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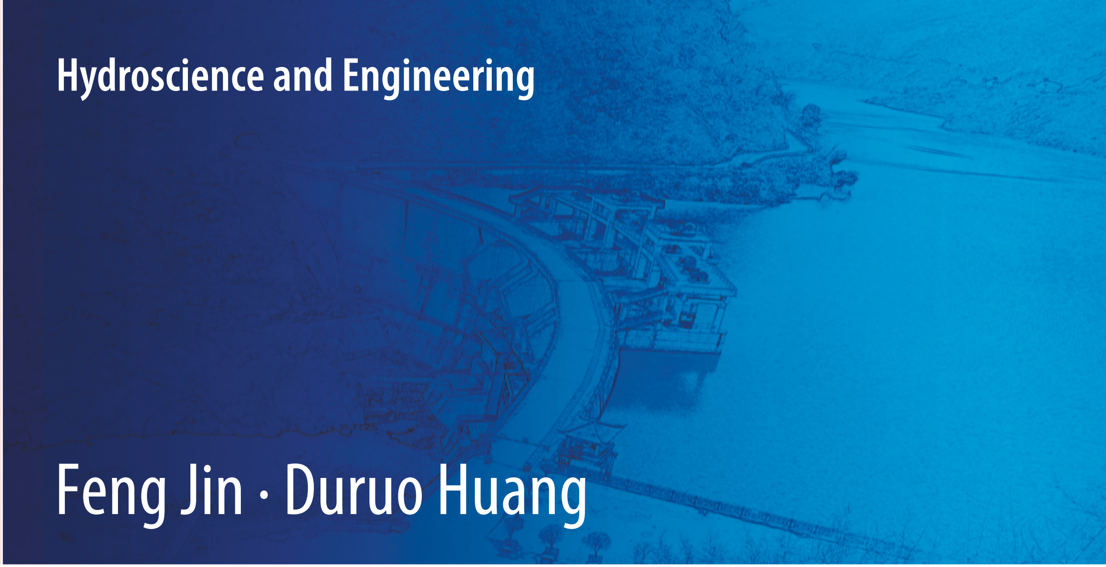

Feng Jin · Duruo Huang

Rock-Filled Concrete Dam

Springer

Hydroscience and Engineering

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ISSN 2730-9002 ISSN 2730-9010 (electronic)
Hydroscience and Engineering
ISBN 978-981-16-8297-1 ISBN 978-981-16-8298-8 (eBook)
https://doi.org/10.1007/978-981-16-8298-8

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Foreword

On behalf of the International Commission on Large Dams (ICOLD), I am pleased to provide a foreword to this book on Rock-Filled Concrete Dams. For centuries, engineers have sought to tame the forces and gather the natural resources provided by our planet to serve and protect humanity. The concept of blocking a natural river course to collect water for irrigation or provide storage against flooding dangers is probably as old as farming for food itself. Yet, even with such a long history of engineering contemplation and optimizations, the engineering profession continues to search for solutions to economic, environment, and social considerations in the development of modern dams and hydroelectric power stations.

The inspirational use of concrete for dams provided engineers with a material of such strength and utility as compared with the structures formed from basic earth and rock materials that dams began to grow in size and utility as engineers fought to keep basic water infrastructure in step with growing populations around the world. As a material for dams, concrete allowed engineers to address the strong seismic and hydrologic forces of nature by molding structures of intricate geometry and optimized mixes of rock, sand, cementing powders, and water—all natural elements—in a sustainable development of renewable resources.

In this book, the author, Prof. Dr. Feng JIN, provides an excellent context of the history of concrete dams from early masonry structures through the development of Portland cement and refined concrete mix development. Professor JIN’s innovation of rock-filled concrete as a material for dams, though recent in refinement, is based on sound engineering principles developed over many millennia. The commitment of modern engineers, especially those in China who quickly recognized the utility and efficiency of these Rock-Filled Concrete Dam structures, is commendable. These engineers and scientists looked beyond standard designs and typical applications for a next-generational development of the profession by taking bold risks and calculated scientific methodologies that move the industry forward.

