DESIGN OF BOREHOLE SEALS IN ROCK FORMATIONS USING EXPERT SYSTEM

Miss Ammarin Warin

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for the Degree of Master of Engineering in Geotechnology

Suranaree University of Technology

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Suranaree University of Technology has approved this thesis submitted in partial fulfillment of the requirements for a Master's Degree.

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วัตถุประสงค์ของงานวิจัยคือการพัฒนาซอฟต์แวร์ระบบผู้เชี่ยวชาญเพื่อใช้ในการออกแบบการอุดหลุมเจาะในชั้นหิน ระเบียบวิธีวิจัยเริ่มต้นด้วยการรวบรวมวรรณกรรมวิจัยที่เกี่ยวข้อง การสร้างโครงข่ายทางความคิดสำหรับการออกแบบ การพัฒนาซอฟต์แวร์ และการตรวจสอบและปรับปรุงซอฟต์แวร์ หลุมเจาะในงานวิจัยนี้จะรวมไปถึงหลุมเจาะที่ใช้ในการสำรวจและผลิตน้ำบาดาลและแร่ โดยซอฟต์แวร์ระบบผู้เชี่ยวชาญที่พัฒนาขึ้นในงานวิจัยนี้เรียกว่าโปรแกรม BSR ใช้โปรแกรม Microsoft Visual Basic 6.0 เป็นกรอบของระบบ เครือข่ายของระบบประกอบด้วยแนวทางและขบวนการในการตัดสินใจซึ่งจะรับข้อมูลคุณลักษณะของพื้นที่จากผู้ใช้ จากนั้นระบบจะจำแนกและประเมินข้อมูลเพื่อนำไปสู่ผลลัพธ์ที่อยู่ในรูปของการออกแบบและการเลือกสรรวัสดุที่ใช้ในการอุด คุณลักษณะของพื้นที่จะประกอบด้วยข้อมูลลักษณะของหลุมเจาะ คุณลักษณะของมวลหิน ระดับน้ำบาดาล ธรณีวิทยาเคมี ความเค้นของหิน แนวโน้มการเคลื่อนตัวของหิน คลื่นไหวสะเทือนและขีดความสามารถของการอุดที่ต้องการ ระบบผู้เชี่ยวชาญจะจำแนกข้อมูลและจะเลือกวัสดุที่ใช้สำหรับอุดแต่ละชั้นหินโดยอาศัยเกณฑ์ที่ได้จากผลการทดสอบและการวิจัยอื่นที่เกี่ยวข้อง วัสดุที่นำมาพิจารณามีหลายชนิดประกอบด้วยซีเมนต์ เบนทอไนต์ กรวด ทราย และดินหรือส่วนผสมของวัสดุเหล่านี้ จากนั้นจะมีการประเมินความสามารถของระบบการอุด (รวมไปถึงวัสดุหินรอบหลุมเจาะ และรอยต่อที่ผนังของหลุมเจาะ) ด้านเสถียรภาพเชิงกลศาสตร์ ด้านความสามารถในการกักเก็บเชิงชลศาสตร์ และด้านความเข้ากันได้ในเชิงเคมี ในขั้นนี้การออกแบบอาจจะมีการปรับเปลี่ยนเพื่อให้มีความเหมาะสมยิ่งขึ้น คำแนะนำในการออกแบบจะรวมไปถึงความยาวชนิดและคุณลักษณะของวัสดุอุดสำหรับหลุมเจาะนั้น ๆ ตัวอย่างของการอุดหลุมเจาะได้ให้ไว้เพื่อแสดงความสามารถของระบบสำหรับลักษณะธรณีวิทยาและลักษณะหลุมเจาะที่หลากหลาย

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AMMARIN WARIN: DESIGN OF BOREHOLE SEALS IN ROCK FORMATIONS USING EXPERT SYSTEM

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EXPERT SYSTEM/ BOREHOLE/ SEAL / ROCK FORMATION/ CEMENT/ BENTONITE/ GRANULAR MATERIALS

The objective of this research is to develop the expert system software for use in the design of borehole seals in rock formations. The task involves literature review of the relevant research, concept formulation, software development, and software reviewing and editing. Boreholes in this research include those used in the exploration and production of groundwater and mineral resources. The computer software is called “BSR Program” (Borehole Sealing in Rock). Microsoft Visual Basic 6.0 is used as an inference engine. The network comprises paths and decision-making procedures that use site characteristics given by the user. It classifies and evaluates the information, and leads to the seal design and material selection. The considered site characteristics include the borehole conditions, rock mass characteristics, groundwater level, geochemistry, in-situ stresses, potential ground deformation, seismic activities, and performance requirements. The system first classifies the input data and selects the sealing material for each rock unit based on the design criteria derived from the relevant experimental researches. A variety of sealing materials (design solutions) is considered, including cementitious, bentonitic, and granular materials, or mixtures of these components. The seal system (seal, host rock, and their interface) performance is then evaluated in terms of the mechanical stability, hydrological integrity, and chemical compatibility. Design modification is then made if appropriate. The design recommendations include length and specifications of sealing material for each rock unit along the borehole. Examples of borehole sealing are also given to demonstrate the system performance under a variety of geologic and borehole conditions.

School of Geotechnology

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Student's Signature ....

Advisor's Signature ....

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Ammarin Warin

TABLE OF CONTENTS

PAGE

TABLE OF CONTENTS (Continued)

PAGE

TABLE OF CONTENTS (Continued)

PAGE

TABLE OF CONTENTS (Continued)

PAGE

LIST OF TABLES

TABLE **PAGE**

LIST OF TABLES (Continued)

TABLE **PAGE**

LIST OF FIGURES

FIGURE **PAGE**

LIST OF FIGURES (Continued)

FIGURE **PAGE**

LIST OF FIGURES (Continued)

FIGURE **PAGE**

LIST OF ABBREVIATIONS

ROMAN ABBREVIATIONS:

A1	=	granular material
A2	=	bentonite
A3	=	pre-compressed bentonite
A4	=	bentonite mixed with gravel or sand
A5	=	Portland cement
A6	=	concrete
A7	=	sulfate-resistance Portland cement
A8	=	sulfate-resistance Portland concrete
a_v	=	coefficient of compressibility
b	=	spacing between cracks
BLF(n)	=	depth of the bottom of the rock unit “n”
C_u	=	coefficient of uniformity
e	=	opening of cracks or fissures
e_{final}	=	final void ratio
$e_{Initial}$	=	initial void ratio
g	=	gravitational acceleration
GT	=	groundwater table
H	=	thickness of formation
k	=	coefficient of permeability

LIST OF ABBREVIATIONS (Continued)

$K_{rock\ mass}$ = rock mass permeability

$K_{rock\ mass}(n)$ = rock mass permeability in rock unit "n"

M1(n) = proposed material for borehole sealing in rock unit "n" by considering groundwater level

M2(n) = proposed material for borehole sealing in rock unit "n" by considering mechanics of the rock and seal

M3(n) = proposed material for borehole sealing in rock unit "n" by considering engineering requirement

M4(n) = proposed material for borehole sealing in rock unit "n" by considering geochemistry

MF(n) = recommended material for borehole sealing in rock unit "n"

n = number of different rock formations intersected by the borehole

P_1 = pressure is applied at the interior

P_2 = pressure is applied at the exterior

r = radius of any point in rock

R_1 = the internal radius

S = empirical constant

t = time

T = time factor

LIST OF ABBREVIATIONS (Continued)

U	=	percent of consolidation

GREEK ABBREVIATIONS:

$\Delta\sigma_v$	=	axial stress
σ_r	=	radial stress
γ_w	=	unit weight of water
σ_θ	=	tangential stress
ν	=	the coefficient of kinematic viscosity for pure water at 20 °C
$\sigma_c(n)$	=	strength of rock unit “n”
σ_{intact}	=	intact rock strength
$\sigma_\phi(n)$	=	tangential stress in rock unit “n”

CHAPTER I

INTRODUCTION

1.1 Rationale and Background

Boreholes in this research include exploration and production holes in the fields of groundwater, mining, and petroleum industries. Borehole sealing is the filling of both active and abandoned boreholes by using sealing materials with the properties similar to the host rock. The boreholes have been drilled through geological formations causing the open holes which are continuous voids in both aquitard and aquifer formations. These voids may allow migration and mixing of groundwater of different quality and may result in contamination of the natural resources. Thus, it is necessary to seal all boreholes effectively to prevent groundwater contamination and environmental impacts. However, in the past these boreholes had been sealed without appropriate system and knowledge. Fuenkajorn and Daemen (1996) indicate that the information about sealing effectiveness of borehole seal after installation may not be assured. In fact, the sealing materials for these boreholes may not last as a long as the host rock. As a result, the research in borehole seals design should be conducted, compiled, and analyzed to develop an efficient and systematic borehole seals design based on the principal of sealing of boreholes in rock formations. A method to help transfer the knowledge of borehole sealing to the industry is the application of a computerized expert system.

An expert system is a computer software that uses knowledge, skills and experiences of the experts for knowledge base to solve difficult and complex problems (Adeli, 1988b). In an expert system, the rules or heuristic that are used to solve problems in a particular area are stored in the knowledge base. Problems are presented to the system in terms of certain information that are known as particular problems. The expert system will try to arrive at a conclusion from the known facts with the help of the knowledge base. The inference engine or the rule interpreter examines the existing facts in the working memory and the rules in the knowledge base. It adds new facts to the working memory when it is available. It also determines the orders in which the rules will be used. The inference engine carries out the information and also consultations to the users when a conclusion is reached.

1.2 Research Objectives

The primary objective of this research is to develop a computerized expert system to be used in the design of borehole seals in rock formations. Knowledge, skills, and experiences of an expert in the borehole seals design will be systematically extracted, compiled, analyzed, recorded, and tested. Microsoft visual basic will be used for the program structure for data input and output. Such fundamental information as geology, hydrology, borehole characteristics, borehole seal objectives, and other engineering limitations and economic requirements will be the data input. The site-specific design recommendations include materials selection and sealing performance requirements are the output. The expert system can be applied in the industries related to geological engineering, groundwater and petroleum technology, civil engineering, environmental engineering, and mining engineering.

1.3 Scope and Limitation of the Study

The scope of this research includes design of borehole seals and material selection for seals (cement, bentonite and crushed rock). The factors considered are rock characteristics, borehole conditions, hydrogeology, seal objectives and requirements, geochemistry, impact from nearby activities, and seismic activities. This research deals with the computerized expert system for design borehole seals in rock, excluding the boreholes sealing in the field of high-temperature, tunnel, and underground mining. No laboratory or field experiments are included in this research. Various sizes of vertical down borehole drilled in a variety of rock types are applicable in the proposed expert system. The system also takes into consideration the chemistry of groundwater and of the surrounding rock formations.

1.4 Research Methodology

The research activities are divided into five tasks.

1) Literature Review: Relevant information, current technology and literatures on borehole seals are compiled and studied. The results are summarized to present the state-of-the-art on sealing in rock. All relevant factors, considerations and guidelines specifically needed in designing the borehole seals include design recommendations are also organized and documented.

2) Network Construction: All material selections, performance requirements and design procedures obtained from literature review and the expert are compiled, organized and examined to ensure that all geological and engineering conditions posed will yield an answer, and that there is no dead-end for each path, and no repetition on the input information. A neural network is developed from design recommendations and all information that have been organized. However, in case there is so little information that the experience of the expert cannot answer (design recommendations), an answer will be obtained in the form of “the design is not possible due to insufficient information”. As a result, the expert will recommend the user to obtain more information.

3) Software Development: The information obtained from task 2 is used to construct an interactive computerized system. Microsoft Visual Basic is used as system shell. The design factors are arranged in the order of their significance and aiming at creating the fastest decision-making.

4) Reviewing and Editing: Internal review have been conducted to detect any apparent flaws in the logic of the system. Code verification with actual cases is necessary to ensure that there is no conflict between the output and the expert’s opinion. The computer software that has been developed is tested in the design of borehole seals in rock formations that differ in geological and engineering properties. The results, analysis and design that are recommended from expert system are compared with more than 10 cases of borehole seals. If a comparison between the expert recommendations and those from the system is different, the system will be reviewed and edited.

5) Thesis Writing: The computer software of the expert system is recorded on a CD and expert system instruction is developed. A comprehensive final document is included in the thesis. The thesis will be submitted to school of geotechnology, Suranaree University of Technology.

1.5 Expected Results

The research results are applicable to the design of borehole in rock formations. The organizations that gain this benefit include the Department of Mineral Resource (DMR), the Public Works Department, the Department of Energy Development and Promotion (DEDP), the Electricity Generating Authority of Thailand (EGAT), Department of Alternative Energy and Department of Efficiency (DAEDE), PTT Exploration and Production Company Limited (PTTEP), and consulting and construction firms in the field of groundwater, oil and gas exploration and production.

1.6 Thesis Contents

The thesis is divided into six chapters. Chapter I states the rationale and background, the research objectives, and the research methodology. Chapter II summarizes the results of literature review on borehole sealing in rock formations and the application of expert system in geotechnical engineering. Chapter III describes the methodology and process of borehole sealing design. Software development is presented in chapter IV. Chapter V gives examples of borehole seals in rock formations for various in geological and engineering conditions. The conclusions and discussions of the research results are presented in chapter VI.

CHAPTER II

LITERATURE REVIEW

This chapter summarizes the results of literature review on borehole sealing in rock formations and on expert system applications in geotechnical engineering.

2.1 Borehole Sealing in Rock Formations

Boreholes in rock formations have been drilled for various purposes, such as industrial and municipal applications, disposal, drainage, testing, exploration, and measurements of physical properties of downhole formations (Smith, 1993). The well known applications of borehore sealing probably are in the fields of oil, gas, and groundwater industries. Other applications of borehole sealing may include underground mining and storage, monitoring of tectonic stress, geothermal recovery and stream production, coal gasification, construction, and nuclear waste repository. The main reasons of for sealing of these applications are to prevent contamination, to support and protect casing from corrosion, to seal off zones of lost circulation, and to prevent blowouts (Daemen and Fuenkajorn, 1996).

2.1.1 Types of Borehole Sealing

Types of borehole sealing have been classified by various industries, based on their sealing objectives. For example, Gray and Gray (1992) classify the sealing of mine openings and boreholes into three categories: permanent, temporary, and semi-permanent sealing. Smith (1994) classifies the sealing of groundwater wells into three categories: temporary sealing, sealing actively used boreholes, and sealing for permanent decommissioning.

Daemen and Fuenkajorn (1996) classify borehole sealing into two main categories: (1) sealing actively used boreholes and (2) sealing unused boreholes.

Sealing actively used boreholes involves sealing of the annular zone between casing or pipe and the host rock and sealing of open boreholes that will be used in the future. The reasons for sealing of actively used boreholes are to protect the casing from corrosion, to prevent blowouts by quickly forming a seal, to protect the casing from shock loads in drilling deeper, and to seal off zones of circulation or thief zones (Economides, Watters and Dunn-Norman, 1998).

Sealing unused boreholes represents permanent sealing, which mainly involves sealing of any abandoned boreholes or wells. The primary function of seals for unused boreholes is to isolate zones of gas or liquid, which mainly emphasizes on environmental protection (Daemen and Fuenkajorn, 1996). The reasons for sealing of unused boreholes are to prevent groundwater contamination, to prevent poor aquifer groundwater from moving between water-bearing zones, to conserve aquifer yield and artesian pressure, and to remove any physical hazard (Smith, 1993).

2.1.2 Sealing Materials

Sealing materials used in the fields of petroleum and groundwater industries are discussed with placing emphasis on types of the materials.

1. Sealing Materials Used in Petroleum Industry

Two main groups of sealing materials for oil and gas wells include the drilling fluid (mud) and the cementitious materials (Smith, 1993). The drilling fluid is important both in placing the sealant and in serving as the plugging fluid between the sealant. The first thing to consider when setting a seal is the condition of the well. The wells that are dry and free of fluid provided a more simplified environment for sealing but the wells which are drilled under adverse conditions are very difficult for setting a seal without mud contamination. Therefore, the drilling fluid can provide an appropriate sealant in the wells within mud (Smith, 1993).

The cementitious materials are divided into two groups; Portland cement and other cementitious materials (Economides et al., 1998).

Portland cement is commonly and widely used in borehole abandonment. Cement properties follow the American Society for Testing and Materials C150 (ASTM C150 Standard Specification for Portland Cement) and the American Petroleum Institute Standard 10 (API). Cement types may be classified as follows (Smith, 1993).

For types I or II Portland cement, neat cement should be mixed at a ratio of one 94-lb sack of Portland cement to 5 to 6 gallons of clean water. Additional water may be required where special additives (e.g., bentonite, sand, or fly ash) are used.

Sand-cement should be mixed at a ratio of 20 to 40% by weight with one 94-lb sack of Portland cement and about 6 to 7 gallons of clean water, where type I or type II (API Class A, B, G or H) Portland cement is used.

Concrete is usually useful for large-volume annular seals, such as in large-diameter wells. The proper utilization of aggregate can affect the permeability of the annular seal, reduce shrinkage, and reduce the heat from hydration generated by the seal. A popular concrete mix consists of five 94-lb sacks of type I or type II Portland cement per one cubic yard of uniform 3/8-inch aggregate. The amount of water added to concrete may be variable to attain proper consistency for placement, setting, and curing.

Accelerators may be added to cement to increase the early strength and decrease the setting time. Calcium chloride is the most common and readily available accelerator. It is generally used between 2 and 4 % by weight of cement. Other additives such as retarders, weight-reducing agents, weighting agents, and lost circulation control agents, are available for cements but are not routinely used for abandonment.

Other special cementitious materials used in the industry include pozzolan, ultrafine cements, epoxy cements, and slag cement (Economides et al., 1998).

Pozzolans are silicious and aluminous materials that have little or no cementitious value but will (in finely divided form and in the presence of moisture) chemically react with calcium hydroxide at ordinary temperatures to form compounds possessing cementitious properties. The most common pozzolan is fly ash, which is a waste product from coal-burning power plants. When pozzolans are used in combination with Portland cement, calcium hydroxide, liberated from the hydration of Portland cement, reacts with aluminosilicates in the pozzolans to form cementitious compounds possessing cohesive and adhesive properties (Neville, 1995).

Ultrafine cements are much smaller in particle size than conventional Portland cements. The average particle size of ultrafine cements is 2 μm, whereas conventional cements could be 50 to 100 μm. The main application of ultrafine cements is for light-weight cement with early strength development. Ultrafine cements are also used in fixing squeeze cementing, repairing casing leaks, shutting off water flows, or resolving similar problems because these cements can penetrate into small openings (Economides et al., 1998).

Epoxy cements are special cements, and most commonly used when the cement is exposed to corrosive fluids. Epoxy does not dissolve in acid, but it is expensive. Therefore, it is normally used only for disposal or injection wells where low pH fluids are found (Economides et al., 1998).

Blast-furnace slag cement is a byproduct of the steel industry. The material on top of the molten steel is removed, cooled, quenched with water, and ground. The material composition is mainly monocalcium silicate, dicalcium silicate, and dicalcium aluminosilicate. These silicates set very slowly (days or weeks required) at room temperature when mixed with water. Blast-furnace slag normally requires temperatures greater than 200 °F to react with water to form calciumsilicate hydrates. By increasing the pH of the slurry of blast-furnace slag and water, the setting process can be accelerated to make the slurry set at room temperature like Portland cement (Micheline, 1998).

2. *Sealing Materials Used in Groundwater Industry*

Sealing materials used in water wells include Portland cement grout, Portland cement-sand grout, Portland cement-bentonite grout, concrete, and pure bentonite (Smith, 1993).

The common recommendations for Portland cement grouts specify one bag (94-lb) of type I Portland cement mixed with 5 to 6 gallons of water. Portland cement-sand grout should be mixed at a ratio of one 94-lb sack of type I Portland cement to 5 to 6 gallons of water with less than 2 parts sand to 1 part cement. Portland cement-bentonite grout should be mixed at a ratio of one 94-lb sack of type I

Portland cement to 5 to 6 gallons of water. Bentonite is added based on cement weight in proportions ranging from 2 to 8 %. Approximately 1 gallon of water is added for each 2 % bentonite that is used. Concrete should be mixed at a ratio of one 94-lb sack of type I Portland cement to 5 to 6 gallons of water with less than 2 parts gravel or crushed rock to 1 part cement. The properties of cement slurries used in abandoned boreholes are tabulated in Table 2.1.

Dry bentonite pellets or chips may be placed directly into the annular space below water where a short section of annular space, up to 10 ft in length, is to be sealed. Bentonite pellets are sometimes poured down into tremie pipes or allowed to free-fall to fill borehole. Bentonite grout mixture without cement should consist of 1 to 2 lbs of powder bentonite per 1 gallon of water.

2.1.3 Properties of Sealing Materials

Properties of sealing materials used in the industries are compiled in this section. The sealing materials in terms of their properties can be classified into four groups, 1) granular materials, 2) bentonitic materials, 3) cementitious materials, and 4) mixtures of bentonite and crushed rock (or sand and gravel). The properties of each group are briefly described as follows.

Granular materials include gravel, sand and crushed rock. These materials have rather high permeability and have a limitation in sealing at deep portion. However, the methods are cheap and available in the market. Permeability of sand with 0.06 to 2.0 mm in size may range between 10^{-2} and 10^{-6} m/s, whereas permeability of gravel with diameter of 2.0 to 60 mm ranges between 1 and 10^{-3} m/s (Freeze and Cherry, 1979). Crushed rock is suitable when absolute consistency of geological chemistry between sealing material and surrounding rock is required

Table 2.1 Properties of cement slurries used in abandoned wells (Smith, 1990).

Product	Recommended water (gal/sack)	Density (lb/gal)	Volume (cu f/skt)	Pumpability or Handing Time	Approximate strength (80 °F/24 hrs)
Portland cement and bentonite					
Portland cement*	5.2	15.6	1.18	3 hr+	1,900 psi
with dispersant	3.5-4.0	16-16.5	1.0-1.10	3 hr+	3,000 psi
Plus 2% bentonite	6.5	14.7	1.36	3 hr+	1,100 psi
Plus 4% bentonite	7.8	14.1	1.55	3 hr+	750 psi
Plus 6% bentonite	9.1	13.5	1.73	3 hr+	360 psi
Plus 8% bentonite	10.4	13.1	1.93	3 hr+	265 psi
Portland cement and sand					
Plus 20% bentonite	5.2**	16.2	1.30	3 hr+	1,700 psi
Plus 40% bentonite	6.2**	16.5	1.48	3 hr+	1520 psi
Other					
Portland cement with 2% calcium chloride (accelerator)	5.2	15.6	1.18	3 hr	3,100 psi
Concrete (Ready mix five to six sacks cement per yard)	-	-	-	-	950 psi
Bentonite (pelletized or chips)	-	-	-	-	Does not set

* Type I, II (API Class A, B or G – 94 lb/sk) referred to as Common, Neat, or Construction cement.
** Additional water may be required depending on particle size of sand.

Gravel, sand and crushed rock should be well graded with at least 16 in coefficient of uniformity (C_u). Their maximum particle size should not exceed 1/10 of borehole diameter (Daemen and Fuenkajorn, 1996).

Bentonite consists of montmorillonite as a dominant mineral. The montmorillonite is classified as smectite clay or so-called swelling clay. The montmorillonite ($[OH]_4Si_8Al_4O_{20}\cdot nH_2O$) is one ditettragonal alumina sheet sandwiched between two layers of silica. Bonding between the sheets is rather loose. This makes montmorillonite unstable. Therefore, bentonite has a property of expanding when placed in water. The swelling pressure ranges between 1 and 15 MPa as result of expansion. The permeability ranges between 10^{-7} and 10^{-11} m/s. The expansion volume can be 12 to 15 times its original dry volume. Its dry density ranges from 1.4 to 1.8 t/m^3 (Pusch and Bergstrom, 1980).

Pre-compressed bentonite is suitable for sealing in borehole in which mechanical and hydraulic performance are required as its expansive stress could be as high as 2.6 MPa (Fuenkajorn and Daemen, 1987). Its permeability is as low as 10^{-14} m/s (Ran, Daemen, Schuhen, and Hansen, 1997). It can be used to seal in the borehole where ground movement and vibration may occur.

The specifications of Portland cement are shown in Tables 2.2 and 2.3. Neat cement is a suitable material for sealing in bedrock in which mechanical and hydrological performance are required as its strength is as high as 26.2 MPa and its permeability is approximately 10^{-7} m/s (Smith, 1994). Sulfate-resistant cement is also suitable for sealing a borehole drilled through saline soil or water. Concrete may be suitable for economic reason because its property are similar to those of cement whereas its price is much lower. The concrete is a mixture between cement and aggregate.

