment and experience indicate that pore pressure beneath a dam or an embankment will be high enough to warrant implementation of drainage measures to mitigate potential slope stability or seepage related concerns.

Drains should be designed to provide adequate drainage capacity and to filter the surrounding soil particles to prevent them from being mobilized into the drain by seepage. These are the drainage and filtering design criteria proposed by Bertram in 1940 for the design of drains in soil (Cedegren, 1989). Failure to satisfy these two design criteria will result in the drain having limited effectiveness in reducing pore pressures.

The performance of drainage measures installed during the construction of a dam or an embankment are usually monitored through the installation of piezometers and monitoring of flow rates from drains.

3.4.2 Neurosurgical Applications

The shunt system currently used to treat hydrocephalus is effectively a drain that reduces CSF pressure. The proposed concept of dissipating the CSF into the skull bones effectively constitutes a reverse drain concept. The spacing and orientation of the individual dissipation ports with regards to any anisotropic porosity of the skull bone will influence the rate of dissipation of the CSF. The rate of excess CSF production must be matched by the capacity of the porous zone of the skull bone to dissipate it. The information obtained from conducting a CT scan site characterization of the skull bone in the proposed area of injection and dissipation to determine the thickness of the porous zone of bone would assist in improving the efficiency of these measures and perhaps provide a means to pick the most optimum location for the dissipation ports from fluid dissipation efficiency and ease of installation perspectives.

The description of CSF as a colourless liquid that is low in cells as well as the nature of its natural circulation throughout the brain and spinal column indicates that there are likely no suspended solids in CSF. Therefore, based on this description, the only foreseeable risks of the permeability of the porous zone of the bone decreasing after insertion of the dissipation ports in a living human being would be due to partial or complete clogging caused by cuttings or bone fragments loosened during drilling or dissipation port insertion and blood clotting due to blood refluxing into the bone from the superior sagittal sinus and mixing with the CSF near the injection device.. However, the potential for clogging should be investigated further should further research indicate that the CSF contain suspended solids or other matter. It is unknown if a reaction within the bone could occur that would cause a reduction of the permeability of the porous zone of the bone in contact with the dissipation port.

Performance monitoring of the CSF pressures in the shunt tubing could provide the neurosurgeon with an additional tool with which to assess the condition of the patient and the effectiveness of the proposed treatment. CSF fluid pressure would most likely be measured in the tubing that leads to the dissipation port with a micro-piezometer. Such instruments are fabricated for bio-medical purposes. CSF pressure measurements could provide performance data which could be incorporated into future improvements on the proposed treatment and related technology. At the very least, regular CSF pressure monitoring may provide warning of impending system failure, providing the neurosurgeon with additional reaction time for initiation of surgical revisions to the system.

4.0 PRELIMINARY GEOTECHNICAL EVALUATION OF PROPOSED TREATMENT

Although permeability testing of the bone has not been conducted, based on inspection of photographs of cadaver bone tissue, the permeability of the porous bone is anticipated to be similar that of fine sand which can have a range in the order of 1 x 10^{-2} cm/sec to 1 x 10^{-3} cm/sec. The presence or absence of more permeable structures such as veins and capillaries or anisotropic conditions could result in a greater range in permeability. Based on this estimated range of permeability, D'Arcy's Law was used to calculate the potential dissipation rate of CSF in skull bone. The following simplifying assumptions were made to facilitate this calculation:

- The porous zone of the bone is uniformly 0.5 cm thick;
- The bone is assumed to be a 1 cm wide strip perpendicular to the superior saggital sinus;
- The CSF is dissipated evenly over the entire thickness of the porous zone of bone;
- The distance between the point of injection and the superior saggital sinus is 2.5 cm;
- The injection pressure head is 0.1 kPa at the point of injection and 0 kPa within the superior saggital sinus; and
- The permeability of the bone between the point of injection is a bulk permeability and accounts for varying permeability associated with any anisotropic permeability, varying bone density, and concentrated seepage paths in capillaries and veins.

The calculated dissipation rates of the CSF in the porous bone structure are $2x10^{-3}$ cm^3/sec and $2x10^{-5}$ cm^3/sec for bone permeabilities of 1 x 10^{-2} cm/sec to 1 x 10^{-4} cm/sec respectively. The previously quoted rate of CSF production, 6 x 10^{-3} cm^3/sec, is higher than this range of calculated dissipation rates over a 1 cm wide strip of bone. Therefore, dissipation widths of approximately 3 cm and 30 cm are required to dissipate the excess CSF for bone permeabilities of 1 x 10^{-2} cm/sec to 1 x 10^{-4} cm/sec respectively. Permeability testing of human skull bone should be tested to verify that the assumed range of permeability is correct.

5.0 RECOMMENDATIONS FROM A GEOTECHNICAL ENGINEERING PERSPECTIVE

The following recommendations for further study are made from a geotechnical engineering perspective:

- Characterize potential CSF dissipation sites and skull bone(s) with multiple CT scans and plot the results of these scans in a three dimensional CAD model that presents bone thickness, thickness of porous zone of bone and location of any major blood vessels, including the superior saggital sinus;
- Prepare thin sections of cadaver skull bone cut at different orientations to the superior saggital sinus and inspect these sections under a high power microscope to determine if there are any preferential orientations of bone porosity that could influence the dissipation rate of CSF.
- Assess whether or not there is a relationship between bone formation and growth patterns to any potential preferential orientations of bone porosity;
- Conduct laboratory permeability testing on cadaver skull bone to establish a lower bound value of the skull bone that could be used to assess the minimum level of effectiveness of the proposed CSF dissipation measures;
- Prepare thin sections of animal skull bone cut at different orientations to the superior saggital sinus an compare these to the cadaver skull tissue sections to see if the structure of the bone is comparable and an appropriate analogy to human skull bones;
- Conduct in-situ permeability testing on live animals to determine the live skull bone permeability if the thin bone section comparison indicates that an animal skull bone is analogous to human skull bone;
- Design CSF dissipation ports such that their dissipation capacity is based on the principles of fluid flow through porous media as detailed herein. The installation of these measures should be guided by the characterization of the skull bone conducted with the three dimensional CAD model of the skull bone(s);
- Investigate the long term potential for clogging of the porous bone with suspended solids or other matter contained in the CSF; and
- Consider incorporating a CSF pressure monitoring program to evaluate the performance of the proposed treatment.

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7.0 REFERENCES

Cedegren, H. R. *Seepage, Drainage and Flow Nets*, John Wiley and Sons Inc., New York, New York, USA.

Drake, S.M. and Sainte-Rose, C. (1995) *The Shunt Book*, Blackwell Science, Cambridge, Massachusetts.

Gregory, R.L. (1966) *The Psychology of Seeing*, Princeton University Press.

Nolte, J. (1988) *The Human Brain – An Introduction to It's Functional Anatomy*, The C.V. Mosby Company, Toronto, Ontario, Canada.

Terzaghi, K. (1943) *Theoretical Soil Mechanics*, John Wiley and Sons Inc., New York, New York, USA.