This book is a strong harmonious representation of hard work and commitment to develop and document the science, and to benevolently share the results of that development with the professional industry. Science and technology exist in our lives and on our planet. Humans discover these technologies when we take the time to look and work hard to understand the science and how it can be applied to improve and protect lives. This book on Rock-Filled Concrete Dams takes the technical and non-technical reader and user through the background and basic technological applications of design and construction for Rock-Filled Concrete Dams based on lessons learned through the investment of time and financial resources of dedicated professionals.

Professor JIN has been the leader along with his team at Tsinghua University in China to take his innovation of Rock-Filled Concrete Dams to become one of the fastest-growing technologies for dam design and construction in China and around the world in the last 20 years. This technology offers great promise of strong and safe dams with optimization of material resources in an environmentally and socially responsible approach to infrastructure development. This book provides a comprehensive resource for the fundamental research around Rock-Filled Concrete Dams, including mechanical behaviors, physical properties, principles to dam design and construction technology. The book will be a great teaching and reference document for researchers, practicing engineers, and graduate students who are interested in fundamental research and applications of the rock-filled concrete dams.

As ICOLD President, I have seen strong commitments to dams and levees around the world. As an organization, ICOLD was formed more than 90 years ago to allow engineers, scientists, and managers to share their knowledge of dams for the betterment of all nations. With 104 countries as national members, ICOLD has an influence on more than 5 billion people in the world through our support of the science and technology of critical infrastructure for dams and levees. With regard to the professional engineering scientific and technological community for dams, I am pleased to acknowledge that the Chinese National Committee on Large Dams (CHINCOLD) is one of the most active national committees of ICOLD. The CHINCOLD delegates to ICOLD, including Prof. JIN, have regularly made outstanding contributions to the promotion of international exchanges and cooperation, especially in setting the current state of the practice for global dam engineering.

This book on Rock-Filled Concrete Dams will add to the global strength of our profession and recognition of the cutting-edge development within the scientific and technological community in China. As ICOLD President, I sincerely support the continued development of Rock-Filled Concrete Dams as critical infrastructure for water resources that will enable the global scientific and technological community to continue to make progress in science and technology as a priority for the well-being of mankind as part of a global awareness for sustainable progress of our human civilization.

I congratulate Prof. JIN and his team on the great success of Rock-Filled Concrete Dams and the development of this book for teaching and reference.

Best regards,

MFRogers

Indianapolis, Indiana, USA

Michael F. Rogers
President, International Commission
on Large Dams/Commission
Internationale des Grands Barrages
(ICOLD/CIGB)

Preface

One score of years has passed since the meeting with Prof. Xuehui AN where, over a cup of coffee, we discussed the potential application of self-compacting concrete in constructing dams and named the technology as rock-filled concrete (RFC). The spark of ideas from that meeting would fuel the unrelenting effort of our research team in the coming years, and now today, we have witnessed the completion of dozens of rock-filled concrete dams. I cannot forget the mixed feelings of excitement and tiredness when a lift of the first RFC dam in Beijing was cast at a summer late night and our hungry team was looking for a restaurant on the silent street. I still vividly remember the feeling of exhaust and thirsty after scaling the mountain at the Dasu dam site, Pakistan, with my assistant Mr. Hu ZHOU, where a rock-filled concrete cofferdam was under design. The feelings of joy and pride are the most profound when visiting completed rock-filled concrete dams and introducing the technology to Chinese and foreign experts.

In 2017, my research team published a Chinese technical book entitled *Rock-filled Concrete Technology* to help domestic engineers better understand the national sector standards for the design and construction of RFC dams. That small book and the sector standards have boosted the application of rock-filled concrete dams, as there were over one hundred and twenty RFC dams that are completed or are under construction in China by the end of July 2021. The RFC technology was awarded Second Prize of the 2017 State Technological Invention Award by the State Council of the People's Republic of China.