Table 2.2 Types of Portland cement classified by the American Society for Testing and Materials C150, ASTM C150 (Smith, 1993).

Type	Description
I	General purpose. Similar to American Petroleum Institute Class A.
II	Moderate resistance to sulfate. Lower heat of hydration than type I. Similar to American Petroleum Institute Class B, G, and H.
III	High early strength. Reduced curing time but higher heat of hydration than type I. Similar to American Petroleum Institute Class C.
IV	Extended setting time. Lower heat of hydration than type I and III. (No American Petroleum Institute Classification.)
V	High sulfate resistance. (No American Petroleum Institute Classification.)

Table 2.3 Types of Portland cement classified by the American Petroleum Institute Standard 10 (Smith, 1990).

Class	**Description**
A	Intended for use from surface to 6,000-ft depth, when special properties are not required. Available only in ordinary type (similar to ASTM C150, type I).
B	Intended for use from surface to 6,000-ft depth, when conditions require moderate to high sulfate resistance. Available in both moderately (similar to ASTM C150, type I) and highly sulfate-resistant types.
C	Intended for use from surface to 6,000-ft depth, when conditions require high early strength. Available ordinary and moderately (similar to ASTM C150, type I) and highly sulfate-resistant types.
D	Intended for use from 6,000-ft to 10,000-ft depth, under conditions of moderately high temperatures and pressures. Available in both moderately and highly sulfate-resistant types.
E	Intended for use from 10,000-ft to 14,000-ft depth, under conditions of high temperatures and pressures. Available in both moderately and highly sulfate-resistant types.
F	Intended for use from 10,000-ft to 16,000-ft depth, under conditions of extremely temperatures and pressures. Available in both moderately and highly sulfate-resistant types.
G	Intended for use as a basic well cement from surface to 8,000-ft depth as manufactured, or can be used with accelerators and retarders to cover a wide range of well depths and temperatures. No additions other than calcium sulfate or water, or both, shall be interground or blended with the clinker during manufacture of class G well cement. Available in both moderately and highly sulfate-resistant types.
H	Intended for use as a basic well cement from surface to 8,000-ft depth as manufactured, and can be used with accelerators and retarders to cover a wide range of well depths and temperatures. No additions other than calcium sulfate or water, or both, shall be interground or blended with the clinker during manufacture of class H well cement. Available in both moderately and highly sulfate-resistant types.

The strength of concrete after 24 days ranges between 20.59 and 49.04 MPa (Kulprasuit, 1995).

Mixture of bentonite and crused rock (or sand and gravel) may have properties similar to those of the pure bentonite whereas the price is lower. The bentonite mixture with at least 30% by weight of bentonite will result in the permeability of 10^{-10} m/s (Ouyang and Daemen, 1996).

2.1.4 Placement Method

This section presents two main stages for the placement method: 1) preparation for borehole sealing and 2) seal installation procedure.

1. Preparation for Borehole Sealing

Preparation is an essential step in providing successful borehole sealing. This step is normally consisted of three tasks 1) removing obstructions and debris from boreholes, 2) removing casing and screen, and 3) conditioning the boreholes.

1) Removing obstructions and debris from boreholes

All debris, pumps, piping, ungrouted liner, or any other obstructions in the well or borehole should be removed. The obstructions may provide local conduits for contamination. The rock or other debris should be carefully drilled or bailed out as much as possible. Other potential contaminations and troublesome materials should be removed as well (Smith, 1994).

2) Removing casing and screen

Casing and screen can be removed by pulling and drilling out methods. The casing can be pulled out by jacking or steady pull-back with the rig casing hoist, or using both procedures simultaneously. Drilled out with a hollow stem auger is a method to remove small diameter shallow plastic casings. If a casing is corroded or otherwise cannot be effectively removed by pulling or drilling out, it should be penetrated to allow sealant to get behind the casing wall and stick to the formation (Smith, 1994).

3) Conditioning the boreholes

The final task for borehole preparation is conditioning of the borehole. One of the methods is borehole circulation. It should be conducted with clear water or light mud (Smith, 1994).

2. Placement Methods

There are three methods for placing the sealing material, 1) pumping grout slurries, 2) pouring, and 3) compaction.

1) Pumping grout slurries

The pumping grout slurry is a method for emplacing cement and bentonite grouts. In order to minimize the permeability and segregation, and to maximize the density and strength, it is strongly recommended that injection takes place from the bottom up, while gradually withdrawing the injection string (Daemen and Fuenkajorn, 1996).

Emplacement under pressure (pressure grouting) is essential when grout is injected into annulus behind perforated casing. Pressurized injection of relatively fluid (low viscosity) grouts may assist in sealing fractures in the host rock, and may reverse some of the flow path enlargement and permeability enhancement that may have resulted from borehole wall relaxation, especially in boreholes that have been opened for a long time (Daemen and Fuenkajorn, 1996).

2) Pouring method

Pouring is appropriate for placing backfill materials (high-solid bentonite, sand, gravel, crushed rock and drill cuttings). Bridging problem may occur at the top of the water column. Hence, the depth should be checked with a weighted tape, wire or rod at regular intervals during the pour-in. The length of the seal in the hole should be checked against the calculations and the reason for any deviation determined. Too little fill-in may indicate that grout is filling a void. Too rapid fill-in suggests bridging (Smith, 1994).

3) Compaction method

Compaction method is desirable for the installation of backfill or any seals formed by bentonite, clay, sand, gravel or crushed rock, or by combinations of these materials. The sealing effectiveness of these particulate media can be enhanced by compaction. Compaction will result in reducing of the permeability and potential settlement, and increasing of the bulk density and strength of the backfill (Daemen and Fuenkajorn, 1996).

2.1.5 Regulations of Borehole Sealing Practice in Thailand

1. Sealing of Water Wells in Groundwater Industry

The Act. of Groundwater (1977) specified that only pure clay or cement is allowed to be used as sealing materials for abandoned groundwater wells (Department of Mineral Resources, Groundwater Division, 1992).

Clay used as sealing material can be from cultivated land or paddy field. Such pure clay should be thoroughly mixed and molded to become small ball as a table tennis ball. After leaving the clay balls to loose moisture or dry up, put the balls into the well continuously to avoid clogging to occur at some portions. In case of clogging, pipe and other tools are prohibited to push or lower down into the well. In this case only clean water should be poured into the well in a proper manner and continuously until the clay balls get loose and drop down to the bottom of the well. Measurement of clay ball volume should be made and recorded to assure that the volume of the poured clay balls matches the volume of borehole. In order to seal borehole by cement, it should be mixed with water by cement mixer and used water-cement ratio of 30 l : 50 kg and the mix is then grouted into the borehole with pressure of at least 50 psi with flow rate of at least 50 gallons/s. The grouting should be done in bottom–up sequence in which the length of each stage equals 30 m. If of settlement occurs, more cement should be added until there is no more settlement.

2. *Sealing of Borehole in Petroleum Industry*

Specifications of borehole sealing in petroleum industry in Thailand can be found in the ministerial regulation no. 5 (1971) and its revision in the ministerial regulation no. 12 (1981). Specifications related to abandoned well are issued in the ministerial regulation verse 39 and specifications related to what should be done after abandonment and how to finish the work are issued in verse 40 of the ministerial regulation (Department of Mineral Resources, Mineral Fuel Division, 1981).

Verse 39 of the ministerial regulation specifies that before abandonment of the well, the contractor should submit report explaining the reasons and method of abandonment to the Director General for consideration. The abandonment will be carried out after it is approved.

Verse 40 of the ministerial regulation specifies that after completion of work or when the contract is expired or withdrawn, the contractor should follow the following regulations

1) re-create the ground or water to be the same as before as much as possible,

2) provide wall or fence around the future used hole, trench or well created by the contractor to prevent any harm to human or animal,

3) back-fill the unused hole, trench or well to be the same as before as much as possible, except any other requests by the Director General or agreements between the contractor and the client or property's owner,

4) remove concrete base, structure, building, machine, equipment and any other materials, which is not further used, out from the exploration or extraction well area, and burn out all of petroleum waste in such area as well, except any other requests by the Director General, and

5) remove or destroy any obstructions, disturbances or anything that is harmful to transportation, fishery, properties of the Kingdom or human, except any other requests by the Director General.

The contractor, the expired contract contractor or the withdrawal contract contractor should fulfill the specifications within three months after completion of work, expired date or withdrawal date.

In subheading 3) of the ministerial regulation verse 40 involves back filling of abandoned hole, trench and well. Details related to usage of materials and sealing methods are specified below.

(1) For wells without casing, sealing of groundwater aquifer, oil or gas layer to prevent leakage and contamination will be carried out by using cement material to seal from at least 50 m below the bottom of such aquifer or layer up to at least 50 m above the uppermost of such aquifer or layer, as illustrated in Figure 2.1.

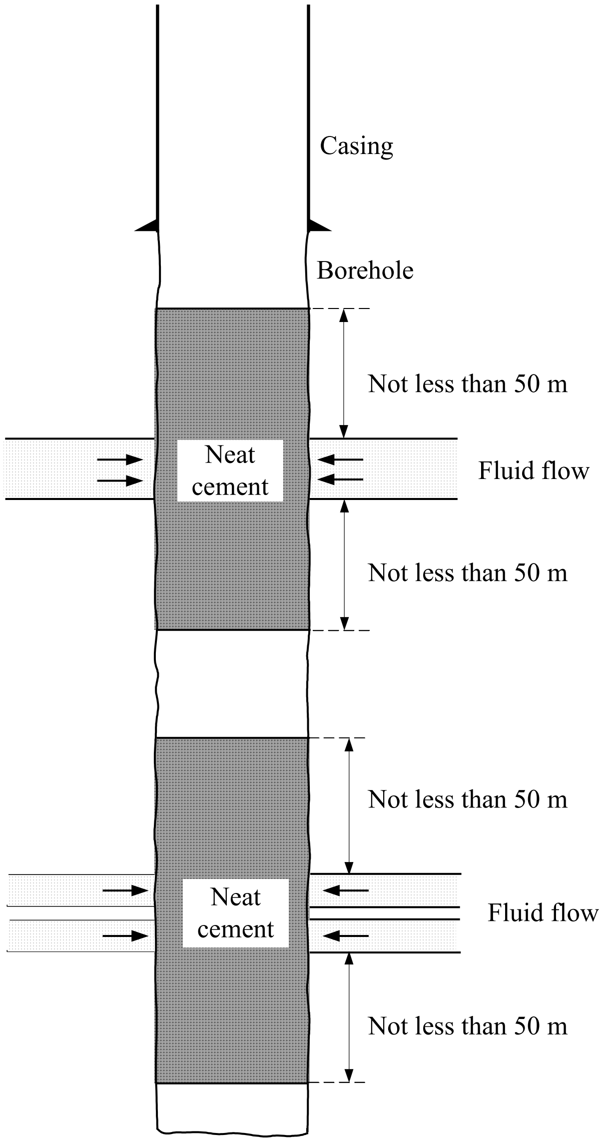

Figure 2.1 Sealing the well without casing (modified from Department of Mineral Resources, Mineral Fuel Division, 1981).

(2) There are two ways for sealing at the joint between the casing shoe and the uncased portion;

1) sealing with cement from at least 50 m below the joint up to at least 50 m above the joint, as illustrated in Figure 2.2, and
2) using mechanical plug at the bottom–end of the casing and sealing with cement up to at least 20 m above the mechanical plug, as illustrated in Figure 2.3.

(3) There are two ways for sealing at squeezed cement portion as follows;

1) using mechanical plug above every squeezed portions, as illustrated in Figure 2.4, and
2) sealing with cement from at least 50 m below the squeezed cement portion up to at least 50 m above and repeat at every squeezed cement portion in the same manner as illustrated in Figure 2.5.

(4) Sealing at the joint between two casings can be done by using mechanical plug at the ring space and using cement to seal from at least 50 m below the joint up to at least 50 m above the joint, as illustrated in Figure 2.6.

(5) Sealing in space between two casings by using cement seal from the inner casing shoe up to less than 100 m above the outer casing shoe and using cement grout with the thickness of at least 100 m above the cement seal, as illustrated in Figure 2.7.

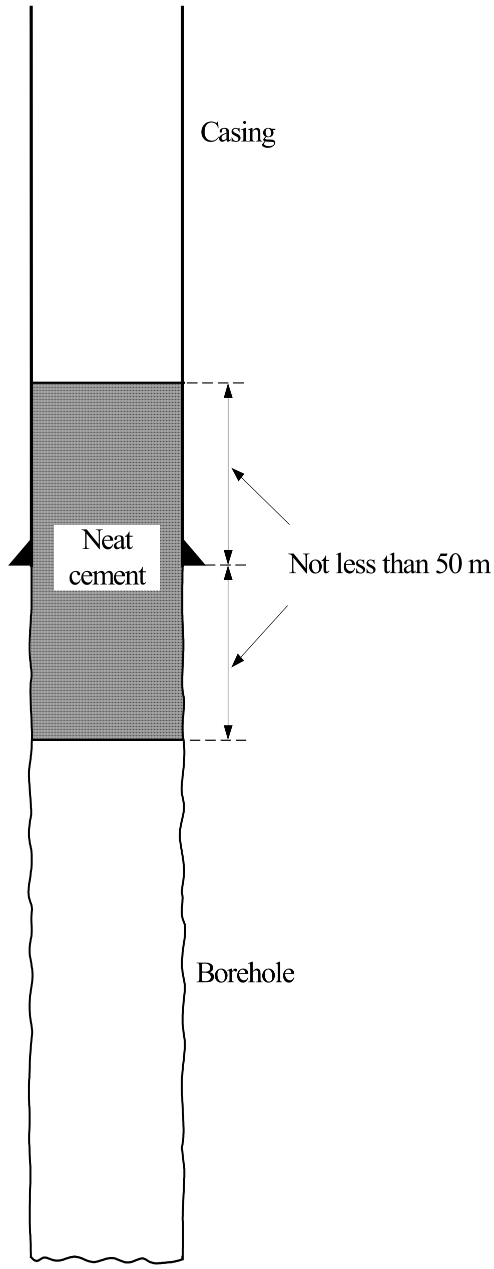

Figure 2.2 Sealing at the joint between the casing shoe and uncased portion by using cement (modified from Department of Mineral Resources, Mineral Fuel Division, 1981).

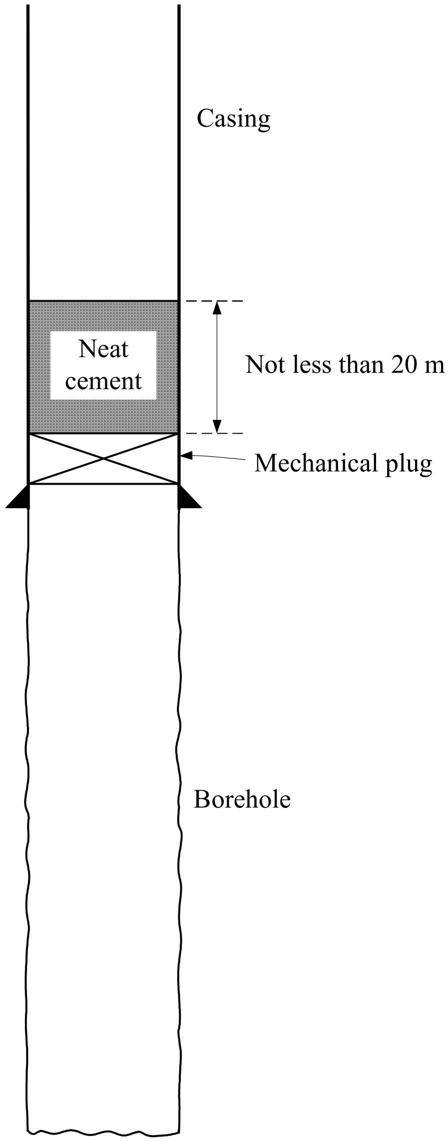

Figure 2.3 Sealing at the joint between the casing shoe and uncased portion by using mechanical plug (modified from Department of Mineral Resources, Mineral Fuel Division, 1981).

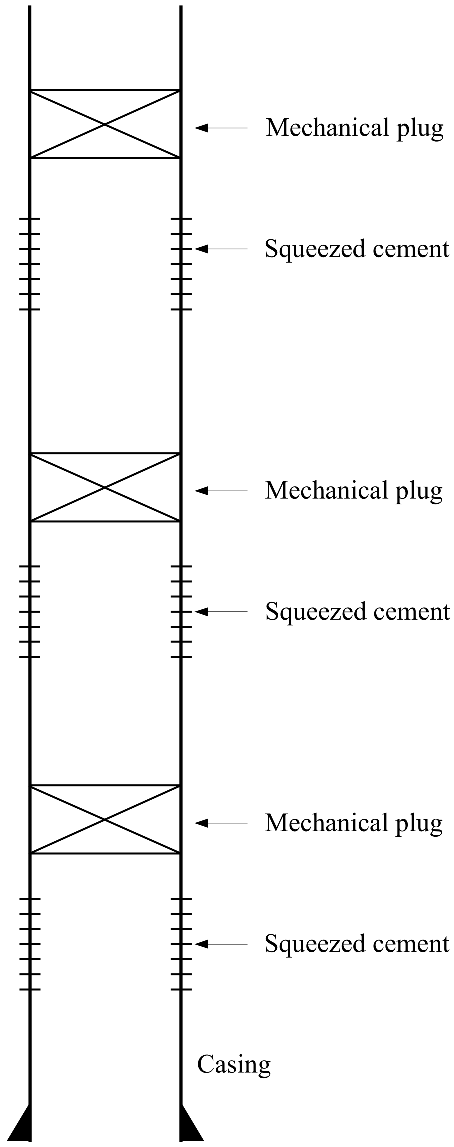

Figure 2.4 Sealing at squeezed cement portion by using mechanical plug (modified from Department of Mineral Resources, Mineral Fuel Division, 1981).

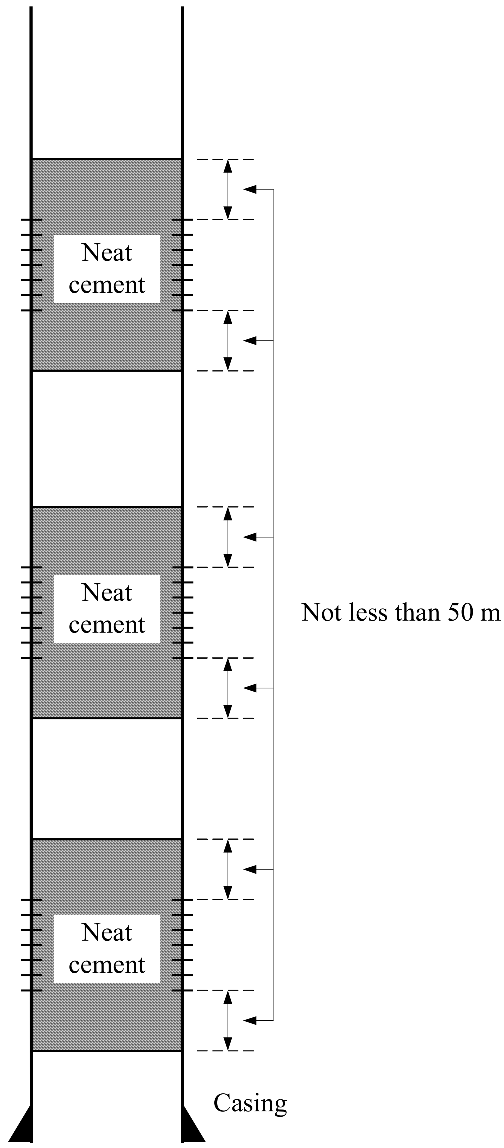

Figure 2.5 Sealing at squeezed cement portion by using cement (modified from Department of Mineral Resources, Mineral Fuel Division, 1981).

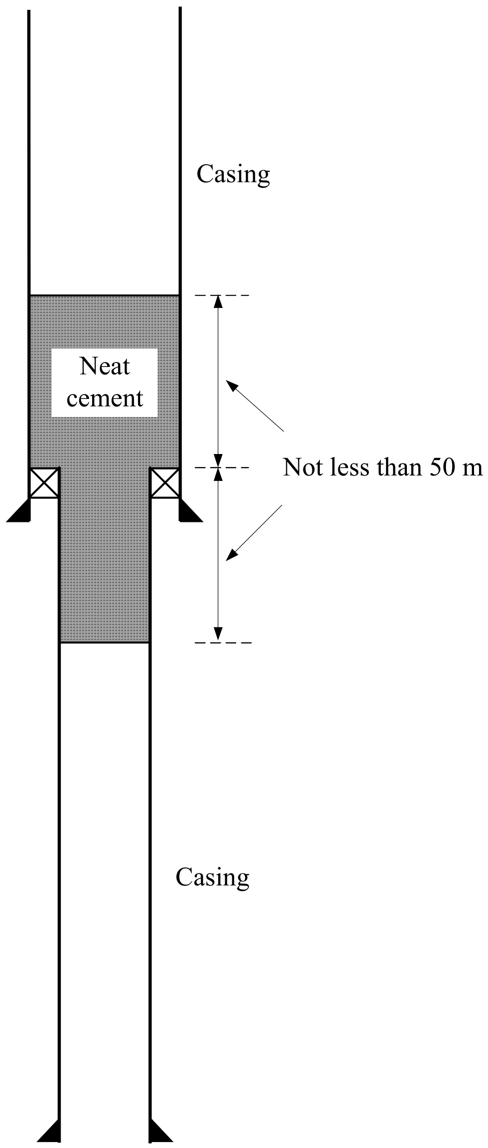

Figure 2.6 Sealing at the joint between two casings (modified from Department of Mineral Resources, Mineral Fuel Division, 1981).

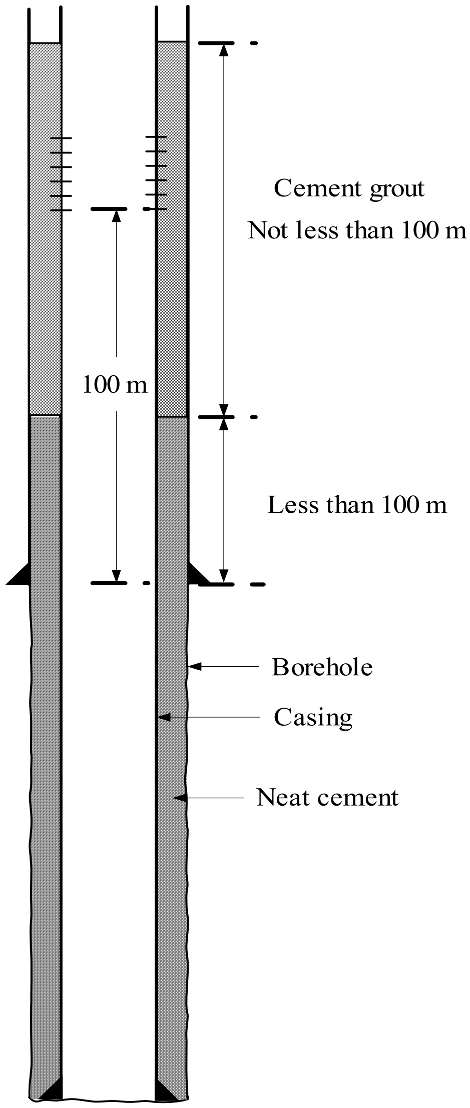

Figure 2.7 Sealing in space between two casings (modified from Department of Mineral Resources, Mineral Fuel Division, 1981).

(6) Sealing at the top of the well can be divided into two cases;

a) borehole on land should be plugged with cement with the thickness of at least 200 m up to the top of borehole, as illustrated in Figure 2.8, and

b) borehole offshore should be plugged with cement with the thickness of at least 200 m up to the top of borehole, as illustrated in Figure 2.9.

2.1.6 Regulations of Borehole Sealing Practice in the United States

1. Abandonment Rules of Water Wells

Abandonment rules of Test Holes, Partially Completed Wells, and Completed Wells recommended by ANSI/AWWA June 24,1981 are divided into three sections; general, sealing requirements, and records of abandonment procedures (Smith, 1993).

1) General

Abandoned test holes, including test wells, uncompleted wells, and completed wells shall be sealed.

(1) Need for sealing of wells; eliminate physical hazard, prevent contamination of groundwater, conserve yield and hydrostatic head of aquifers, and prevent intermingling of desirable and undesirable water.

(2) Restoration of geological conditions: the guiding principle to be followed by the contractor in the sealing of abandoned wells is the restoration, as far as feasible, of the controlling geological conditions that existed before the well was drilled or constructed.

