Sudan University of Science and Technology

College of Graduate Studies

كلية الدراسات العليا

Assessment of Curtain Grouting Used in the Foundation Treatment at Dam Complex of Upper Atbara River

تقييم ستائر الحقن المستخدمة في تحسين الأساسات في مجمع سدود أعالي نهر عطبرة

By

Mujab Abdelgani Shakartallah A. Elgadir

A Thesis Submitted in Partial Fulfillment for the Degree of Master of Construction Engineering at Sudan University of Sciences and Technology

Supervisor: Prof. Eltayeb Hassan Onsa

July 2019

بسم الله الرحمن الرحيم

قال تعالى:

﴿قَالَ مَا مَكَّنِّي فِيهِ رَبِّي خَيْرٌ فَأَعِينُونِي بِقُوَّةٍ أَجْعَلْ بَيْنَكُمْ وَبَيْنَهُمْ رَدْمًا﴾

صدق الله العظيم

سورة الكهف- الآية 95

DECLARATION

I, the signing here-under, declare that I'm the sole author of the M.Sc. thesis entitled: *Assessment of Curtain Grouting Used in the Foundation Treatment at Dam Complex of Upper Atbara*, which is an original intellectual work. Willingly, I assign the copy-right of this work to the College of Graduate Studies (CGS), Sudan University of Science and Technology (SUST). Accordingly, SUST has all the rights to publish this work for scientific purposes.

Mujab Abdelgani Shokartallah ....

Date:

DEDICATION

I dedicate this work to my mother who has been the source of love of reading and respect for education.

ACKNLODGEMENTS

ABSTRACT

Curtain Grouting (CG) is a procedure mainly used to control water seepage in dams by sealing off fissures or joints in bedrock, granular soil pockets and minor cavities; hence CG can be considered as foundation improvement method. This process involves grouting a line, or several lines, of holes in sequence along the water cut-off zone and requires specialized instrumentation to monitor grout pressure and flow parameters. Geological and geotechnical properties of the rock and soil to be grouted are important parameters influencing the design of the curtain grouting.

The Dams Implementation Unit (DIU) at the Ministry of Water Resources, Irrigation and Electricity (MWRIE) was responsible for the implementation of Dam Complex of Upper Atbara Project (DCUAP). This dam complex comprises two dams namely: Rumela Dam and Burdana Dam on Upper Atbara and Setit Rivers in the eastern Sudan. The purpose of this study is to review and assess the design of the grout curtain which was used to treat the foundation properties at the different sections along the dam axis.

In this study, general description of curtain grouting design in DCUAP is made. The materials used in grouting and the grouting pressures values are presented. The general procedure, equipment used and methodology of curtain grouting construction in the DCUAP are presented, as well as the tests used in the quality control of grouting works.

Curtain grouting is applied in 14 sections along the Rumela and Burdana dams. In this study 300 meters section at Right Bank of Burdana dam (Chainage 1+600 to 1+900) has been selected for assessment. The grouting works in the selected section had been studied and the grout results had been analyzed to determine the quality of grouting works regarding achievement the desired goals in terms of reducing permeability in the foundation of the dams. As well as quantifying the amount of the solid matters of curtain grouting used in the grouting process in that section and then comparing it with the quantities indicated in the project's bill of quantities.

The analysis of the selected section data concluded that the permeability was improved by about 85% from the original value. The estimated amount of grout given solid material in the design documents (Bill of Quantities) is found to be much higher compared to the real grout absorption in the site which was less than the contract amount by more than 18 times. This result clarifies the importance of

post project assessment studies, like this study, in the proper estimation of CG material types and quantities for future dam projects.

المُستَخلَص

ستائر الحقن للأساسات هي طريقة شائعة تُستخدم أساساً للتحكم في تسرُب المياه من السدود عن طريق ملأ التشققات في الصخور والفراغات في التربة الحصوية وكذلك الكهوف الصغيرة، وبالتالي يمكن اعتبار ستائر الحقن إحدى طريق تحسين خواص الأساسات. طريقة ستائر الحقن تتضمن حقن خط واحد أو عدة خطوط من الحفر في شكل سلسلة على طول منطقة حجز المياه. وهذه العملية تتطلب أجهزة خاصة لقياس الضغط والتدفق لمادة الحقن. يتأثر تصميم ستائر الحقن بالخصائص الجيولوجية والجيوتقنية لتربة الأساس المراد معالجتها بالحقن.

مجمع سدي أعالي عطبرة هو المشروع محل الدراسة وهو يتم إنشاؤه حالياً بواسطة وحدة تنفيذ السدود التابعة لوزارة الموارد المائية والري والكهرباء السودانية. مجمع سدي أعالي عطبرة يتكون من سدين هما: سد رُوميلة الذي يقع علي مجرى نهر أعالي عطبرة وسد بُردانة الذي يقع على مجرى نهر ستيت في شرق السودان. الغرض من هذه الدراسة هو تقييم ستائر الحقن المستخدمة لمعالجة الأساسات في أجزاء متعددة على طول مسار مجمع سدي أعالي عطبرة.

تشمل هذه الدراسة، وصفاً عاماً لخطوات تصميم ستائرالحقن في المشروع المذكور من حيث الأعماق التصميمية والضغط المستخدم للحقن والخلطة الأسمنتية ومكوناتها. كما تم شرح الطريقة التي استخدمت في تنفيذ أعمال الحقن في الموقع، وكذلك اختبارات مراقبة الجودة لأعمال الحقن.

تم تطبيق طريقة ستائر الحقن في 14 مقطع على طول سدي رميلة وبردانة، ولتقييم كفاءة الحقن والتأكد من تحقيقه للنتائج المطلوبة حسب التصميم تم أخذ مقطع طوله حوالي 300 متر من سد بُردانة (الجنزير من B1600 إلى B1900) وتم تحليل نتائج الحقن للأساسات عندها. كما تم عرض نتائج أعمال الحقن لهذا المقطع وتم تحليل هذه النتائج لتحديد جودة أعمال الحقن ومدى تحقيق الأهداف المرجوة منها من حيث تقليل النفاذية في أساسات السد. وكذلك تم قياس كمية المواد الصلبة المستخدمة في عملية الحقن في هذا المقطع ومن ثم مقارنتها مع الكميات الموضوعة في جداول الكميات للمشروع.

وخلص تحليل بيانات المقطع الذي تمت دراسته إلى أن النفاذية قد تحسنت إلى حوالي 85% من قيمة النفاذية الأصلية لتربة الأساس. كما وجد أن كمية مواد الحقن المقدرة في جداول الكميات عالية جداً مقارنة مع كمية مواد الحقن الحقيقية في الموقع والذي وُجد أنه أقل من الكميات الموضوعة في العقد بأكثر من 18 مرة. وتوضح هذه النتيجة أهمية دراسات التقييم للمشاريع المنفذة، مثل هذه الدراسة، في التقدير السليم لنوع وكميات مواد الحقن في مشاريع السدود المشابهة في المستقبل.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF SYMBOLS AND ABBREVIATIONS

DCUAP	Dam Complex of Upper Atbara Project
D	Depth in meter
d	Depth of bottom of stage below ground surface in meters.
F	Final point of the grouting,
GIN	Grouting index number
kPa	Kilo pascal
L	Test interval length of the representative test sample,
LU	Lugeon value,
P	Pressure in (bar),
P_B	Pressure at base of hole in kpa
P_F	Final grout pressure,
P_o	Reference pressure = 1 MPa
Q	Total volume of water discharged
q	Flow rate = Q/t where
t	Total time of test,
V_F	Actual grout take
α	Unit system coefficient
α_o	Factor depending on rock conditions

CHAPTER ONE

CHAPTER ONE

INTRODUCTION

1.1 Dam Complex of Upper Atbara Back Ground

The Dams Implement Unit (DIU) at the Ministry of Water Resources and Irrigation, Electricity (MWRIE) was responsible for the implement of Dam Complex of Upper Atbara Project (DCUAP).

This Project is under construction while this Thesis is in writing.

1.1.1 Location

The Dam Complex of Upper Atbara Project (DCUAP) is situated on the Atbara River and the Setit River, approximately 20 km upstream of their confluence, 80 km south of Kashm el Girba and approximately 30 km upstream of the small town of Esh Showak in the Gedaref Governorate in East of Sudan.
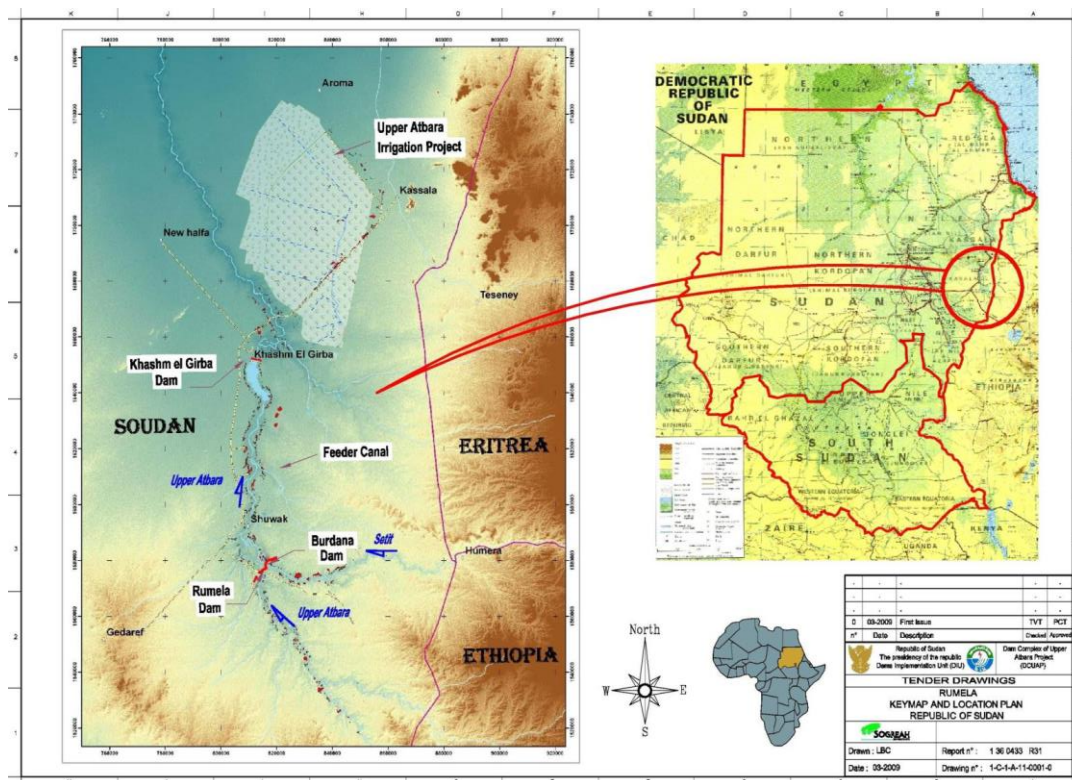
Figure 1-1 Dam Complex of Upper Atbara project Location

1.2 Project Aims

The objective of the project is to support the development of Eastern Sudan, through enhancement of agriculture production by Supply of irrigation water for a new land in Upper Atbara Irrigation Project which consisting of 150,000 hectares (370,000 acres), and also increase agriculture production in the New Halfa area currently irrigated by Khashm El-Girba Dam.

The project also aimed to generation of hydropower, where it will generate about (320

MW) at Rumela Power Station which comprises of 4 Kaplan Turbines, 80 MW for each unit).

The project also will Increase the average productivity of fish to 1700 ton/year and Provide additional employment opportunities for the local people.

Additionally the project will provide potable water utilizing locally available water resources from the Atbara and Setit rivers.

The project will alleviate of the problem of siltation into the Khashm El Girba reservoir.

1.2.1   Main Dam Components

RUMELA PROJECT	BURDANA PROJECT
• A Zoned Earth Fill Dam (ZEFD) with crest level at El. 524.80 m, up to 55 m in height above foundation and with a crest length of 1,070 m, across the Upper Atbara valley. The EFCD will be founded on alluvial sediments of about 15 m thickness in the channel of the Upper Atbara River. The left bank and right bank embankments will be founded on rock. • Embankment Dykes at both river banks, with crest level at El. 524.80 m, of 3,997 m total length and an interface with the Burdana Project. • A reinforced concrete spillway structure in the dam with crest level at El. 524.80 m, about 78 m wide, 56 m long and 55 m high, integrating 3 bottom level outlet bays equipped with a total number of three radial gates, 1 low level outlet equipped with one radial gate and 2 surface sluice bays, each equipped with one flap gate. The downstream following stilling basin extends 164 m in length and has a net width of 40 m. • Power Station, comprising Headrace Approach Canal, Power Intake, 4 surface Penstocks, Powerhouse and Tailrace Canal. The powerhouse has an installed capacity of 320 MW, equipped with 4 Francis turbine generating units of vertical axis, each with a rated capacity of 80 MW. • A reinforced concrete Headworks structure of the feeder canal to Gadarif Water Supply Project comprising three	• A Zoned Earth Fill Dam (ZEFD) with crest level at El. 524.80 m, up to 50 m in height above foundation and with a crest length of 940 m, across the Setit valley. The EFCD will be founded on alluvial sediments of about 15 m thickness in the channel of the Upper Atbara River. The left bank and right bank embankments will be founded on rock. • Embankment Dykes at both river banks, with crest level at El. 524.80 m, of 5,750 m total length and an interface with the Rumela Project. • A reinforced concrete spillway structure in the dam with crest level at El. 524.80 m, about 132 m wide, 56 m long and 52 m high, integrating 6 bottom level outlet bays equipped with a total number of six radial gates, 2 low level outlet equipped with two radial gate and 4 surface sluice bays, each equipped with one flap gate. The downstream following stilling basin extends 141 m in length and has a net width of 88 m.

concrete ducts of total discharge 150 m³/s
• Connection Canal Connecting the catchment areas of Setit River and Upper Atbara River for optimised water resources management
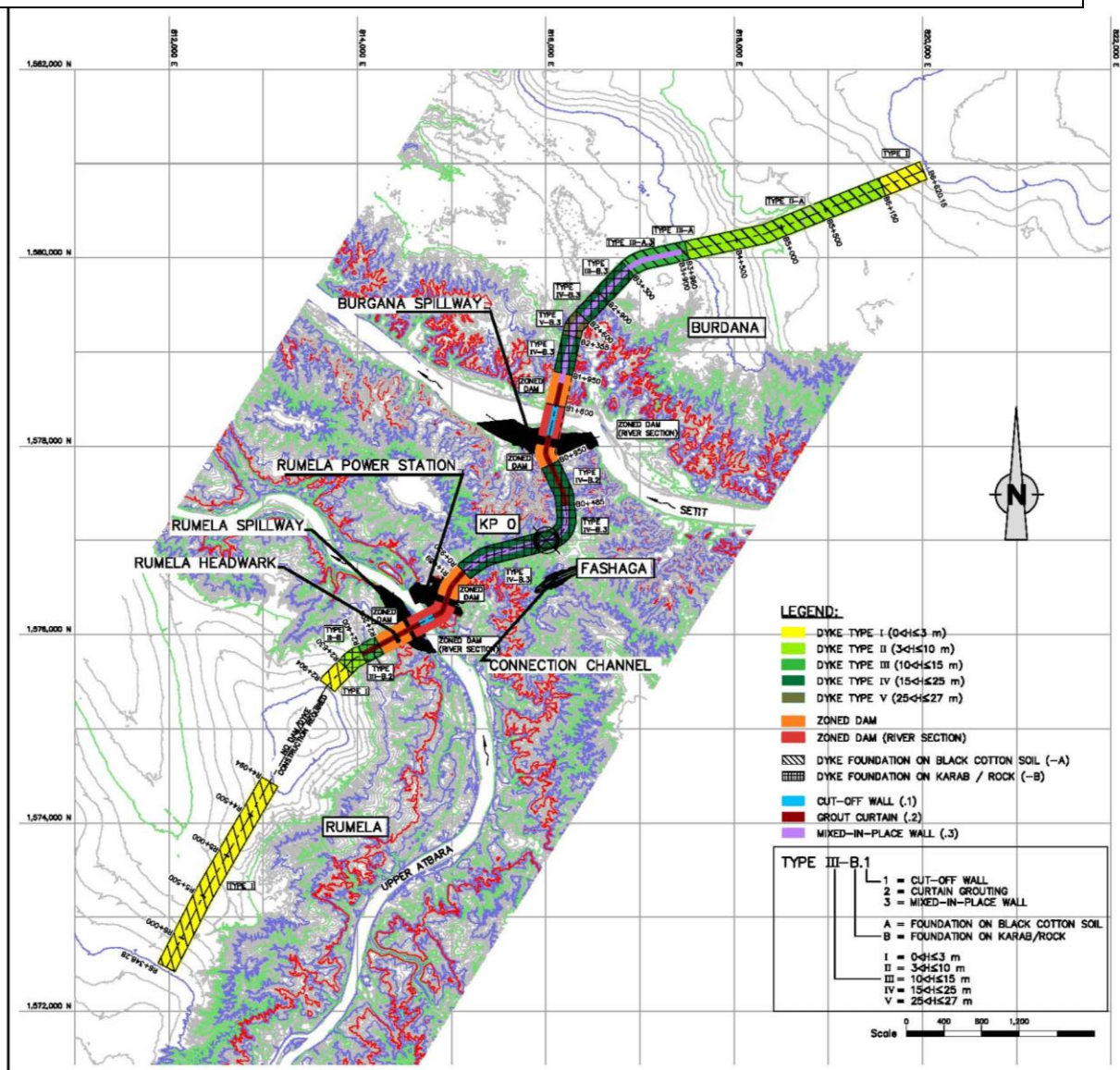
Figure 1-2 General Layout of Dam Complex of Upper Atbara Project

1.2.2 Foundation treatments in DCUAP

Both dams are located on Nubian Sandstone Formation overlain by Karab Formation, cotton soil and alluvial terrace material. So there were three different methods or technique to treat the foundation under the earth dams and concrete structures.

The alluvial fill in Atbara and Setit Rivers were too thick and hence the dam bodies had to be founded on the sand, gravelly sand and sandy gravel with sufficient density. For stability and economic reasons a Plastic Concrete Cut-off wall formed the sealing element. It is expected to prevent percolation and erosion below the foundation at rivers bed.

The Mixed-In-Place Cut-off Wall (MIP CoW) is constructed in two areas. Area 1 is at Fashaga, between Rumela and Burdana dam, and Area 2 is located at Burdana Right Bank. Those Areas, as per the available Geotechnical information, the subsoil consists of sands, gravels, silty sands, silty gravelly sands, coarse gravel layers and mixtures thereof. The presence of low plastic clay layers cannot be excluded.

1.3 Curtain Grouting

1.3.1   Grouting - or injection - is a procedure to improve the strength properties of the subsoil or to diminish its permeability. Open voids in porous soils or in jointed rocks often impair the strength and/or the imperviousness of the underground, which, under this restriction, cannot be stressed as required. Early in this century, the idea arose of improving the restricted properties by filling the voids.

After a stepwise development a special new constructional method was introduced and has become a very important factor in curing soils and rocks of originally unsatisfactory properties.

The grouting is carried out to:

– Reduce leakage through the dam foundation, i.e. through the defects;

– Reduce seepage erosion potential;

– Reduce uplift pressures (under concrete gravity dams when used in conjunction with drain holes);

– Reduce settlements in the foundation (for concrete gravity, buttress and arch dams).

The foundations for most dams more than 15 m high built on rock, and for some which are smaller, are treated by grouting. Grouting consists of drilling a line or lines of holes from the cutoff level of the dam into the dam foundation and forcing cement slurry, or chemicals under pressure into the rock defects, that is joints, fractures, bedding partings and faults. Figure 1.3 shows an example:
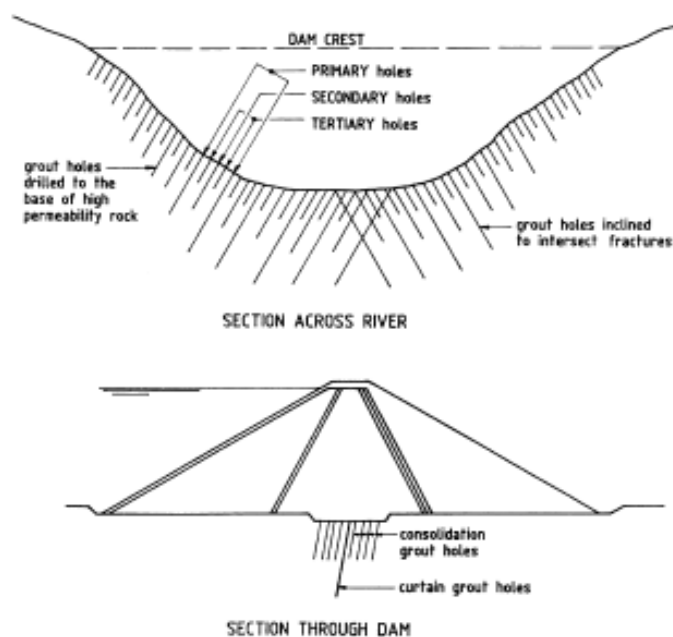
Figure 1-3 An example of embankment dam foundation grouting.

1.3.2   Most foundation grouting uses cement grout: Portland cement mixed with water in a high speed mixer to a water-cement ratio (mass water/mass cement) of between 0.5 and 5 to form slurry, readily pumpable and able to penetrate defects in the rock in the dam foundation.

Most foundation grouting uses cement grout: Portland cement mixed with water in a high speed mixer to a water-cement ratio (mass water/mass cement) of between 0.5 and 5 to form slurry, readily pumpable and able to penetrate defects in the rock in the dam foundation.

If the dam is on a soil foundation (e.g. sand) or if the fractures in the rock are very narrow, chemicals can be used instead of cement. Chemicals tend to be more expensive so are only used where cement grout would not be successful.