With help from experts of the Technical Committee on Cemented Material Dams, the International Commission on Large Dams (ICOLD), the ICOLD Bulletin *Cemented Material Dam: Design and Practice—Rock-filled Concrete Dam* has been approved by the General Assembly of ICOLD in November 2021, and will be issued soon. I believe that dam engineers all over the world can be greatly benefited from that Bulletin. The aim of this book is to demonstrate the cause and origin of the design and construction criteria of rock-filled concrete dams in the Bulletin. Therefore, the book summarizes not only the latest research results on rock-filled concrete technology but also the industrial practice of design and construction. The authors hope this book can encourage more engineers and researchers to investigate and improve

RFC technology and further to benefit from the design and construction of RFC dams in China and beyond.

The development of rock-filled concrete technology calls for a collaborative effort by a large group of researchers and practitioners around the world. The book testifies to the collective efforts and commitments from the whole community. In particular, the idea of combining masonry and self-compacting concrete to build dams was refined after discussion with Prof. Hajime OKAMURA of the University of Tokyo and Prof. Chuhan ZHANG of Tsinghua University. In the early development years, Dr. Matabee MAEDA and his colleagues at Maeda Corporation and Prof. Masahiro OUCHI of Kochi University of Technology, Japan, provided technical support on self-compacting concrete. Prof. Jianjun SHI of Nanhua University, China and Prof. Surendra P. SHAH of Northwestern University, USA, supported the rock-filled concrete lab experiments. Prof. Qingyou WANG from Tsinghua University, Mr. Zundang XIE in Yellow River Engineering Consulting Co., Ltd., and Mr. Kai JIANG in the Department of Water Resource, Shanxi Province helped our team build the first rock-filled concrete dams. Many results in this book were conducted by post-doctoral fellows and graduate students on our research team at Tsinghua University, such as doctors Changjiu CHEN, Miansong HUANG, Shiqing HE, Chunna LIU, Guoxuan HAN, Xinwei TANG, Yuetao XIE, Songgui CHEN, Chuanhu ZHANG, Yiyang WANG, and Xiaorong XU; masters Le LI, Hao LIU, Dingcai PAN, Shuo WANG, and Aijun WANG; and postgraduate students Wenju LIU, Mostafa ELSHERBENY, Ting LIANG, Yu ZHENG, Hamed, and Liqun FU. Professors Guanglun WANG, Jinting WANG, Yanjie XU, Yuande ZHOU, Jianwen PAN, and Qicheng SUN on our team contributed their thoughts and supervision. The material of design and construction comes from many design institutes, such as those based in Zunyi, Ankang, Qinghai, and Qujing. The authors would also like to thank Prof. Gang WANG of Hong Kong University of Science and Technology for his important comments and additional editorial assistance, and thank Mr. Ning LIN, Ms. Jingwen WANG, Mr. Zilong CAO, Ms. Haixia HUANG, Mr. Zhuo WANG and Mr. Houran ZHAO for their help in editing the work.

Due to limited space, many people and organizations that have contributed to the development of RFC technology cannot be listed here. The authors would like to express their deepest appreciation to these people and organizations. This book could not be finished without the continuous encouragement and hard work of Prof. Duruo HUANG, the coauthor of this book. It is to my greatest delight to see the RFC technology has been carried on by the next generation.

Beijing, China
August 2021

Feng Jin

Contents

About the Authors

Prof. Feng Jin is a leading researcher in dam engineering in China. He is Changjiang Chair Professor, Chair of Academic Committee and former Head of Department of Hydraulic Engineering at Tsinghua University. Prof. Jin has made original and significant contributions to the invention and development of the rock-filled concrete dam, which has revolutionized the practice of dam construction in China. He has been awarded the prestigious national awards five times from the State Council in the past 20 years, including the National Technology Invention Award 2nd Prize, the National Science and Technology Progress Award 2nd Prize, the National Natural Science Award 3rd Prize, and more than ten science and technology awards by State Ministries. He has been granted more than 30 national patents, published more than 300 research papers, including more than 100 SCI journal papers. Results from Prof. Jin's research group are widely utilized in engineering practice, and he is one of the lead authors of National Sector Standards including *Technical Guide for Rock-Filled Concrete Dams, Construction Specification for Rock-Filled Concrete of Hydropower and Water Conservancy Engineering*, the local standard of Guizhou Province named *Technical Code for Rock-Filled Concrete Arch Dams*, and the ICOLD Bulletin *Cemented Material Dam: Design and Practice—Rock-Filled Concrete Dam.*