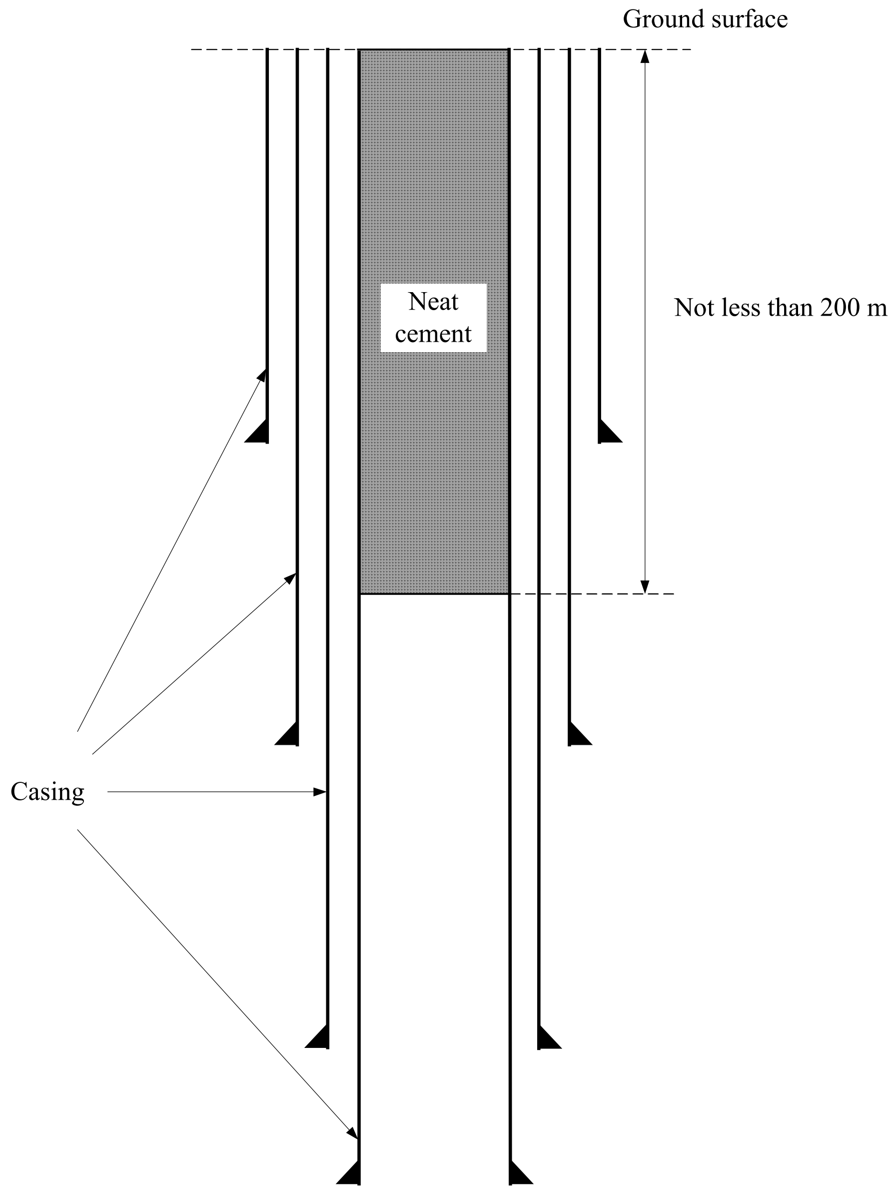

Figure 2.8 Sealing at the top of the borehole (modified from Department of Mineral Resources, Mineral Fuel Division, 1981).

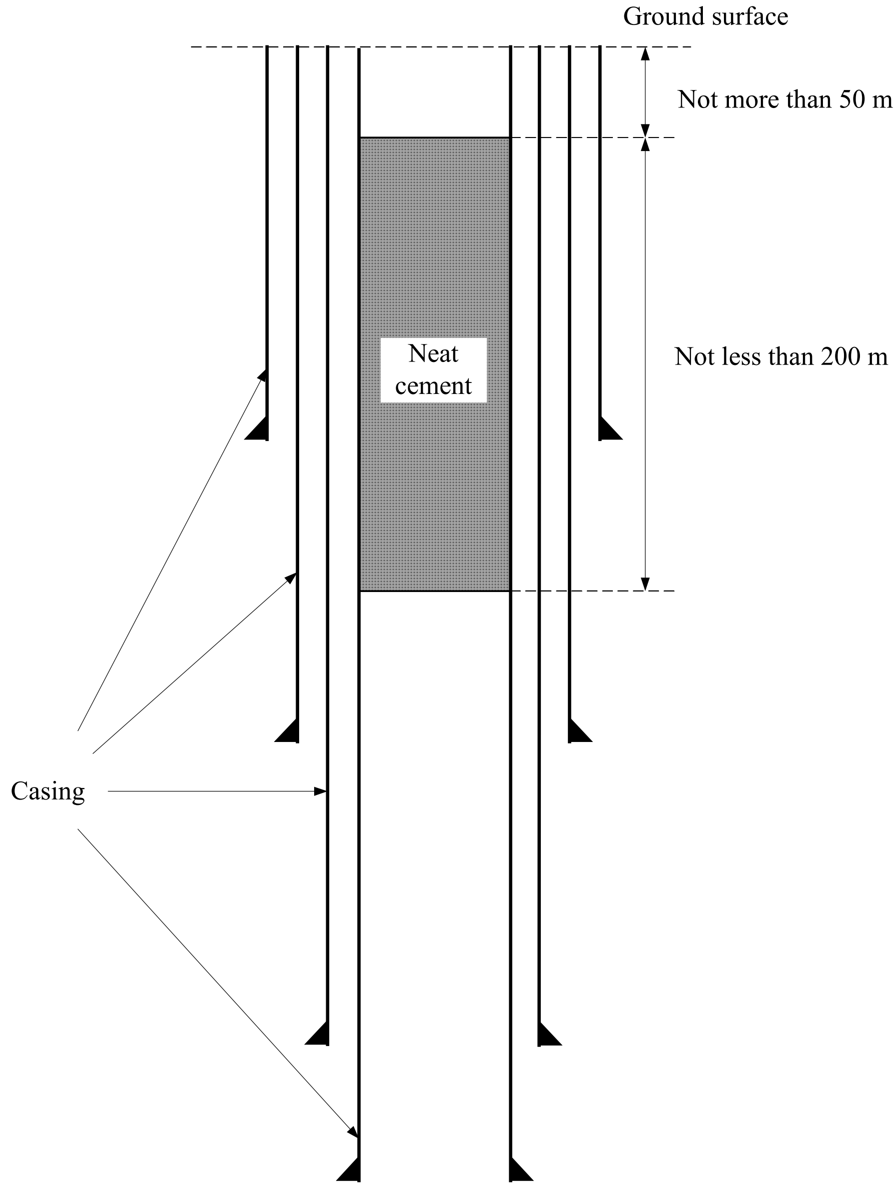

Figure 2.9 Sealing at the top of the borehole on offshore (modified from Department of Mineral Resources, Mineral Fuel Division, 1981).

2) Sealing requirements

A well shall be measured for depth before it is sealed to ensure freedom from obstructions that may interfere with effective sealing operations.

(1) Liner pipe removal. Removal of liner pipe from wells may be necessary to ensure placement of an effective seal.

(2) Exception to removing liner pipe. If the liner pipe cannot be readily removed, it shall be perforated to ensure proper sealing.

(3) Sealing materials and placement. Concrete, cement grout, or neat cement and sealing clays shall be used as primary sealing materials and shall be placed from the bottom upward by methods that avoid segregation or dilution of the material.

3) Records of abandonment procedures

Completed accurate records shall be kept of the entire abandonment procedure to provide detailed records for possible future reference and to demonstrate to the governing state or local agency that the hole was properly sealed.

(1) Depth sealed. The depth of each layer of all sealing and back-filling materials shall be recorded.

(2) Quantity of sealing material used. The quantity of sealing materials used shall be recorded. Measurements of static water levels and depths shall be recorded.

(3) Changes recorded. Any changes in the well made during the plugging, such as perforating casing, shall be recorded in detail.

2. *Abandonment Rules of Oil and Gas Wells*

Abandonment rules of oil and gas wells of federal regulations in the United States include general requirements, approvals, and permanent abandonment (Smith, 1993).

1) General Requirements

The lessee shall abandon all wells in a manner to ensure downhole isolation of hydrocarbon zones, protection of freshwater aquifers, clearance of sites so as to avoid conflict with other uses of the Outer Continental Shelf (OCS), and prevention of migration of formation fluids within the wellbore or to the seafloor. Any well that is no longer used or useful for lease operations shall be plugged and abandoned in accordance with the provisions of this subpart. However, no production well shall be abandoned until its lack of capacity for further profitable production of oil, gas or sulfur has been demonstrated to the satisfaction of the district supervisor. No well shall be plugged if the plugging operations would jeopardize safe and economic operations of nearby wells, unless the well poses a hazard to safety or the environment.

2) Approvals

The lessees shall not commence abandonment operations without prior approval of the district supervisor. The lessee shall submit a request on Form MMS-332, Notice of Intent/Report of Well Abandonment, for approval to abandon a well and a subsequent report of abandonment within 30 days from completion of the work in accordance with the following:

(1) Notice of Intent to Abandon Well. A request for approval to abandon a well shall contain the reason for abandonment including supportive well

logs and test data, a description and schematic of proposed work including depths, type, location, length of plugs, the plans for mudding, cementing, shooting, testing, casing removal, and other pertinent information.

(2) Subsequent report of abandonment. The subsequent report of abandonment shall include a description of the manner in which the abandonment or plugging work was accomplished, including the nature and quantities of materials used in the plugging, and all information listed in paragraph (a) of this section with a revised schematic. If an attempt has been made to cut and pull any casing string, the subsequent report shall include a description of the methods used, size of casing removed, depth of the casing removal point, and the amount of the casing removed from the well.

3) Permanent abandonment

(1) Isolation of zones in open hole. In uncased portions of wells, cement plugs shall be set to extend from a minimum of 100 ft below the bottom to 100 ft above the tip of any oil, gas, or freshwater zones to isolate fluids in the strata in which they are found and to prevent them from escaping into other strata or to the seafloor. The placement of additional cement plugs to prevent the migration of formation fluids in the wellbore may be required by the district supervisor.

(2) Isolation of open hole. Where there is an open hole below the casing, a cement plug shall be placed in the deepest casing by the displacement method and shall extend a minimum of 100 ft above and 100 below the casing shoe. In lieu of setting a cement plug across the casing shoe, the following methods are acceptable:

a) A cement retainer and a cement plug shall be set. The cement retainer shall have effective back pressure control and shall be set not less than 550 ft and not more than 100 ft above the casing shoe. The cement plug shall extend at least 100 ft below the casing shoe and at least 650 ft above the retainer.

b) If lost circulation conditions have been experienced or are anticipated a permanent-type bridge plug may be placed within the first 150 ft above the casing shoe with a minimum of 50 ft of cement on top of the bridge plug. This bridge plug shall be tested in accordance with Paragraph (g) of this section.

(3) Plugging or isolating perforated intervals. A cement plug shall be set by the displacement method opposite all perforations that have not been squeezed with cement. The cement plug shall extend a minimum of 100 ft above the perforated interval and either 100 ft below the perforated interval or down to a casing plug, whichever is the lesser. In lieu of setting a cement plug by the displacement method, the following methods are acceptable, provided the perforations are isolated from the hole below:

a) A cement retainer and a cement plug shall be set. The cement retainer shall have effective back pressure control and shall be set not less than 50 ft and not more than 100 ft above the top of the perforated interval. The cement plug shall extend at least 100 ft below the bottom of the perforated interval with 50 ft placed above the retainer.

b) A permanent-type bridge plug shall be set within the first 150 ft above the top of the perforated interval with at least 50 ft of cement on top of the bridge plug.

c) A cement plug that is at least 200 ft long shall be set by the displacement method with the bottom of the plug within the first 100 ft above the top of the perforated interval.

(4) Plugging of casing stubs. If casing is cut and recovered leaving a stub, the stub shall be plugged in accordance with one of the following methods:

a) A stub terminating inside a casing string shall be plugged with a cement plug extending at least 100 ft above and 100 ft below the stub. In lieu of setting a cement plug across the stub, the following methods are acceptable:

- A cement retainer or a permanent–type bridge plug shall be set not less than 50 ft above the stub and capped with at least 50 ft of cement, or
- A cement plug that is at least 200 ft long shall be set with the bottom of the plug with in 100 ft above the stub.

b) If the stub is below the next larger string, plugging shall be accomplished as required to isolate zones or to isolate and open hole as described in paragraphs 1) and 2) of this section.

(5) Plugging of annular space. Any annular space communicating with any open hole and extending to the mud line shall be plugged with at least 200 ft of cement.

(6) Surface plug. A cement plug that is at least 150 ft in length shall be set with the top of the plug within the first 150 ft below the mud line. The plug shall be placed in the smallest string of casing that extends to the mud line.

(7) Testing of plugs. The setting and location of the first plug below the surface plug shall be verified by one of the following methods:

a) The lessee shall place a minimum pipe weight of 15,000 lb on the cement plug, cement retainer, or bridge plug. The cement placed above the bridge plug or retainer is not required to be tested.

b) The lessee shall test the plug with a minimum pump pressure of 1,000 lb/in^2 with a result of no more than a 10% pressure drop during a 15-minute period.

(8) Fluid left in hole. Each of the respective intervals of the hole between the various plugs shall be filled with fluid of sufficient density to exert a hydrostatic pressure exceeding the greatest formation pressure in the intervals between the plugs at time of abandonment.

(9) Clearance of location. All wellheads, casings, pilings, and other obstructions shall be removed to a depth of at least 15 ft below the mud line or to a depth approved by the district supervisor. The requirement for removing subsea wellheads or other obstructions and for verifying location clearance may be reduced or eliminated when, in the opinion of the district supervisor, the wellheads or other obstructions would not constitute a hazard to other users of the seafloor or other legitimate uses of the area.

(10) Requirements for permafrost areas. The following requirements shall be implemented for permafrost areas:

a) Fluid left in the hole adjacent to permafrost zones shall have a freezing point below the temperature of the permafrost and shall be treated to inhibit corrosion.

b) The cement used for cement plugs placed across permafrost zones shall be designed to set before freezing and to have a low heat of hydration.

2.1.7 Borehole Sealing Research

Sealing of borehole in rock has been developed approximately 25 years ago. The intensive research and development of this technology have been done by Prof. Jaak J.K. Daemen (Fuenkajorn and Daemen, 1996). Most of the research has been emphasized on the mechanical, hydrological and chemical properties of sealing materials. Parts of research have involved with design of borehole sealing in rock.

Fuenkajorn and Daemen (1987) study mechanical relationship between cement, bentonite and surrounding rock. The study deals with the mechanical interaction between multiple plugs and surrounding rock and identification of potential failure. Two conceptual plug designs are studied. Pipe tests have been performed to determine the swelling pressures of 60 mm diameter bentonite plugs and of 64 mm diameter cement plugs. The axial and radial swelling pressures of a bentonite plug specimen are 7.5 and 2.6 MPa after adsorbing water for 5 days. The maximum radial expansive stresses of the cement plugs cured for 25 days are 4.7 and 2.7 MPa for system 1 and system 3 cement. Results from the experiment indicate that in order to obtain sufficient mechanical stability of bentonite seal, the sealing should be done below groundwater level. If cement material is used to seal in hard rock, the mechanical stability will be higher than sealing in soft rock.

Akgun (1996) conducts a research on bond strength of cement grout seals in rock. The objective of the research is to study the relationship between the strength of cement grout and the length-to-radius ratio of cement specimen. The strength values (axial strength, bond strength, and peak shear strength) are obtained from the push-out tests of the cement grout borehole plugs with various diameter and length placed in welded tuff cylinders. The results from the test show that the three strength measures decrease with increasing plug radius and with decreasing plug length. The specimen with plug the length-to-radius ratio of eight has a highest axial strength. The result of the test indicates that in order to gain enough mechanical stability in permanently sealing of borehole with cement, length-to-radius ratio of cement grout should equal or greater than eight.

Ouyang and Daemen (1996) carry out the experiments on borehole sealing in rock by using bentonite and mixture of bentonite and crushed tuff. The experiment includes laboratory investigation of the sealing performance of bentonite and of bentonite mixed with crushed tuff plugs under various conditions. Permeability tests of the samples include longitudinal flow test, polyaxial permeability test, high-temperature permeability test, and piping test. The mixture of bentonite and crushed tuff is consisted of 15%, 25% and 35% by weight of bentonite. Results of longitudinal flow test reveal that permeability value is low when high coefficient of uniformity crushed rock is used in the bentonite mix. The permeability decreases as quantity of bentonite increases. Results of polyaxial permeability test show that the permeability in horizontal flow is higher than that in vertical flow. The differential permeability between the two directions increases as quantity of bentonite increases. Results of high-temperature permeability test indicate that the highest permeability value is at temperature of 35 °C, and at temperature of 60 °C. Results of piping test reveal that permeability in the vertical flow does not change when water is allowed to drain out from the hole provided at the bottom while water flow out from the side hole is less than 2%. Results of testing indicate that by using bentonite mixed with crushed tuff as sealing material, the quantity of bentonite should not be less than 35% by weight. The crushed rock or coarse grain aggregate should be well graded and have the minimum coefficient of uniformity of 16. The mixing and compaction should meet the standard proctor compaction or higher than the standard.

South and Fuenkajorn (1996) present an experimental method to assess the performance of cement borehole seals (plugs) under laboratory conditions. The prime goals of the experiment is to obtain experimental data regarding the effectiveness of sealing. The conceptual approach used to evaluate borehole seal in this study is to compare flow through a sealed borehole in rock with flow through intact rock under varying stress conditions. The intact rock specimen is placed under axial and confining stresses to simulate stress field at depths of about 1000, 600, and 300 m. The intact rock is tested, and the rock bridge cored from the specimen. The plug is placed and tested while the specimen remains under the stress field. The results from the test suggest that flow rate through the specimens with the same permeability with those of the cement and surrounding rock. The analysis by computer simulation shows a linear flow rate in specimen that permeability ratio of cement to surrounding rock exceeds 100. The tension zone does not increase when the stress from cement expansion is less than 75 % of tangential stress acting at the borehole wall.

Suggestions for designing of borehole sealing obtains from the testing results are as follows.

1) Expansion cements are adequate to provide good performance for borehole seal under changing stress conditions.
2) Cement is recommended for sealing in stiff rock, as it will result in the best hydraulic bond at the interface.
3) Permeability of sealing material should be less than or equal to 10 times of rock mass permeability.
4) Cement should be used under groundwater level because shrinkage and cracks may occur when it dries, and eventually may result in higher permeability.
5) In order to seal the borehole effectively, cement or bentonite should be designed at appropriate location in the borehole. In case of using bentonite as a sealing material, cement should be used to intercalate as a key seal.

Agkun (1997) conducts a series of push-out tests to determine the suitable material to seal a large borehole in rock salt formation. The adopted material in his study and testing is cement which has two different expansion properties, self-stress I cement and salt-bond II cement. The self-stress I is the mix between 659 g of self-stress cement and 493 g of NaCl-saturated brine. The salt-bond II cement is formed by 1000 g of class H, 450 g of NaCl-saturated brine, 450 g of liquid additive D604 and 4.4 g of antifoam agent (M45). The rock salt cylinder specimen is hollowed out. Cement is filled in the rock salt specimens with the length to radius ratio of two. The specimens are cured for eight days before testing. Results of testing show that friction between self-stress cement and rock specimen is 2.2 MPa or 22% of friction between rock salt itself, whereas friction between salt-bond cement and rock specimen is 6.1 MPa or 60% of friction between rock salt itself. In order to obtain sufficient mechanical stability of borehole sealing, salt-bond II cement is recommended.

Ran et al. (1997) study the dynamic compaction properties of bentonite. The objective of the study is to determine the properties of bentonite seal and to evaluate the method of dynamic compaction for an effective bentonite shaft seal. Extensive laboratory dynamic compaction tests have been conducted to study the densification of granular bentonite mixed with distilled and deionized water or with brine from the Waste Isolation Pilot Plant (WIPP). Results from the test reveal that the dynamic compaction can densify bentonite to a dry density of 1.86 Mg/m^3 when mixed with WIPP brine and 1.74 Mg/m^3 when mixed with distilled and deionized water. At these densities bentonite exhibits permeabilities in the order of 1.0×10^{-19} m^2. Therefore for using compacted bentonite as a sealing material, saline water is recommended in the mix because it should result in a higher dry density lower porosity and lower permeability than using distilled water.

Akgun and Daemen (2002) study the degrees of saturation of the cement plugged cylinder that affects strength of the expansive cement by conducting push-out test. The study factor include the relationship between the degree of saturation versus the strength of cement, as well as the radius of sealing sample versus the strength of cement. Rock specimen is a cylinder shaped tuff with hollowed out at the center. Radius of the hollows are 6.35, 12.7, 25.4 and 50.8 mm. The outer radius ranges between 38.1 and 93.66 mm. Degree of saturation of the test samples are divided into three levels 1) completely dry, 2) low saturated degree, and 3) medium saturated degree. The test reveal that the axial strength (friction between cement and rock) and the shear strength are high in the sample with higher degree of saturation, and are lower in the smaller specimen diameter. The results from the test indicate that in order to obtain low permeability and high strength seals, the location of cement sealing should be submersed in groundwater.

2.2 Expert System

2.2.1 Fundamentals

An expert system is an intelligent interactive computer program that can play the role of a human expert by using heuristic knowledge or rules of thumb. The heuristics are usually accumulated by a human expert over a number of years (Adeli, 1998a).

The structure of expert system has three main components (Figure 2.10); 1) a knowledge base, 2) an inference mechanism, and 3) a user interface (Sinha and Sengupta, 1989).

1) A knowledge base is the repository of information available in a particular domain. The knowledge base may consist of well established and documented definitions, facts and rules, as well as judgmental information, rules of thumbs and heuristics.

2) An inference mechanism controls the reasoning strategy of the expert system by making assertions, hypotheses and conclusions. In rule-base system, for example, the inference mechanism determines the order in which rules should be invoked and resolves any conflict among the rules when several rules are satisfied.

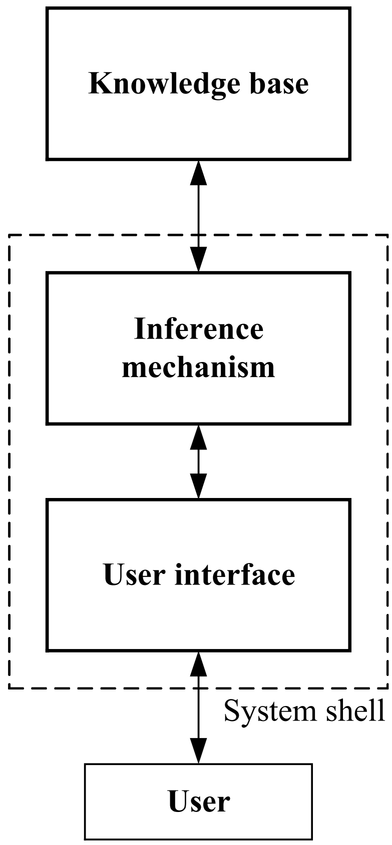

Figure 2.10 Structure of expert system (modified from Sinha and Sengupta, 1989).

3) The user interface allows the user to interact with the expert system and query the expert system. It may include natural language processors, menus, multiple windows, icons or graphics.

Advantages of expert systems concluded by Adeli (1988a) are as follows;

1) knowledge is more explicit, accessible and expandable,

2) the knowledge base can be gradually and incrementally developed over an extended period of time,

3) a general system with one inference mechanism can be developed for different types of applications simply by changing the knowledge base,

4) the same knowledge may be used in different problems by possibly employing different inference mechanisms,

5) an expert system can explain its behavior through an explanation facility,

6) an expert system can check the consistency of its knowledge entities or rules and point out the faulty ones through a debugging facility, and

7) an expert system is not biased and does not make cursory or irrational decisions.

2.2.2 Expert System Research in the Field of Geomechaniacal Engineering

The expert systems in the field of geotechnical engineering have been developed for 20 years. Examples of expert system that have been compiled and reviewed include the expert system for rock classification and parameter assessment, expert systems for design and assessment underground openings, expert systems for mining damage assessment, and expert systems for groundwater flows assessment.

Some of the expert systems for rock classification and parameter assessment have been developed by Butler and Franklin (1990) and Cai, Zhao, and

Hudson (1998). Butler and Franklin (1990) develop the expert system for rock mass classification that used Barton's Q system and Beinaiwski's rock mass rating (RMR) system. Cai et al. (1998) develop the expert system called Rock Engineering System (RES). The RES has the potential to solve rock engineering problems as a completely integrated system. It needs to take into account the coupled interaction mechanisms and the dynamic interaction process of all the parameters potentially relevant to engineering objectives.