1.3.3   Foundation grouting takes two forms:

– Curtain grouting;

– Consolidation grouting.

Curtain grouting is designed to create a narrow barrier (or curtain) through an area of high permeability. It usually consists of a single row of grout holes which are drilled and grouted to the base of the permeable rock, or to such depths that acceptable hydraulic gradients are achieved. For large dams on rock foundations, dams on very permeable rock or where grouting is carried out in soil foundations, 3, 5 or even more lines of grout holes may be adopted. Multiple row curtains are also adopted if it was impracticable to excavate the foundation to below the limit of the infilled joints. The holes are drilled and grouted in sequence to allow testing of the permeability of the foundation (by packer testing) before grouting and to allow a later check on the effectiveness of grouting from the amount of grout accepted by the foundation ("grout take").

Thus in Figure 1.3 primary holes are drilled first, followed by secondary and then tertiary. The final holes spacing will commonly be 1.5m or 3m, but may be as

close as 0.5 m. This staged approach allows control over the amount and effectiveness of the grouting.

Consolidation or "blanket" grouting for embankment dams is designed to give intensive grouting of the upper layer of more fractured rock in the vicinity of the dam core, or in regions of "high" hydraulic seepage gradient, e.g. under the plinth for a concrete face rockfill dam. It is usually restricted to the upper 5 m to 15 m and is carried out in sequence but commonly to a predetermined holes spacing and depth.
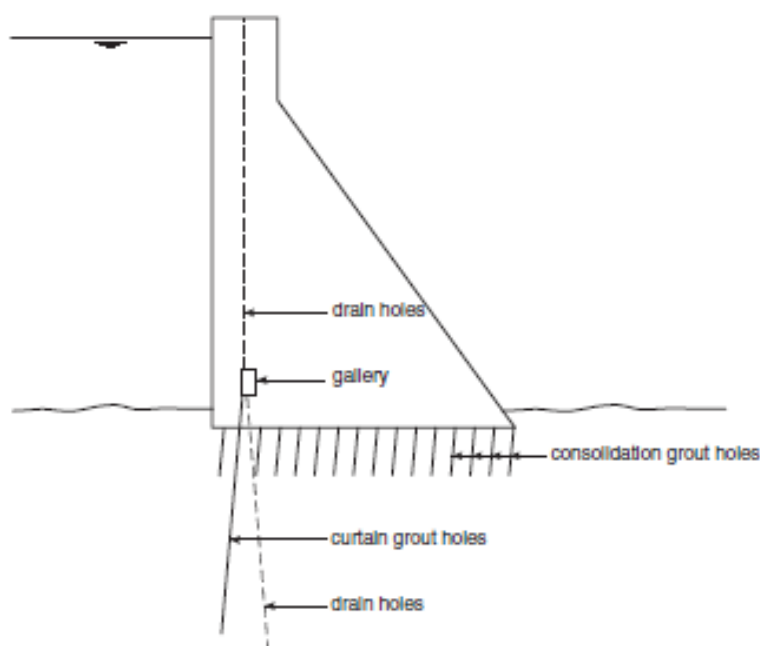
Figure 1-4 Curtain and consolidation grouting for concrete gravity dams.

Figure 1-4 shows a section through a concrete gravity dam. The curtain grouting is located near the upstream face of the dam and usually carried out from a gallery in the dam; sometimes from the upstream heel of the dam. It is designed to reduce seepage through the foundations and, in conjunction with the borehole drain holes, to control uplift pressures.

1.4 Objective of the Thesis

The main objectives of this dissertation are:
- Describing the general design, its background, theoretical basis, as well as the outline of the curtain grouting design.
- Study the results of the grouting works performed at Dam Complex of Upper Atbara Project. The focus is on inspecting if requirements regarding inflow are met.

1.5 Research Methodology

The literature on earth dams foundation grouting was reviewed. Sources include books, journals, scientific papers and online material from the internet. It is from the literature

review that conceptual and methodological background of the entire research was established. The methodology is based on review the methods of statement which used to construct the curtain grouting and contact consolidation grouting used in Dam Complex of Upper Atbara. They were obtained from the site reports of Dam Complex of Upper Atbara Project (Author: Dams Implement Unit). The scope of this study is mainly limited to evaluation the curtain grouting used to treatment the foundation of the appointed dam.

1.6 Thesis Organizational Outline

A brief description of each chapter included in this study is presented below.

Chapter 1 is an introduction of this thesis, including the need for the present research, and briefly describes the contents of each chapter. In Chapter 2 the Literature Review presents a review of the idea of grout curtains and current methodologies used to assess the effectiveness of grout curtains which entail Lugeon, hydraulic conductivity and pore pressure values. Chapter 3 presents a curtain grouting design and execution at Dam Complex of Upper Atbara and feature a detailed explanation of the preliminary design of general grouting concepts and will handle actual execution of the curtain grouting work along the earth dam access. In Chapter 4 the Discussion of Result will feature and discusses the results from analysis of grouting work in a particular location representing the all dam. Finally in Chapter 5 the Conclusions and Recommendation summarizes the findings and conclusions of this research and offers recommendations for future related research.

CHAPTER TWO

CHAPTER TWO

LITERATURE REVIEW

2.1   Introduction

Water seepage is a common problem in almost all dam sites. This may have a significant impact on the environment, the construction, and the long-term operation of the project hence it is important to have a good understanding of the groundwater regime and geological features of a site at planning and design stage, so that the water leakage can be properly controlled. As dams continue to age, groundwater seepage issues are becoming more prevalent. If groundwater seepage issues are left unaccounted for, significant problems can cultivate.

Past history has shown that groundwater seepage under dams and other impoundments can cause significant problems not just for the owner, but to the surrounding communities. Problems associated with prolonged groundwater seepage under dams and impoundments have led to breaches. For example, the Teton Earthen Dam located in the eastern part of Idaho failed due to excessive seepage through the earth fill dam. The permeable loess core material combined with rock fissures along the abutments of the dam, allowed for significant seepage through and around the dam (Arthur, 1977). Figure 2-1: shows a picture of the Teton Earthen Dam failure.

Figure 2-1: Teton Earthen Dam Failure in 1976 (Arthur, 1977).

The seepage through the earthen dam caused structural degradation ultimately leading to the breach of the dam. Tremendous damage resulted in the breach of the Teton Earthen Dam. Significant flooding occurred in the communities just downstream of the dam. Damages were estimated to be nearly one billion dollars. Unfortunately, the flooding due to the breach of the dam claimed 14 lives. As can be seen, groundwater seepage under dams can introduce significant issues to the structural integrity of dams and other impoundments.

To avoid such horrific circumstances like the Teton Earthen Dam failure, the use of grout

curtains has been proven to successfully mitigate groundwater seepage issues that are typically encountered at dams and other impoundments. Grout curtain walls are being incorporated in more dam construction designs since it is currently the most effective approach to mitigating seepage problems. Grout curtains are a cost effective way to diffuse seepage issues due to the low cost of the grout material. It is important to note that prior to the 1950's steel sheet piles were utilized to create impermeable walls similar to grout curtains as pointed out by Powers et al. (2007). However, literature (Powers et al., 2007) has shown that grout curtain walls outperform impermeable walls constructed of steel sheet piles with respect to factors such as cost and seepage mitigation. The mere cost of steel has precluded the use of steel sheet piles as a viable solution for seepage mitigation.

2.2   Design of the Grout Curtain

2.2.1   General

The approach to the design of a grout curtain is not similar to conventional design of civil structures using approved codes the same that to design a building. Indeed there are no rules based on a statistical analysis of the risk. The purpose of a dam can be different in each case, so is the location, the type of the dam and the geological context. That's why the curtain grout cannot be designed like another construction and must be thought of differently.

In this section of the report the essential ingredients for a grout curtain design will be described.

The main purpose of a grout curtain is ensuring the dam safety and to reduce leakage from the dam foundation. It is sometimes stated that foundation grouting is the final foundation exploration.

In addition to safety considerations, the cost of the stored water has become an increasingly important consideration in the design of measures to reduce the potential for seepage loss. Therefore, it is increasingly important that the design of the grouting program incorporate due consideration of the geologic and hydrologic characteristics of the site and that the best available technology be used. In this regard, the available as-built data from other dam sites in comparable geologic terrain should be reviewed. Nonetheless, caution must be exercised when drawing conclusions from those data; subsurface conditions potentially conducive to seepage loss or structural settlement can vary greatly from one part of a geologic formation to another, so identical conditions are unlikely to be encountered at any two sites within the same geologic formation. Moreover, recognizing that more is likely to be learned about the subsurface geologic conditions at any given site as each hole is drilled and grouted; the project specifications should provide built-in flexibility for the grouting program to be modified appropriately during the course of the work to achieve the most effective results.

2.2.2   Geology of the dam site:

General Practice for the design of a grout curtain it was important to gather as much data

as possible about the geology of the dam site. A detailed site investigation was necessary and included:

1. Geological surface mapping

2. Study of aerial photographs

3. Study of cores and other information from drill holes

4. Permeability testing

The object was to produce a detailed geological section of the dam site. The drilling cores and permeability tests bring additional data which helped the interpretation of the geological surface mapping and aerial photographs. Core drillings also provided the opportunity to carry out permeability tests and petrographic analysis of core samples. A thorough study had needed to understand the geology and the hydrogeological behavior of all the area. The first results to be analyzed were the permeability tests and the analysis of core.

2.2.3   Grout Curtain Depth

Grout curtain depth in U.S. grouting practice has traditionally been selected on the basis of geometry and a formula based on the planned hydraulic head, producing a somewhat shallower curtain than the European practice of selecting a curtain depth equal to the height of the dam, as reported by Ewert (2003). The principal objective of formula approaches is to lengthen the seepage path to some value consistent with the width of the dam footprint or core width. However, although this approach may protect the dam itself from the effects of seepage or leakage, the amount of seepage will not necessarily be reduced. Therefore, if the water is valuable or if the foundation might conceivably develop internal erosion (piping) at a depth greater than that which would be indicated by a geometrical or formula approach, consideration should be given to extending the curtain down to a relatively impervious layer or zone. However, to avoid construction of a partially or wholly "dangling" grout curtain, geologic conditions rather than geometry and nominal head at the foundation surface should be the major factor in selection of curtain depth in essentially all cases. This consideration may in some cases lead to design and construction of a curtain that is asymmetric. [Weaver 2007]

Borehole deviation can become a significant control on the practical depth to which a grout curtain can be extended because excessive deviation can leave untreated "windows" between holes. The amount of deviation will depend on the site geological conditions, the drilling equipment used, and the care with which the drilling is done. Ewert (2003) suggested that the maximum achievable depth for an overlapping curtain is 50 m in poor conditions and as much as 150 m in favorable conditions. These supposed maximum depths become unimportant if relatively impermeable conditions are present at shallower depths. In general, a layer or zone with a permeability of 1 Lu or less may be sought, but terminating the curtain in a layer or zone with a permeability of 10 Lu may be acceptable for some projects (Wilson and Dreese 1998).

Extending the curtain to an impervious layer rather than to some formula-based depth is

particularly important in karstic limestone terrain, where loss of water through solution conduits could cause damage downstream or could prevent the reservoir from filling. Also worthy of consideration in this regard is the fact that infillings in karst may erode out over a period of years, so early good performance is no guarantee of satisfactory longterm performance. This potential detriment can be defended against by such strategies as installing multiple-row curtains, constructing a secant pile cutoff, flushing or mining out cavern infillings, and grouting at sufficiently high pressures to displace and/or thoroughly "invade" any clay infillings. [Weaver 2007]

2.2.4   Grout pressures

Grout pressures are usually limited to prevent hydraulic fracture of the rock.

There are two schools of thought on grout pressure:

- Those who limit grout pressures to below those which would lead to hydraulic fracture;
- Those who believe hydraulic fracture is preferred to promote the penetration of the grout.

Robin Fell et al (2005) are advocates of avoiding hydraulic fracturing of the rock, as they are concerned that the fractures opened by the grout will not all be filled by grout and the grouting may worsen the situation rather than improving it. They are not concerned that seepage still occurs through a dam foundation, provided the dam is designed to manage the seepage.

As pointed out by Deere (1982), Deere and Lombardi (1985) and Lombardi (1985), the maximum penetration distance is proportional to the pressure used for grouting. Hence it is desirable to use as high a pressure as practicable without fracturing the rock.

The pressure which can be applied depends on the rock conditions (degree of fracturing, weathering, in situ stresses and depth of the water table) and whether grouting is carried out using a packer which is lowered down the hole at each stage (i.e. downhole with packer grouting), or from the surface. The downhole packer method allows progressively higher pressures.

Houlsby (1977, 1978) and WRC (1981) present graphs to allow estimation of maximum pressures at the ground surface. These are based on the assumption that the maximum pressures at the base of the stage being grouted are given by:

$$P_B = \alpha d$$

Where $P_B \equiv$ pressure at base of hole in kPa; $\alpha \equiv$ factor depending on rock conditions; 70 for "sound" rock; 50 for "average" rock; 25 to 35 for "weak" rock; $d \equiv$ depth of bottom of stage below ground surface in meters.

This allows for the weight of the overlying rock plus some spanning effect and has been found to be satisfactory.

The tendency for rock to fracture or "jack" under grout pressures is reduced by using a

relatively low pressure to start grouting and building up with time. Since much of the pressure in the grout is dissipated in overcoming the viscosity effects in the fracture, this limits the pressure transmitted to outer parts of the grout penetration. Houlsby in WRC (1981) suggests use of a starting pressure of 100 kPa (or less) for 5 minutes, then steadily increasing the pressure over the next 25 minutes until the maximum pressure is reached.

The occurrence of fracturing can be detected by sudden loss of grout pressures at the top of the hole, by increased take, surface leakage or by monitoring levels of the surface above the rock being grouted.

It is recommended by Houlsby that grouting is to "refusal" and that the pressure is maintained for 15 minutes after this to allow time for initial set. Others suggest grouting until take is less than a certain volume in a 15 minute period, e.g. Water Authority of WA (1988) specify grouting is to cease when take is less than 30 litres/20 minutes at 700 kPa or less; 30 litres in 15 minutes at 700–1400 kPa; 30 litres/10 minutes for pressures greater than 1400 kPa. They also indicate pressures should be maintained until "set" has occurred. In practice the maximum pressures will have to be determined by careful monitoring as the grouting proceeds.

2.2.5   Single-Row or Multiple-row

There are two different points (Weaver, 2007) of view about the number of rows that are necessary to drill for a grout curtain. Depending of the height and the bedrock, one or multiple rows grout curtain can be constructed.

On one hand, a simple row will be adequate if the grouting is conducted with good quality assurance with thorough assessment of grouting results and all weak spots treated with appropriate attention. A single row curtain requires tight spacing of holes to ensure that the curtain is continuous. The gradient obtained is steeper than for across a multiple row curtain and can cause problems in a weak material.

On the other hand, a multiple rows curtain is wider and results in a less steep gradient which may be required in weak materials. The spacing between holes can be greater than for a single line curtain and the holes can have an opposite drilling direction to increase the chance of crossing faults. In this last case, the first row has to be completed before beginning on the second one. Finally grout curtain with multiple rows requires more drilling, more grout materials and more time, so is more expensive.

2.2.6   Grouting Injection Pressure

The second factor influencing the grout takes is the grouting injection pressure. It has a decisive influence on the success of a grouting program.

Too high grouting pressures may result in one or more of the following

1. Grout will travel unnecessary far through extensive dilation of fissures and joints in the rock
2. Hydraulic fracturing of the rock mass may occur
3. Washout of infillings in fractures

4.   Uplift in the foundation

All of the above will lead to excessive grout absorption and reduce the quality of the grouting work and may lead to excessive cost.

If the grouting pressure used is too low, the grout material will not completely fill the faults and fissures and the grout curtain will not reduce the leakages and lengthen the seepage path through the bedrock. In this case the cost of the grouting may be wasted and remedial measures may become necessary to rectify the situation.

Therefore the choice of grouting pressure is extremely important.

In the grouting world there are three main different ways to proceed:

1- The GIN-Method: according to LOMBARDI (2003) "the fundamental principle of the GIN-Method (GIN: Grouting Index Number) is to reduce the grouting pressure as a function of the volume of grout injected". The aim of this method is to limit the losses of grout material, simplify the grouting procedure, save the cost of unnecessary permeability tests and reduce the risk of hydro-jacking and hydro-fracturing. A maximum pressure, a maximum volume of grouting and the GIN (a maximum intensity), curve determine the limits of the grouting procedure. The monitoring during the execution of the grouting works allows knowing when these limits are reached, and then the process is stopped. It can be presented as following in the Figure 2-2.
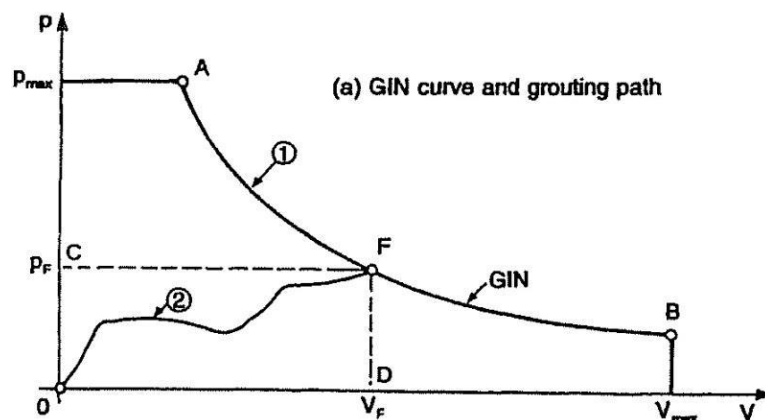
Figure 2-2: Grouting process of a single borehole

(1) Limiting curve, (2) actual grouting path, (F) final point of the grouting, (P_F) final grout pressure, (V_F) actual grout take, [LOMBARDI, 2003]

2-   The U.S. practice: it indicates that the injection pressure should be set relative to the overlying rock thereby:

$$P = 0.25 \times D$$

3- The European practice: it indicates that the injection pressure should be set relative to the overlying rock thereby:

$$P = D$$

Where: $P \equiv$ pressure in (bar), $D \equiv$ depth in meter

Observing these formulas, it may be concluded that the European practice is to use 4 times higher pressures than with the U.S. practice. In recent years the European and American practices have been moving more to a consensus about grouting pressures (Weaver, 2007).

2.2.7   Grout Mixes

The third factor which influences the grout takes is the grout mix used. Using adequate mixes during the grouting process has a determinant effect on the success of the program and the grouting costs. The best mix is the one which allows reducing the maximum leakage with the minimum of material. If the mix is too thick, it is difficult to pump and could not penetrate faults and fissures far enough. But if it's too thin, a lot of material will be lost in inefficient grouting. So different mixes have to be designed before the beginning of the grouting operation to have optimum grout mix for each encountered situation.

Traditionally people were using thin mixes with high W/C ratios. Bentonite was used to prevent segregation and excessive bleeding.

Pressure tests were used to determine the initial mix used, for the beginning of the grouting in each hole. Then depending on the evolution of the grouting and particularly on the grout absorption and the variation of pressure, the mix was changed.

Nowadays, with the use of super-plasticizers, the grout mixes have changed. The new additives allow pumping of thicker mixes with lower W/C ratios. It allows filling smaller fault with less material than when a thinner grout is used and decrease the losses of grout. Even if the mix recipe has changed, the principle of the process has been conserved.

Cement grout is a suspension of the cement particles in water. The particles are mostly silt sized, but conventional cement will have some fine sand particles. The grout particles aggregate in water to give a coarser distribution than the cement powder. The particle size distribution is affected by the addition of plasticizers, which act as deflocculating agents. This mainly affects the finer particles. With plasticizers, Type A and C Portland cements have a maximum size of about 0.05–0.08 mm, while the microfine cements tested had a maximum size of about 0.02–0.025 mm.

2.2.8   Contact Grouting - Consolidation Grouting

The main goals of both consolidation and contact grouting are to reduce seepage losses and seepage velocity through the upper part of the rock mass thereby increasing the intensity of the grouting in the part of the rock mass where the gradients are highest. In effect this is to construct a multiple row grout curtain near the surface of the rock.

The term consolidation grouting is mainly used for grouting under concrete dams where potential erosion of core material is not a problem. The major additional purpose is to strengthen the bedrock in anticipation of the load of the dam. The filling of the fractures

with grout material prevents the settlement of the rock due to the closure of these fractures.

In earth dams contact grouting has the additional benefits of helping to prevent wash out of core material through open fissures in the dam foundation. The depth of the holes, it's determined by the thickness of the permeable zone (if a more permeable zone is present at the top of the bedrock). To protect the core of the dam, the blanket grouting is conducted in conjunction with a surface treatment (grout material or concrete to fill all the cracks on the surface to stop surface leakages).

Consolidation grouting and/or contact grouting are commonly conducted with two or three rows parallel to the grout curtain. It's convenient to arrange it in the same manner as for a multiple-row curtain and coordinate them with curtain closures. These grouting operations have to be completed before the beginning of the curtain grouting; thus allow for sealing of the surface before the curtain grouting.

2.3   Grout Installation Techniques

There are three primary grout installation techniques that are widely used today in the civil engineering industry. The three grout curtain techniques that are commonly used today which are highlighted in the research done by Yong-Jiang and Xing-Wang (2012) include:

- jet-grouting,
- high-mobility grouting,
- compaction grouting.

The goal of all three installation techniques is to simply prevent seepage from occurring under water retaining structures, specifically dams.

Jet-grouting is a technique that uses high velocity and high pressure jets to hydraulically replace poor rock or in-situ soil material with a cementatious material known as grout. Specialized machinery connected to a grout monitoring system allow for the placement of grout. The process of jet-grouting is fairly simplistic. High velocity grout jets connected to a drill-stem allow for in-situ soil to be eroded then mixed. The composition of in-situ soil and grout is commonly referred as soilcrete (Hayward Baker, 2014). Figure 2-3 illustrates the installation of a soilcrete column using jet-grouting.