Some of the expert systems for design and assessment underground openings have been developed by Gokay (1993) and Halabe and Einstein (1994). Gokay (1993) applies Hudson criteria (1992) to develop the expert system to assist in rock engineering decisions relating to mine excavation. The system deals with rock mass type and structure; in situ stress state; hydro-geology; mining methods. It is assisted by excavation stability, location, and orientation information. Halabe and Einstein (1994) develop the expert system (SIMSECTION) that acts as the user interface for DAT (Decision Aids for Tunneling). The expert system assists the user with the definition of the problem and provides consistency checking before performing an analysis.

Some of the expert systems for mining damage assessment have been developed by Reddish, Dunham, and Yao (1994) and Yu and Vongpaisal (1996). Reddish et al. (1994) present the expert system called ESDAS (Expert Structural Damage Assessment System). This system is developed to evaluate damage due to mining subsidence. The system uses a risk assessment technique based on certainty factors to predict the likely damage to a particular structure that is subject to mining subsidence. Yu and Vongpaisal (1996) describe a new blast damage criterion that has been developed with special reference to mining operations. It can be used for assessing damage by incorporating vibration level, rock properties, site characteristics, and effects of ground support systems.

Some of the expert systems for groundwater flows assessment have been developed by Davey-Wilson and May (1989) and Davey-Wilson (1991, 1993). They propose a software called Ground Water Expert (GWX) which is the expert system developed to provide appropriate methods for groundwater control in excavation.

CHAPTER III

DESIGN METHODOLOGY AND PROCESS

The design methodology and process for borehole sealing in rock formation are presented in this chapter. They follow the method suggested by Bieniawski (1992). The design process for sealing of boreholes in rock comprises eight design stages, including (1) identifying the performance objectives, (2) determining the functional requirements and constraints, (3) collecting relevant information, (4) developing the design solutions, (5) analyzing the design components, (6) synthesizing and defining the specifications, (7) system evaluation and design optimization, and (8) design recommendations and implementation.

3.1 Statements of Problem

The performance objectives or design issues of the seals should be clearly identified. Engineers should first determine whether sealing of their borehole is necessary, or whether the borehole can remain opened (or unplugged) without causing an environmental impact. It should be recognized that some opened boreholes do not cause groundwater contamination. Such boreholes may be small, shallow and drilled in heavily fractured rock mass above groundwater table. Some borehole may need only concrete cap or steel cover for a safety purpose, while leaving the entire length opened. A complex and permanent seal system, however, may be required in some boreholes where long-term isolation of liquid or gas is addressed as an important issue, e.g., boreholes connecting to the depleted oil or gas reservoirs or to the sources of contaminants.

3.2 Functional Requirements and Constraints

Defining the functional requirements is probably the most important step in any engineering design. There are two functional requirements for the seal design: 1) to provide the mechanical support to the rock around the borehole, and 2) to minimize the circulation of groundwater or any fluid along the borehole. Some borehole needs one of these requirements, some may need both, depending upon the site characteristics and performance requirements. If a borehole penetrates two or more rock units with different intrinsic properties or if a very deep borehole situates in a single rock unit, the functional requirements must be identified for each rock unit or each borehole section that subjected to different geologic conditions, such as stress states and groundwater pressures.

Suh (1990) classifies the engineering constraints into two categories: system constraints and input constraints. For borehole sealing practices, the system constraints are related to the chemical compatibility between the seals and the surrounding rock and groundwater, and to the seal specifications. The input constraints involve the availability of the local resources normally identified in terms of budget, equipment, personnel experience, and sealing materials. These constraints should be identified and considered in the design evaluation.

3.3 Collection of Information

The seal should be designed such that its properties and behavior (performance) are traceable to the site-specific conditions. The design parameters include borehole conditions, rock mass characteristics, groundwater conditions, geochemistry, in-situ stresses, ground deformation and seismic activities.

3.3.1 Borehole Conditions

It is necessary to know, to the greatest extent practicable, the geometry of the hole, i.e. its true diameter, and of its casing, its location, depth, and any installations (e.g. pumps, pipes and cables). For long-abandoned holes it is likely that some debris may have been dumped in the hole. Any damage or weakness zone around the opening could soften the surrounding rock and hence reduces the mechanical and hydraulic bonds. It is desirable to caliper log the hole. Measuring the actual size of the hole as a function of depth and rock unit will allow a correct determination of the amount of sealing materials to be emplaced. Video logging is also desirable, as it allows a visual determination of down-hole conditions.

3.3.2 Rock mass Characteristics

Strength, stiffness and permeability of all rock units through which the borehole penetrates should be determined. The strength is used to evaluate the mechanical stability of the rock adjacent to the borehole wall. The strength and stiffness usually affect the mechanical interaction at the seal-rock interface, which governs the axial resistance of the seal. The strength of rock ($\sigma_{rock\ mass}$) can be determined by using the equation that given by Hoek and Brown (1980).

$$\sigma_{rock\ mass} = s^{1/2} \cdot \sigma_{intact} \tag{3.1}$$

where s = empirical constant, and

σ_{intact} = intact rock strength (MPa).

The spacing, aperture and orientation of joints or fractures should be mapped along the borehole length. These discontinuities could provide a leakage path of the gas or water to bypass the seal. The permeability of the rock mass will also determine the maximum hydraulic conductivity of the seal to be installed. The rock mass permeability ($K_{rock\ mass}$) may be estimated from the joint spacing and joint aperture as given by Hoek and Bray (1981).

$$K_{rock\ mass} = (ge^3)/(12\nu \cdot b) \tag{3.2}$$

where g = gravitational acceleration (981 cm/sec^2),

e = opening of cracks or fissures (cm),

b = spacing between cracks (cm), and

ν = the coefficient of kinematic viscosity (0.0101 cm^2/sec for pure water at 20 °C).

3.3.3 Groundwater Conditions

The location, type and quality of all water-bearing formations should be mapped along the borehole length. Depth of groundwater table is one of the main factors governing the location and length of seals. Infiltration, surface flooding and potential for fluctuation of groundwater table should be taken into consideration. The groundwater conditions control the magnitude of the hydraulic pressures and gradients imposed on the seals. The moisture content of the surrounding rock may affect the long-term properties of the seals. Saturated and unsaturated zones usually require different types and properties of seal. The groundwater pressure is also required for calculating the axial resistance of the cementitious seals, and for evaluating the potential piping and erosion of the bentonitic seals. To prevent dislodging of bentonitic seals, the maximum pressure gradients induced by water or gas at the seal ends should be determined. For sealing of groundwater wells, the pressure gradient is related to the depth of seal and hydraulic head of groundwater. The pressure gradient is an important design parameter for sealing a borehole connected to liquefied gas and compressed air storage cavern, and for sealing oil and gas wells. The maximum pressure gradients also determine the minimum length of the seal.

3.3.4 Geochemistry

Chemical compatibility between the seals, surrounding rock and groundwater is important for long-term or permanent sealing. Thus, the type of cement selected for preparation of cementitious seals should be compatible with groundwater chemistry. Using crushed rock obtained from the seal location or depth also minimizes the potential for the chemical incompatibility between the seals and the existing environment. For example, crushed salt has been considered for sealing of borehole in rock salt where plastic creep deformation (closure) of the borehole wall will consolidate the seal, and hence reduces the seal porosity and permeability (Stormont and Finley, 1996).

3.3.5 In-situ Stresses

For sealing of deep boreholes, the magnitude and ratio of horizontal principal stresses are important, particularly where the surrounding rock has relatively low strength. Failures or cracks along the hole length induced by a high concentration of tangential stresses could degrade the seal performance. These cracks could also become a preferential flow path. Confining pressure at the seal location should be known in order to evaluate the mechanical interaction at the seal-rock interface. The Kirsch's solution may be used to calculate the radial and tangential stresses at the seal-rock interface where it subjected to the internal pressure (seal/bentonite expansive stress) and the external in-situ stresses (Hoek and Brown, 1980; Fuenkajorn and Daemen, 1991b). The tangential stresses in rock around the borehole should not induce radial cracks along the borehole wall. The equations for calculating the radial stress (σ_r) and tangential stress (σ_θ) are given by Jager and Cook (1979).

$$\sigma_r = P_2 [1 - (R_1^2/r^2)] + (P_1 R_1^2/r^2) \quad (3.3)$$

$$\sigma_\theta = P_2 [1 + (R_1^2/r^2)] - (P_1 R_1^2/r^2) \quad (3.4)$$

where R_1 = the internal radius,

r = radius of any point in rock,

P_1 = pressure is applied at the interior, and

P_2 = pressure is applied at the exterior.

3.3.6 Potential Ground Deformation

Borehole in or near the subsidence areas or the unstable slopes and embankments may be subjected to large strains under tension, compression, bending and torsion. The magnitude and rate of such movements should be identified. Soft seals, especially those with healing characteristics can accommodate large straining without detrimental effects on the seal performance.

3.3.7 Seismic Activities

The characteristics and frequency of occurrence of seismic activities caused by earthquake or blasting should be considered. If the ground vibration is relatively small, cement seal may be appropriate. If a large tectonic movement is possible at the seal location, a soft and plastic seal should be considered.

3.4 Determination of Design Solutions

This stage involves formulation of concepts to arrive at the design solutions. Each design solution represents a group of design components (or seal types selected along the length of the boreholes) that meet the corresponding functional requirements previously defined. Creativity, imagination and heuristics can be incorporated here. Several distinctively different design solutions may be obtained for a single borehole. This means that more than one seal type can be selected for a certain portion of the hole. There are eight types of sealing material proposed in this research, including 1) granular material, 2) bentonite, 3) pre-compressed bentonite, 4) bentonite mixed with granular material, 5) portland cement, 6) sulfate-resistant cement, 7) concrete, and 8) sulfate-resistant concrete. The summaries of sealing material properties are shown in Table 3.1.

To assist in selecting appropriate seal types, some key criteria that have derived from the relevant laboratory and in-situ experiments, are summarized as follows.

1) The seal permeability should not exceed 10 times the rock mass permeability at the seal location (Daemen and Fuenkajorn, 1996).

2) The cement should not be installed above the groundwater table, i.e. it should remain saturated (Fuenkajorn and Daemen, 1987).

3) The granular materials should have the minimum coefficient of uniformity of 16, with the maximum particle size less than one-tenth of the borehole diameter and the minimum particle size greater than the joint aperture (Ouyang and Daemen, 1996).

Table 3.1 Summaries of sealing material properties.

Sealing materials	Approximate permeability (m/s)	Approximate strength (MPa)
Granular materials		
- Sand (0.06 – 2 mm)	10^{-2}-10^{-6}	-
- Gravel or crushed rock (2 – 60 mm)	1-10^{-3}	-
Bentonitic materials		
- Powder, chips or tablet bentonite	10^{-7}-10^{-11}	-
- Pre-compressed bentonite	10^{-14}	2.6 (expansive stress)
Cementitious materials		
- Cement	10^{-7}	26.2
- Concrete	10^{-7}	20.59 - 49.04
Mixture materials		
- Mixture of bentonite and granular materials	10^{-10}	-

4) To provide sufficient axial resistance the key seal (cement, concrete or pre-compressed bentonite) should have a minimum length-to-diameter ratio equal to 4 when installed in intact portion of borehole, and equal to 8 when installed in the zone with some fractures (Akgun, 1996). The key seal is the seal that provides mechanical support to the seals above and to the surrounding rock.

5) Cement and concrete seals should not be installed in heavily fractured zone (Daemen and Fuenkajorn, 1996).

6) The radial stresses induced by the expansion of cement or by the swelling of bentonite should be less than the tangential compressive stresses induced by the in-situ stress (Fuenkajorn and Daemen, 1987).

7) A rigid seal (cement or concrete) should not be installed where excessive ground deformation is anticipated, e.g. subsidence zone or slope movement (Daemen and Fuenkajorn, 1996).

8) The long-term consolidation or settlement (Sowers, 1979) of bentonitic and granular materials should not exceed 1-2 times the borehole diameter.

9) Crushed rock obtained from the seal location or depth should be used where the maximum chemical compatibility is required (Stormont and Finley, 1996).

10) Seals formed by mixing bentonite with granular materials or crushed rock should have the amount of bentonite more than 35% by weight (Ouyang and Daemen, 1996).

11) Bentonite and granular materials should be pre-compressed or compacted bentonite or compacted in the borehole where ground vibration or seismic activity is expected (Daemen and Fuenkajorn, 1996).

12) Cement mixed with sulfate or chloride resistant additives should be used where the groundwater contains sodium chloride more than 500 ppm, or sodium sulfate more than 1000 ppm (Setthapootra, 1994).

3.5 Analysis of Design Components

This stage involves the analysis of components of design solutions. The components of each sealing material are presented as follows

1) Granular material, including sand, gravel or crushed rock.

2) Bentonite, including various forms of sodium bentonite such as powder, chip, tablet and granular bentonite.

3) Pre-compressed bentonite, essentially the chip, tablet or granular bentonite mixed with appropriate moisture content and compressed to a desired volume.

4) Bentonite mixed with granular material powder, chip, tablet or granular bentonite and sand, gravel or crushed rock.

5) Portland cement, including Portland cement type I to type IV.

6) Sulfate-resistant cement, or Portland cement type V.

7) Concrete, Portland cement type I to type IV mixed with sand, gravel or crushed rock.

8) Sulfate-resistant concrete, Portland cement type V mixed with sand, gravel or crushed rock.

3.6 Synthesis and Specifications

In this stage, the selected seal for each rock unit or each depth interval are compiled into a seal system for the borehole. The seal system represents all seals designed for the entire length of the borehole, the seal-rock interface, and the surrounding rock mass. Since there may be more than one design solutions for a single borehole, more than one set of seal system may be obtained at this stage.

The seal characteristics of all design components should be defined as specific as possible. The specifications of granular materials and their mixtures involve the maximum and minimum particle sizes, and the coefficient of uniformity as well as the mixing ratio. The specifications for the compacted and pre-compressed bentonite seals should include the mixing ratio, compaction effort, input energy, optimum moisture content, and maximum dry density (Ran et al., 1997). The specifications for cement and concrete seals should include the types of cement and their mixing ratio.

3.7 System Evaluation and Optimization

Each design solution is evaluated in terms of the mechanical interaction and chemical compatibility between the seal, as well as the constructability of the seal system. The formation thickness and seal depth should be re-evaluated in term of practicality of the installation. The consolidation of bentonitic seals should be determined. If the bentonite settlement is more than borehole diameter (calculated up to 1000 years), key seal (cement) should be installed at each 30 meters interval. The percentage of consolidation of bentonitic seals as a function of time and ground vibration recommended by Sower (1979) can be calculated as follows.

$$U = -655.74(T)^6 + 2733(T)^5 - 4475.2(T)^4 + 3680.2(T)^3 - 1660.9(T)^2 + 470.84(T) + 0.2541 \quad (3.5)$$

$$T = [t\,(1+e_{initial})\,k] / [\gamma_w\,(H/2)^2 * a_v] \quad (3.6)$$

$$a_v = [e_{initial} - e_{final}] / [\Delta\sigma_v] \quad (3.7)$$

where U = percent of consolidation (%),

T = time factor,

a_v = coefficient of compressibility (m^2/kN),

t = time (second),

k = coefficient of permeability (m/s),

$e_{Initial}$ = initial void ratio,

e_{final} = final void ratio,

$\Delta\sigma_v$ = axial stress (MPa),

γ_w = unit weight of water (kN/m^3), and

H = thickness of formation (m).

The seal length and type may be adjusted or modified to increase the simplicity of the design and emplacement procedure. This process may be considered as design iteration.

Optimization theory and associated techniques such as those given by Siddall (1982) may be applied to select the most suitable design solution (seal system). The availability of the materials and equipment, economic constraints, personal experiences, and the local regulations and practices should be considered.

3.8 Design Recommendations and Implementation

The design recommendations involve the preparation of a comprehensive design report. It should include the site characteristics, performance requirements, types, amount (length) and specifications of the seal, installation procedure, and cost estimate. The methods and results of analysis and synthesis for all design alternatives may be provided. Cross-section of the borehole showing the geological and hydrological conditions and the location of the seal system components should be included.

The last stage of the design process is the implementation of the seal design. Due to the uncertainty of the geological conditions and the complexity of the installation procedure, the last design may be again adjusted or modified to satisfy the actual rock behavior and borehole conditions encountered during the construction process.

CHAPTER IV

DEVELOPMENT OF THE EXPERT SYSTEM SOFTWARE

This chapter describes the structures and flowcharts used in the development of the expert system software. The design methodology and process for borehole sealing described in the previous chapters are transformed into the software. Two main issues are discussed here, 1) the system shell (or the program used to interact with the user), and 2) the flowcharts showing the complete network of the expert system.

4.1 System Shell

Visual Basic (version 6.0) software is employed for the expert system shell in this research due to its notable application such as Graphical User Interface (GUI). It allows the user to operate in graphical manner. It is also simply to develop the application. The software supports the application in partial manner, for example, the commands will be written after the created and well tested software components are put together. The software is also able to support other information management system, such as Access, FoxPro, SQL, Sever of Microsoft or dBase, Oracle and Sybase. The software is however unable to support the complex or multi-steps calculation. This is the weakness of the software (Spear and Spear, 2000).

The data acquisition is considered as the most significant part in developing the program. The form in the retrieval information collects information through 2 channels, firstly, application “Text box” and secondly, input by the users through application “Option button”.

An output includes three main components; 1) retrieval information, 2) preliminary evaluation, and 3) recommendations for borehole sealing design.

1) The system shows the information obtained though the application “Text box” as the retrieval information output.

2) In the case where the system is not able to design due to lack of some information, “Message box” asking for the remaining (missing) data will be shown in the preliminary output.

3) The design recommendations are shown only when the system recognizes that the input information meets all requirements and the designing of borehole sealing in each rock unit and the evaluation of the seal system have been proceeded. Recommendations on sealing materials for each rock unit are shown by “Text box” as the design results.

4.2 Expert System Flowcharts

The expert system software for the design of borehole sealing in rock formations consists of three major parts, 1) data acquisitions and design recommendations, 2) preliminary evaluation, and 3) design calculation (Figure 4.1). Flowcharts of each part are explained in this section.

For simplicity of presentation, several symbols for materials and factors are firstly defined. The symbols used in the expert system flowcharts as described below are the same with the ones used in the software. The symbols and the corresponding meanings are listed as follows.

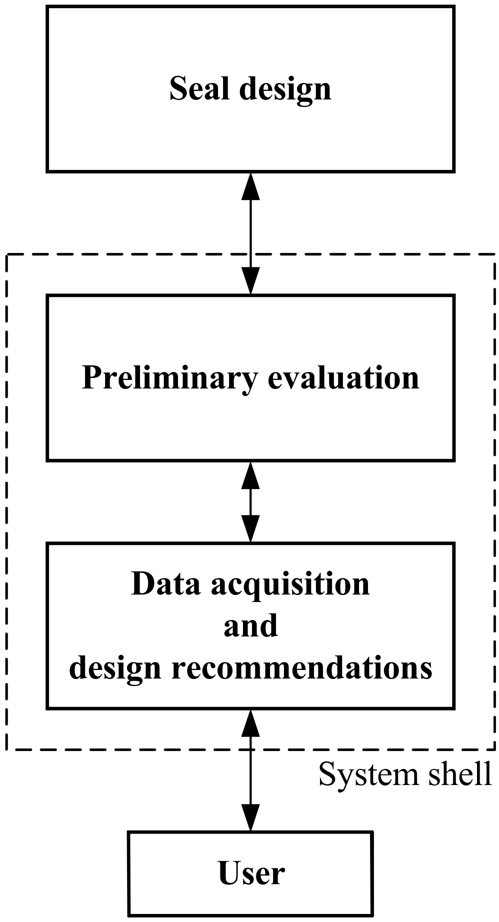

Figure 4.1 Structure of expert system software for borehole seal design in rock formations.

GT	=	groundwater table,
BLF(n)=	depth of the bottom of the rock unit "n",	
A1	=	granular material,
A2	=	bentonite,
A3	=	pre-compressed bentonite,
A4	=	bentonite mixed with gravel or sand,
A5	=	Portland cement,
A6	=	concrete,
A7	=	sulfate-resistance Portland cement,
A8	=	sulfate-resistance Portland concrete,
M1(n)	=	proposed material for borehole sealing in rock unit "n" by considering groundwater level,
M2(n)	=	proposed material for borehole sealing in rock unit "n" by considering mechanics of the rock and seal,
M3(n)	=	proposed material for borehole sealing in rock unit "n" by considering engineering requirement,
M4(n)	=	proposed material for borehole sealing in rock unit "n" by considering geochemistry,
$\sigma_\phi(n)$	=	tangential stress in rock unit "n",
$\sigma_c(n)$	=	strength of rock unit "n",
$K_{rock\ mass}(n)$	=	rock mass permeability in rock unit "n",
MF(n)	=	recommended material for borehole sealing in rock unit "n", and
n	=	number of different rock formations intersected by the borehole.

4.2.1 Flowchart for Data Acquisition

The flowchart for the data acquisition is illustrated in Figure 4.2. The information retrieved from the user includes 1) general borehole information, 2) borehole conditions, 3) geochemistry, 4) groundwater level, 5) engineering requirements, 6) geology, and 7) geomechanics.

4.2.2 Flowcharts for Preliminary Evaluation

The flowcharts of the preliminary evaluation of the input are illustrated in Figures 4.3 and 4.4. The input information to be checked by the system can be classified into two groups. Firstly, the additional information which is automatically acquired from system database, if it is not provided by the user. Secondly, the unexpected information from the user. In order obtain the borehole sealing recommendations, the necessary information is required. If the information is not provided at the first time, the system will request the missing information again. And if the information is not provided at the second time, the system will inform that the design of borehole sealing is not possible due to lack of necessary information.

4.2.3 Flowcharts for seal design

The seal design flowchart incorporates all design rules, including the rules for designing of borehole sealing in each rock unit and the rules for evaluating the efficiency of the seal system (seal, rock, and their interface).

The flowcharts for the design rules in each rock unit lead to the most suitable material for each rock unit. There are eight types of material that can be selected by the system, as follows 1) granular material, 2) bentonite, 3) pre-compressed bentonite, 4) bentonite mixed with granular material, 5) Portland cement, 6) sulfate-resistant Portland cement, 7) concrete, and 8) sulfate-resistant concrete.

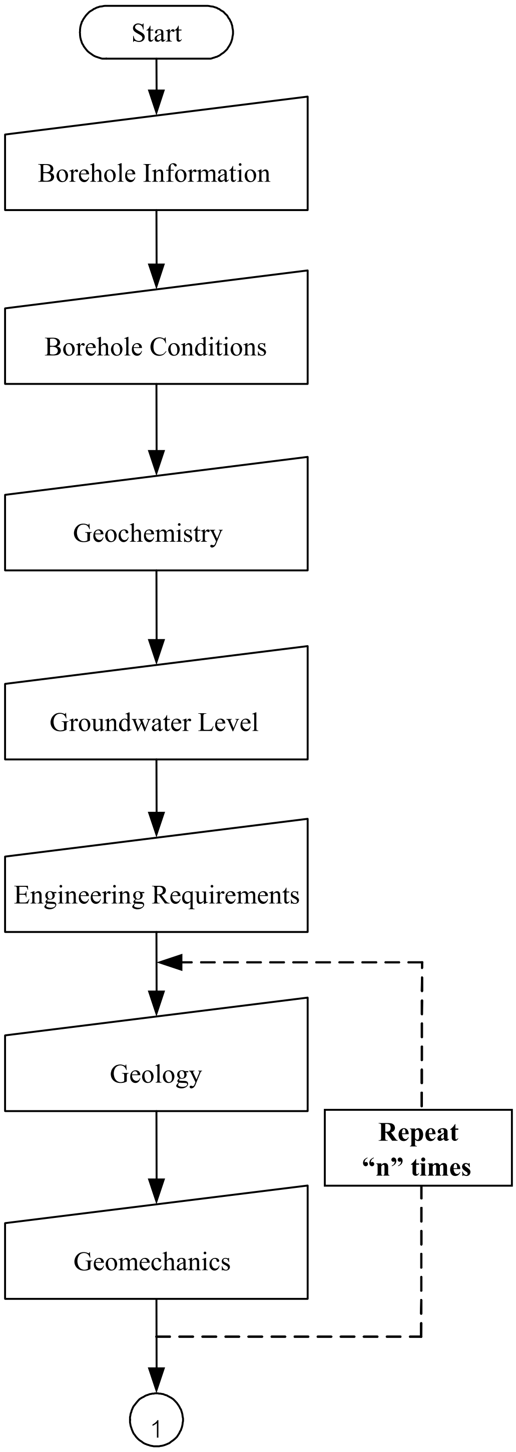

Figure 4.2 Data acquisitions flowchart. "n" = number of different rock formations intersected by the borehole.

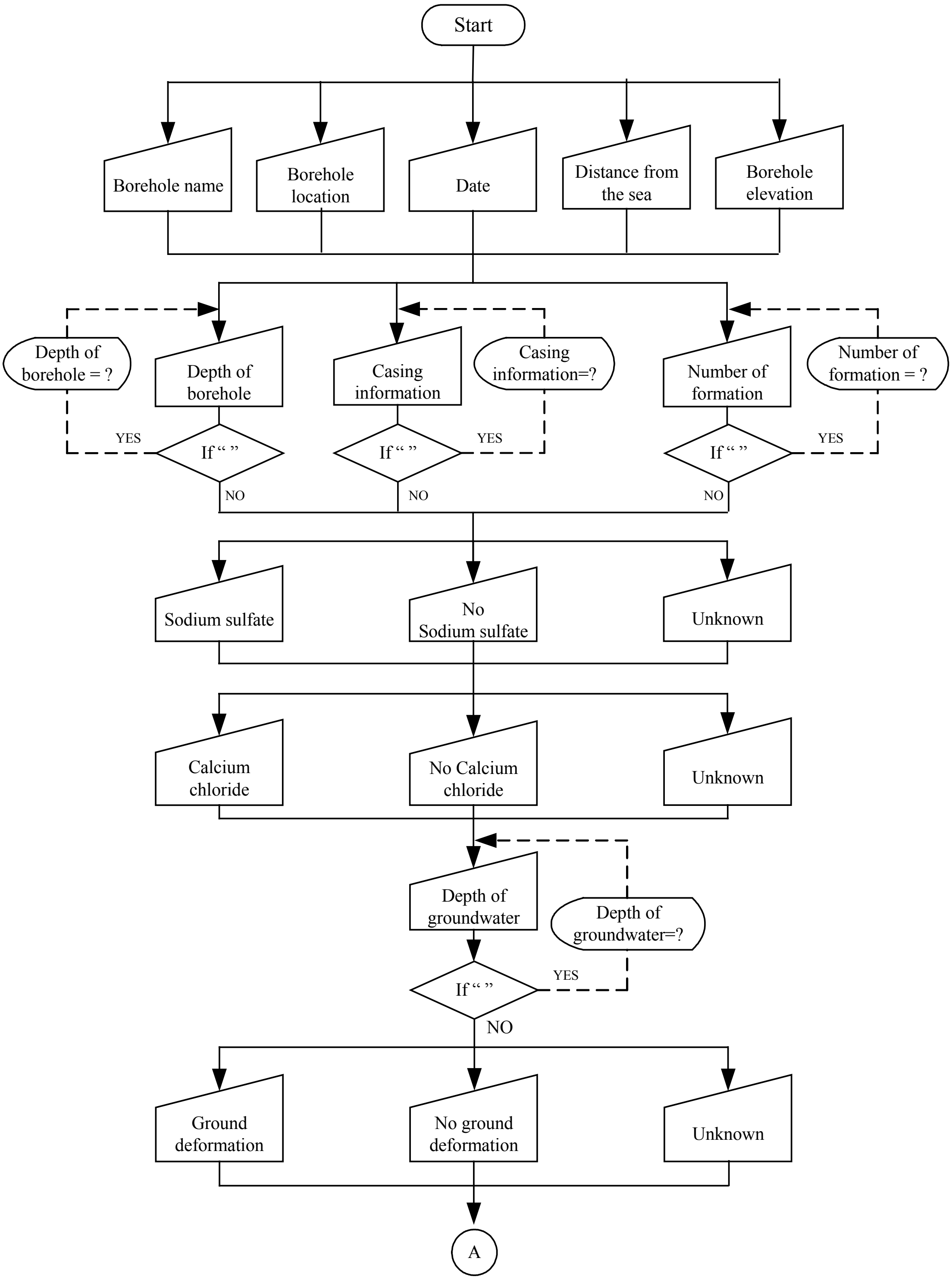

Figure 4.3 The first part of preliminary evaluation flowchart.

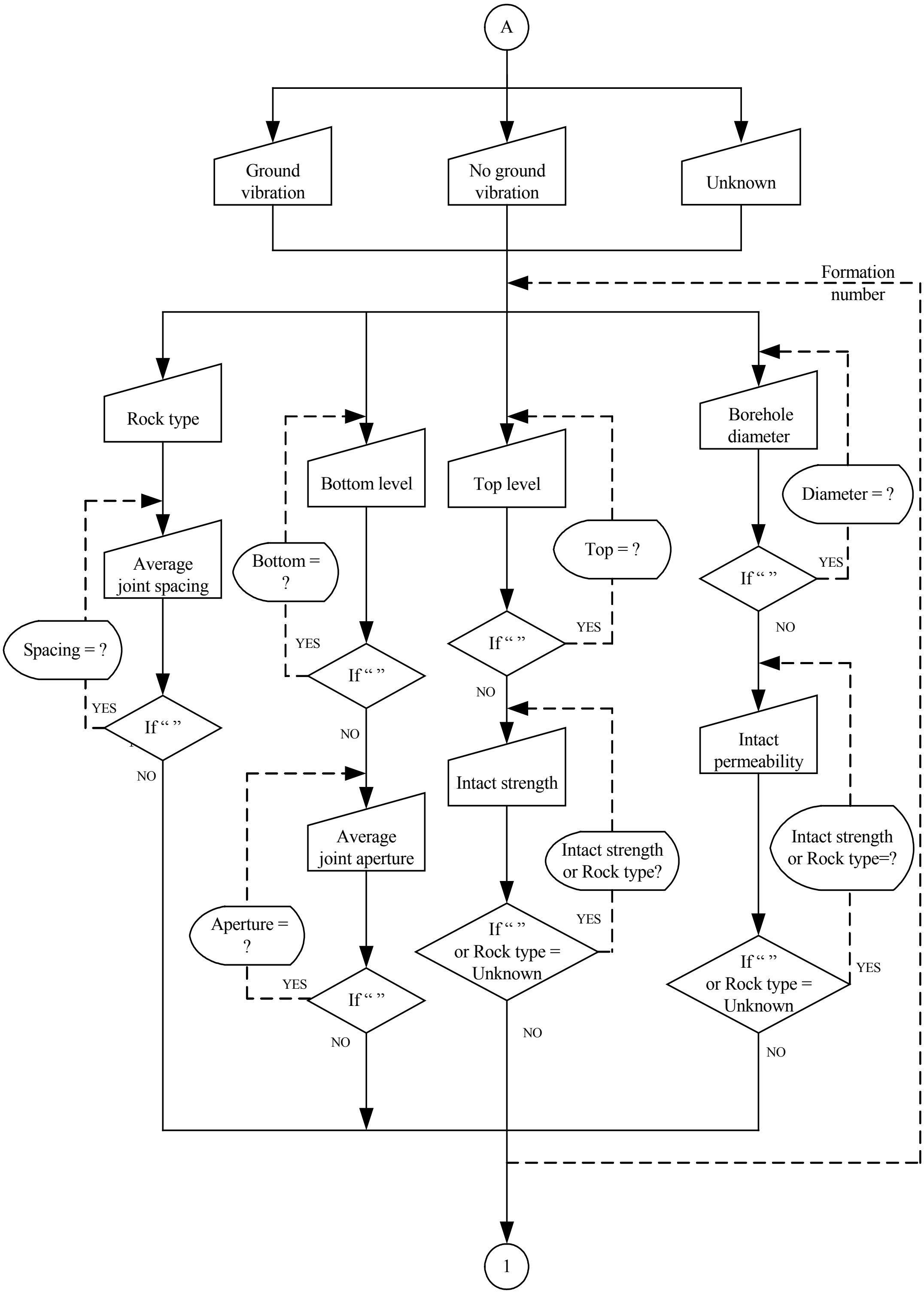

Figure 4.4 The final part of preliminary evaluation flowchart.

The factors to be considered in selecting the materials include 1) groundwater level, 2) geomechanics, 3) hydraulics, 4) engineering requirements, 5) groundwater chemistry, and 6) particle sizes of granular material.

The system makes two iterations in the design for each rock unit. In the first round, the six factors are considered to obtain the most suitable material for each rock unit (Figures 4.5 through 4.8). Three out of the six factors, mechanics, hydraulics and engineering requirements, are considered again in the second round. The second round consideration flowcharts are illustrated in Figures 4.9 through 4.11.

The flowcharts containing rules for evaluating the efficiency of the seal system are shown in Figures 4.12 and 4.13. Here, the following issues are evaluated, 1) settlement of bentonite, 2) practical depth for using granular materials and pre-compressed bentonite, and 3) comparison of the formation thickness to simplify the seal or to reduce the number of different seal types in a borehole.

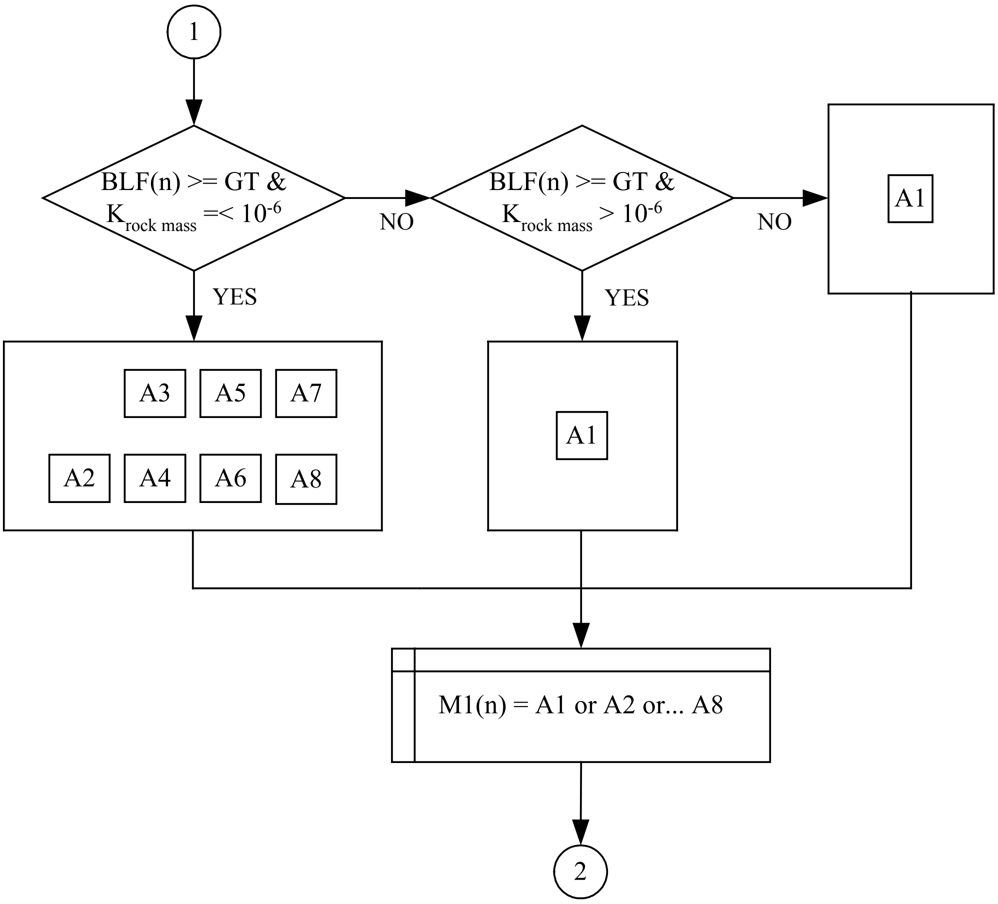

Figure 4.5 Formation seal design flowchart in the part of groundwater level and rock mass permeability considerations in the first round.

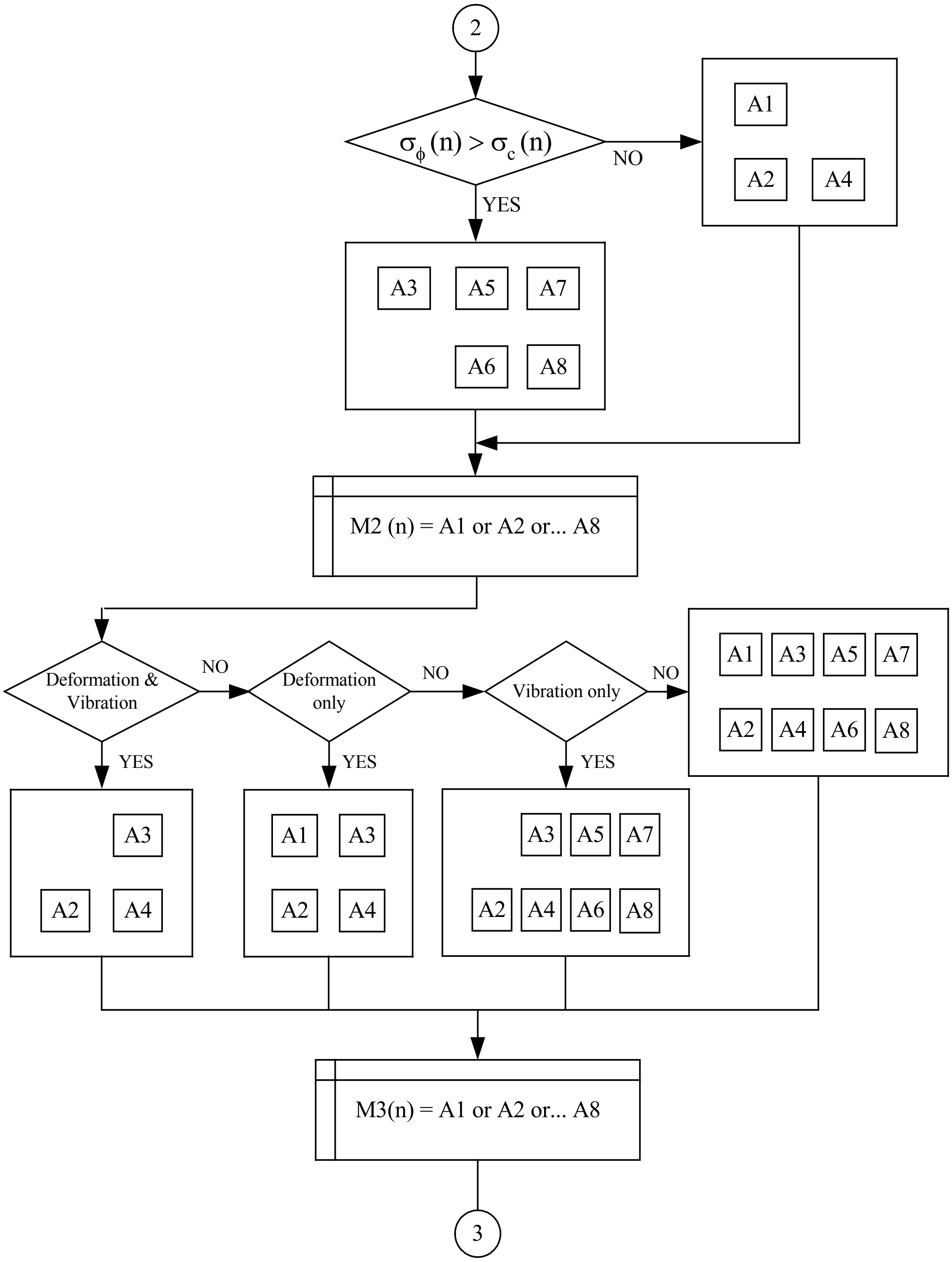

Figure 4.6 Formation seal design flowchart in the part of mechanics and engineering requirements considerations in the first round.

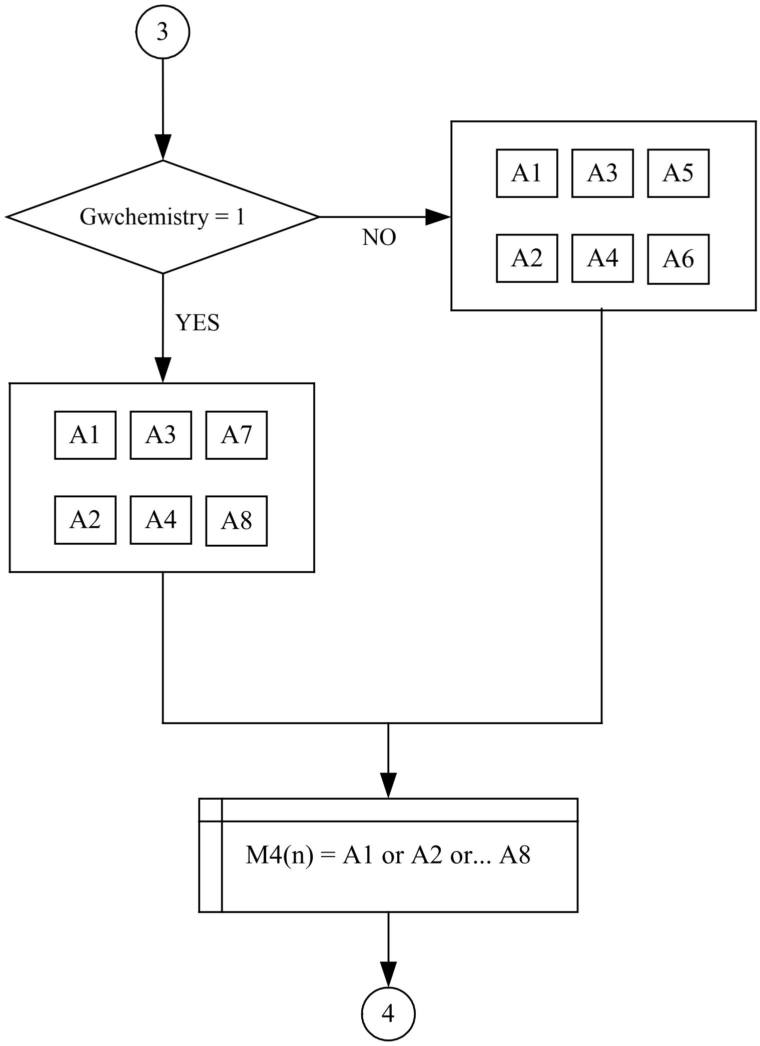

Figure 4.7 Formation seal design flowchart in the part of groundwater chemistry consideration in the first round.

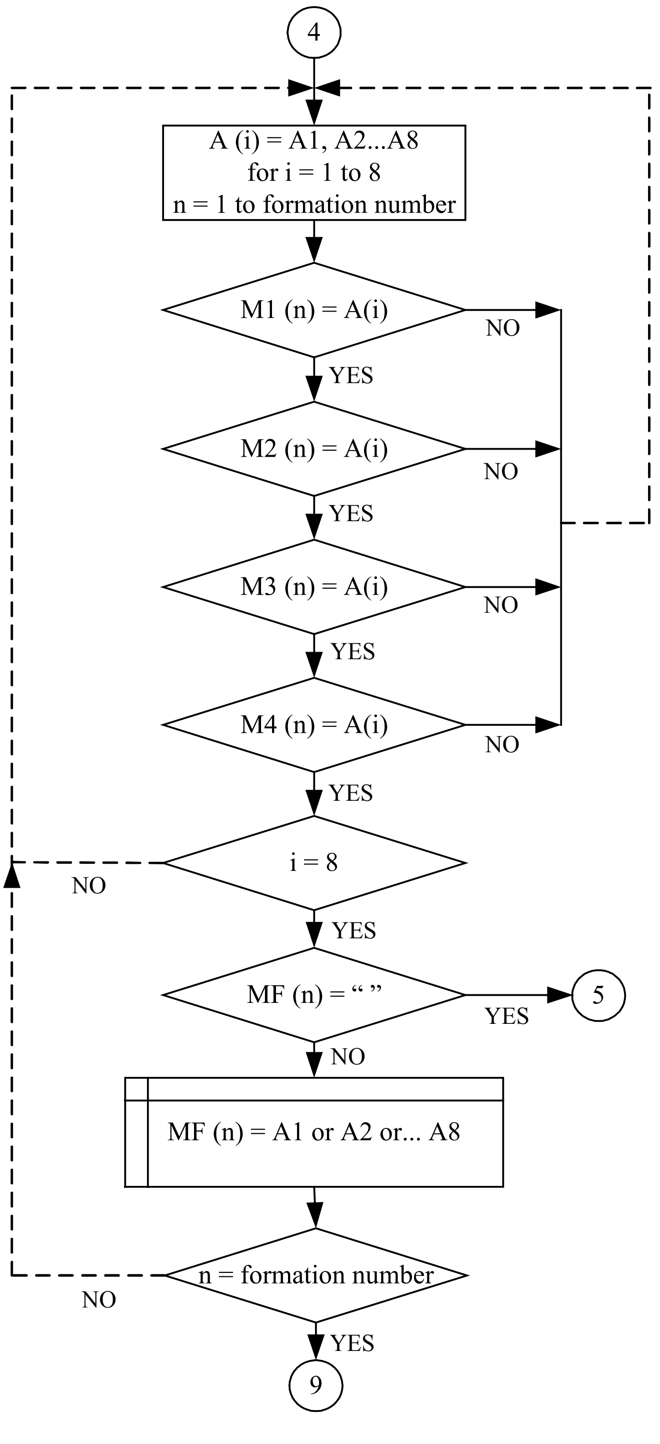

Figure 4.8 The final part of formation seal design flowchart in the first round.

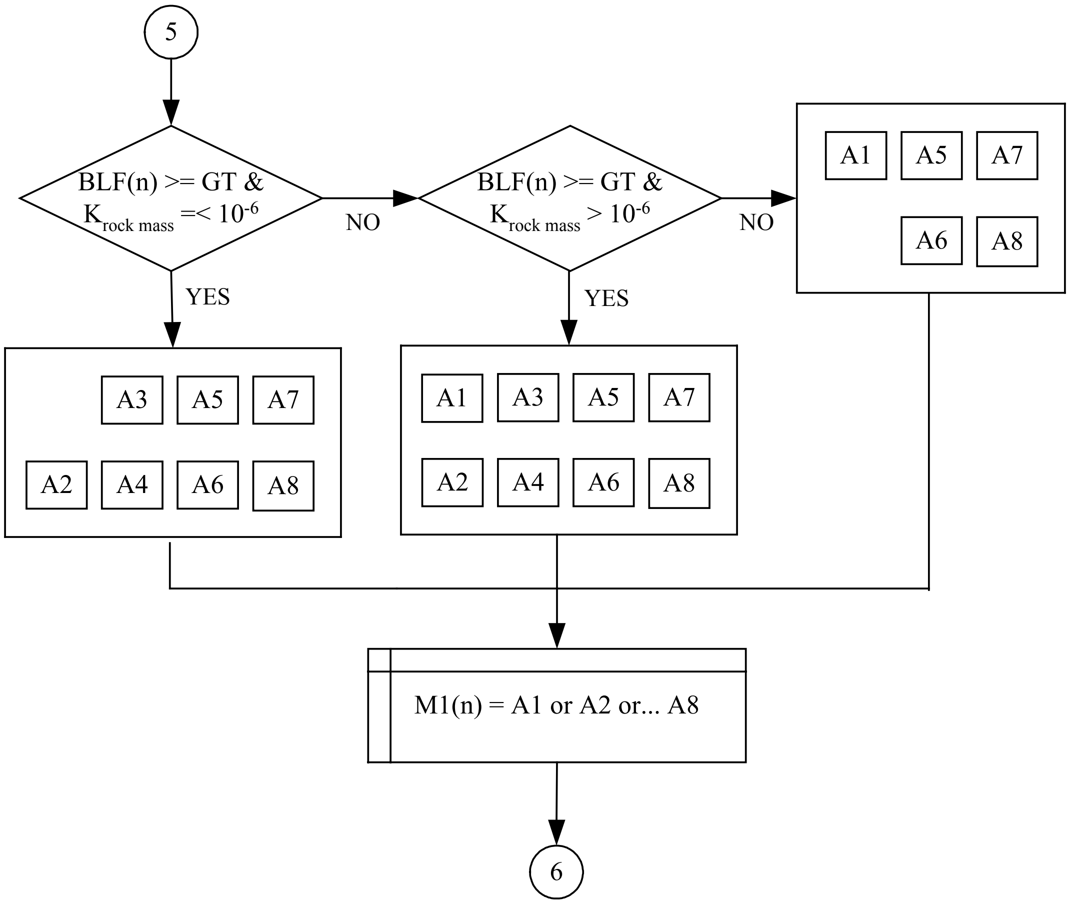

Figure 4.9 Formation seal design flowchart in the part of groundwater level and rock mass permeability considerations in the second round.