Given adequate time for set-up, the soilcrete columns cure and become high strength, low permeability material. Soilcrete columns are installed at predetermined locations where seepage issues are expected. Soilcrete columns are installed to help prevent groundwater seepage from occurring under dams and other impoundments. This technique is very versatile since grouting can take place above or below the ground water table and can be used in a wide range of soils from high plasticity clays to cohesionless sands.

High-mobility grouting uses the flow of a pressurized cementatious grout material. Over time, the grouting material enters into the crevices of the underlying soil causing the grout and soil to bind together. Figure 2-4 presents the high-mobility grouting technique.
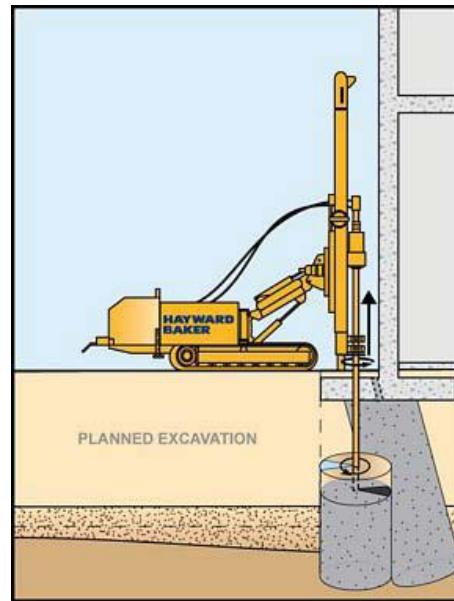
Figure 2-3: Installation of a soilcrete column using jet-grouting (Hayward Baker, 2014).
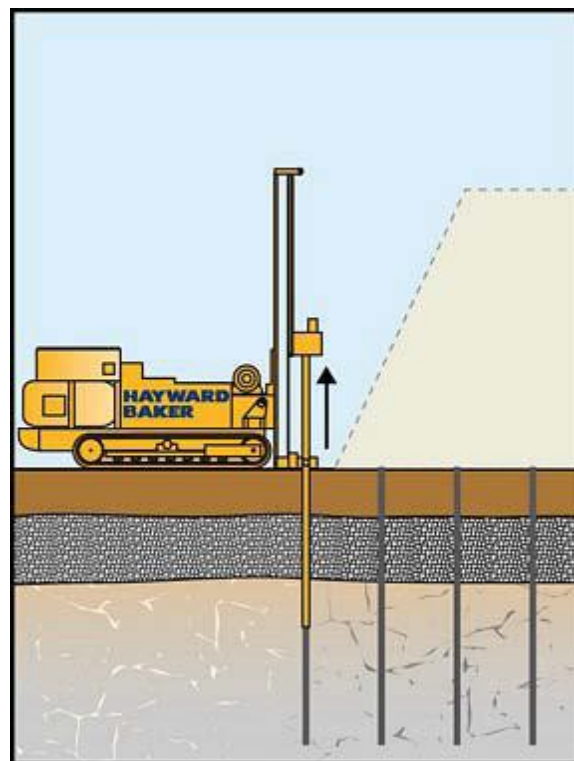
Figure 2-4: Illustration of the high-mobility grouting technique (Hayward Baker, 2014).

When performing high-mobility grouting for dams or other impoundments, it is imperative that the size of the pores or void spaces of the underlying soil material are matched to the particle size of the grout being applied. Having the appropriate grout with respect to particle size will allow for the grout material to enter the pore and void spaces of the underlying soil material. If the particle size of the grout is larger than the pore and

void spaces of the underlying soil, grout will unable to enter the pore and void spaces.

This type of grouting allows for increased strength properties such as cohesion, as well as decreased permeability.

Compaction grouting is another common technique used by industry today.

Compaction grouting utilizes low viscosity grout to displace and densify loose soils.

Also, compaction grouting is performed to stabilize large void spaces known as sinkholes by using a low-mobility grout mixture (Hayward Baker, 2014). The pressurized grout is injected into the ground by a pipe. As the grout is continuously injected, the pipe is slowly raised, forming a bulb like structure. For further clarity refer to Figure 2-5, which illustrates the compaction grouting technique.
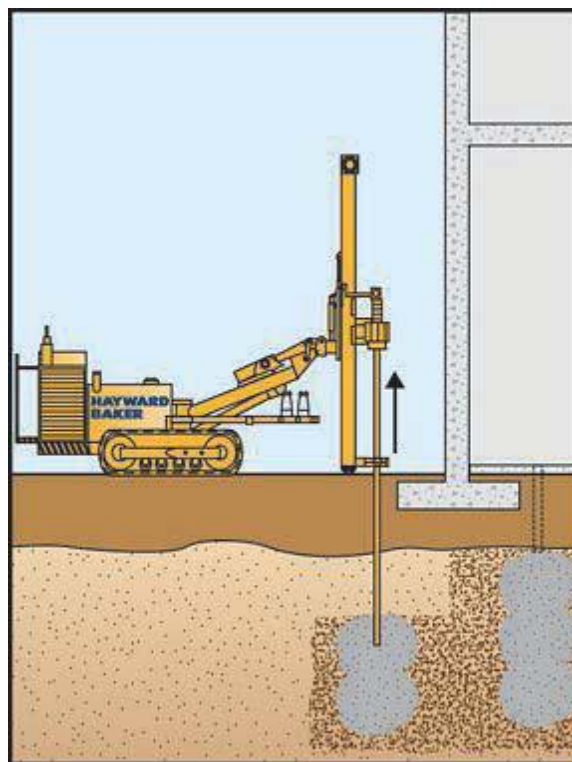
Figure 2-5: Compaction grouting technique (Hayward Baker, 2014**).**

The injected grout displaces the loose surrounding material. During the displacement and expansion of the grout material, geotechnical properties such as density, friction angle, and stiffness are increased. This technique reduces permeability while providing additional strength to existing underlying stratigraphy.

2.4   Current Methodologies to Assess Grout Curtain Effectiveness

There are many methods to assess grout curtain effectiveness such as:

1. Monitoring Lugeon values,
2. Measuring hydraulic conductivity,
3. Monitoring pore pressures and,
4. Willowstick technology.

This research concentrates on monitoring Lugeon values method. In the following section the above four methods briefly outlined:

2.4.1   Monitoring Lugeon Values

Monitoring Lugeon values during the installation of a grout curtain is the current state-of-the-practice for assessing grout curtain effectiveness. Lugeon values are defined as the injected volume of water in a length of time per length of rock beneath the reference elevation (Lugeon, 1933). The most common units attributed to the Lugeon value is 1 liter/minute per meter at a reference pressure of 1 MPa. Although the Lugeonvalue is similar to hydraulic conductivity, the Lugeon value is typically used in rock masses in which water travels through cracks in rocks, whereas hydraulic conductivity is used in conjunction with water traveling through soil pore space. Monitoring Lugeon values has many benefits. Benefits of ascertaining Lugeon values include the determination of flow characteristics provide a sound basis for the selection of an appropriate grout mix, and most importantly for quality control purposes (Weaver, K. and Bruce, D., 2007). Lugeon values are used combined with qualitative measures such as engineering judgment and rules-of-thumb (Bruce, 1982; Quinn et al., 2011; Berhane and Walraevens, 2013) to address the effectiveness and structural integrity of grout curtain walls. Lugeon values have been increasingly used as a means to assess quality control of grouting operations due to technological advancements in data acquisition systems and real time monitoring equipment. According to Houlsby (1976), quality assurance of a grout curtain with the use of Lugeon values is a key component to assessing the effectiveness of a grout curtain. A typical real time monitoring equipment and data acquisition system currently used in industry can be seen in Figure 2-6. The combination of real time monitoring equipment and data acquisition systems have allowed researchers (Sasaki and Tosaka, 2012; Sadeghiyeh et al., 2013) to monitor Lugeon values during grout curtain installation procedures. As the costs for real time monitoring systems and data acquisition systems start to decline due to competitive markets, Lugeon values are going to become even more widely used.

Figure 2-6: Typical real time monitoring and equipment and data acquisition system (Quinones-Rozo, 2010).

2.4.1.1 Lugeon Test Procedures

The most common insitu testing procedure used to assess the need for foundation grouting at dams and other impoundments is the Lugeon test, also known as the packer test. The original Lugeon test was developed by Maurice Lugeon in 1933. With technological advancements in real time monitoring equipment, much research has been conducted on the applicability of the original Lugeon test over the years. Research done by Houlsby (1976) resulted in an updated Lugeon test that allows for tests to be conducted over a wider range of pressures, while using the same principles used in the development of the original Lugeon test. The updated Lugeon test, commonly referred to as the modified Lugeon test, is the current industry standard for ascertaining Lugeon values. Unlike the original Lugeon test developed by Maurice Lugeon, the modified Lugeon test consists of 5 consecutive stages. The first three stages are completed at increasing pressures while the last two stages are completed at decreasing pressures.

During each stage, water pressure is held constant, while pumping as much water through the test interval as possible. A schematic figure illustrating a Lugeon test configuration is presented in Figure 2-7.
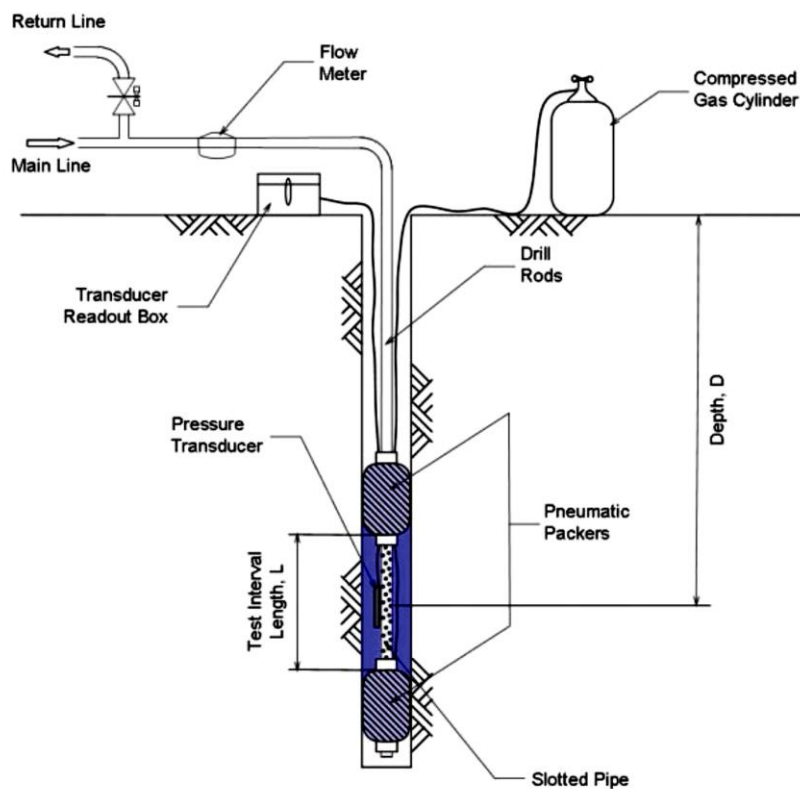
Figure 2-7: Schematic Lugeon test set-up (Quinones- Rozo, 2010).

During each stage, flow rate and pore pressure measurements are taken. These measurements are subsequently used to calculate a Lugeon value based on an equation presented in Houlsby (1976) and Quinones-Rozo (2010). The equation presented in Houlsby (1976) and Quinones-Rozo (2010) is the standard equation that is currently being used by industry to determine Lugeon test values, which can be seen in Equation 1.

$$LU = \alpha \left(\frac{q}{L}\right)\left(\frac{P_o}{P}\right) \underline{\hspace{3cm}} (1)$$

Where LU=Lugeon value, α = unit system coefficient, q = flow rate = Q/t where Q = total volume of water discharged and t = total time of test, L = test interval length of the representative test sample, P_o = reference pressure = 1 MPa and P = water injection pressure.

Under ideal conditions (i.e., homogeneous and isotropic) one Lugeon is equivalent to 1.3×10^{-5} cm/sec (Fell et al 2005). Table (2-1) describes the conditions typically associated with different Lugeon values, as well as the typical precision used to report these values (Quiñones-Rozo, 2010).
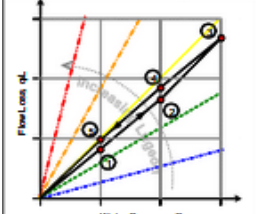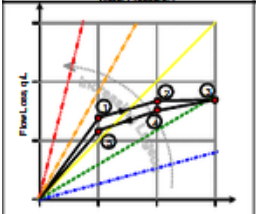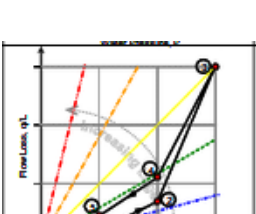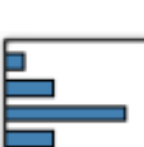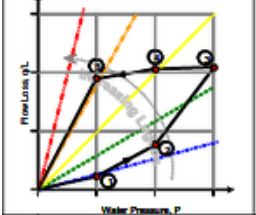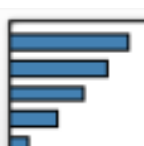
Table 2-1 Conditions of rock mass discontinuities associated with different Lugeon values

Lugeon Range	Classification	Hydraulic Conductivity Range (cm/sec)	Condition of rock mass Discontinuities	Reporting precision (Lugeons)
< 1	Very Low	$<1\times10^{-5}$	Very tight	<1
1 - 5	Low	1×10^{-5}- 6×10^{-5}	Tight	± 0
5- 15	Moderate	6×10^{-5}- 2×10^{-4}	Few partly open	± 1
15 - 50	Medium	1×10^{-5}- 6×10^{-5}	Some open	± 5
50 - 100	High	1×10^{-5}- 6×10^{-5}	Many opens	± 10
> 100	Very High	1×10^{-5}- 6×10^{-5}	Open closely spaced or void	> 100

The current Lugeon interpretation practice is mainly derived from the work performed by Houlsby (1976). On his work, geared towards establishing grouting requirement, Houlsby proposed that representative hydraulic conductivity values should be selected based on the behavior observed in the Lugeon values computed for the different pressure stages.

Houlsby (1976) classified the typical behaviors observed in practice into five different groups. Table 2-2 presents a graphic summary of the five behavior groups defined by Houlsby (1976), as well as representative Lugeon value that should be reported for each group.

Table 2-2 Summary of current Lugeon interpretation practice (as proposed by Houlsby, 1976)

BEHAVIOR	WATER LOSS VS PRESSURE PATTERN	LUGEON PATTERN	DESCRIPTION	REPRESENTATIVE LUGEON VALUE
LAMINAR			All Lugeon values about equal regardless of the water pressure	Average of Lugeon values for all stages
TURBULENT			Lugeon values decrease as the water pressures increase. The minimum Lugeon value is observed at the stage with the maximum water pressure	Lugeon value correspomding ti the highest water pressure (3rd stage)
DILATION			Lugeon values vary proportionally to the water pressures. The maximum Lugeon value is observed at the stage with the maximum water pressure	Lowest Lugeon value recorded, corresponding either to liw or medium water pressure (1st, 2nd, 4th, 5th stage)
WASH OUT			Lugeon value increase as the test proceeds. Discontinuities infillings are progressively washed-out by the water	Highest Lugeon value recorded (5th stage)
VOID FILLING			Lugeon value decrease as the test proceeds. Either non-persistent discontinuities are progressively being filled or swelling is taking place.	Final Lugeon value (5th stage)

2.4.1.2   Shortcoming of the Lugeon Test

Selecting an appropriate representative sample at a test site is a major drawback to the Lugeon test. The range of a single Lugeon test with a length interval of 10 feet is said to only encompass a 30 foot radius around the bore hole of interest (Bliss and Rushton,

1984). Since a Lugeon test only accurately depicts a limited area surrounding a bore hole, it is imperative to have a proper representative sample that takes into account the underlying soil material. However, if proper representative samples of the underlying soil material are obtained, Lugeon values are an appropriate measure to help aid in the quantification of the effectiveness of a grout curtain.

2.4.2 Measuring Hydraulic Conductivity

Grout curtain effectiveness is sometimes evaluated based on the degree of which in-situ hydraulic conductivity is reduced. In a previous study (Cotton and Matheson, 1990) conducted to evaluate the effectiveness of a grout curtain, hydraulic conductivity measurements were used to quantify effectiveness. In this study, effectiveness of a grout curtain was based on hydraulic conductivity measurements with varying grout curtain depths. This study found that an effective grout curtain is not achieved until the grout curtain hydraulic conductivity values is three to four orders of magnitude less than that of the surrounding material. However, the Cotton and Matheson (1990) study used hydraulic conductivity values through a homogenous soil mass as opposed to a fractured mass often times seen while grouting.

2.4.3 Monitoring Pore Pressures

Determining the effectiveness of a grout curtain using solely pore pressure measurements is uncommon. However, one researcher compared predicted and observed behavior of pore water pressure inside an Alavian earthfill dam in Iran (Aminfar et al., 2009). This study also investigated the effects pore water pressures had on the foundation of the dam by looking at the distribution of pore water pressures. Beyond this study, there is little data that has been presented using solely pore pressures to evaluate the effectiveness of a grout curtain.

2.4.4 Willowstick

Willowstick is a recently developed technology that attempts to define and model complex subsurface water systems using electromagnetic fields (White Paper, 2016). Willowstick technology utilizes the placement of strategically placed electrodes in conjunction with a power supply to help enhance magnetic fields that can assist in modeling preferential groundwater flow paths (White Paper, 2016). Figure 2-8 illustrates modeling done by Willowstick technology. Unlike typical electromagnetic and resistivity methods, the Willowstick technology understands that flow paths can be effectively modeled using electrode probes due to their thorough understanding of water content and subsurface electrical conductivity (White Paper, 2016). This technology was developed to be a cost effective method to modeling complex subsurface water systems. The traditional method of direct observation through the drilling of wells is too time consuming, labor intensive and expensive. The Willowstick technology capitalizes on low cost and increased safety factors. However, this may be considered state-of-the-art, it is not currently widely used by consultants. The research presented herein focused on readily available technologies currently used in industry. The Willowstick Technology was not used for this research. It is presented briefly herein for completeness. Further,

future research using this technology is recommended.
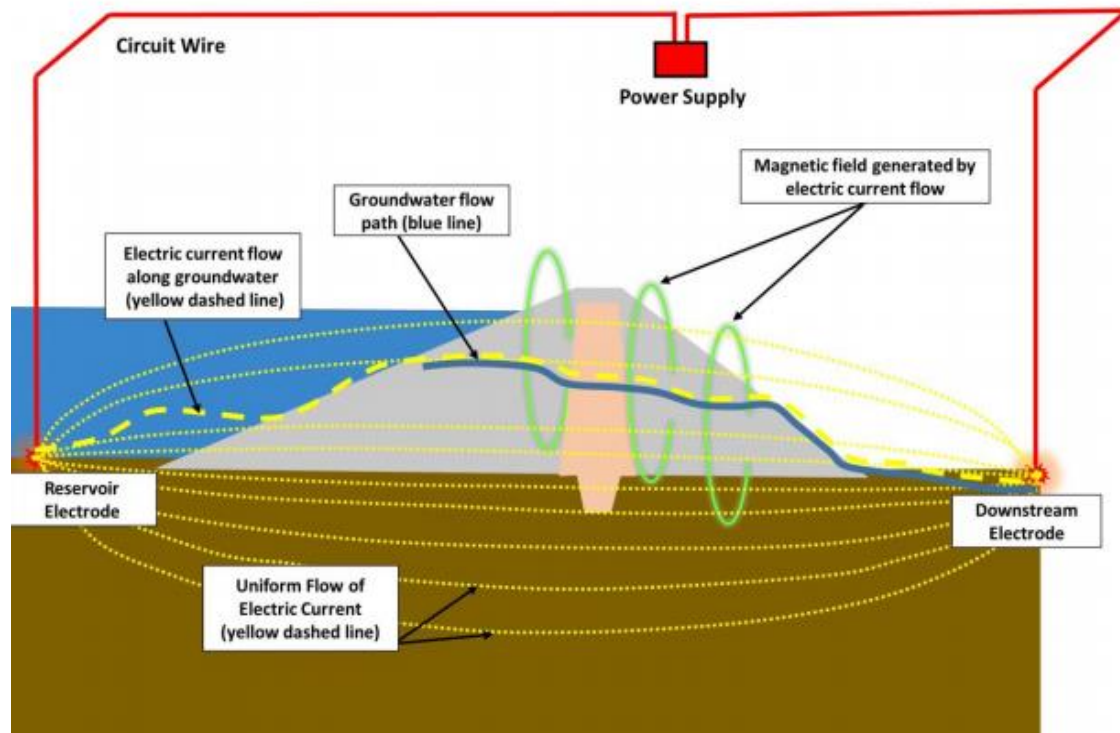
Figure 2-8: Typical Willowstick Configuration to Detect Dam Seepage (White Paper, 2016).

CHAPTER THREE

CHAPTER THREE

CASE STUDY: DESIGN AND EXECUTION OF CURTAIN GROUTING IN DAM COMPLEX OF UPPER ATBARA PROJECT

3.1 Introduction

The Dam Complex of Upper Atbara Project (DCUAP) comprises the following main components: (see figure (A-1) in Appendix A)

- A complex of combined embankment dams of Rumela (max. 55 m high, 1,070 long dam including max. 17 m high dykes, 3,997 m long) and of Burdana (max. 50 m high, 940 m long including max. 17 m high and 5,750 m long dykes);
- Huge spillway structures of reinforced concrete for Rumela dam and for Burdana dam for flood control and to secure the earth embankment dams against overtopping;
- Power station equipped with four generating units with vertical axis Francis turbines.
- Headworks at the left bank of Upper Atbara River (Rumela Project).
- Connection canal between Upper Atbara and Setit catchments.