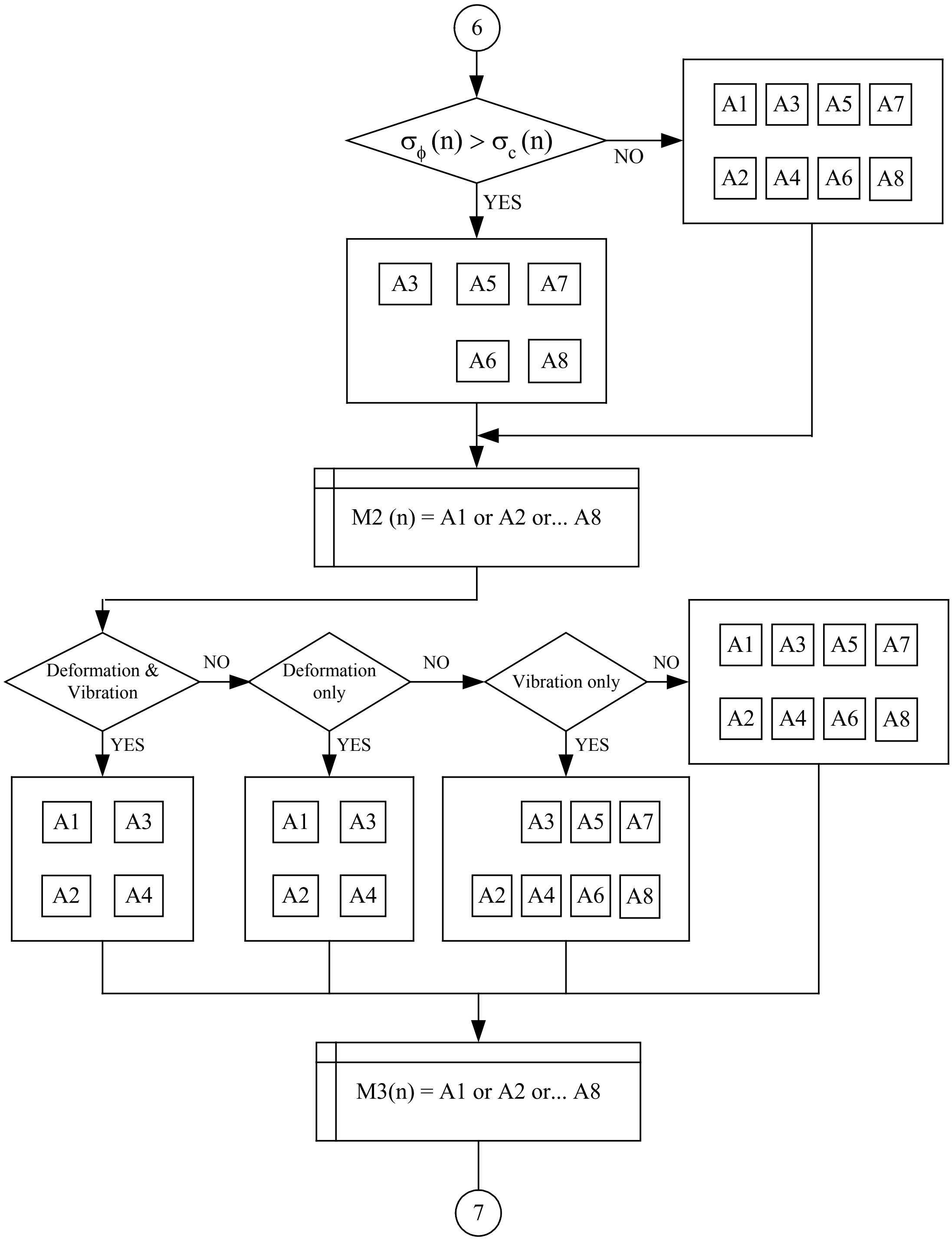

Figure 4.10 Formation seal design flowchart in the part of mechanics and engineering requirements considerations in the second round.

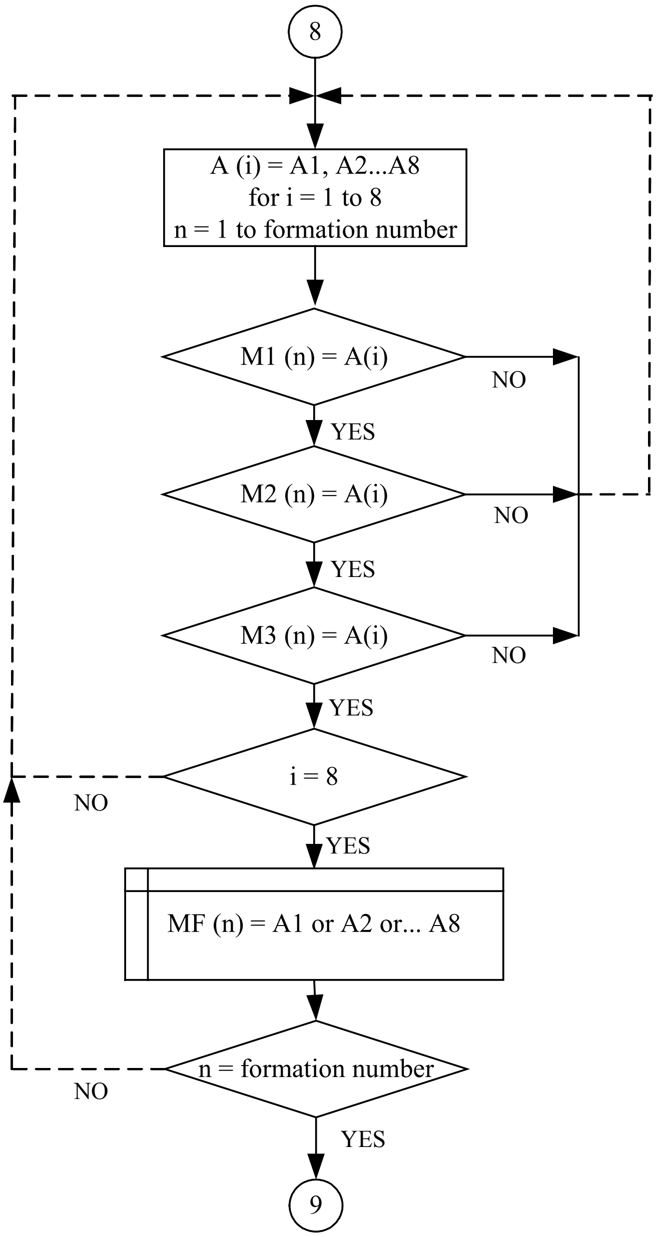

Figure 4.11 The final part of formation seal design flowchart in the second round.

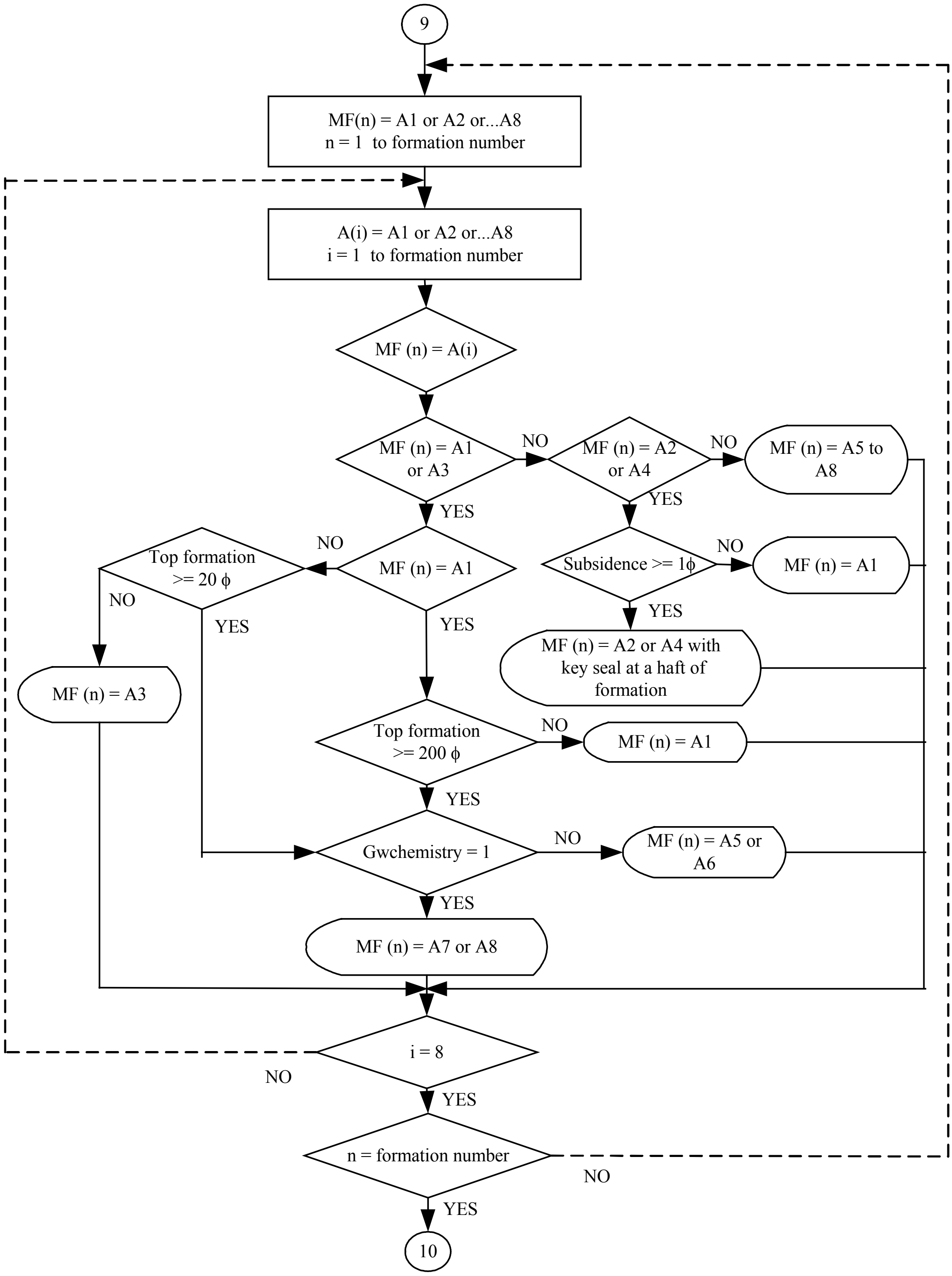

Figure 4.12 The first part of seal system evaluation flowchart.

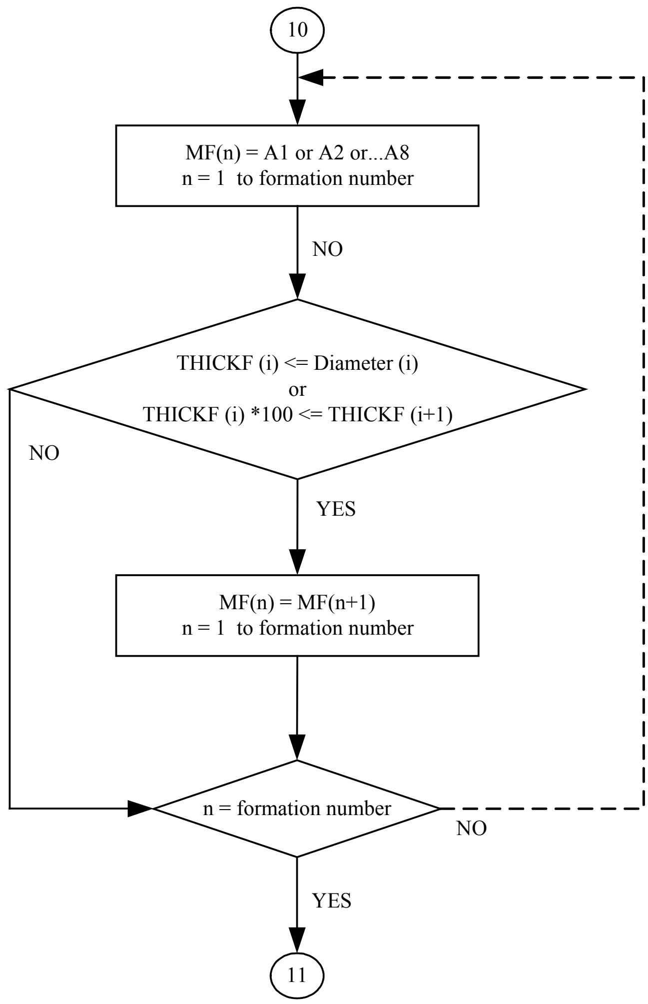

Figure 4.13 The final part of seal system evaluation flowchart.

CHAPTER V

BOREHOLE SEALING DESIGN EXAMPLES

Examples of borehole sealing design by the expert system software are presented in this chapter. The physical conditions of boreholes among these examples are varied in terms of geochemistry, groundwater level, rock characteristics, geomechanics, and engineering requirements. The objective of using a variety of conditions is mainly to demonstrate the design capability of the developed expert system. The borehole examples concentrate on the abandoned groundwater wells and exploration boreholes in mining industry.

5.1 Borehole Diameter and Joint Aperture Considerations

Diameter of borehole and joint aperture affect the design of granular seals. The maximum particle size of granular materials therefore depends on the borehole diameter, whereas the minimum particle size depends on the joint aperture. The specifications of granular materials are, therefore, varied for different borehole sizes and joint apertures. Examples of borehole sealing design in different borehole sizes and joint apertures are illustrated in Figures 5.1 and 5.2 and Tables 5.1 and 5.2.

5.2 Ground Deformation and Ground Vibration Considerations

Ground deformation in rock formations is a design limitation for cementitious materials. Ground deformation may cause cracking and eventually may result in

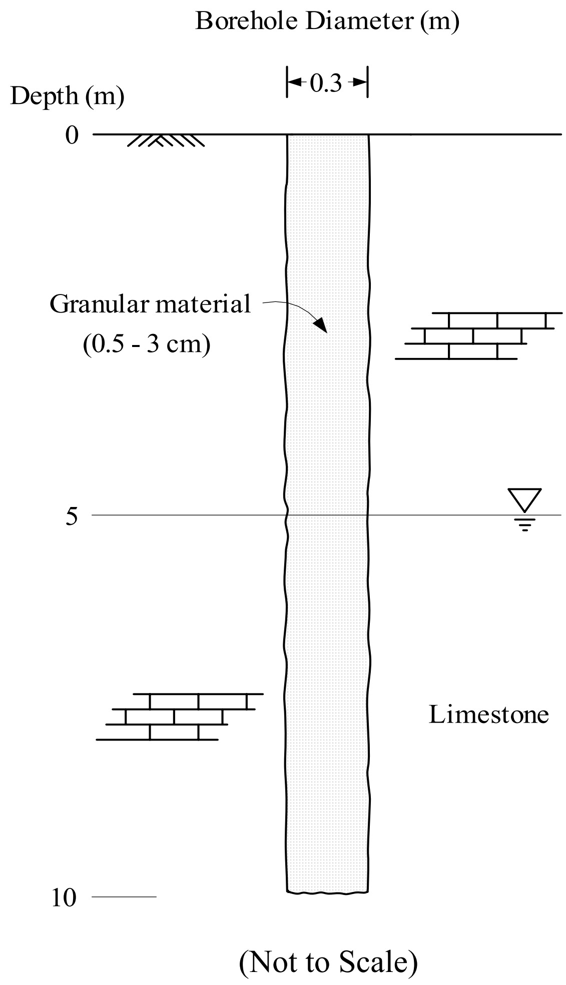

Figure 5.1 Borehole sealing design with borehole diameter and joint aperture considerations (borehole diameter is 0.3 m and joint aperture is 0.5 cm).

Table 5.1 Borehole sealing design example for Figure 5.1.

<table>
<tr><th colspan="2">Input</th><th>Seal Design</th></tr>
<tr><td colspan="2">General Data:</td><td rowspan="17">Formation No. 1
From 0 m to 10 m : Granular materials, particle sizes from 0.5 cm to 3 cm (Fine to coarse gravel).</td></tr>
<tr><td>1. Depth (m)</td><td>10</td></tr>
<tr><td>2. Formation Number (Unit)</td><td>1</td></tr>
<tr><td>3. Groundwater Table (m)</td><td>5</td></tr>
<tr><td>4. SO_4 (ppm)</td><td>None</td></tr>
<tr><td>5. NaCl (ppm)</td><td>None</td></tr>
<tr><td>6. Ground Deformation</td><td>None</td></tr>
<tr><td>7. Ground Vibration</td><td>None</td></tr>
<tr><td colspan="2">Formation No. 1</td></tr>
<tr><td>1. Rock Type</td><td>Limestone</td></tr>
<tr><td>2. Depth to top level (m)</td><td>0</td></tr>
<tr><td>3. Depth to bottom level (m)</td><td>10</td></tr>
<tr><td>4. Borehole Diameter (m)</td><td>0.3</td></tr>
<tr><td>5. Joint Spacing (m)</td><td>1</td></tr>
<tr><td>6. Joint Aperture (cm)</td><td>0.5</td></tr>
<tr><td>7. Intact Rock Strength (MPa)</td><td>80</td></tr>
<tr><td>8. Intact Rock Permeability (m/s)</td><td>1.00E-07</td></tr>
<tr><td colspan="2">Calculation Results:
Formation No. 1</td><td rowspan="4">Remarks:</td></tr>
<tr><td>1. Rock Mass Strength (MPa)</td><td>5.060</td></tr>
<tr><td>2. Rock Mass Permeability (m/s)</td><td>1.01E-01</td></tr>
<tr><td>3. Tangential Stress (MPa)</td><td>0.996</td></tr>
</table>

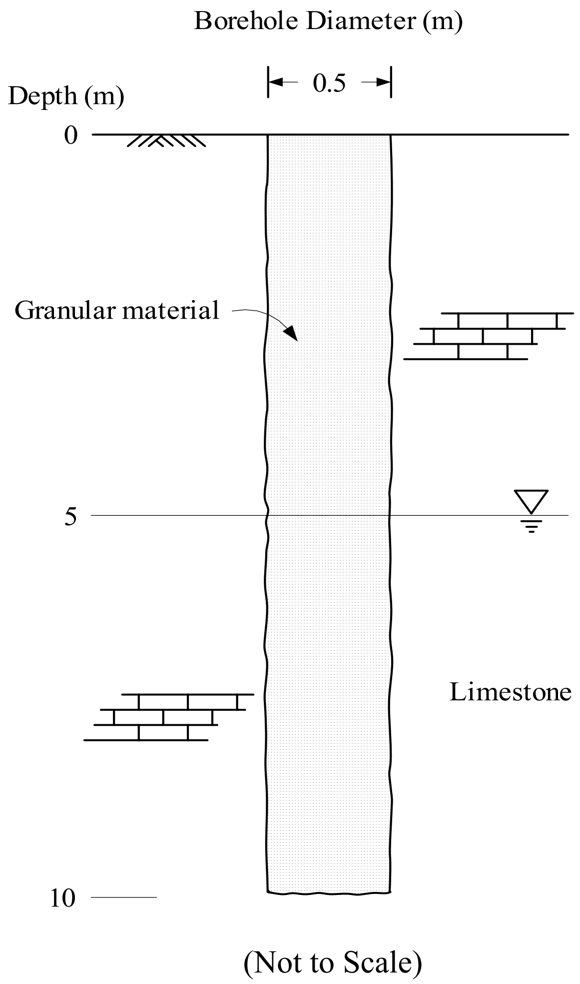

Figure 5.2 Borehole sealing design with borehole diameter and joint aperture considerations (borehole diameter is 0.5 m and joint aperture is 0.3 cm).

Table 5.2 Borehole sealing design example for Figure 5.2.

Input		**Seal Design**
General Data:		**Formation No. 1**
1. Depth (m)	10	From 0 m to 10 m : Granular materials, particle sizes from 0.3 cm to 5 cm (Fine to coarse gravel).
2. Formation Number (Unit)	1	
3. Groundwater Table (m)	5	
4. SO_4 (ppm)	None	
5. NaCl (ppm)	None	
6. Ground Deformation	None	
7. Ground Vibration	None	
Formation No. 1		
1. Rock Type	Limestone	
2. Depth to top level (m)	0	
3. Depth to bottom level (m)	10	
4. Borehole Diameter (m)	0.5	
5. Joint Spacing (m)	1	
6. Joint Aperture (cm)	0.3	
7. Intact Rock Strength (MPa)	80	
8. Intact Rock Permeability (m/s)	1.00E-07	
Calculation Results: **Formation No. 1**		**Remarks:**
1. Rock Mass Strength (MPa)	5.060	
2. Rock Mass Permeability (m/s)	2.19E-02	
3. Tangential Stress (MPa)	0.996	

higher permeability of the cement seals. The cementitious materials should be avoided where ground deformation may occur. Ground vibration may cause settlement of bentonitic materials. A key seal may be required to prevent large settlement (Figure 5.3 and Table 5.3).

5.3 Depth Consideration

Due to the fact that tangential stresses at the borehole wall increase with depth, consideration of mechanical property of surround rock and sealing materials is necessary in the design of seals in deep borehole. Stability of sealing material depends on stresses at the borehole wall and strength of the surrounding rock mass. If the stress is higher than rock mass strength, cracking or breaking may occur in the surrounding rock as a result of over stressing. In deep portion of the borehole, cement material should be used to support and to increase lateral pressure on the borehole wall, and eventually results in an increasing of the mechanical stability of the borehole. Example of borehole sealing design in deep borehole is illustrated in Figure 5.4 and Table 5.4.

5.4 Groundwater Chemistry Consideration

Saline groundwater or water with high amount of sodium sulfate and sodium chloride may cause chemical reaction between the water and sealing material, and hence result in a lower durability. In saline water, sealing material that have no chemical action with sulfate or can resist saline water should be used (Figure 5.4 and Table 5.5).

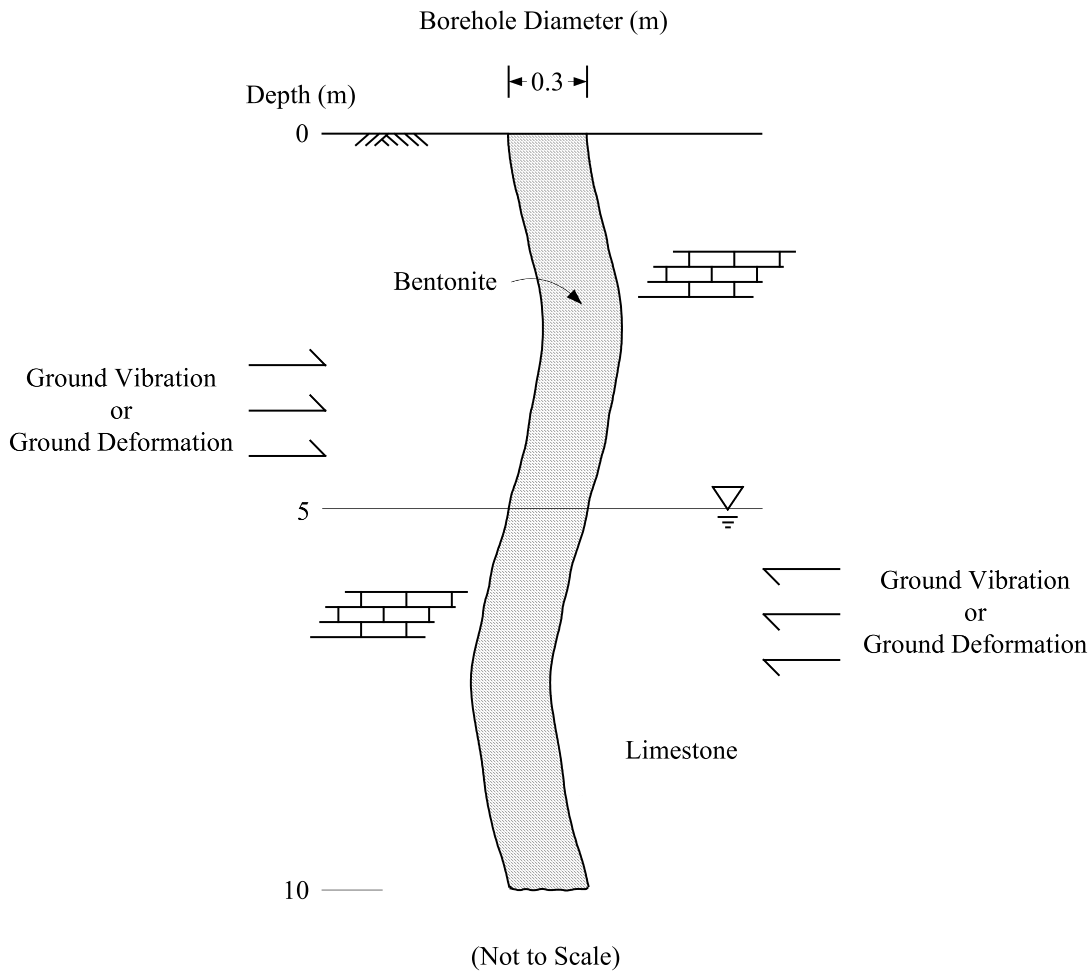

Figure 5.3 Borehole sealing design with ground deformation and ground vibration considerations.