The locations where grouting works are applied under foundation of the project components are divided into sections as see in **Table 3-1**.

Table 3-1: Chainages of Curtain Grout along the Dam Axis

Rumela Dam		Burdana Dam	
Location	Chainage*	Location	Chainage*
Left Bank Dyke	2+425.00 - 2+200.00	Left Bank Dyke	0+512.00 - 1+089.00
Left Bank Dam	2+200.00 - 1+881.72	Left Bank Dam	1+089.00 - 1+133.20
Spillway	1+881.72 - 1+782.50	Spillway	1+133.20 - 1+275.05
Left Bank Abutment	1+782.50 - 1+708.00	Right Bank Dam	1+279.05 - 1+376.02
River Section	1+708.00 - 1+555.00	River Section	1+376.20 - 1+532.00
Right Bank Abutment	1+555.00 - 1+378.45	Right Bank Dam	1+532.00 - 1+900.00
Power Intake	1+378.45 - 1+264.53		
Right Bank Dam	1+264.53 - 0+917.22		

 *chainge is measured from KP0 see figure (A-1) in Appendix A

For two mainly goals; prevention of erosion and reduction of the overall permeability; the foundation below the main dams, spillways, power Intake and Headworks has been treated using curtain grouting.

3.2 Design of Curtain Grouting in DCUAP

3.2.1 Geological Investigations and Setting

The first step to design a grout curtain is to gather all available geological information and draw a geological longitudinal section of the dam site. In the case of the DCUAP the information encompasses mainly a detailed study of the drilling cores and of the permeability tests. In the following sections the available geological data will be

described and conclusions made for the design of the grout curtain.

The geological Investigations started during 1973 to 1975 by Geological Survey Department of Sudan geological survey; boreholes drilling, test pits, laboratory testing and geophysical seismic refraction survey were carried out. Geological mapping study was included in the thesis report of Chialvo (1975). Second Investigations was during 1975 to 1976; core, auger drilling and test pits with sampling and in-situ testing were carried out by Swiss boring Company and Geological Department of University of Khartoum. The third Investigations in 2007 consisted of coring; auger drilling, test pits, in-situ and laboratory testing were carried out by Sogreah.

Latest Investigation was in 2010, Additional Investigations campaign was carried out by Lahmeyer International to fill the gaps and to extend the knowledge for a safe foundation. A few in-situ and laboratory tests requested to support the design parameters.

In general, the both dams embankment of the Dam Complex of Upper Atbara Project are located on Nubian Sandstone Formation overlain by Karab Formation, cotton soil and alluvial terrace material. The Nubian sandstone is intersected by basalt and/or dolerite dykes as well as joints, master joints, faults and bedding planes. See Figure (3-1).

In general, the drillings have proved that the strength of the conglomerate and sandstone ranges from moderate to low. In many cases, the cores of the sandstone are friable and parts of the bedrock were only recovered as sand, i.e. the clayey matrix was so weak that the sandstone disintegrated in the course of the drilling process.

There is a generalized and continuous aquifer in the Nubian sandstones underlying nearly all the area. Discontinuous small aquifers can be observed in the Karab formations where the layers are below the river beds. The aquifer is fed by infiltration of river water essentially during the flood season and drained by the same river during the dry season.
Figures A-2, A-3 and A-4 in Appendix (A) Show an example for geological drilling log with Lugeon test results at studies stage and part of geological section along the Dam Axis.

◻ Modern alluvium: pebbles gravel and sand

◻ Gravely and sandy old alluvial terraces

◻ Black cotton soil on the plateau

◻ Karab formed of brown clay, silt, sand and gravel

◻ Undifferentiated Nubian sandstones from coarse sandstone to weak mudstone,
with collapsed block and detritic fan and slope colluviums formation
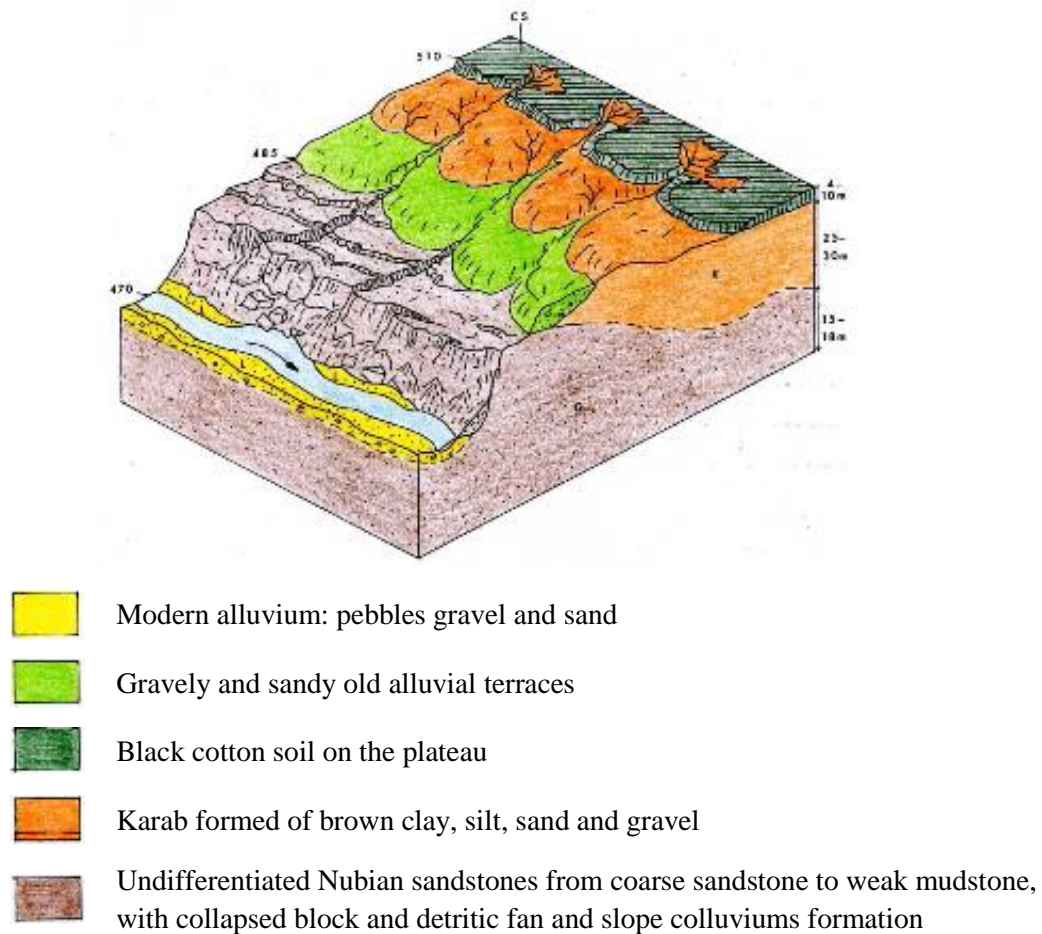
Figure 3-1: Different types of ground in the region and their relative position on the dam sites and ancillary from Chialvo

3.2.2   Depth of Curtain Holes

Water pressure tests have proved that parts of the rock mass are pervious and in order to reduce the potential water losses from the reservoir, it is recommended to seal the open joints and bedding planes below the foundation of the concrete structures and the dam. The criterion for the lower limit of the grout curtain was selected to be 5 Lugeon units (LU) for technical and economic reasons. Due to the geological conditions the final depth of the grout curtain will be deep as compared to the height of the dam. In order to overcome this deficiency and to intersect more open fractures, it was recommended to tilt the grout holes against the main dip direction of the joints and to check whether the general depth of 40 m can be maintained for the grout curtain. The following tentative depths of the curtain (beneath ground surface) are compiled in **Table 3-2**.

Table 3-2 Design depths of curtain grouting along Dam

Rumela Dam		Burdana Dam	
Location	Curtain Depth	Location	Curtain Depth
Power intake	35 to 40 m	Right bank	25 to 30 m
Right bank	30 to 40 m	Setit River	20 to 30 m
Atbara River	35 to 40 m	Left bank	30 to 40 m
Left bank	25 to 40 m	Spillway	35 to 40 m
Spillway	30 to 35 m		

During execution of the sealing works the final depth of the curtain has to be checked at regular intervals. In case the permeability exceeds 5 LU, the grout curtain should be deepened for another 5 m under the concrete structures or for consecutive 12 m on both left and right side below the dam.

The grout holes have been drilled vertically for technical reasons and under protection of casing.

3.2.3   Staggering Sequences of Grout Holes

1 : Series A is drilled with primary spacing
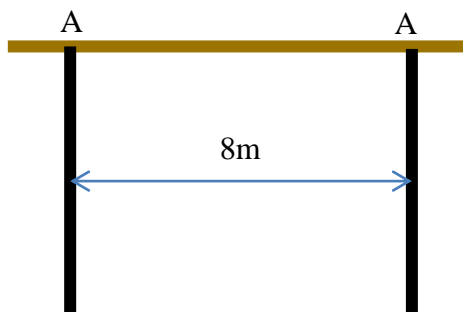
2: Series B is drilled and split the secondary spacing
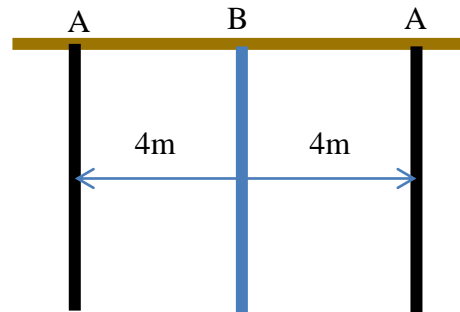
3: Series C is drilled and split the tertiary spacing
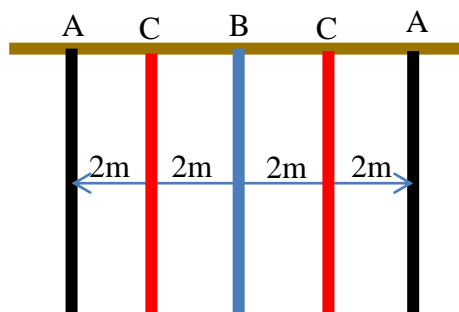
Figure 3-2: Slit-spacing method for grouting the holes

Grout curtain had been constructed by the slit-spacing method with all holes in the

curtain having the same depth. Curtain grouting is arranged in one line on the axis of the dam. Primary holes (A-series), secondary holes (B-series) and tertiary holes (C-series) have the same spacing and inclination. The primary (A) spacing used was 8 m and splits made by secondary (B) 4m and tertiary (C) 2m until the required permeability was reached. See Figure (3.2).

Figure A-5 in Appendix (A) show curtain grouting design depth and staggering sequences for grout holes at right bank dam in Burdana Dam.

3.3 Execution of Curtain Grouting in DCUAP

The curtain grouting works on the grout cap, with a single row in the middle of dam axis, holes distance of 2m. Holes diameter were 56mm. The curtain grouting started by the drilling of pilot holes (with core recovery), then the primary holes with a distance of 8m. Secondary holes with a distance of 8m were midway between the primary holes, and tertiary holes with a distance of 4m were midway between the primary holes and the secondary holes. The final hole's numbers, depth, position and inclination and orientation, water cement ratio, grouting pressure and flow rate etc. have been determined in design documents.

The drilling and grouting woks for Burdana Dam and Dyke include 4 parts: left bank dyke, left bank dam, riverbed dam and right bank dam. This method statement is peculiar to the execution method for the drilling and grouting works on right bank in Burdana dam with the chainage from CH B1+600 to CH B1+900.

3.3.1 Materials used in grouting

3.3.1.1 Cement
According to Dam specifications, portland cement with a specific surface area of 4000 cm^2/g (ASTMC204) had to be used. No cement particle had to be retained on U.S. Standard Sieve No.200 (0.075mm).

The blast-furnace cement CEM Ⅲ/B from Sharjah used for grouting work.

3.3.1.2 Water
The water used in grouting is clean and clear water having the characteristics of mixing water used in concrete.

3.3.1.3 Bentonite
Bentonite was used, during the mixing and grouting, to enable the sensitivity of the mortar, by keeping cement particles and sand suspended, and to minimize the disintegration of water in the cement water mixture. All of the grouts and mortar grouts in the grouting procedure were used by adding Bentonite in a ratio between 1.5 to 3% of the cement amount. The Bentonite used was Super Gel 102 from India IMC Company.

3.3.1.4 Admixture
The plasticizer (water-reducing agent) PCA-1, was used for grouting works.

3.3.1.5   Sand

(1) Sand in grout were planned to be used for small portions of the work in highly fissured or fractured rock zones, or big crack or void. The grading of sand is shown as **Table 3-3**

Table 3-3 Grading of Sand Used for Grouting

U.S. Standard Sieve	Square-mesh Sieve Opening	Percentage Passing (By weight)
No.100	0.150 mm	50 - 100
No.200	0.075 mm	0 - 50

 (2) Sand should not contain more than 3% of flat or elongated particles having a maximum dimension in excess of four times the minimum dimension.

3.3.2   Grout mix

According to the Dam Contract the water/cement ratio (W/C) may vary from 5:1 to 0.5:1, in consideration of geological condition in this project area, stable grout with water cement ratios from 2:1 to 0.5:1 were to be used for grouting works, to improve the properties of grout mix, certain percentage of bentonite and plasticizer (PCA-1) added into the grout mix.

Laboratory test had been performed on different W/C ratios grout mixes from 2:1 to 0.5:1. According to the grout mix test results, the following tabulated grout has been used for the grouting works of this project. Please see Table 3-3 and see Figure A-6 in Appendix (A)

Table 3-4 Grout mixes selected for grouting work

Sample No.	W:C	Benton ite (%)	Sand (%)	PCA-I (%)	Density (g/cm^3)	Viscosity (s)	Bleeding Rate (%)	28d UCS (Mpa)
CG2-3-2	1.5：1	2.0		1.0	1.34~1.39	29~34	≤5	9.5
CG3-3-1	1：1	2.0		0.8	1.49~1.53	34~42	≤4	17.7
CG4-2-1	0.8：1	1.5		0.8	1.53~1.61	36~45	≤4	30.8
CG5-2-1	0.5：1	1.5		0.8	1.74~1.82	/	≤2	33.8
SG1-2	0.5：1	1.5	10	1.0	1.78~1.86	/	≤2	42.7
SG2-3	0.5：1	2.0	20	1.2	1.82~1.91	/	≤2	39.8
SG3-3	0.5：1	3.0	30	1.2	1.82~1.91	/	≤2	40.7

The routine test of grout mix has been carried out every three months or per 400t cement. At the same time, the Density, Marsh Viscosity and Temperature of grout mix have been checked and recorded every batch of grout mix at batching plant.

The temperature of grout shall not exceed 40℃ throughout the mixing and agitating period up to the time of injection. If the grout is more than 1 hours after mixing, the grout should be wasted and discarded accordingly.

For the geological condition with small grout take, the grout with a w:c ratio of 1.5:1 has been considered

3.3.3   Construction equipment and facilities

The main drilling and grouting equipments for grouting process are listed in Table 3-4.See figures (A-8, 9, 10, 11, 12, 13 and 14) in Appendix (A)

Table 3-5 Main equipment for grouting process

Description	Type
Drilling rig	XY-2
Air compressor	XAVS836
Grouting Pump	3SNS
Centrifugal water pump	D100
Grouting packer (hydraulic type)	DYS
Grouting Recorder	CFEC-GMS-2008
High-speed Mixer	1500L
Low-speed Agitator	D-200
Grout-mixing Plants	JB-1.5
Water level indicator	SWJ-90 50M
Inclinometer	KXP-1S
Manometers	1~4MPa
Dial indicator	
Slurry test instrument	
Fast reaction switch for stopping pump	

3.3.4   Installation of Uplift Monitoring Device

In order to avoid ground uplifts because of high pressure or other factors during grouting process, uplifting monitoring device installed to monitor the uplift of grout cap or rock mass.

Generally, it's considered that the installing the uplift monitoring device for every grout cap concrete block, namely, one uplifting monitoring device one concrete block. The depth of uplift monitoring hole should be no less than 15m. The Structure and installation are shown in Figure 3-3.
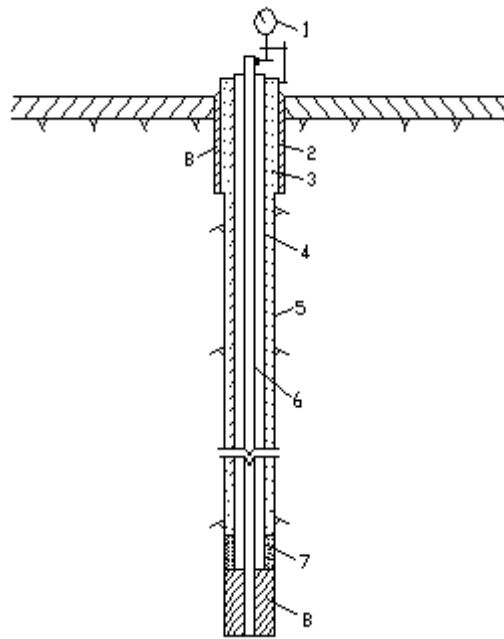
1-Dial gauge 2-Collar pipe 3-Fine sand 4-Protectiver pipe 5-Hole 6-Internal pipe

7-Sealing material (clay) 8-cement grout

Figure 3-3 Uplift Monitoring Device

During grouting, especially during grouting in upper rock mass, process control shall be strengthened and uplift shall be carefully monitored. Besides, concrete cover and surrounding rock mass should also be monitored. Once there is concrete crack or other uplift damage hint, grouting work shall be immediately stop and shall be prompt notified. The reason shall be clarified and treatment shall be performed.

3.3.5   Construction procedure of Curtain Grouting

The curtain grouting on right bank dam is arranged as single row with 2m interval, and the bottom line is about EL.467m. The curtain grouting hole has been started by the drilling of primary holes with a distance of 8m. Secondary holes with a distance of 4m were midway between the primary holes, and tertiary hole with a distance of 2m were midway between the primary holes and the secondary holes.

Curtain grouting works had performed by the procedure of split spacing method, which means: firstly, Primary hole, secondly, Secondary hole, thirdly, Tertiary hole. Normally, the ascending grouting procedure had adopted, while the geological condition was complicated, such as highly weathered or fractured, where ascending grouting procedure is unsuitable, then descending grouting procedure could have been used after approval from the Engineer.

The ascending grouting procedure and descending grouting procedure are shown as **Figures 3-4** and **3-5.**

```
┌─────────────────────────────┐
│    Setting up of drill rig  │
└─────────────────────────────┘
              │
              ▼
┌─────────────────────────────┐
│    Drilling to design depth │
└─────────────────────────────┘
              │
              ▼
┌─────────────────────────────┐
│          Flushing           │
└─────────────────────────────┘
              │
              ▼
┌─────────────────────────────┐
│       Setting packer        │
└─────────────────────────────┘
              │
              ▼
┌─────────────────────────────┐
│ Water pressure test (bottom stage) │
└─────────────────────────────┘
              │
              ▼
┌─────────────────────────────┐
│    First stage grouting     │◄─────────┐
└─────────────────────────────┘          │  Redrilling and regrouting
              │                           │
              ▼                           │
┌─────────────────────────────┐          │
│    Completion criterion?    │──────────┘
└─────────────────────────────┘   No
         │ Yes
         ▼
┌─────────────────────────────┐
│    Second stage grouting    │◄─────────┐
└─────────────────────────────┘          │  Redrilling and regrouting
              │                           │
              ▼                           │
┌─────────────────────────────┐          │
│    Completion criterion?    │──────────┘
└─────────────────────────────┘   No
         │ Yes
         ▼
┌─────────────────────────────┐
│     Next stage grouting     │◄─────────┐
└─────────────────────────────┘          │  Redrilling and regrouting
              │                           │
              ▼                           │
┌─────────────────────────────┐          │
│    Completion criterion?    │──────────┘
└─────────────────────────────┘   No
         │ Yes
         ▼
┌─────────────────────────────┐
│   Grouting for other stage  │
└─────────────────────────────┘
              │
              ▼
┌─────────────────────────────┐
│        Hole sealing         │
└─────────────────────────────┘
```

Figure 3-4: Ascending grouting procedure

```
                    ┌─────────────────────────────┐
                    │    Setting up of drill rig   │
                    └──────────────┬──────────────┘
                                   ▼
                    ┌─────────────────────────────┐
                    │     Drilling of first stage   │
                    └──────────────┬──────────────┘
                                   ▼
        ┌────────────────────────────────────────────────┐
        │ Flushing hole, water pressure test (if need) and grouting │◄──┐
        └──────────────────┬─────────────────────────────┘   │
                           ▼                         Redrilling and regrouting
                ┌────────────────────────┐              │
                │   Completion criterion? │──────────────┘
                └───────────┬────────────┘        No
                       Yes  ▼
        ┌────────────────────────────────────────────────┐
        │ Drilling, flushing and water pressure test (if need) for second │
        └──────────────────┬─────────────────────────────┘
                           ▼
                ┌────────────────┐
                │     Grouting    │◄──────────────┐
                └───────┬────────┘       Redrilling and regrouting
                        ▼                        │
                ┌────────────────────────┐        │
                │   Completion criterion? │────────┘
                └───────────┬────────────┘    No
                       Yes  ▼
        ┌────────────────────────────────────────────────┐
        │ Drilling, flushing and water pressure test(if need) for next stage │
        └──────────────────┬─────────────────────────────┘
                           ▼
                ┌────────────────┐
                │     Grouting    │◄──────────────┐
                └───────┬────────┘       Redrilling and regrouting
                        ▼                        │
                ┌────────────────────────┐        │
                │   Completion criterion? │────────┘
                └───────────┬────────────┘    No
                       Yes  ▼
        ┌────────────────────────────────────────────────┐
        │ Drilling, flushing and water pressure test(if need) and grouting for other stage │
        └──────────────────┬─────────────────────────────┘
                           ▼
                ┌────────────────┐
                │   Hole sealing  │
                └────────────────┘
```

Figure 3-5 Descending grouting procedure

3.3.5.1 Drilling

(1) Drilling without core recovery

The holes drilled through the embedded PVC pipe to the rock foundation. XY-2 geological rotary drill has been used for curtain drilling works.