Table 5.3 Borehole sealing design example for Figure 5.3.

<table>
<tr><th colspan="2">Input</th><th>Seal Design</th></tr>
<tr><td colspan="2">General Data:</td><td rowspan="17">Formation No. 1
From 0 m to 10 m : Bentonite or mixture of bentonite with granular materials, particle sizes less than 5 cm.</td></tr>
<tr><td>1. Depth (m)</td><td>10</td></tr>
<tr><td>2. Formation Number (Unit)</td><td>1</td></tr>
<tr><td>3. Groundwater Table (m)</td><td>5</td></tr>
<tr><td>4. SO_4 (ppm)</td><td>None</td></tr>
<tr><td>5. NaCl (ppm)</td><td>None</td></tr>
<tr><td>6. Ground Deformation</td><td>Yes</td></tr>
<tr><td>7. Ground Vibration</td><td>Yes</td></tr>
<tr><td colspan="2">Formation No. 1</td></tr>
<tr><td>1. Rock Type</td><td>Limestone</td></tr>
<tr><td>2. Depth to top level (m)</td><td>0</td></tr>
<tr><td>3. Depth to bottom level (m)</td><td>10</td></tr>
<tr><td>4. Borehole Diameter (m)</td><td>0.3</td></tr>
<tr><td>5. Joint Spacing (m)</td><td>1</td></tr>
<tr><td>6. Joint Aperture (cm)</td><td>0.5</td></tr>
<tr><td>7. Intact Rock Strength (MPa)</td><td>80</td></tr>
<tr><td>8. Intact Rock Permeability (m/s)</td><td>1.00E-07</td></tr>
<tr><td colspan="2">Calculation Results:
Formation No. 1</td><td rowspan="4">Remarks:</td></tr>
<tr><td>1. Rock Mass Strength (MPa)</td><td>5.060</td></tr>
<tr><td>2. Rock Mass Permeability (m/s)</td><td>1.01E-01</td></tr>
<tr><td>3. Tangential Stress (MPa)</td><td>0.996</td></tr>
</table>

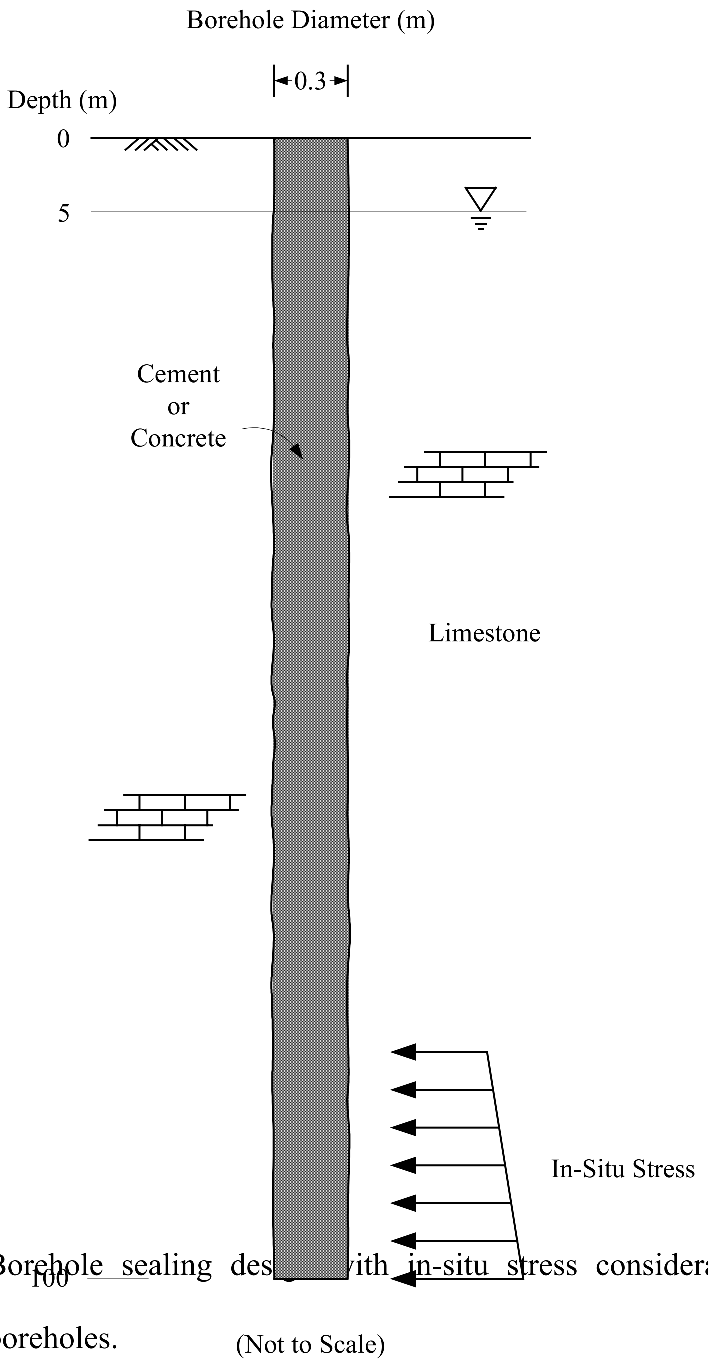

Figure 5.4 Borehole sealing design with in-situ stress consideration for deep boreholes.

Table 5.4 Borehole sealing design example for Figure 5.4.

<table>
<tr><th colspan="2">Input</th><th>Seal Design</th></tr>
<tr><td colspan="2">General Data:</td><td rowspan="17">Formation No. 1
From 0 m to 100 m : Cement type I to IV or mixture of cement type I to IV with granular materials, particle sizes less than 3 cm.</td></tr>
<tr><td>1. Depth (m)</td><td>100</td></tr>
<tr><td>2. Formation Number (Unit)</td><td>1</td></tr>
<tr><td>3. Groundwater Table (m)</td><td>5</td></tr>
<tr><td>4. SO_4 (ppm)</td><td>None</td></tr>
<tr><td>5. NaCl (ppm)</td><td>None</td></tr>
<tr><td>6. Ground Deformation</td><td>None</td></tr>
<tr><td>7. Ground Vibration</td><td>None</td></tr>
<tr><td colspan="2">Formation No. 1</td></tr>
<tr><td>1. Rock Type</td><td>Limestone</td></tr>
<tr><td>2. Depth to top level (m)</td><td>0</td></tr>
<tr><td>3. Depth to bottom level (m)</td><td>100</td></tr>
<tr><td>4. Borehole Diameter (m)</td><td>0.3</td></tr>
<tr><td>5. Joint Spacing (m)</td><td>1</td></tr>
<tr><td>6. Joint Aperture (cm)</td><td>0.5</td></tr>
<tr><td>7. Intact Rock Strength (MPa)</td><td>80</td></tr>
<tr><td>8. Intact Rock Permeability (m/s)</td><td>1.00E-07</td></tr>
<tr><td colspan="2">Calculation Results:
Formation No. 1</td><td rowspan="4">Remarks:</td></tr>
<tr><td>1. Rock Mass Strength (MPa)</td><td>5.060</td></tr>
<tr><td>2. Rock Mass Permeability (m/s)</td><td>1.01E-01</td></tr>
<tr><td>3. Tangential Stress (MPa)</td><td>9.956</td></tr>
</table>

Table 5.5 Borehole sealing design example for Figure 5.4.

Input		Seal Design
General Data:		**Formation No. 1** From 0 m to 100 m : Cement type V or mixture of cement type V with granular materials, particle sizes less than 3 cm.
1. Depth (m)	100	
2. Formation Number (Unit)	1	
3. Groundwater Table (m)	5	
4. SO_4 (ppm)	1200	
5. NaCl (ppm)	600	
6. Ground Deformation	None	
7. Ground Vibration	None	
Formation No. 1		
1. Rock Type	Limestone	
2. Depth to top level (m)	0	
3. Depth to bottom level (m)	100	
4. Borehole Diameter (m)	0.3	
5. Joint Spacing (m)	1	
6. Joint Aperture (cm)	0.5	
7. Intact Rock Strength (MPa)	80	
8. Intact Rock Permeability (m/s)	1.00E-07	
Calculation Results: **Formation No. 1**		**Remarks:**
1. Rock Mass Strength (MPa)	5.060	
2. Rock Mass Permeability (m/s)	1.01E-01	
3. Tangential Stress (MPa)	9.956	

5.5 Rock Mass Strength Consideration

Rock mass strength affects the ability to withstand stress at the seal locations. Collapse of borehole does not usually occur in high strength rock mass, even at great depth. Sealing material used in high strength rock mass at deep seat may not have to support the borehole wall. Example of borehole sealing design by consideration of rock mass strength is shown in Figure 5.5 and Table 5.6.

5.6 Consolidation Consideration

Due to the fact that bentonite may consolidate with time, sealing borehole with bentonite should limit the consolidation to be less than the borehole diameter (calculated by adopting 1000 years period). To prevent large consolidation, key seal should be used at every 30 m depth interval. The key seal can be cement or pre-compressed bentonite (Figure 5.5 and Table 5.6).

5.7 Rock Type Consideration

For the borehole intersecting different rock types, the seal design should be location (or depth) specific. This is due to the difference in physical, hydrological and mechanical properties of the rocks, as shown in Figure 5.6 and Tables 5.7 and 5.8.

5.8 Formation Thickness Consideration

For the seal design where the formation thickness is smaller than the borehole diameter, the adopted sealing material should be the same as the material used at the upper or lower formations by consideration of the practicality of the sealing process, as illustrated in Figure 5.7 and Tables 5.9 and 5.10.

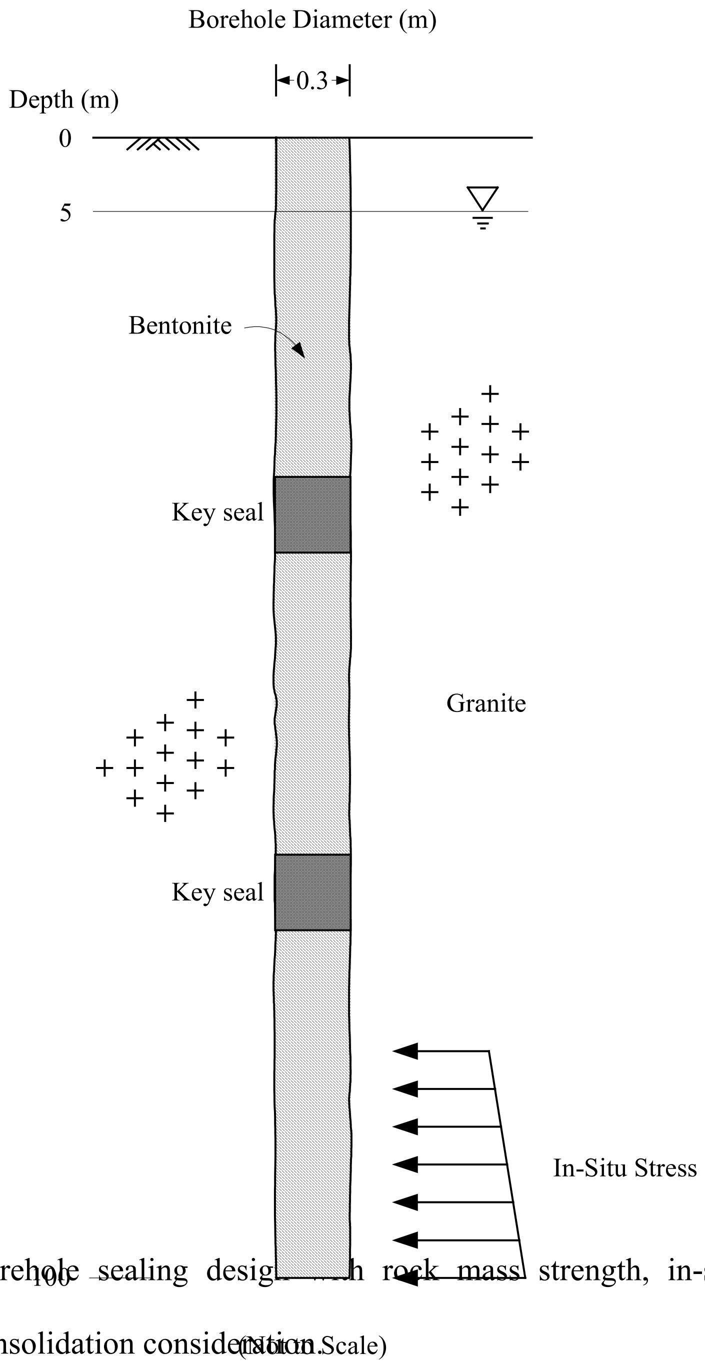

Figure 5.5 Borehole sealing design with rock mass strength, in-situ stress and consolidation consideration.

Table 5.6 Borehole sealing design example for Figure 5.5.

Input		**Seal Design**
General Data:		**Formation No. 1** From 0 m to 100 m : Bentonite or mixture of bentonite with granular materials, particle sizes less than 3 cm.
1. Depth (m)	100	
2. Formation Number (Unit)	1	
3. Groundwater Table (m)	5	
4. SO_4 (ppm)	None	
5. NaCl (ppm)	None	
6. Ground Deformation	None	
7. Ground Vibration	None	
Formation No. 1		
1. Rock Type	Granite	
2. Depth to top level (m)	0	
3. Depth to bottom level (m)	100	
4. Borehole Diameter (m)	0.3	
5. Joint Spacing (m)	1	
6. Joint Aperture (cm)	0.01	
7. Intact Rock Strength (MPa)	200	
8. Intact Rock Permeability (m/s)	1.00E-08	
Calculation Results: **Formation No. 1**		**Remarks:**
1. Rock Mass Strength (MPa)	200	
2. Rock Mass Permeability (m/s)	1.30E-06	
3. Tangential Stress (MPa)	9.956	

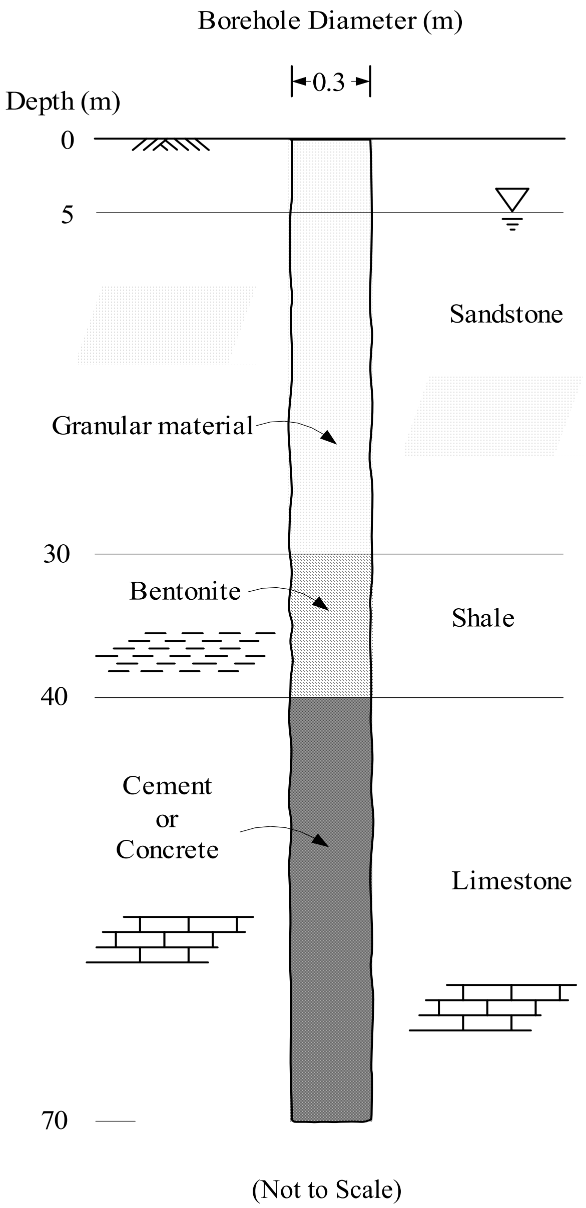

Figure 5.6 Borehole sealing design with rock types consideration (there are more than one rock type in borehole).

Table 5.7 Borehole sealing design example for Figure 5.6.

<table>
<tr><th colspan="2">Input</th><th>Seal Design</th></tr>
<tr><td colspan="2">General Data:</td><td rowspan="26">Formation No. 1
From 0 m to 30 m : Granular materials, particle sizes from 0.3 cm to 3 cm (Fine to coarse gravel).
Formation No. 2
From 30 m to 40 m : Bentonite or mixture of bentonite with granular materials, particle sizes less than 3 cm.
Formation No. 3
From 40 m to 70 m : Cement type I to IV or mixture of cement type I to IV with granular materials, particle sizes less than 3 cm.</td></tr>
<tr><td>1. Depth (m)</td><td>70</td></tr>
<tr><td>2. Formation Number (Unit)</td><td>3</td></tr>
<tr><td>3. Groundwater Table (m)</td><td>5</td></tr>
<tr><td>4. SO_4 (ppm)</td><td>None</td></tr>
<tr><td>5. NaCl (ppm)</td><td>None</td></tr>
<tr><td>6. Ground Deformation</td><td>None</td></tr>
<tr><td>7. Ground Vibration</td><td>None</td></tr>
<tr><td colspan="2">Formation No. 1</td></tr>
<tr><td>1. Rock Type</td><td>Sandstone</td></tr>
<tr><td>2. Depth to top level (m)</td><td>0</td></tr>
<tr><td>3. Depth to bottom level (m)</td><td>30</td></tr>
<tr><td>4. Borehole Diameter (m)</td><td>0.3</td></tr>
<tr><td>5. Joint Spacing (m)</td><td>2</td></tr>
<tr><td>6. Joint Aperture (cm)</td><td>0.3</td></tr>
<tr><td>7. Intact Rock Strength (MPa)</td><td>65</td></tr>
<tr><td>8. Intact Rock Permeability (m/s)</td><td>1.00E-07</td></tr>
<tr><td colspan="2">Formation No. 2</td></tr>
<tr><td>1. Rock Type</td><td>Shale</td></tr>
<tr><td>2. Depth to top level (m)</td><td>30</td></tr>
<tr><td>3. Depth to bottom level (m)</td><td>40</td></tr>
<tr><td>4. Borehole Diameter (m)</td><td>0.3</td></tr>
<tr><td>5. Joint Spacing (m)</td><td>0</td></tr>
<tr><td>6. Joint Aperture (cm)</td><td>0</td></tr>
<tr><td>7. Intact Rock Strength (MPa)</td><td>30</td></tr>
<tr><td>8. Intact Rock Permeability (m/s)</td><td>1.00E-11</td></tr>
</table>

Table 5.8 Borehole sealing design example for Figure 5.6 (continued).

Input		Seal Design
Formation No. 3		
1. Rock Type	Limestone	
2. Depth to top level (m)	40	
3. Depth to bottom level (m)	70	
4. Borehole Diameter (m)	0.3	
5. Joint Spacing (m)	1	
6. Joint Aperture (cm)	0.2	
7. Intact Rock Strength (MPa)	80	
8. Intact Rock Permeability (m/s)	1.00E-07	
Calculation Results: **Formation No. 1**		
1. Rock Mass Strength (MPa)	4.110	
2. Rock Mass Permeability (m/s)	1.09E-02	
3. Tangential Stress (MPa)	2.987	
Formation No. 2		
1. Rock Mass Strength (MPa)	30.000	
2. Rock Mass Permeability (m/s)	1.00E-11	**Remarks:**
3. Tangential Stress (MPa)	2.987	
Formation No. 3		
1. Rock Mass Strength (MPa)	5.060	
2. Rock Mass Permeability (m/s)	6.48E-03	
3. Tangential Stress (MPa)	6.969	

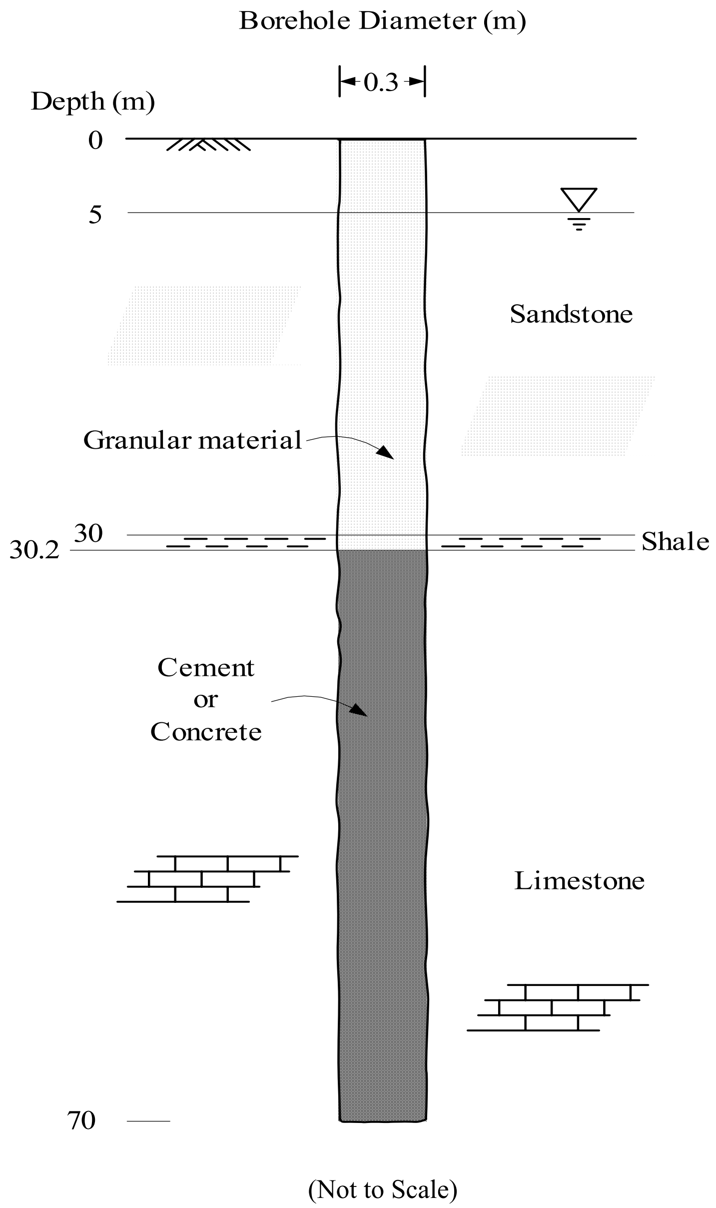

Figure 5.7 Borehole sealing design with formation thickness consideration.

Table 5.9 Borehole sealing design example for Figure 5.7.

Input		**Seal Design**
General Data:		**Formation No. 1**
1. Depth (m)	70	From 0 m to 30 m : Granular materials,
2. Formation Number (Unit)	3	particle sizes from 0.3 cm to 3 cm (Fine to
3. Groundwater Table (m)	5	coarse gravel).
4. SO_4 (ppm)	None	**Formation No. 2**
5. NaCl (ppm)	None	From 30 m to 30.2 m : Granular materials,
6. Ground Deformation	None	particle sizes from 0.3 cm to 3 cm (Fine to
7. Ground Vibration	None	coarse gravel) same Formation No.1.
Formation No. 1		**Formation No. 3**
1. Rock Type	Sandstone	
2. Depth to top level (m)	0	From 30.2 m to 70 m : Cement type I to IV
3. Depth to bottom level (m)	30	or mixture of cement type I to IV with
4. Borehole Diameter (m)	0.3	granular materials, particle sizes less than 3
5. Joint Spacing (m)	2	cm.
6. Joint Aperture (cm)	0.3	
7. Intact Rock Strength (MPa)	65	
8. Intact Rock Permeability (m/s)	1.00E-07	
Formation No. 2		
1. Rock Type	Shale	
2. Depth to top level (m)	30	
3. Depth to bottom level (m)	30.2	
4. Borehole Diameter (m)	0.3	
5. Joint Spacing (m)	0	
6. Joint Aperture (cm)	0	
7. Intact Rock Strength (MPa)	30	
8. Intact Rock Permeability (m/s)	1.00E-11	

Table 5.10 Borehole sealing design example for Figure 5.7 (continued).

Input		**Seal Design**
Formation No. 3		
1. Rock Type	Limestone	
2. Depth to top level (m)	30.2	
3. Depth to bottom level (m)	70	
4. Borehole Diameter (m)	0.3	
5. Joint Spacing (m)	1	
6. Joint Aperture (cm)	0.2	
7. Intact Rock Strength (MPa)	80	
8. Intact Rock Permeability (m/s)	1.00E-07	
Calculation Results: **Formation No. 1**		
1. Rock Mass Strength (MPa)	4.110	
2. Rock Mass Permeability (m/s)	1.09E-02	
3. Tangential Stress (MPa)	2.987	
Formation No. 2		
1. Rock Mass Strength (MPa)	30.000	
2. Rock Mass Permeability (m/s)	1.00E-11	**Remarks:**
3. Tangential Stress (MPa)	3.007	
Formation No. 3		
1. Rock Mass Strength (MPa)	5.060	
2. Rock Mass Permeability (m/s)	6.48E-03	
3. Tangential Stress (MPa)	6.969	

5.9 Groundwater Level Consideration

Types of material to be used depend on moisture or saturated condition of the borehole which is mainly governed by groundwater level. Some material is not suitable for dry borehole, such as cement and bentonitic group. Whereas, granular material is able to use in both dry and wet conditions. The granular material is, therefore, adopted at the portion above and below, groundwater level, as illustrated in Figure 5.8 and Tables 5.11 and 5.12.

5.10 Joint Spacing Consideration

Different joint spacings in rock mass induce a difference in rock mass strength, and hence result in different sealing materials to be used. Examples of borehole sealing in rock mass with different joint spacing are illustrated in Figures 5.9 and 5.10 and Tables 5.13 and 5.14.

5.11 Discussions

The borehole sealing examples presented in this chapter reveal that the proposed expert system is able to provide design recommendations for the boreholes under a variety of conditions and environments. Comparisons made among these examples also show the capability and flexibility of the software. The design recommended by the expert system may increase the construction cost, nevertheless it is based on the technical basis supported by relevant experimental knowledge and experience.

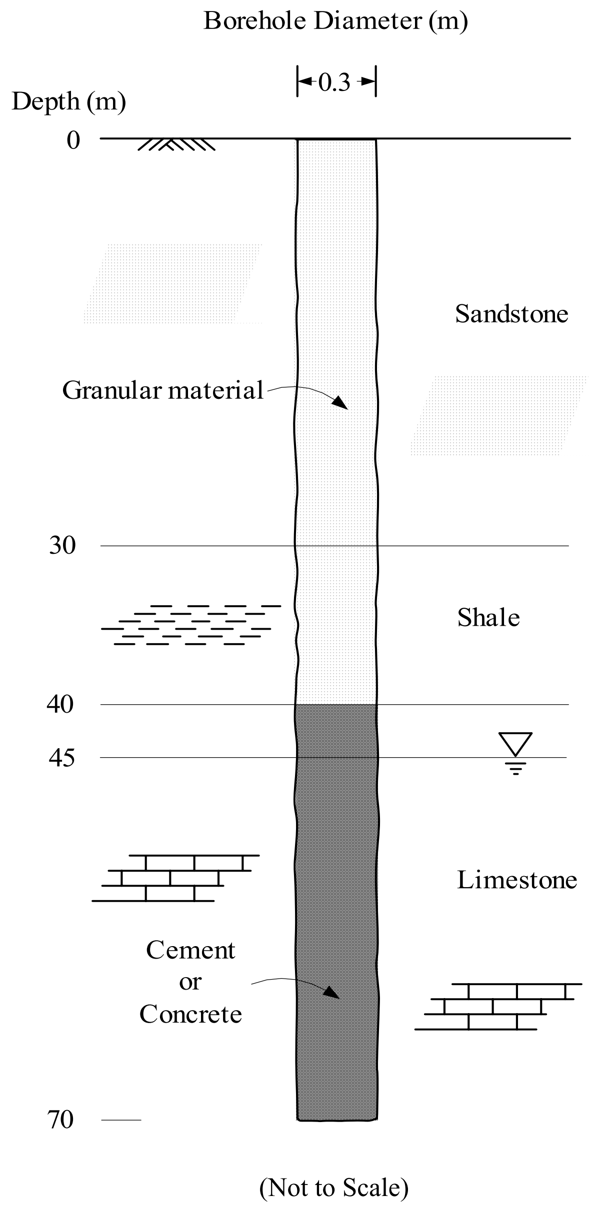

Figure 5.8 Borehole sealing design with groundwater level consideration.

Table 5.11 Borehole sealing design example for Figure 5.8.

<table>
<tr><th colspan="2">Input</th><th>Seal Design</th></tr>
<tr><td colspan="2">General Data:</td><td rowspan="26">Formation No. 1
From 0 m to 30 m : Granular materials, particle sizes from 0.3 cm to 3 cm (Fine to coarse gravel).
Formation No. 2
From 30 m to 40 m : Granular materials, particle sizes not greater than 3 cm (Fine to coarse gravel).
Formation No. 3
From 40 m to 70 m : Cement type I to IV or mixture of cement type I to IV with granular materials, particle sizes less than 3 cm.</td></tr>
<tr><td>1. Depth (m)</td><td>70</td></tr>
<tr><td>2. Formation Number (Unit)</td><td>3</td></tr>
<tr><td>3. Groundwater Table (m)</td><td>45</td></tr>
<tr><td>4. SO_4 (ppm)</td><td>None</td></tr>
<tr><td>5. NaCl (ppm)</td><td>None</td></tr>
<tr><td>6. Ground Deformation</td><td>None</td></tr>
<tr><td>7. Ground Vibration</td><td>None</td></tr>
<tr><td colspan="2">Formation No. 1</td></tr>
<tr><td>1. Rock Type</td><td>Sandstone</td></tr>
<tr><td>2. Depth to top level (m)</td><td>0</td></tr>
<tr><td>3. Depth to bottom level (m)</td><td>30</td></tr>
<tr><td>4. Borehole Diameter (m)</td><td>0.3</td></tr>
<tr><td>5. Joint Spacing (m)</td><td>2</td></tr>
<tr><td>6. Joint Aperture (cm)</td><td>0.3</td></tr>
<tr><td>7. Intact Rock Strength (MPa)</td><td>65</td></tr>
<tr><td>8. Intact Rock Permeability (m/s)</td><td>1.00E-07</td></tr>
<tr><td colspan="2">Formation No. 2</td></tr>
<tr><td>1. Rock Type</td><td>Shale</td></tr>
<tr><td>2. Depth to top level (m)</td><td>30</td></tr>
<tr><td>3. Depth to bottom level (m)</td><td>40</td></tr>
<tr><td>4. Borehole Diameter (m)</td><td>0.3</td></tr>
<tr><td>5. Joint Spacing (m)</td><td>0</td></tr>
<tr><td>6. Joint Aperture (cm)</td><td>0</td></tr>
<tr><td>7. Intact Rock Strength (MPa)</td><td>30</td></tr>
<tr><td>8. Intact Rock Permeability (m/s)</td><td>1.00E-11</td></tr>
</table>

Table 5.12 Borehole sealing design example for Figure 5.8 (continued).

Input		**Seal Design**
Formation No. 3		
1. Rock Type	Limestone	
2. Depth to top level (m)	40	
3. Depth to bottom level (m)	70	
4. Borehole Diameter (m)	0.3	
5. Joint Spacing (m)	1	
6. Joint Aperture (cm)	0.2	
7. Intact Rock Strength (MPa)	80	
8. Intact Rock Permeability (m/s)	1.00E-07	
Calculation Results: **Formation No. 1**		
1. Rock Mass Strength (MPa)	4.110	
2. Rock Mass Permeability (m/s)	1.09E-02	
3. Tangential Stress (MPa)	2.987	
Formation No. 2		
1. Rock Mass Strength (MPa)	30.000	
2. Rock Mass Permeability (m/s)	1.00E-11	**Remarks:**
3. Tangential Stress (MPa)	3.007	
Formation No. 3		
1. Rock Mass Strength (MPa)	5.060	
2. Rock Mass Permeability (m/s)	6.48E-03	
3. Tangential Stress (MPa)	6.969	

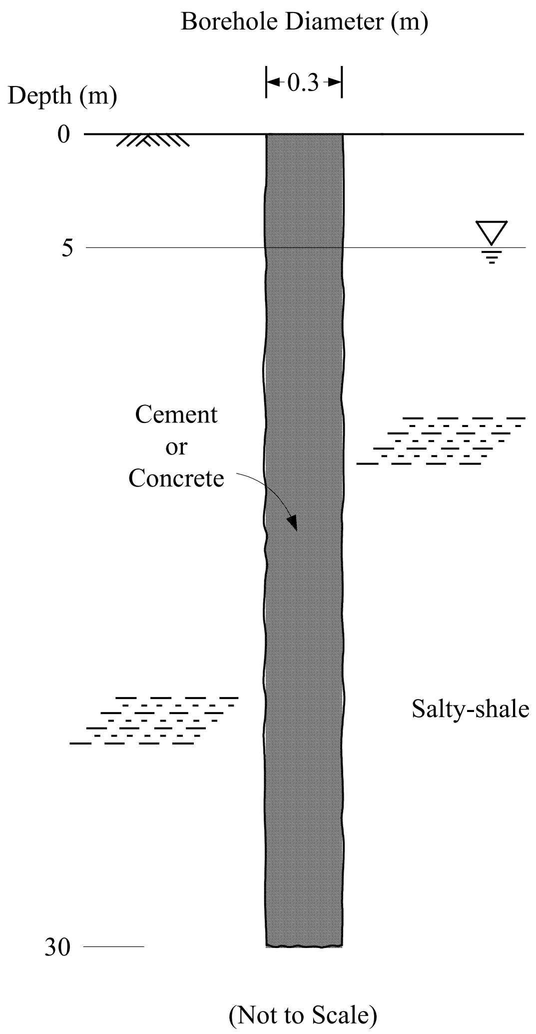

Figure 5.9 Borehole sealing design with joint spacing consideration (joint spacing is 0.1m).

Table 5.13 Borehole sealing design example for Figure 5.9.

Input		Seal Design
General Data:		**Formation No. 1** From 0 m to 30 m : Cement type I to IV or mixture of cement type I to IV with granular materials, particle sizes not greater than 3 cm**.**
1. Depth (m)	30	
2. Formation Number (Unit)	1	
3. Groundwater Table (m)	5	
4. SO_4 (ppm)	None	
5. NaCl (ppm)	None	
6. Ground Deformation	None	
7. Ground Vibration	None	
Formation No. 1		
1. Rock Type	Slaty-shale	
2. Depth to top level (m)	0	
3. Depth to bottom level (m)	30	
4. Borehole Diameter (m)	0.3	
5. Joint Spacing (m)	0.1	
6. Joint Aperture (cm)	0.03	
7. Intact Rock Strength (MPa)	15	
8. Intact Rock Permeability (m/s)	1.00E-08	
Calculation Results: **Formation No. 1**		**Remarks:**
1. Rock Mass Strength (MPa)	0.047	
2. Rock Mass Permeability (m/s)	2.19E-04	
3. Tangential Stress (MPa)	2.987	

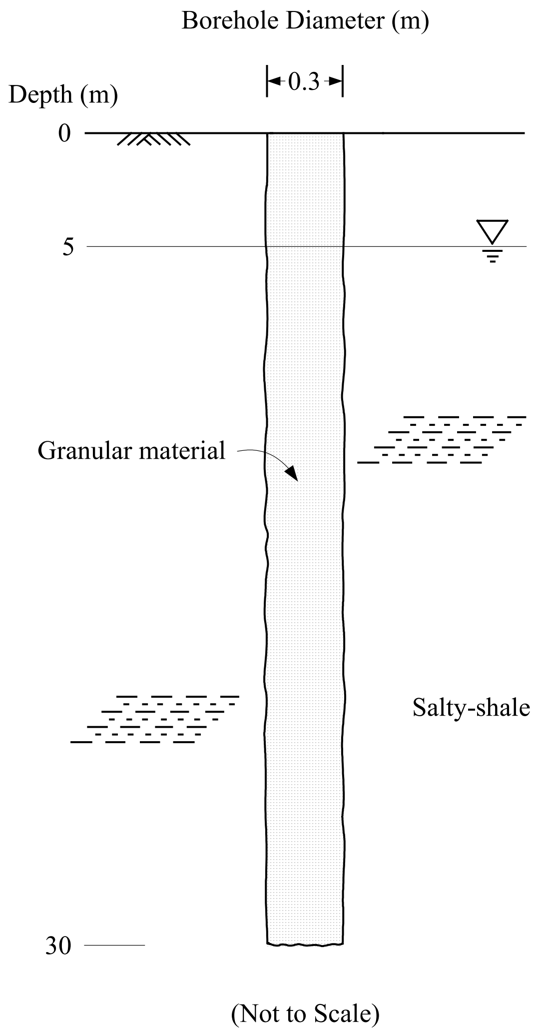

Figure 5.10 Borehole sealing design with joint spacing consideration (joint spacing is 3.5 m).

Table 5.14 Borehole sealing design example for Figure 5.10.

<table>
<tr><th colspan="2">Input</th><th>Seal Design</th></tr>
<tr><td colspan="2">General Data:</td><td rowspan="17">Formation No. 1
From 0 m to 30 m : Granular materials, particle sizes from 0.03 cm to 3 cm (Medium sand to coarse gravel).</td></tr>
<tr><td>1. Depth (m)</td><td>30</td></tr>
<tr><td>2. Formation Number (Unit)</td><td>1</td></tr>
<tr><td>3. Groundwater Table (m)</td><td>5</td></tr>
<tr><td>4. SO_4 (ppm)</td><td>None</td></tr>
<tr><td>5. NaCl (ppm)</td><td>None</td></tr>
<tr><td>6. Ground Deformation</td><td>None</td></tr>
<tr><td>7. Ground Vibration</td><td>None</td></tr>
<tr><td colspan="2">Formation No. 1</td></tr>
<tr><td>1. Rock Type</td><td>Slaty-shale</td></tr>
<tr><td>2. Depth to top level (m)</td><td>0</td></tr>
<tr><td>3. Depth to bottom level (m)</td><td>30</td></tr>
<tr><td>4. Borehole Diameter (m)</td><td>0.3</td></tr>
<tr><td>5. Joint Spacing (m)</td><td>3.5</td></tr>
<tr><td>6. Joint Aperture (cm)</td><td>0.03</td></tr>
<tr><td>7. Intact Rock Strength (MPa)</td><td>15</td></tr>
<tr><td>8. Intact Rock Permeability (m/s)</td><td>1.00E-08</td></tr>
<tr><td colspan="2">Calculation Results:
Formation No. 1</td><td rowspan="4">Remarks:</td></tr>
<tr><td>1. Rock Mass Strength (MPa)</td><td>4.743</td></tr>
<tr><td>2. Rock Mass Permeability (m/s)</td><td>2.19E-04</td></tr>
<tr><td>3. Tangential Stress (MPa)</td><td>2.987</td></tr>
</table>

CHAPTER VI

DISCUSSIONS, CONCLUSIONS AND RECOMMENDATIONS

This chapter presents the discussions, conclusions, and recommendations for future research needs. The scope and limitations of the expert system software are the main issues to be discussed. The methods and results of the study are concluded. Some borehole characteristics and installation conditions that are excluded from this research are identified. Future research needs are recommended.

6.1 Discussions

Discussions related to the scope and limitation of the expert system software can be summarized as follows;

1) Design of borehole sealing studied in this research is emphasized on the borehole sealing in exploration and production of groundwater and mining industries that are still lack of an appropriate technology. The borehole in petroleum industry is not emphasized in the research because of its advanced design technology. In addition, the appropriate system and knowledge is already existing in the petroleum industry.

2) Most sealing materials proposed in this research are available in local area and are widely used in most industries (cement, bentonite, and granular materials).

3) Although the design recommended by the expert system in this research may result in a higher cost than those from the conventional (traditional) method, the borehole sealing design by the expert system is more systematic and as based on many researches and studies that have been performed for more than 20 years.

4) The design recommendations in this research are rather conservative when compared with the current practices because material selection (sealing design) is based on the criteria from the experimental results from the relevant researches.

5) The proposed expert system is capable of providing design recommendations for the boreholes under a variety of conditions and environments (borehole sealing design examples as shown in Chapter 5).

6) Intact rock strength and intact rock permeability are the database in this software but the database does not cover the rock mechanics properties of all rock types. Some permeability of intact rock such as marble, coal, gabbro, and basalt are missing from the database because the published rock mechanics properties are inadequate.

7) The simplifying equations such as the equation for calculating the rock mass permeability, the equation for calculating the radial and tangential stress are applied in this software. The rock mass permeability as given by Hoek and Bray (1981) is estimated from the joint spacing and joint aperture without the joint set number consideration. The radial and tangential stresses are calculated by assuming that the rock density gradient is 1.1 psi/ft.

8) The methods or procedures for solving the problems during sealing operation are not provided in the design recommendations.

6.2 Conclusions

The objective of this research is to develop an expert system software for use in the design of borehole sealing in rock formations. The boreholes in this research include exploration and production boreholes in groundwater and mining industries. The research are carried out in five stages; literature review, concept formulation, software development, software reviewing and editing, and report writing.

Many relevant research literatures are reviewed in the first step. The literatures include borehole sealing in rock formation and application of an expert system in geological engineering field. The borehole sealing research including laboratory experiments and field tests have been studied. The knowledge gained from literature review and recommendations from the borehole sealing expert, are compiled and analyzed for network construction. The network comprises paths and decision-making procedures that use site characteristics given by the user, classify and evaluate the information, and lead to the seal design and material selection. The considered site characteristics include the borehole conditions, rock mass characteristics, groundwater level, geochemistry, in-situ stresses, potential ground deformation, seismic activities, and performance requirements. The mechanical and hydraulic bonds represent their functional requirements. The system first classifies the input data and selects the sealing material for each rock unit based on the design criteria derived from the relevant experimental researches. A variety of sealing materials (design solutions) is considered, including cementitious, bentonitic, granular materials, and mixtures of these components. The seal system (seal, host rock, and their interface) performance is then evaluated in terms of the mechanical stability, hydrological integrity, and chemical compatibility. Design modification (changing of the sealing portion length or type of sealing material) is then made if appropriate. The design recommendations include length and specifications of sealing material for each rock unit along the borehole. The flowchart of the expert system is constructed for use in the development of software. The Microsoft Visual Basic version 6.0 is employed as the system shell. This allows the user to interact with the system while inputting the information in order to obtain the design recommendations. The expert system capability is assessed under a of variety of borehole conditions and environments. The results indicate that the system is capable of designing and selecting suitable seal materials for a variety of borehole conditions.

6.3 Recommendations for Future Research

The expert system for the design of borehole sealing in rock formations has never been developed. Expert system developed in this research can be considered as a preliminary software, and hence future improvements are required. The further studies are suggested as follows.

1) The database of the software should include mechanics properties of a variety of rock types.

2) The system should be applicable to the boreholes located under the river, pond or dam, and frozen environment.

3) More advanced equations for calculating rock mass permeability and redial and tangential stresses around boreholes should be used in the calculations.

4) Actual boreholes sealing information should be compiled for use as database and case studies.

5) Some software such as Prolog, Visual C^{++}, and Java may be used because they are alternatives for the system shell selections.

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APPENDIX

SOFTWARE INSTRUCTION

SOFTWARE INSTRUCTION

1. System requirements.
    1.1 CPU speed should exceed 700 MHz,
    1.2 RAM should be greater than 64 MB,
    1.3 Disk space should be greater than 40 MB,
    1.4 Display Controller has resolution of 1024 x 728 or more, and
    1.5 WINDOWS 2000 or WINDOWS XP as operating system.
2. The procedure for installation of the "BSR" (Borehole Seal Design in Rock Formations) is described as follows.
    2.1 Install BSR Program by double click at "SETUP_1" icon and click "Next" button until the page showing "ready to installation" appears, then click "Install".
    2.2 Install system shield wizard for BSR Program by double click at "SETUP_2" icon. For setup type page, choose Custom type. For the destination location page, change to C:\BSR drive. Other pages click "Next" button until the page showing "ready to installation" appears, then click "Install".
    2.3 After installation the program can be executed by double click at the "BSR" icon.
3. The first page of the program shows the logo of Suranaree University of Technology and the software name "BOREHOLE SEAL DESIGN IN ROCK FORMATIONS USING EXPERT SYSTEM".

4. The second page shows borehole sealing model and the main menu. The menu consists of 3 buttons; "About", "Cancel", and "Next". When click at "About" button, the background, concept, scope and limitations, and work flow of the program will appear.
5. The user agreement is shown on the third page. The user can go to the next page after the agreement acceptance is selected.
6. The fourth page shows general borehole information, including physical characteristics of borehole, groundwater level, geochemistry, and engineering requirements.
7. The fifth page and the following pages ask for information of each rock unit, including, rock type, depth, borehole diameter, average joint spacing, average joint aperture, intact rock strength, and intact rock permeability. Example for borehole data is shown in Figure A- 1.

    7.1 Rock type, input full name, such as Sandstone or sandstone.

    7.2 Depth, input from top to bottom, such as 0 m to 20 m.

    7.3 Borehole diameter, input actual size of borehole in each rock formation, such as 30 cm.

    7.4 Average joint spacing is necessary data for the input. In case of massive rock (no joint spacing), the average joint spacing of zero should be given.

    7.5 Average joint aperture for the case of massive rock should be represented by zero.

    7.6 Intact rock strength, there are two cases:

    1) In case of unknown rock type, intact rock strength is required.

2) In case of known rock type, select one of the following: Sandstone, Claystone, Shale, Limestone, Basalt, Granite, Schist, Chert, Chalk, Rocksalt, Potash, Coal, Siltstone, Marble, Phylite, Tuff, Rhyolite, Gabbro, Amphibolite, Quartzite, Slaty Shale, or Dolomite.

7.7 Intact rock permeability, there are two cases:

1) In case of unknown rock type, intact rock permeability is required.
2) In case of known rock type, select one of the following: Sandstone, Claystone, Shale, Limestone, Basalt, Granite, Schist, Rocksalt, Siltstone, or Dolomite.

8. The output page consists of borehole information retrieved from the user and borehole sealing design recommendations. The output will appear, when the "Submit" button in the last page of data input is clicked following by clicking at "OK" button to answer the question "Do you want to display report?"

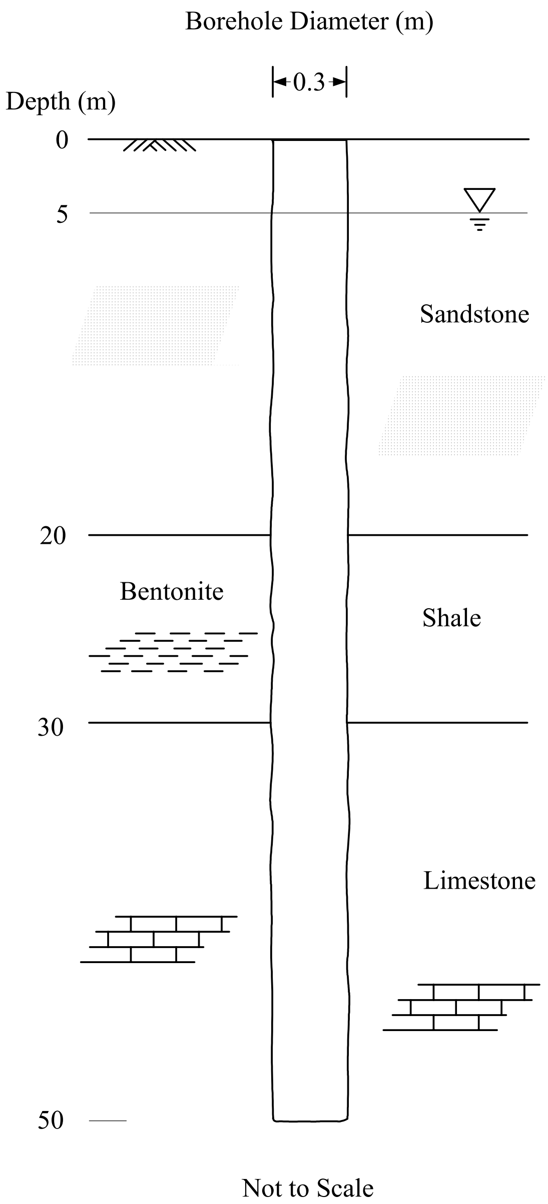

Figure A-1 Borehole example for input data.

BIOGRAPHY

Miss Ammarin Warin was born on the 29th of January 1978 in Mae Hong Son province. She earned her Bachelor's Degree in Geological Engineering from Suranaree University of Technology (SUT) in 2000. After graduation, she continued with her Master's degree in the School of Geotechnology, Institute of Engineering at SUT with the major in Geological Engineering. Between 2001-2003, she was a research assistant and teaching assistant at SUT. Her expertises are in the areas of soil and rock mechanics, borehole sealing in rock, underground excavations, and foundation engineering.