The rotary or percussion drilling method has been used for non-coring drilling.

 (2) Drilling with core recovery

All guide holes and control holes have been drilled with core recovery.

XY-2 geological rotary drill with coring type bits is to be used for core recovery. A core recovery of at least 95% should be assured in sound rock and 80% in weathered and fractured rock and in soils of any nature. Drilling should be stopped and the cores

removed from the barrel as often as is necessary to secure the required core recovery. The maximum run should be controlled within 3m.

Enough strong core boxes, 1.1 m long, of wood, should have been available on the site. In the boxes provided with hinged covers and with longitudinal spacers that was formed 5 separate compartments so that each box was hold cores from 5 m of the hole.

The core should be carefully extracted from the core barrel and stored in core boxes in the correct orientation and sequence. All cores should be marked with an arrow in the direction of drilling. Wooden blocks which fit between the longitudinal spacers with a clear and durable black inscription of the depth should be placed between each core run. The core boxes should be stored in weatherproof sheds in warehouse on site.

Figure 3-6: Rotary Drill XY-2

3.3.5.2 Location & Inclination of Drilling Hole

According to the requirements of Technical Specification, holes should be drilled within ±20cm of the positions and an accuracy of within 1 degrees of the angle of inclination specified.

The inclination of curtain holes has been measured by KXP-1S inclinometer.

3.3.5.3 Flushing of Drilling Hole

All holes should be thoroughly flushed from the bottom with high flow rate of water under pressure immediately after drilling. Water flushing should be continuing until the return water runs clear.

3.3.5.4 Water Pressure Test

The Lugeon test carried out in the pilot hole before grouting and control hole after grouting. Lugeon test is adopted for water pressure test. Generally, the length of test section is 5m.

The water pump had to be centrifugal type so as to produce stable flow and pressure. The test pressure used is shown in **Table 3-6**.

Table 3-6 Pressure for Lugeon Test

Stage No.	Depth （m）	Pressure (MPa)					Remark
		Phase 1	Phase 2	Phase 3	Phase 4	Phase 5	
1	0.0～5.0	0.1	0.2	0.3	0.2	0.1	
2	5.0～10.0	0.1	0.2	0.3	0.2	0.1	
3	10.0～15.0	0.1	0.3	0.5	0.3	0.1	
4	15.0～20.0	0.1	0.3	0.5	0.3	0.1	
5	20.0～25.0	0.3	0.5	0.7	0.5	0.3	
6	25.0～30.0	0.3	0.5	0.7	0.5	0.3	
7	30.0～35.0	0.3	0.5	1.0	0.7	0.5	
8	35.0～40.0	0.3	0.5	1.0	0.7	0.5	
9	40.0～45.0	0.3	0.5	1.0	0.7	0.5	

Discharge measurements should be started only after a stable pressure has been established. For each pressure stage, water discharge should be measured every minute for 10 minutes per pressure stage. The time for each pressure stage should be at least 10 minutes and the total time for a completed Lugeon test comprising 5 phases of pressure should be at least 50 minutes.

If, due to high absorption, it is not possible to maintain the required pressure, the pump should be operated at its maximum discharge rate for 10 minutes and the pressure should be measured at 2 minutes intervals.

The lugeon test should be executed using centrifugal water pump. Before and after lugeon test the water level should be measured and recorded

3.3.5.5 Grouting

Grouting should be normally performed in stages by using the ascending stage method with hydraulic packer. For grouting holes required for water pressure test in full depth, water pressure test should be carried out in stages by using the descending stage method during drilling works, and then the holes should be grouted in stages by using the ascending stage method after the completion of all water pressure tests. In case poor geological condition is encountered, the descending stage method in stages can also be adopted for grouting works. In downstage grouting, enough time should be allowed for the grout to set before the next stage is commenced.

- *Length of grouting stage*
  Generally, the length of each grouting stage is 5m, if the permeability of the stage is less than 5 Lugeon, the stage may be included in the next stage.

But if poor geological condition is encountered, the length of grouting stage can be shortened.

- *Curtain grouting pressure*

According to Specification, fissure splitting should be avoided. The maximum grout pressure to be applied shouldn't be more than 2.5 MPa.

The pressure values listed in the following Table 3-6 are proposed for the curtain grouting on right-bank dam.

Table 3-7 Reference Pressure Value of Curtain Grouting

Depth of hole (m)	0-5	5-10	10-15	15-20	20-25	25-30	30-35
Pressure (MPa)	0.3	0.5	0.7	0.8	0.9	1.0	1.1
Depth of hole (m)	35-40	40-45	45~50	50~55	55~60	60~65	≥65
Pressure (MPa)	1.2	1.3	1.4	1.5	1.5	1.6	1.6

The grouting pressure should be the pressure of the inflow mixtures in the pipe at the collar of the hole, the fluctuation range of pressure should be less than 10% of the grouting pressure and the fluctuation extent be recorded carefully. The average grouting pressure at certain interval should be recorded by automatic grouting recorder.

- *Mixtures and water cement ratio (W/C)*

Stable mixtures, cement with addition of bentonite, should be used for curtain grouting. Water-cement ratio (by weight) varying from 1:1 to 0.5:1.

During the grouting the water/cement ratio should be decreased (the grout thickened), If necessary, until the required pressure is reached. If with the thickest mix, the required pressure cannot be reached, the grouting should be stopped, and the stage washed. Grouting should be resumed after 24 hours.

The grout mix has to be changed to a thicker mix when 1000 liters have been pumped without success.

- *Criterion for termination of grouting*

It is recommended that grouting of any hole should be considered as completed when at the refusal pressure the rate of grout less than 2 L/min per 5 m section during 5 minutes.

If the grout take of the bottom stage is more than 50kg/m or the lugeon value is more than 5, then a deeper stage may be necessary for grouting.

- *Hole sealing*

In case ascending stage grouting method is adopted for curtain grouting, the grout hole can be backfilled using cement mortar of W:C:S=0.5:1:10(SG1-2) after completing grouting.

In case descending stage grouting method is adopted for curtain grouting, the hole sealing has to be performed in full depth of hole by grouting mixtures with a W/C of 0.5:1 after completion of grouting.

If due to sedimentation of mixtures after completion of hole sealing, the empty

part of the upper hole has to be filled with dry-pack mortar and smoothed by hand.

- ***Treatment methods for special circumstance***
    a. During drilling process, if the stratum collapsing or drill bit clogging is encountered, stop drilling and record the depth, grouting this stage and after sufficient time for setting, the drilling works can be resumed.
    b. During grouting, in case sudden rise or drop of grouting pressure, sudden increase or decrease of grout take etc. are encountered, the cause should be investigated immediately, then adopting relevant treatment method.
    c. If, during grouting, there is a communication between the holes, the communicating position and volume should be found out. If communicating position is located at structural joint or underground instrument, the grouting works should be stopped immediately. When the communication is between grouting holes, specific plug should be caulked at 0.5~1m above the communicating section of the communicated holes. Continuing grouting and after completion of grouting and the grout has been set for 12 hours, then re-drilling, washing, drilling and grouting of the communicated holes.
    d. For the hole or section of a hole with gushing water during drilling, the pressure and volume of overflow water should be measured and recorded before grouting. When grouting, the gushing water pressure should include into the grouting pressure.
    e. While calculating the Lugeon value of the stage with overflow water, the pressure of overflow water should be considered.
    f. The grouting must be continuously performed without interruption. In case of interruption, grouting should be resumed as soon as possible. While resuming grouting, the grouting will be carried out with the same water-cement ratio as used at the start of grouting. If the injection rate is almost the same as before interruption, the grouting can be carried out with the water-cement ratio before interruption.
    g. For the stage with high injection rate, and the accumulated cement consumption more than 150kg/m, the area of structural joint and other places should be patrolled and checked carefully; traceable material may be used if necessary. If grout leakage is found, it should be treated by the methods mentioned in Item C. If there is no grout leakage, it should be grouted until the termination criterion of grouting is achieved. Measurements such as grouting interruption, intermittent grouting and grout set cannot be used.

- ***Treatment for stages with high mixtures consumption.***
    a. Reducing grouting pressure and limiting injection rate.
    b. With addition of accelerator in the thickest cement mixtures.
    c. More thicker cement-sand mixtures to be grouted.
    d. Intermittent grouting.

3.3.5.6   Inspection Hole (Check Hole)

1) The inspection hole drilled and cored with a diameter of 76mm. The water pressure test in sections of 5m performed within 30 days after the completion of curtain grouting in each unit. The pressure of water pressure test shouldn't be more than 10bar, or 80% of the grouting pressure, whichever is lower.

2) After the completion of water pressure test of inspection hole in full depth, the grouting and hole sealing should be performed with a caulker at hole orifice in full depth one time according to grouting requirements. The pressure of grouting and hole sealing should be the minimum grouting pressure at relevant area. The hole sealing is to be carried out by the methods above mentioned.

Figure 3-7: 3 SNS grouting pump and pressure control device

CHAPTER FOUR

CHAPTER FOUR

RESULTS AND DISCUSSION

4.1 Introduction

This chapter describes the analysis and discussion of the grouting works on Right Bank Dam foundation between CH. B1+600 to CH. B1+900 of Burdana dam in Dam Complex of Upper Atbara.

The section between CH. B1+ 600 to CH. B1+900 is presented by a layout with geological setting shown in Figure 4-1. Also layout of all grout, check and pilot holes and the evaluation of the grout takes as well as results of the permeability tests (Lugeon tests) had comprised in Figure (4-2).

The grouting works started with the vertical contact/consolidation grouting on both sides of the dam axis. Upstream, the depth of the E-series was limited to 6 m. The E-series is divided into primary holes with 8 m spacing, secondary holes with the same spacing but in staggered arrangement. The tertiary holes finally reduced the gap between primary and secondary holes from 4 m to 2 m spacing.

The same arrangement was designed downstream of the dam axis with a series called F. However, the total depth was limited to 3 m for the normal low takes.

Curtain grouting is arranged in one line on the axis of the dam. Primary holes (A-series), secondary holes (B-series) and tertiary holes (C-series) have the same spacing and inclination like those from contact/consolidation grouting. Only in case of high takes > 50 kg/m, the grout holes had to be re-drilled and deepened for another 5 m. However, the depth of the curtain depends on the permeability of the bedrock. The results of previous core drillings with Lugeon tests provide a first guideline for the bottom of the curtain. If no information is available, every 20th A-hole is designed as pilot hole, i.e. it must be drilled with full core recovery in 5 m sections followed by Lugeon tests comprising at least 5 pressure stages. The final depth of the pilot hole is defined by > 5 LU (Lugeon Units), which is the criterion for curtain grouting for the Upper Atbara Projects (DCUAP).

After completion of curtain grouting, check holes will be drilled with full core recovery and continuous Lugeon testing under inclined conditions to intersect as many grout holes as possible.

This method provides the efficiency criteria for the reduced permeability obtained in the bedrock as compared to the initial state.

Curtain grouting is completed when the LU remains below 5; i.e. the respective criteria for pervious bedrock. Sections above this value must be re-grouted in the check hole according to the Contract.

4.2   Geological Setting for the Section under Study

In general, the geological conditions are known through exploratory drill holes and also from pilot hole and check holes. The geological section has drawn using correlation between all available bore holes logs. The foundation of the grout cap was mapped geologically and the depth of the curtain was explored by pilot holes A6, A42 and A142.

Figure (4-1) describes the geological section of right bank dam (B1+600 to B1+900) for Burdana Dam. The geology is composed of Sandstone layer to more than 43 m depth intercalated with Silty sandstone layer (17.8 to 19.5m & 28.0 to 29.5m) with average thickness of (1.7&1.5m respectively) and also intercalate with Siltstone layer (25.5 to 27.5m) with average thickness 2 m.

4.3   Results of Lugeon Tests

The permeability of the bedrock was investigated by Lugeon tests before and after grouting. The vertical pilot holes A6, A42 and 142 present the data for the first case and three inclined check holes for the second case.

Before grouting, the permeability decreases in general in the sandstone with increasing depth. The variations of pressure steps within one test indicate for many stages the gradual filling of the voids in the joint system.

  After grouting the permeability was found to be reduced in the sandstone in CH1, CH2 and CH3 over the depth. However, the character of the Lugeon tests indicates a gradual filling of the void system.

The three check holes reached into the design depth of curtain. The permeability tests display complete success of the grouting works. At all pressure stages the criterion for acceptance remained below 5 LU. The summary of pilot holes and check holes Lugeon test results shown in **Table 4-3**.

4.4   Grouting Works

The first activity for grouting comprised contact/consolidation grouting to seal mainly artificial cracks caused by the excavation works of the foundation of the dam. Hence the depth is limited to 6 m upstream of the dam axis and to 3 m on the downstream side.

The grout pressure was strictly limited to 2 bars in order to avoid any hydraulic fracturing with excessive takes and consequently any upheave of the grout cap.

In a second step, curtain grouting was arranged to seal potential leakage paths below the dam. The depth is based on the sequence of strata and/or the permeability of the bedrock. According to the Contract, the grout pressure was also limited to avoid artificial cracking of bedding and/or joint planes for both technical and economic reasons.

4.4.1   Contact/Consolidation Grouting Results and Analysis

Figure 4-2 displays the grout takes in kg/m on the location map. The results can be summarised as follows in Table 4-1

Table 4-1 Distribution of Solid Takes with Contact/Consolidation Grouting

Upstream (E-series, 6 m deep)		Downstream (F-series, 3 m deep)	
Ranking	Content [%]	Ranking	Content [%]
Very low	-	Very low	-
Low	15	Low	46
Intermediate	64	Intermediate	38
High	21	High	15

The variation of grout takes with regard to the sequence of grouting is compiled in **Table 4-2** below:

Table 4-2 Range of Solid Takes with Contact/Consolidation Grouting

Upstream (E-series, 6 m deep)		Downstream (F-series, 3 m deep)	
Sequence	Range [kg/m]	Sequence	Range [kg/m]
Primary hole	10.5 - 47.8	Primary hole	8.0 - 75.5
Secondary hole	10.5 - 44.9	Secondary hole	8.8 - 43.1
Tertiary hole	10.9 - 48.4	Tertiary hole	8.6 - 45.8

[More contact/consolidation grouting details shown in **Tables 4-5** and **4-6**]

Due to the special conditions of this type of grouting, i.e. sealing natural joints and artificial cracks at the rock surface, a logic ranking within the sequence of grouting cannot be expected. However, the distribution of solid takes on the layout (vide Figure 4-2) permits the evaluation of the direction of potential leakage paths which have been sealed by the grouting works.

4.4.2   Curtain Grouting Results and Analysis

In the section shown in **Figure 4-2**, the depth of the curtain ranged from 34 m in the NNE to 29 m in the SSW.

According to the statistics, the curtain grouting totally consumed cement 94892.87kg, Bentonite 1892.22kg and PCA-I 759.55kg. The sequence holes (primary) unit take is 29.38kg/m, the sequence B holes (secondary) unit take is 21.17 kg/m, the sequence C holes (tertiary) unit take is 14.45 kg/m and the average unit take is 19.87 kg/m. See **Table 4-4.**

Permeability and sequence of strata were explored by vertical pilot holes A6, A42 and A142 down to 30.15, 30.58 and 34.76 m respectively. Check holes CH 1, CH2 and CH 3 were drilled after curtain grouting finished. The former three intersect the primary, secondary and tertiary grout holes.

The permeability results before and after grouting are summarised in the following **Table 4-3.**

The holes for the curtain were grouted from bottom to top starting with A-series as primary holes, in distances of at least 8 m to avoid any circulation with adjacent grout holes. In general it is expected that the primary holes absorb the highest takes of grout mix.

As a matter of fact very low to intermediate takes have been observed in primary (A) holes at the NNE part and low takes at the SSW part of this grouting section. Secondary and tertiary holes took very low to low quantities at the NNE part. It had also very low takes in the SSW part of the section. The majority of the grouted stages display very low to low takes in the silty-sandstone.

It has to be concluded that the very low to low takes in all grout holes resemble the true permeability, whereas the intermediate takes are caused by opening of joint and/or bedding planes in this impervious, but sensitive rock type.

The efficiency of the sealing works display low to very low takes in the sandstone, which indicates a more or less homogeneous series with few open joints and/or bedding planes.

The range of grout takes is compiled below displaying the normal sequence of decreasing takes from the first to the last sequence which indicates the general success of the sealing works.

- Primary holes (A)   6.7 – 108.0   kg/m

- Secondary holes (B) 6.2 – 60.9   kg/m

- Tertiary holes (C)   3.9 – 40.4   kg/m

The evaluation of the grout takes in the check holes reveals that CHl, CH2 and CH3 consumed 2.8 to 40 kg/m (on average 6.3 kg/m) after grouting primary to tertiary holes.

The efficiency of the grouting is represented by the respective Lugeon units of the permeability tests.

Total grouting solid material calculated from curtain grouting and contact/consolidation grouting at Burdana Dam, dyke and under Spillway shown in payment documents when we compare it with tender document shown in Figure A-7 & A-8 in Appendix (A), we found that the beg different (about 18 times) between estimated materials value and the actual material used in grouting issues.

Total actual grout solid material= 971 Ton

Consolidation grout total solid matters take =170326.14kg
Curtain grout total solid matters take = 590720.02kg (from payment documents)

Total estimated grout solid material = 22,290 Ton
As shown in figure (A-7) & (A-8)

Table 4-3 Permeability before and after curtain grouting with primary to tertiary grout holes

Pilot Hole									
	A6			**A42**			**A142**		
	Rock	LU	k_f[m/s]	Rock	LU	k_f[m/s]	Rock	LU	k_f[m/s]
1st Stage	Sdst.	10.1	1.3×10^{-6}	Sdst.	7.4	1.0×10^{-6}	Sdst.	37.3	4.8×10^{-6}
2nd Stage	Sdst.	28.9	3.8×10^{-6}	Sdst.	28.6	3.7×10^{-6}	Sist./ Sdst	6.1	0.8×10^{-6}
3rd Stage	Sdst	8.0	1.0×10^{-6}	Sdst	43.5	5.6×10^{-6}	Sdst	8.9	1.2×10^{-6}
4th Stage	Sdst	24.6	3.2×10^{-6}	Sist./ Sdst	10.3	1.3×10^{-6}	Sist./ Sdst	15.5	2.0×10^{-6}
5th Stage	*Sdst	47.7	6.2×10^{-6}	Sdst	6.0	0.8×10^{-6}	Sdst	2.8	0.4×10^{-6}
6th Stage	Sdst./Sist.	8.2	1.1×10^{-6}	Sdst./Sist.	0.8	0.1×10^{-6}	Sdst./Sist.	13.7	1.8×10^{-6}
Average		**21.3**	$\mathbf{2.8\times10^{-6}}$		**16.1**	$\mathbf{2.1\times10^{-6}}$		**14.1**	$\mathbf{1.8\times10^{-6}}$

Check Holes (after grouting primary to tertiary series)									
	CH1			**CH2**			**CH3**		
	Rock	LU	k_f[m/s]	Rock	LU	k_f[m/s]	Rock	LU	k_f[m/s]
1st Stage	Sdst.	4.0	0.5×10^{-6}	Sdst.	5.9	0.8×10^{-6}	Sist./ Sdst	1.3	0.2×10^{-6}
2nd Stage	Sdst.	4.5	0.6×10^{-6}	Sdst.	4.0	0.5×10^{-6}	Sdst./Sist.	1.7	0.2×10^{-6}
3rd Stage	Sdst.	4.6	0.6×10^{-6}	Sdst.	3.4	0.4×10^{-6}	Sist.	2.4	0.3×10^{-6}
4th Stage	Sist./ Sdst.	4.0	0.5×10^{-6}	Sist.	3.2	0.4×10^{-6}	Sist.	1.0	0.1×10^{-6}
5th Stage	Sdst.	3.6	0.5×10^{-6}	Sdst./Sist.	1.4	0.2×10^{-6}	Sist.	0.8	0.1×10^{-6}
6th Stage	Sdst.	2.1	0.3×10^{-6}	Sist.	2.2	0.3×10^{-6}	Sdst.	1.4	0.2×10^{-6}
7th Stage	Sdst.	1.8	0.2×10^{-6}	Sist.	3.0	0.4×10^{-6}	Sdst./Sist.	0.5	0.1×10^{-6}
8th Stage	Sdst./Sist.	2.6	0.3×10^{-6}	-	-	-	-	-	-
9th Stage	Sist.	2.5	0.3×10^{-6}	-	-	-	-	-	-
Average		**3.3**	$\mathbf{0.4\times10^{-6}}$		**3.3**	$\mathbf{0.4\times10^{-6}}$		**1.3**	$\mathbf{0.2\times10^{-6}}$

(* high value based on cracking of joint and/or bedding planes); sdst. = sandstone, sist. = siltstone

Table 4-4 Comprehensive Statistic Table of Curtain grouting

Project: Dam Complex of Upper Atbara Project   Location: Right Bank Dam (Ch B1+600 - Ch B1+900)

Item	Seq.	Hole No.	Length grouted (m)	Dry material Injected (kg)	Unit take (kg/m)	Unit take (kg/m)section[Stage Qty./Frequency]					
						Total stages Qty.	2-20	20-60	60-150	150-300	>300
Curtain grouting	A	39	1228.24	36085.00	29.38	250	125	91	34	0	0
						100.0%	50.0%	36.4%	13.6%	0.0%	0.0%
	B	39	1229.26	26022.23	21.17	250	151	98	1	0	0
						100.0%	60.4%	39.2%	0.4%	0.0%	0.0%
	C	156	2452.47	35436.41	14.45	499	365	134	0	0	0
						100.0%	73.1%	26.9%	0.0%	0.0%	0.0%
	Total	234	4909.97	97543.64	19.87	999	641	323	35	0	0
						100.0%	64.2%	32.3%	3.5%	0.0%	0.0%

Table 4-5 Comprehensive Statistic Table of Contact/Consolidation grouting E series (Upstream

Project：Dam Complex of Upper Atbara Project   Location：Right Bank Dam (Ch B1+600 - Ch B1+900)

Item	Seq.	Hole No.	Length grouted (m)	Dry material Injected (kg)	Unit take (kg/m)	Unit take(kg/m) section[Stage Qty./Frequency]				
						Total stage Qty.	1-5	5.1-15	15.1-30	>30.1
Contact/Consolidation grouting	I	37	229.89	7939.20	34.53	37	0	0	20	17
						100.0%	0.0%	0.0%	54.1%	45.9%
	II	37	227.47	6072.09	26.69	37	0	0	22	15
						100.0%	0.0%	0.0%	59.5%	40.5%
	III	75	465.99	8141.00	17.47	75	0	22	53	0
						100.0%	0.0%	29.3%	70.7%	0.0%
	Total	149	923.35	22152.29	23.99	149	0	22	95	32
						100.0%	0.0%	14.8%	63.8%	21.5%

Table 4-6 Comprehensive Statistic Table of Contact/Consolidation grouting F series (Downstream)

Project：Dam Complex of Upper Atbara Project   Location：Right Bank Dam (Ch B1+600 - Ch B1+900)

Item	Seq.	Hole No.	Length grouted (m)	Dry material Injected (kg)	Unit take (kg/m)	Unit take(kg/m) section[Stage Qty./Frequency]				
						Total stage Qty.	1-5	5.1-15	15.1-30	>30.1
Contact/Consolidation grouting	I	38	121.04	3281.53	27.11	38	0	1	19	18
						100.0%	0.0%	2.6%	50.0%	47.4%
	II	37	117.12	2466.01	21.06	37	0	16	16	5
						100.0%	0.0%	43.2%	43.2%	13.5%
	III	74	237.47	3188.84	13.43	74	0	52	22	0
						100.0%	0.0%	70.3%	29.7%	0.0%
	Total	149	475.63	8936.38	18.79	149	0	69	57	23
						100.0%	0.0%	46.3%	38.3%	15.4%

FIGURE (4 -2): GEOLOGICAL SECTION OF RIGHT BANK DAM (C1-B)
CH1+600--CH1+900

Figure 4-1 Geological Section of Right Bank Dam (C1-B) Ch1+600--Ch1+900
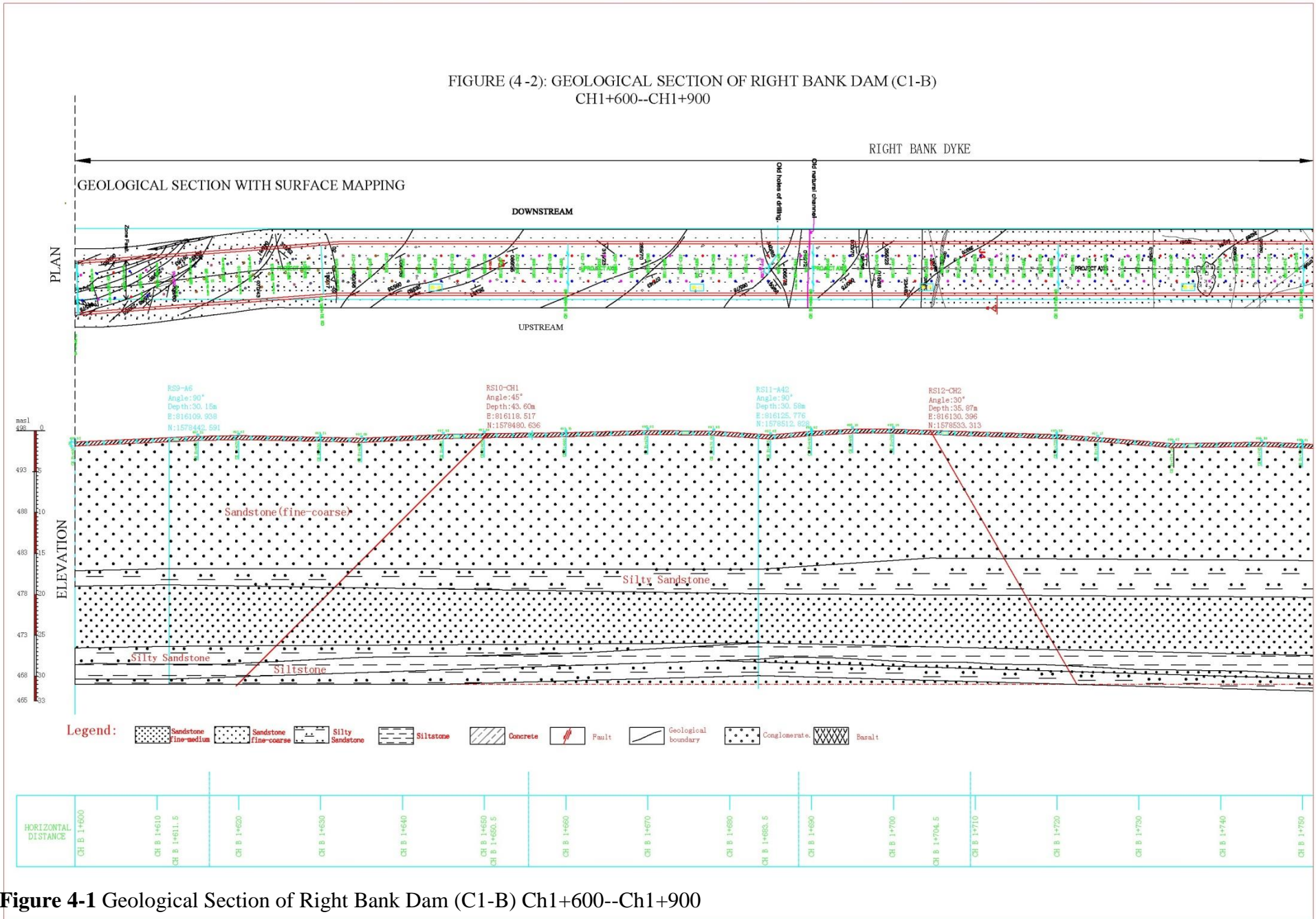
Cont. FIGURE (4 -2): GEOLOGICAL SECTION OF RIGHT BANK DAM (C1-B)
CH1+600--CH1+900
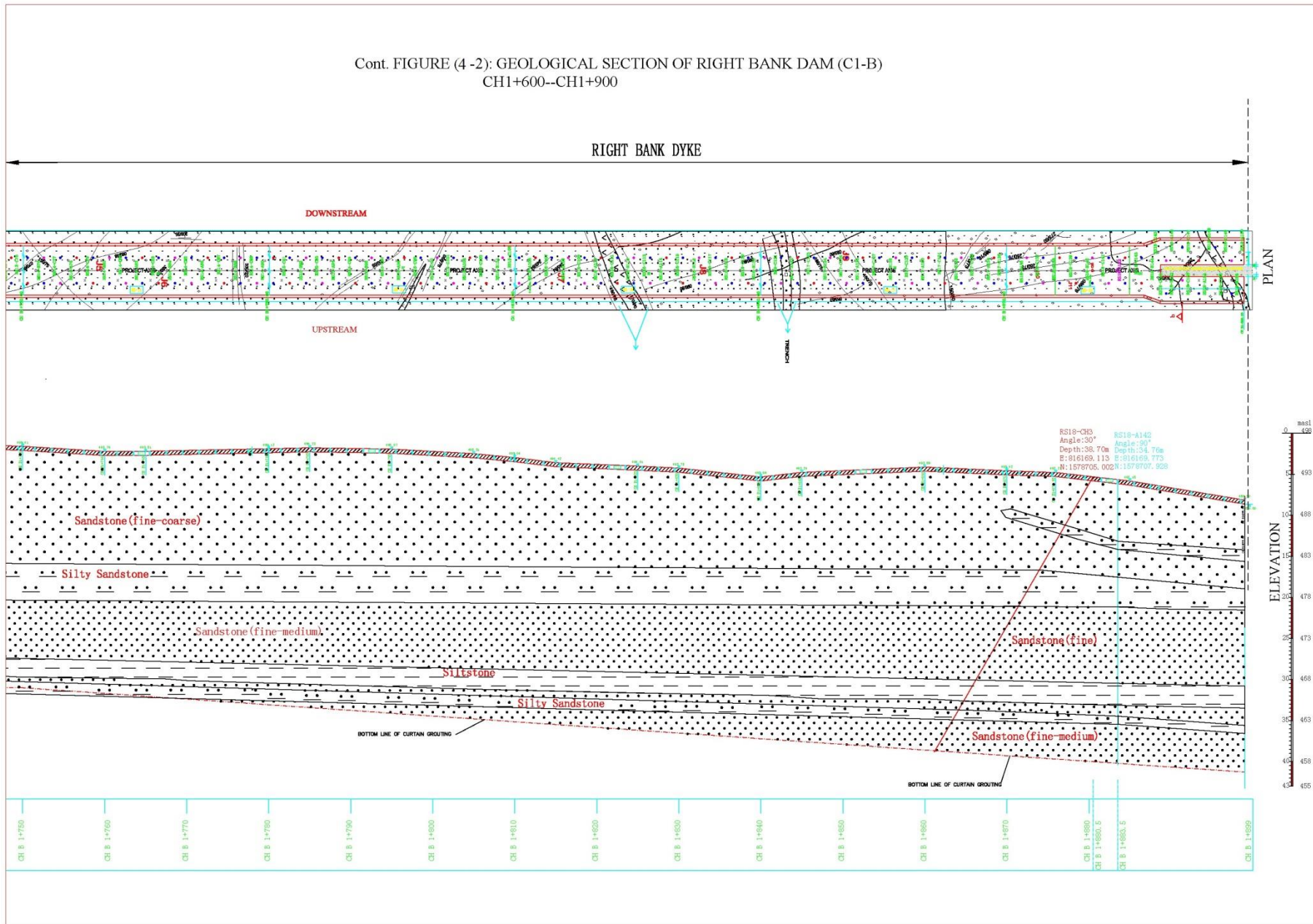
Cont. Figure 4-1 Geological Section of Right Bank Dam (C1-B) Ch1+600--Ch1+900
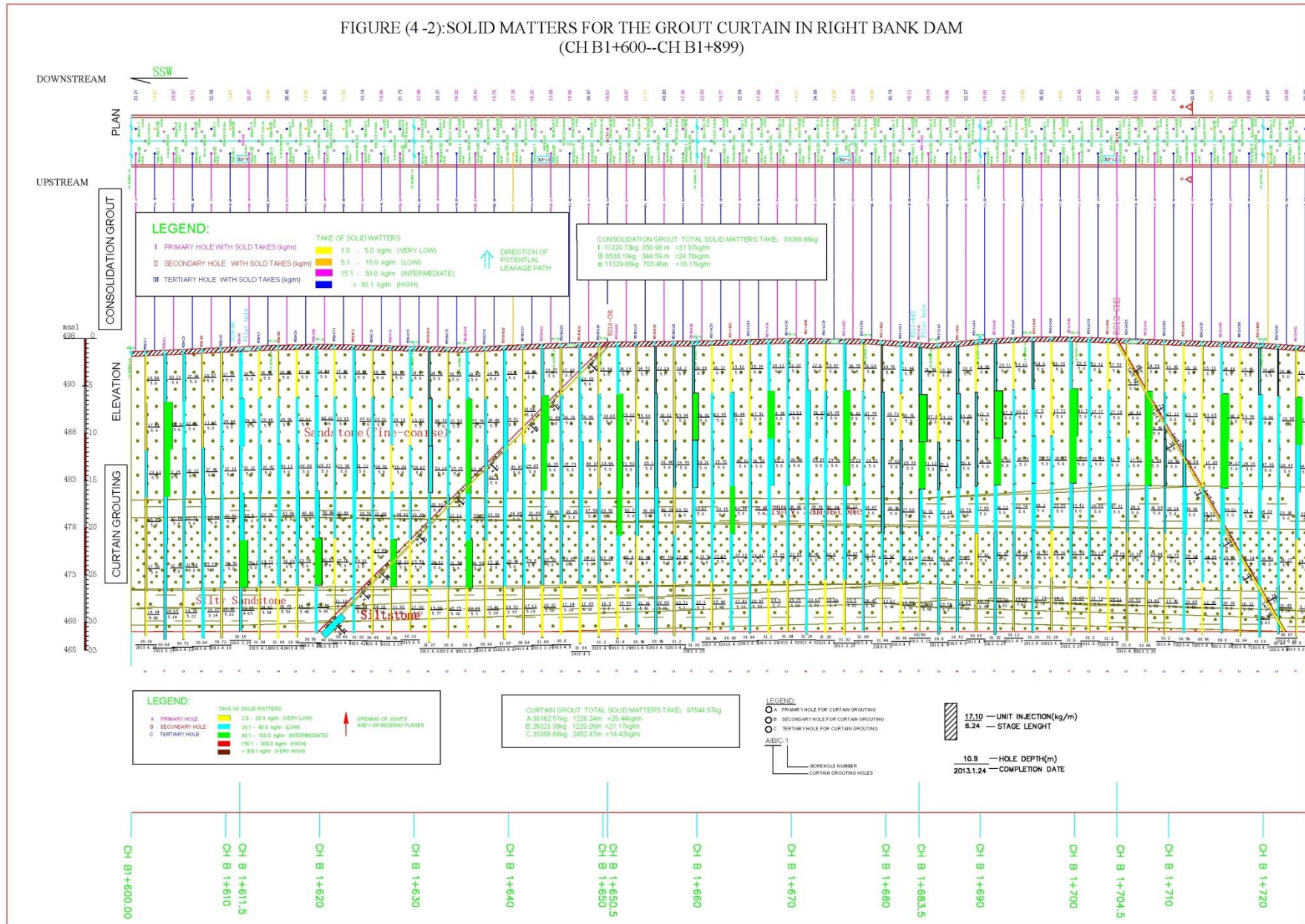
Figure 4-2 Solid Matters for the Grout Curtain In Right Bank Dam (CH B1+600--CH B1+899)
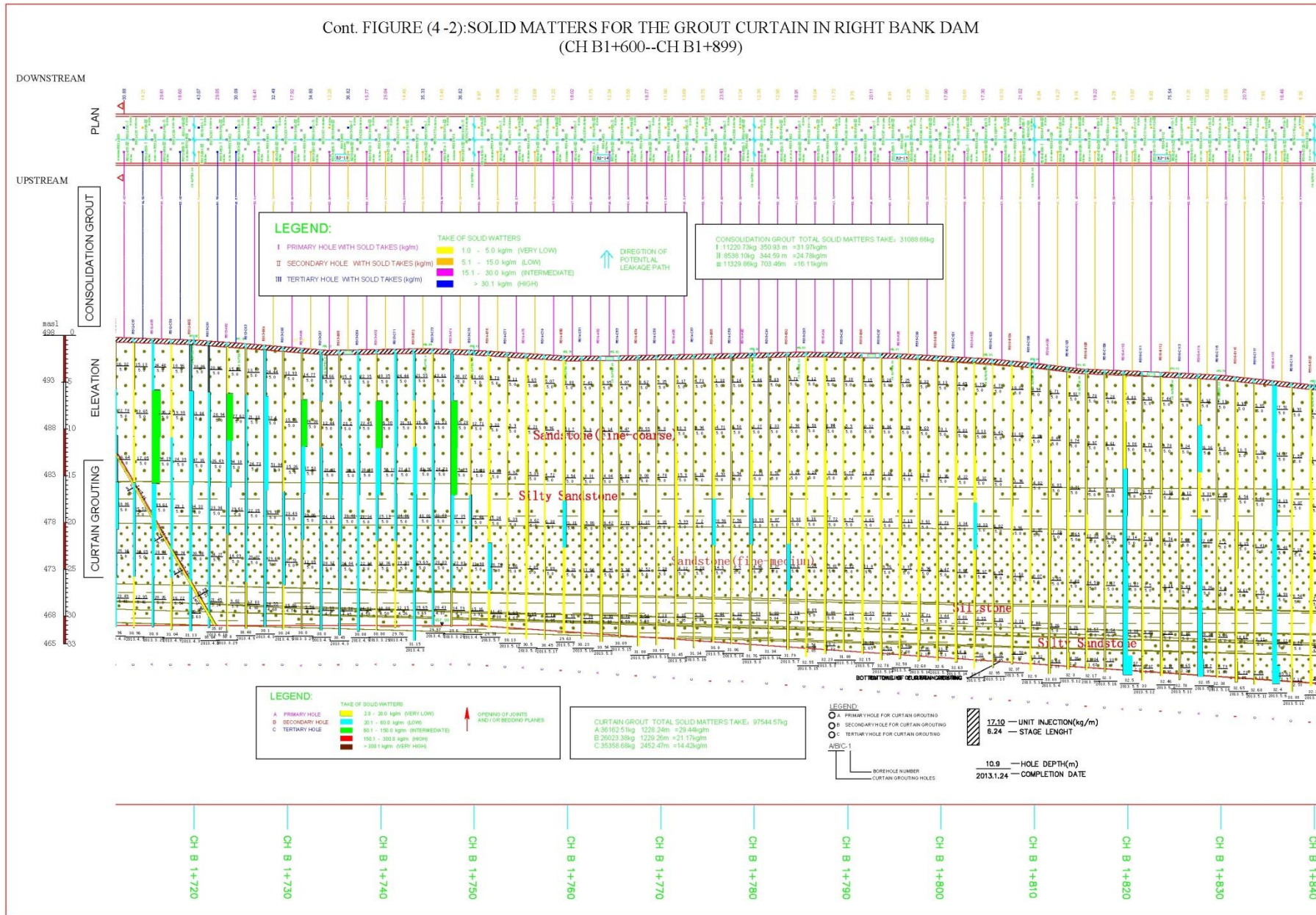
Cont. Figure 4-2 Solid Matters for the Grout Curtain In Right Bank Dam (CH B1+600--CH B1+899)
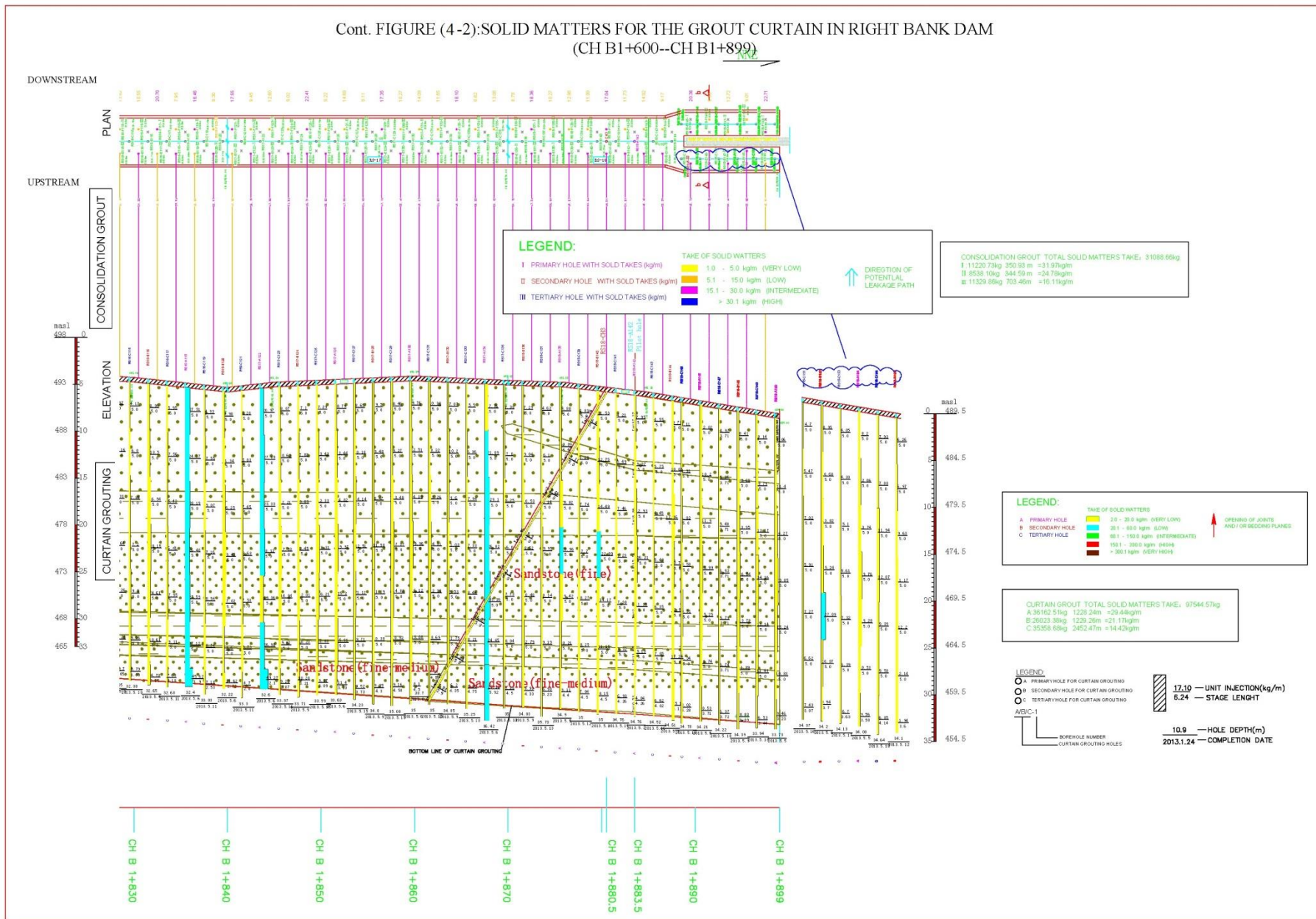
Cont. Figure 4-2 Solid Matters for the Grout Curtain In Right Bank Dam (CH B1+600--CH B1+899)

CHAPTER FIVE

CHAPTER FIVE

CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions of the Grouting Works

From the discussion and analysis of the grouting results performed in this thesis some conclusions can be drawn, regarding the original/general design, the local adaption, and the evaluation of the grouting results. Those include:

5.1.1 Initial Curtain Grouting Design

1- The first curtain grouting design refers to highly feasible of it to keep the reservoir as watertight as possible by reducing the leakages under the dam.
2- It's recommended to apply the percussion drill method as fast and economic means for the grout holes. Uphole grouting with a cement-bentonite mix was the preferred procedure for all sealing works.
3- The criterion for the lower limit of the grout curtain was selected to be 5 Lugeon units (LU) for technical and economic reasons.
4- Maximum pressure is recommended to be 1 bar below hydraulic fracturing.

5.1.2 Evaluation of Grouting Results

1- The grouting works succeeded and met the requirements of the design for subsection analyzed, where the Lugeon value of the check hole after grouting was less than (5) LU.
2- The grout take for primary, secondary and tertiary holes (A, B and C series) displaying the normal sequence of decreasing takes from the first to the last sequence which indicates the general success of the sealing process.
3- The analysis of Lugeon values for pilot holes before grouting and check holes after grouting concluded that the permeability improved to about 85%.
4- The estimated grout takes in the design documents (BoQ) is very higher compared to the real grout absorption in the site which is less than the contract by more than 18 times approximately.

5.2   Recommendations for Future Researches

The work on this project has highlighted several areas where further work would be of benefit in the Sudan. There are future researches that can be done in order to aid the development of better grouting techniques, as well as optimization of the grouting process. Few ideas for future researches are outlined below:

1- Expanding on analysis of DCUAP's curtain grouting and compare it with another dam projects in Sudan, as well as looking into bill of quantities, budget and cost for the grouting works at the different projects.

2- Evaluation of the curtain grouting performance during the DCUAP operation.

3- Redesign for curtain grouting applied at the DCUAP and compare it with the Tender Design.

4- Further inspect in the penetration ability and properties of different grouting cements, also inspecting new combinations of cement with additives.

5- Study the possibility of using chemical grouting in the dam foundation improvement and its environmental impact.

References

1. Aminfar, M. H., et. al (2009). "Change of pore water pressure inside the foundation of alavian earthfill dam, iran: A comparison between observed and predicted values." Journal of Applied Sciences (Faisalabad) 9.

2. Arthur, H. (1977). "Teton Dam Failure." Engineering Foundation Conference Proceedings, New York.

3. Berhane, G. and Walraevens, K. (2013). "Evaluating core drilling and lugeon test for the proposed geba dam site, Northern Ethiopia." Abstracts - Colloquium of African Geology (CAG) 24.

4. Bliss, J., Rushton, K. (1984). "The reliability of packer tests for estimating the hydraulic Conductivity of aquifers." Quarterly Journal of Engineering Geology.

5. Bruce D.A. (1982). "Aspects of Rock Grouting Practice on British Dams." ASCE Geotechnical Engineering Specialty Conference on Grouting, New Orleans, LA February 10-12, 1982.

6. Chialvo, J.: Etude des sites de barrage de Rumela et Burdana. Thesis, Grenoble, (1975)

7. Cotton, E.N. and Matheson, G.M., (1990) "Numerical Simulation of Concrete Dam Foundation Seepage and Uplift Pressure Distribution", Rock Mechanics Contributions and Challenges, Hustrulid and Johnson, Eds., Balkema, Rotterdam

8. Dam Complex Of Upper Atbara Project (DCUAP), Design Review Report, Lahmeyer International, June 2010

9. Dam Complex of Upper Atbara Project (DCUAP), Geological Report SOGREAH, October 2009

10. Dam Implementation Unit, Sudan, 2017 "Dam Complex of Upper Atbara Project Design and Construction Documents"

11. Deere, D.U. (1982), "Cement-Bentonite Grouting For Dams." Proceedings of the ASCE Specialty Conference in Grouting in Geotechnical Engineering, New Orleans, Louisiana, Feb. 10-12.

12. Cement-bentonite grouting for dams, in Issues in Dam Grouting, ASCE Getech. Engineering, Editor Baker, W.H.

13. Deere, D.U. and Lombardi, G. (1985). Grout slurries-thick or thin, in Issues in Dam Grouting, Editor Baker, W.H., ASCE Geotech. Engineering Division, Denver.

14. Ewart, F.K. (1985). Rock grouting with emphasis on dam sites. Springer-Verlag.

15. Ewert, F.K. (1985). "Rock Grouting with Emphasis on Dam Sites". Springer Verlag Berlin Heidelberg

16. Fell, R., MacGregor, P. & Stapledom, D. and Bell, G.(2005). Geotechnical Engineering of Dams, A.A. Balekma, London.

17. Geotechnical Investigation Final Report for Dam Complex of Upper Atbara Project (DCUAP), Part 1: Field Works Reports, Vol. VI, Appendices F H, ESD, January 2009

18. Hayward Baker. (2014), Website, http://www.haywardbaker.com/WhatWeDo/ Techniques/Default.aspx, February 15th, 2014

19. Hong, W., et. al (2003). "Cut-off effect by rock grouting in the area of dam foundation". ISOPE-2003: Thirteenth (2003) International Offshore and Polar Engineering Conference; Honolulu, HI; USA; 25-30 May 2003 (May 25).

20. Houlsby, A. C. (1990). "Construction and Design of Cement Grouting". Wiley Series of Practical Construction Guides.

21. Houlsby, A.C., (1976). "Routine Interpretation of Lugeon Water Test." Quarterly Journal of Engineering Geology.

22. Lombardi, G. (2003), "Grouting of Rock Masses" ASCE Third International Conference on Grouting and Ground Treatment - New Orleans, Louisiana, United States.

23. Lugeon, M. (1933). Barrage et Geologie. Dunod. Paris.

24. Powers, P., Corwin, A., Schmall, P. and Kaeck, E. (2007). "Construction Dewatering and Groundwater Control-New Methods and Applications," John Wiley and Sons, Inc., Hoboken, New Jersey, Third Edition.

25. Quinones-Rozo, C. (2010). "Lugeon Test Interpretation, Revisted." Collaborative Management of Integrated Watersheds.

26. Quinn, P. M., J.A. Cherry and B.L. Parker, (2011). "Quantification of non-Darcian flow observed during packer testing in fractured sedimentary rock." Water Resources Research,

27. Sadeghiyeh, S. M., M. Hashemi, and R. Ajalloeian. (2013). "Comparison of permeability and groutability of Ostur dam site rock mass for grout curtain design." Rock Mechanics and Rock Engineering,

28. Kenji, S. and Hiroyuki, T. (2012). "The study of quantification method for nondarcy effect in lugeon-test." Journal of Japan Society of Dam Engineers,

29. Upper Atbara Dam Final Report of Investigation by Boreholes. Swissboring, May 1975

30. Weaver, K. D. – Bruce, D. A. (2007). "Dam Foundation Grouting: Revised and Expanded Edition". American Society of Civil Engineers, ASCE Press.

31. Willowstick Technologies LLC, (2016) "Willowstick Technology Used For Mapping and Modeling Groundwater Systems." White Paper, Willowstick Technologies, LLC, Draper, Utah.

32. Wilson, D.B and Dreese, T.L. (1998) "Grouting Technologies for Dam Foundations", Proceedings of the 1998 Annual Conference Association of State Dam Safety Officials, October 11-14, Las Vegas, Nevada.

33. Wilson, D.B., and T.L. Dreese. (1997). "Grout curtain design for dams." Proc. of the Association of State Dam Safety Officials, 14th Annual Conference, Pittsburgh, PA, September 7-10, Compact Disc.

Appendix (A)

- **Grout Design Documents**
- **Execution equipment**
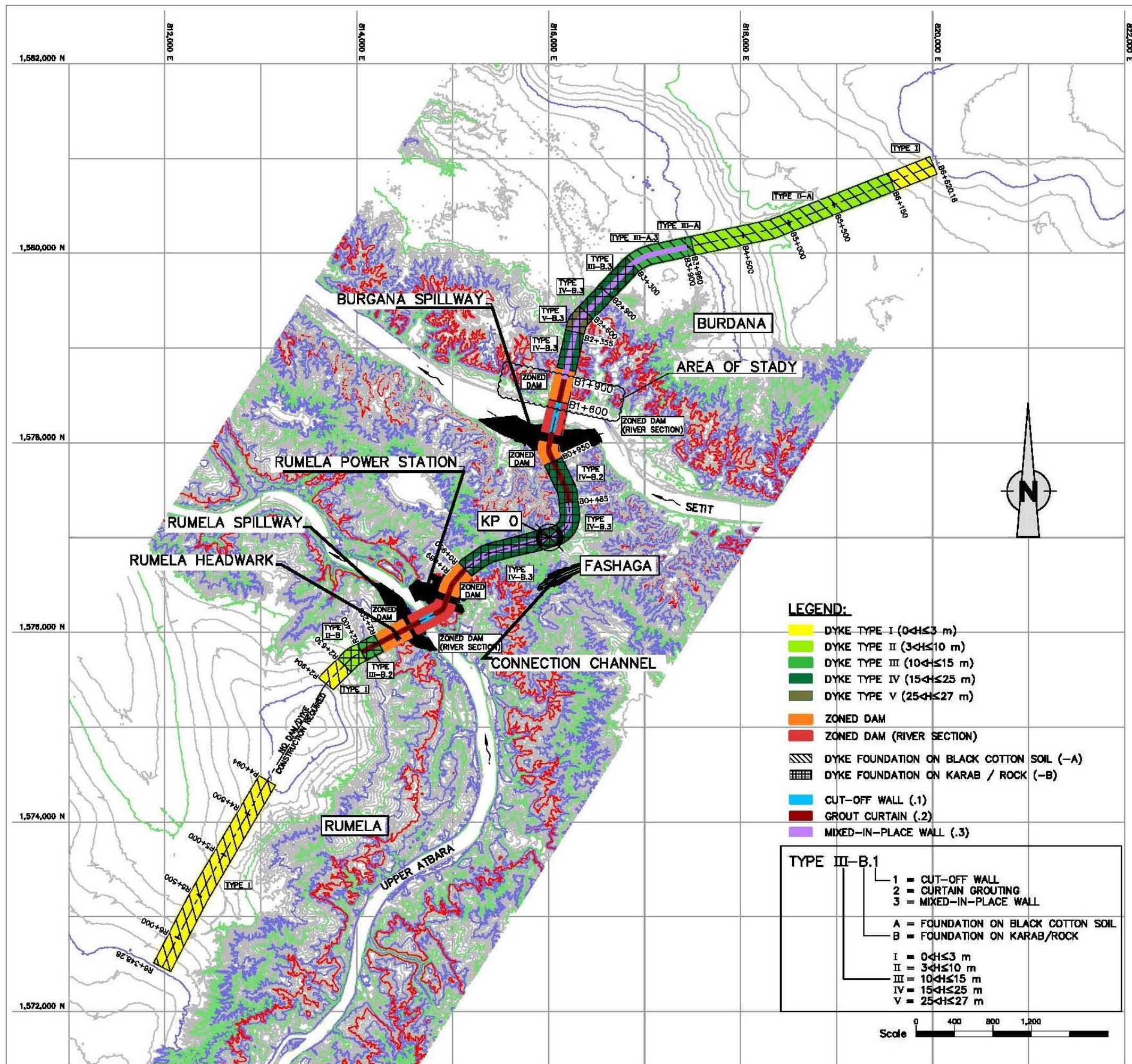
Figure (A-1): General layout for Dam Complex of Upper Atbara Project (DCUAP) Showing KP0 Point and Area of Study

Figure (A-2): Geological drilling log with Lugeon test results for Bore Hole. No. 202

CONTRACTOR: E.S.D.	Geological Log	SOGREAH CONSULTANTS

BOREHOLE No:-B202

Entrance Level:497.12

Coordinates: E: 816187.68　　N:1578636.66

Commencement Date:12/3/2007
Completion Date :24/4/2007

Piezometer:- Piezometer PVC Diameter 2"

Rig: Amrican No (5)　　　　scale 1:100　　　　Logger: Elbashir Oshi Mohamed

Depth(m)	Tool	Casing ∅ ±0.00	Elevation (Above Sea Level / From Ground Surface)	Thickness of layers	profile	Description	Formation	RQD %	Core Recovery %	ROP cm/min	RPM r/min	Lugeon	Remarks

Core Barrel 4 inches and 101 mm ,diamond pits size 4 inches and 101 mm ,drill pipe dim (mm)

5" -23m

497.12 -0.00　1.50　Missed　0.00

495.62 -1.50

2.15　Off whitish to pale reddish very coarse locally pebble massive sst,angular to sub rounded, v.p.s,cemented by iron and minor kaolin,hard　29.7

493.52 -3.65

492.52 -4.60　?　29.0

1.80　Slightly reddish massive medium grained sst,sub angular to subrounded grains,ps,cemented by iron and kaolin,hard.　59.2

490.72 -6.40

-7.00　0.60　Slightly reddish massive pebble sst,vps,cemented by iron and kaolin,vh

-7.60　0.60　Pale reddish x-bedded coarse sst,h-vh

489.07 -8.05　0.45　Offwhitish grey pebble x-bedded sst.

?　46.5

488.07 -9.05

487.02 -10.10　1.05　Whitish reddish v.coarse,coarse upper part,massive sst.

-10.75　?

1.25　Whitish reddish x-bedded coarse sst,subang-subr,ps,cemented by iron and kaolin,h-vh.　61.5

485.12 -12.00

3.00　Whitish reddish x-bedded medium grained sst,subr-r,ps,cemented by iron and kaolin, mh-h.　56.0

482.12 -15.00

?

481.12 -16.00

-16.30　0.30　Whitish reddish fine sst.　0.00

?

479.12 -18.00

7.30　Thickly bedded slightly reddish coarse locally v.c interval,massive-x-bedded sst,subr-r,p-vps,cemented by iron and kaolin ,mh-h　14.0　19.1

Presence of casing to solve stuck problem

471.62 -25.30

-25.40　?　98.6

3.90　Slightly reddish grey massive fine sst,subr-r,p-ns, cemented by iron and kaolin, friable-mh　55.3

467.82 -29.30

?

Remarks:
4.2m 14/3/2007
11.0m 31/3/2007
12.1m 23/3/2007
13.98m 17/6/2007
14.58m 29/5/2007
14.9m 24/4/2007

NUBIAN SST.

Contractor　　　　Consultant　　　　Client
....　　.........................　　.........................

Cont.: **Figure (A-2):** Geological drilling log with Lugeon test results for BH. No. 202

CONTRACTOR: E.S.D. Geological Log **SOGREAH CONSULTANTS**

BOREHOLE No:- B202

Entrance Level: 497.12

Coordinates: E: 816187.68   N: 1578636.66

Commencement Date: 12/3/2007
Completion Date: 24/4/2007

Piezometer:- Piezometer PVC Diameter 2"

Rig: Amrican No (5)

scale 1:100

Logger: Elbashir Oshi Mohamed

Depth (m)	Tool	Casing Ø	Elevation Above Sea Level	From Ground Surface	Thickness of layers	profile	Description	Formation	RQD %	Core Recovery % Depth	ROP cm/min Depth	RPM r/min	Lugeon	Remarks
60.0														
61.0						?			0.00		61.0			
62.0			435.42	-61.7 / -62.0	0.30		Whitish grey fine sst,p-ms,friable.		0.00		62.0			
63.0			434.12	-63.0		?					63.0			
64.0									48.8	54.6	64.0			
65.0										65.5	65.0			
66.0									37.0	44.3	66.0		No absorption	
67.0										67.8	67.0			
68.0											68.0			
69.0							Whitish grey of silty nature in the upper most parts to dark bluish brownish grey and brownish grey, greenish grey color massive to laminated mudstone, mh-h.		47.3	85.0 / 70.0	69.0			
70.0					13.70						70.0			
71.0									60.0	70.0	71.0			
72.0								N U B I A N S S T.		72.5	72.0		No absorption	
73.0									22.4	30.0	73.0			
74.0											74.0			
75.0									0.00	75.0	75.0			
76.0									0.00	76.0	76.0			
77.0			420.42	-76.7			Lightish grey massive medium grained, localized brownish spots, subr-r grains, p-ms, rich in kaolin and hard.		92.7	100	77.0			
78.0					3.30						78.0			
79.0										79.0	79.0			
80.0			417.12	-80.0					32.0	64.0 / 80.0	80.0			
81.0														
82.0														
83.0														
84.0														
85.0														
86.0														
87.0														
88.0														
89.0														
90.0														

Tool column: Core Barrel 4 inches and 101 mm ,almond pits size 4 inches and 101 mm ,drill pipe dim (mm)

Contractor ....   Consultant ....   Client ....

Cont.: **Figure (A-2):** Geological drilling log with Lugeon test results for BH. No. 202

CONTRACTOR: DIUGD

CONSULTANTS: LAHMEYER

Project : DCUAP
Location : Burdana Axis Right Bank
Coordinates: E: 816135.35
N:1578556.97
Elevation (ground): 504.85
Elevation (monument): 505.15

Borehole No. : B-514
Depth : 36.00m
Inclination (degree): 90°
Azimuth (degree): 0°
Casing Dia:113 mm
Core barrel bit Dia:101 mm

Date commenced: 24.07.2011
Date completed: 01.08.2011
Type of drilling rig: Rotary Rig(2)
Operator: Mohamed
Geological log: Mohamed Adel
Sheet No: 2 of 3

Layer (N)	Elevation(m)	Depth(m)	Thickness of layer(m)	Geological profile	Weathering	Strength	Geological description	Section of Permeability Tests (Falling Head / Lugeon Test)	Core recovery / Reverse Circulation %	RQD %	Flush water return %	SPT Blows /cm & N value	Pressure used for drilling(MPa)	Speed of drilling rotation (RPM)	Joint characteristics (Angle of dip Degree)	Shape Roughness Coating	Spacing very wide / wide / medium / close	Ground Water Level (m) Date	Sampling(m)
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
					✔	✔			87	46	10		50		✔				coring
6			4.50		✔	✔	Brownish to whitish grey , medium to coarse grained SAND STONE , cemented by caoline .	From 16.00m to 21.00m	100	72	10		50						coring
					✔	✔			100	75	70		50						coring
	485.350	19.50			✔	✔			100	63	30		50		✔			14.88	coring
7			4.50		✔	✔	Whitish to yellowish grey ,fine to medium grained SAND STONE , cemented by caoline .	From 21.00m to 26.00m	100	83	80		50		✔				coring
					✔	✔			100	87	90		50						coring
	480.850	24.00			✔	✔	Whitish to yellowish grey , coarse grained SAND STONE .		100	28	40		50		✔				coring
8	479.450	25.40	1.40		✔	✔			100	78	70		50		✔				coring
9			2.60		✔	✔	Whitish to yellowish grey , fine grained SILT STONE .	From 26.00m to 31.00m	100	87	90		55						coring
	476.850	28.00			✔	✔	Yellowish to dark grey , fine granied SAND STONE .		100	67	90		55		✔				coring
10	475.750	29.10	1.10		✔	✔			100	65	90		55					20.16	coring
11																			

Legend: Silt · Clay · Gravel · Fine sandstone · Medium sandstone · Coarse sandstone · Sand · Mud stone · Silt stone · Conglomorate

Angle of dip
Fz ——Fractured zone
Wz ——Weathered Zone

Shape:
P——plane
C——curved
I——irregular

Roughness:
S——smooth
R——rough
J——jagged

Coating:
F——Iron oxide
K——kaolinite
B——Calcite
A——Clay
C——Chlorite

Spacing:
VW——Very wide >2m
W ——Wide 600mm-2m
M ——Medium 200mm-600mm
C ——Closed 60mm-200mm

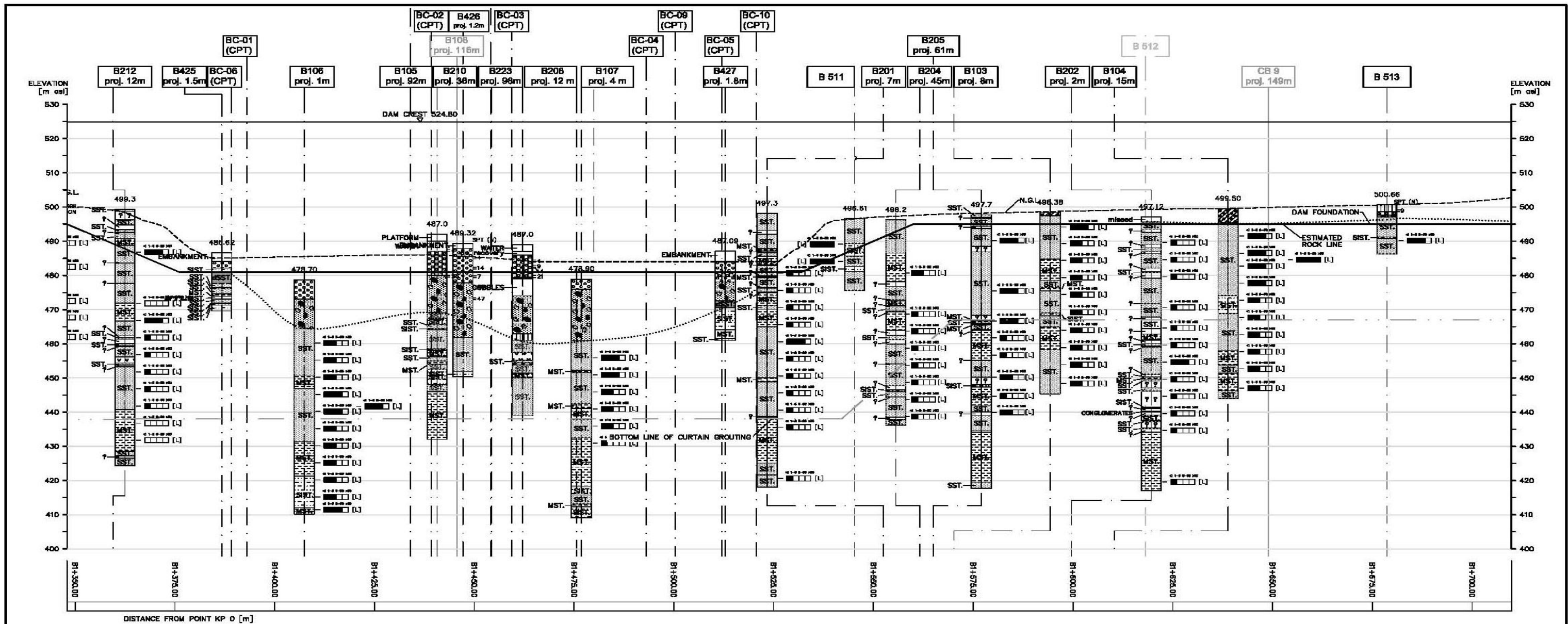**Figure (A-3):** Geological drilling log with Lugeon test results for Bore Hole No. 514

CONTRACTOR: DIUGD

CONSULTANTS: LAHMEYER

Project : DCUAP
Location : Burdana Axis Right Bank
Coordinates: E: 816135.35
N:1578556.97
Elevation (ground): 504.85
Elevation (monument): 505.15

Borehole No. : B-514
Depth : 36.00m
Inclination (degree): 90°
Azimuth (degree): 0°

Casing Dia:113 mm
Core barrel bit Dia:101 mm

Date commenced: 24.07.2011
Date completed: 01.08.2011
Type of drilling rig: Rotary Rig(2)
Operator: Mohamed
Geological log: Mohamed Adel
Sheet No: 1 of 3

Layer (N)	Elevation(m)	Depth(m)	Thickness of layer(m)	Geological profile	Weathering	Strength	Geological description	Section of Permeability Tests (Falling Head / Lugeon Test)	Core recovery / Reverse Circulation %	RQD %	Flush water return %	SPT Blows /cm & N value	Pressure used for drilling(MPa)	Speed of drilling rotation (RPM)	Joint characteristics Angle of dip (Degree)	Shape Roughness Coating	Spacing very wide medium close	Ground Water Level (m) Date	Sampling(m)
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
1	499.350	5.50	5.50				Brownish grey , fine to coarse grained silty SAND with gravels	Depth of test =3m,Permeability(k)=0.58m/d,6.71E-04cm/s / Depth of test =6m,Permeability(k)=0.08m/d,9.81E-05cm/s				7 40 11 >51 / 9 16 17 33							D.S./SPT/D.S./SPT/D.S.
2	497.350	7.50	2.00				Brownish grey , fine grained silty clayey SAND.					9 24 27 >51							SPT/D.S.
3	495.850	9.00	1.50		✔	✔	Brownish grey , medium to coarse grained SAND STONE .	Depth of test =9m,Permeability(k)=0.08m/d,9.29E-05 cm/s	87	24	90	50 51 >51	50					0.00	SPT/coring
4	493.350	11.50	2.50		✔	✔	Whitish grey , fine grained SAND STONE .	From 10.00m to 15.00m	100	84	90		50						coring
5	489.850	15.00	3.5		✔	✔	Yellowish to reddish , medium to coarse grained SAND STONE cemented by kaoline .	Interpreting The Results Lugeon Value	100	100	90		50						coring
					✔	✔			89	73	90		50		✔			coring
					✔	✔			82	36	10		50		✔		5.50	coring

Legend:
- Silt
- Clay
- Gravel
- Fine sandstone
- Medium sandstone
- Coarse sandstone
- Sand
- Mud stone
- Silt stone
- Conglomorate

Angle of dip
Fz ——Fractured zone
Wz ——Weathered Zone

Shape:
P——plane
C——curved
I——irregular

Roughness:
S——smooth
R——rough
J——jagged

Coating:
F——iron oxide
K——kaolinite
B——Calcite
A——Clay
C——Chlorite

Spacing:
VW——Very wide >2m
W——Wide 600mm-2m
M——Medium 200mm-600mm
C——Closed 60mm-200mm

Cont.: **Figure (A-3):** Geological drilling log with Lugeon test results for BH. No. 514

CONTRACTOR: DIUGD

CONSULTANTS: LAHMEYER

GEOLOGICAL LOG

Project : DCUAP
Location : Burdana Axis Right Bank
Coordinates: E: 816135.35
N:1578556.97
Elevation (ground): 504.85
Elevation (monument): 505.15

Borehole No. : B-514
Depth : 36.00m
Inclination (degree): 90°
Azimuth (degree): 0°

Casing Dia:113 mm
Core barrel bit Dia:101 mm

Date commenced: 24.07.2011
Date completed: 01.08.2011
Type of drilling rig: Rotary Rig(2)
Operator: Mohamed
Geological log: Mohamed Adel
Sheet No: 3 of 3

Layer (N)	Elevation(m)	Depth(m)	Thickness of layer(m)	Geological profile	Weathering	Strength	Geological description	Section of Permeability Tests (Falling Head / Lugeon Test)	Core recovery / Reverse Circulation %	RQD %	Flush water return %	SPT Blows /cm & N value	Pressure used for drilling(MPa)	Speed of drilling rotation (RPM)	Joint characteristics Angle of dip (Degree)	Shape Roughness Coating	Spacing very wide wide medium close	Ground Water Level (m) Date	Sampling(m)
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
11			3.40				Whitish to yellowish grey , fine grained SILT STONE .		100	98	90		55						coring
	472.350	32.50						From 31.00m to 36.00m	100	80	90		55					20.18	coring
12			3.50				Dark to yellowish grey , fine grained SILT STONE .		100	95	90		55						coring
									100	100	90		55						coring
	468.850	36.00							100	95	90		55					20.53	coring
							End of Borehole (36.00 m)												

Legend:
Silt · Fine sandstone · Sand · Conglomorate
Clay · Medium sandstone · Mud stone
Gravel · Coarse sandstone · Silt stone

Angle of dip
Fz ——Fractured zone
Wz ——-Weathered Zone

Shape:
P——plane
C——curved
I——irregular

Roughness:
S——smooth
R——rough
J——jagged

Coating:
F——iron oxide
K——kaolinite
B——Calcite
A——Clay
C——Chlorite

Spacing:
VW——Very wide   >2m
W——Wide   600mm-2m
M——Medium   200mm-600mm
C——Closed   60mm-200mm

Cont.: **Figure (A-3):** Geological drilling log with Lugeon test results for BH. No. 514

Figure (A-4): Geological section along the axis of Burdana dam

Cont.: **Figure (A-4):** Geological section along the axis of Burdana dam

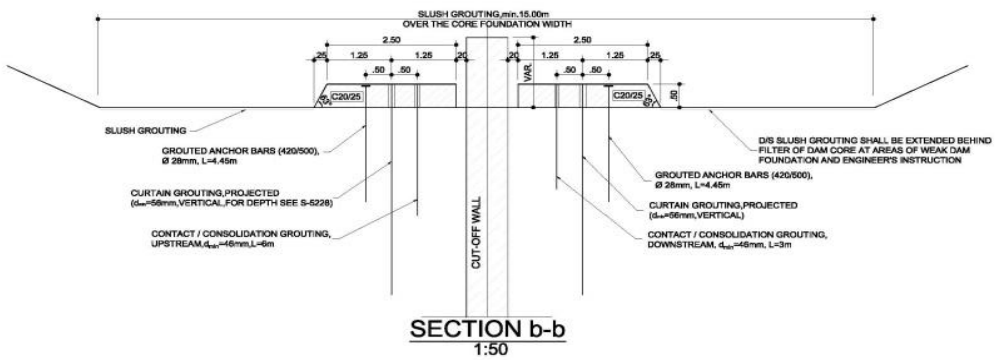**Figure (A-5):** Curtain Grouting Design Depth and Staggering Sequences for Grout Holes (CH B1+600_CH B1+900)

cont.: **Figure (A-5):** Curtain Grouting Design Depth and Staggering Sequences for Grout Holes (CH B1+600_CH B1+900)

Grouting Trial Mix & Test Results

Sample No.	W/C	Sand (%)	Admixture (%)		Density (g/cm³)				Marsh cone (s)				Fan-Viscosimeter (mPa.s)			Decantation (Bleeding) (%)	Volume Change Test (%)			Setting Time (h:min)		Compressive Strength(MPa)	
			Bentonite	PCA-1	(1)	(2)	(3)	Ave.	(1)	(2)	(3)	Ave.	R600	R300	PV		h	h₂	VCR (%)	Initial	Final	7 days	28 days
CG1-1-1	2:1		2.0	0.8	1.260	1.265	1.270	**1.265**	31.0	31.2	30.4	**30.9**	23	17	**6**	**11.0**	7.07	6.1	**-13.20**	25:07	29:13	1.518	4.702
CG1-1-2	2:1		2.0	1.0	1.240	1.245	1.240	**1.242**	31.0	30.5	30.0	**30.5**	18	14	**4**	**10.0**	7.07	5.7	**-19.33**	33:20	40:48	1.673	3.873
CG1-1-3	2:1		2.0	1.2	1.220	1.225	1.225	**1.223**	31.0	30.5	31.0	**30.8**	17	13	**4**	**8.0**	7.07	5.6	**-20.27**	38:55	46:35	1.510	3.809
CG1-2-1	2:1		3.0	0.8	1.280	1.290	1.290	**1.287**	33.0	32.0	32.4	**32.5**	24	18	**6**	**5.0**	27.1	24.8	**-8.49**	34:40	46:06	1.596	4.900
CG1-2-2	2:1		3.0	1.0	1.287	1.285	1.280	**1.284**	31.9	31.8	32.0	**31.9**	25	20	**5**	**3.0**	27.1	23.9	**-11.81**	35:10	46:36	1.296	4.600
CG1-2-3	2:1		3.0	1.2	1.282	1.283	1.283	**1.283**	32.8	32.0	32.2	**32.3**	25	19	**6**	**5.0**	27.1	23.4	**-13.65**	40:40	46:55	1.267	4.000
CG2-1-1	1.5:1		1.0	0.8	1.290	1.300	1.325	**1.305**	29.3	28.4	29.0	**28.9**	17	11	**6**	**9.0**	7.07	5.5	**-22.63**	21:20	22:40	4.219	5.016
CG2-1-2	1.5:1		1.0	1.0	1.300	1.310	1.315	**1.308**	31.0	30.3	30.5	**30.6**	17	12	**5**	**10.0**	7.07	5.8	**-18.39**	34:40	37:00	4.708	7.000
CG2-1-3	1.5:1		1.0	1.2	1.290	1.285	1.310	**1.295**	29.8	29.7	29.9	**29.8**	17	12	**5**	**12.0**	27.1	22.7	**-16.24**	56:25	59:40	3.849	7.800
CG2-2-1	1.5:1		1.5	0.8	1.342	1.340	1.340	**1.341**	31.0	30.0	30.0	**30.3**	18	13	**5**	**8.0**	27.1	21.8	**-19.56**	36:00	38:50	3.186	7.900
CG2-2-2	1.5:1		1.5	1.0	1.340	1.342	1.340	**1.341**	30.5	30.0	30.5	**30.3**	19	14	**5**	**6.0**	27.1	23.3	**-14.02**	28:40	29:50	3.032	8.200
CG2-2-3	1.5:1		1.5	1.2	1.338	1.340	1.339	**1.339**	31.0	30.1	31.2	**30.8**	19	14	**5**	**7.0**	27.1	23.0	**-15.13**	35:36	37:51	2.782	6.800
CG2-3-1	1.5:1		2.0	0.8	1.350	1.353	1.360	**1.354**	32.0	32.0	31.9	**32.0**	23	17	**6**	**4.5**	27.1	24.3	**-10.33**	24:25	26:05	3.002	6.700
CG2-3-2	1.5:1		2.0	1.0	1.345	1.350	1.353	**1.349**	32.0	32.3	32.5	**32.3**	25	19	**6**	**4.0**	27.1	24.3	**-10.33**	29:40	33:00	2.860	9.500
CG2-3-3	1.5:1		2.0	1.2	1.340	1.339	1.335	**1.338**	33.5	33.5	33.2	**33.3**	24	18	**5**	**6.0**	27.1	23.5	**-13.28**	25:50	29:10	2.920	8.100

Remark: PV means Plastic viscosity.

Approved mix to be used in grouting works

Figure (A-6): Summary of Grouting Trial Mix and Test Results

Bill of Quantities and Price Schedules
Contract C1B – Civil Works and Hydro-Mechanical Equipment
Part 1 – Civil Works – Bill of Quantities

Republic of Sudan - Dam Implementation Unit
Dam Complex of Upper Atbara Project (DCUAP)

C	BURDANA DAM			Civil works			Currency USD
Price Number	Work Item	Unit of Quantity	Quantity	UNIT PRICE FOREIGN	UNIT PRICE LOCAL	TOTAL PRICE FOREIGN	TOTAL PRICE LOCAL
C370	**Construction Joints**						
C373	Waterstop Type 3, elastomer waterstops Tricosal Type FMS 310 or equivalent	m	85	29.57	4.24	2,513.28	360.06
C374	Joint Filler styrofoam / fiber board 10mm bitumen coated on both sides	m²	850	8.00	2.00	6,800.00	1,700.00
C400	CUT-OFF DIAPHRAGM WALL						
C400	**Plastic concrete cut-off wall**						
C401	Plastic concrete cut-off wall	m²	13,810	783.68	171.77	10,822,620.80	2,372,143.70
C500	DRILLING AND GROUTING						
C510	**Outside drilling and grouting**						
C511	Continuous core drilling for grout curtain						
C511.01	setting up	U	135	58.50	16.31	7,897.50	2,201.85
C511.02	drilling using reverse procedure	l.m	4,270	71.53	16.84	305,433.10	71,906.80
C511.03	drilling using progress procedure	l.m	1,070	55.34	13.12	59,213.80	14,038.40
C512	Destructive drilling for grout curtain						
C512.01	setting up	U	405	58.50	16.31	23,692.50	6,605.55
C512.02	drilling using reverse procedure	l.m	12,790	71.53	16.84	914,868.70	215,383.60
C512.03	drilling using progress procedure	l.m	3,200	55.34	13.12	177,088.00	41,984.00
C513	Destructive drilling for contact consolidation						
C513.01	setting up	U	3,610	58.50	16.31	211,185.00	58,879.10
C513.02	drilling	l.m	32,490	48.37	10.62	1,571,541.30	345,043.80
C516	Grouting for grout curtain						
C516.01	setting up	U	540	58.50	16.31	31,590.00	8,807.40
C516.02	grouted sections using reverse procedure	U	4,265	588.72	187.36	2,510,890.80	799,090.40
C516.03	grouted sections using progress procedure	U	1,068	675.93	209.53	721,893.24	223,778.04
C517	Grouting for contact consolidation						
C517.01	setting up	U	3,610	58.50	16.31	211,185.00	58,879.10
C517.02	grouted sections deeper than 8 m	U	3,610	487.45	155.74	1,759,694.50	562,221.40
C518	**Dry grout materials**						
C518.01	cement	t	9,170	379.00	41.24	3,475,430.00	378,170.80
C518.02	bentonite	t	2,300	475.11	45.33	1,092,753.00	104,259.00
C518.03	sand	t	6,420	12.18	6.59	78,195.60	42,307.80
C518.04	Additives	t	230	1,121.34	73.16	257,908.20	16,826.80
C519	Water test						
C519.01	Lugeon	U	60	403.63	136.88	27,917.80	8,182.80

Total of solid material = 17,120 Ton

**Figure (A-7):** Burdana Dam's solid material tender quantities

Bill of Quantities and Price Schedules
Contract C1B - Civil Works and Hydro-Mechanical Equipment
Part 1 - Civil Works - Bill of Quantities

Republic of Sudan - Dam Implementation Unit
Dam Complex of Upper Atbara Project (DCUAP)

E	BURDANA SPILLWAY			Civil works				Currency USD
Price Number	Work Item	Unit of Quantity	Quantity	UNIT PRICE		TOTAL PRICE		
				FOREIGN	LOCAL	FOREIGN	LOCAL	
E375	Joint Filler styrofoam / fiber board 20mm bitumen coated on both sides	m²	2,000	25.39	2.86	50,780.00	5,720.00	
E377	Elastic sealing component Type Sika or equivalent	kg	500	10.60	2.36	5,300.00	1,180.00	
E378	Bituminous coating (2 coats included) for contraction joints	m²	4,000	8.00	2.00	32,000.00	8,000.00	
E379	Waterproof bridge expansion joints, including steel parts, elastomeric parts, welded anchor bars, and corrosion protection.	m	150	6.84	0.49	1,026.00	73.50	
E500	DRILLING AND GROUTING							
E517	Grouting for contact consolidation							
E517.01	setting up	U	1,650	58.50	16.31	96,525.00	26,911.50	
E517.02	grouted sections deeper than 5 m	U	1,650	487.45	155.74	804,292.50	256,971.00	
E518	Dry grout materials							
E518.01	cement	t	2,610	379.00	41.24	989,190.00	107,636.40	
E518.02	bentonite	t	660	475.11	45.33	313,572.60	29,917.80	
E518.03	sand	t	1,830	12.18	6.59	22,289.40	12,059.70	
E518.04	Additives	t	70	1,121.34	73.16	78,493.80	5,121.20	
E519	Water test							

Total Solid Mterials = 5170

Figure (A-8): Burdana Spillway solid material tender quantities
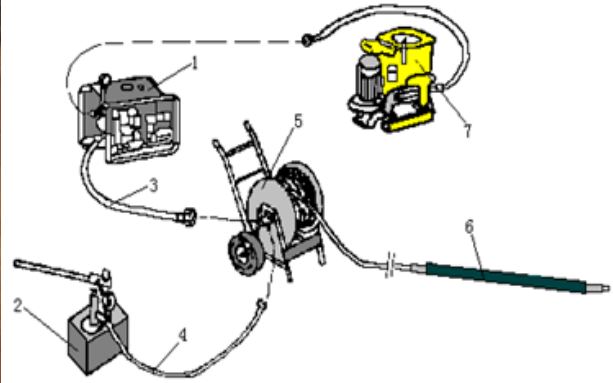
Figure A-9 : DYS Serial hydraulic (pneumatic) packer
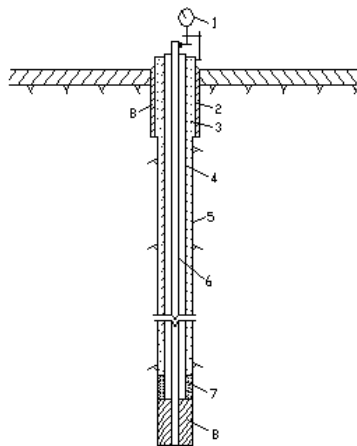
1-Dial gauge, 2-Collar pipe, 3-Fine sand, 4-
Protectiver pipe, 5-Borehole, 6-Internal pipe 7-
Sealing material (Bentonite), 8-cement grout

Figure A-10 : Up-lift Monitoring Device
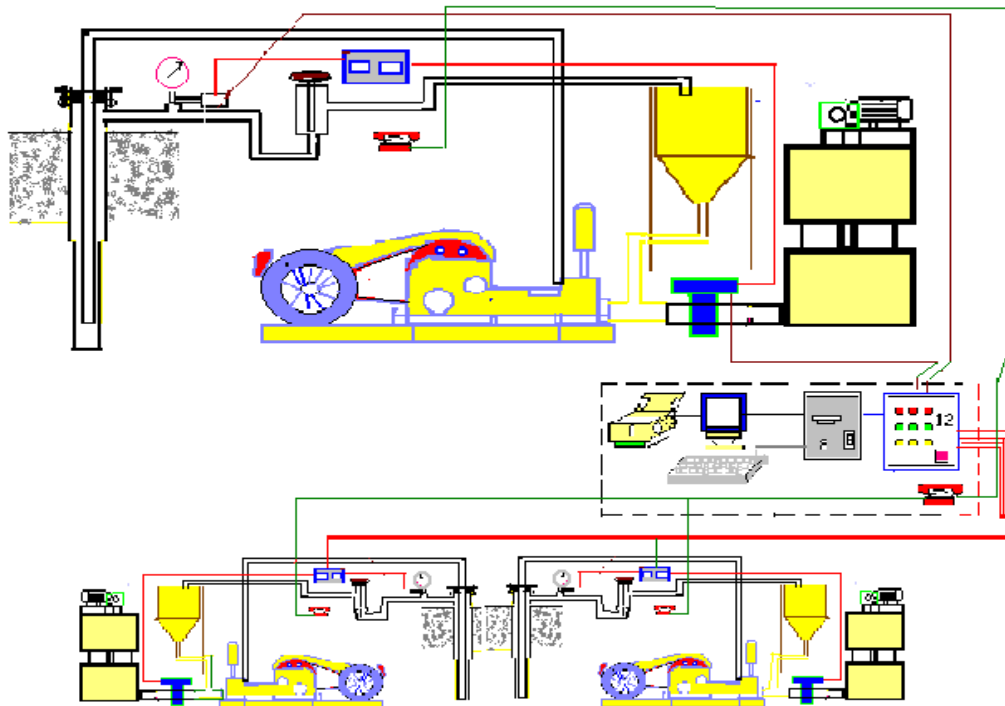
Figure A-11 : agitator J150×2

Figure A-12 : high speed mixer ZJ-800

Figure A-13 : JB-1.5 grout mixing plant

Figure A-14 : CFEC-GMS-2008 Grouting monitoring system

Figure A-15: Grouting data acquisition & treatment system

Marshal Cone test   Mud Balance test

Figure A-16 : Grout Quality Control Tests (Viscosity and Density)