Prof. Jin has been served as Principal Investigator for dozens of research projects and provided expert support to more than 20 large-scale hydraulic projects, including Three Gorges Project, Xiaowan, Ertan, Xiluodu, Xiangjiaba projects, etc. He is presently Vice Chairman of Hydraulic Structure Committee of Chinese Hydraulic Engineering Society, Vice Chairman of Hydraulic Engineering Education Committee at the Ministry of Education, and Member of Technical Committee on Capacity Building of the International Commission on Large Dams.

Prof. Duruo Huang is Associate Professor and Associate Head of Department of Hydraulic Engineering at Tsinghua University. Her primary research interests are in dam engineering and engineering seismology, with emphases on innovate dam construction material, seismic performance of high dams, earthquake ground motion characterization and seismic ground response analysis. She is principle investigator of researches funded by National Natural Science Foundation of China and State

Key Laboratory of Hydroscience and Engineering. She published more than 50 SCI papers. Presently, she is member of technical committees of International Society for Soil Mechanics and Geotechnical Engineering (ISSMGE), and editorial board of International Journal of Ocean and Coastal Engineering. She maintains an active consulting practice to assist engineering firms with problems in dam design and earthquake engineering. She was awarded Outstanding Young Scholars Award of Tsinghua University (top honor for faculty members under 35 years old) in 2020, Bright Spark Lecture Award by ISSMGE in 2020, National Thousand Talents Plan Professorship for Young Scholars in 2018, and Ringo Yu Prize for Best Ph.D. Thesis in Geotechnical Studies in 2017.

Abbreviations

AEA	Air-entraining admixture
AFM	Atomic force microscopy
AMRGZ	Administration for Market Regulation of Guizhou Province
ASTM	American Society for Testing and Materials
BIS	Bureau of Indian Standards
BSE	Backscatter electron
C/P	Cement–powder ratio
CECS	China Association for Engineering Construction Standardization
CFD	Computational fluid dynamics
CFRD	Concrete-faced rockfill dam
CHINCOLD	Chinese National Committee on Large Dams
CIM4R	Construction Information Model for RFC Dams
CM	Cementitious material
CMD	Cemented material dam
CMOD	Crack mouth opening displacement
CTE	Coefficient of thermal expansion
CVC	Conventional vibrated concrete
DEM	Discrete element method
HSCC	High-performance self-compacting concrete
ICOLD	International Commission on Large Dams
ISO	International Organization for Standardization
ITZ	Interfacial transition zone
JSCE	Japan Society of Civil Engineers
LBM	Lattice Boltzmann method
MERI	Maharashtra Engineering Research Institute
MOHURD	Ministry of Housing and Urban–Rural Development of the People's Republic of China
MSS	Maximum sand size
MWR	Ministry of Water Resources of the People's Republic of China
NEA	National Energy Administration of the People's Republic of China
OPC	Ordinary Portland cement

PAC	Preplaced aggregate concrete
RCC	Roller compacted concrete
REV	Representative element volume
RFC	Rock-filled concrete
RRFC	Riprap rock-filled concrete
SAC	Standardization Administration of the People's Republic of China
SCC	Self-compacting concrete
SCCEPG	Self-Compacting Concrete European Project Group
SCM	Self-compacting mortar
SEM	Scanning electron microscopy
SF	Slump flow
SPUC	Self-protected underwater concrete
SSD	Saturated surface dry
UPA	Underwater protective agent
USACE	US Army Corps of Engineers
USBR	US Bureau of Reclamation
VF	V-funnel flow time
VMA	Viscosity modifying admixture
VRFC	Vibrated rock-filled concrete
W/C	Water/cement ratio
W/CM	Water/cementitious material ratio
W/P	Water/powder ratio by volume

Chapter 1
Introduction

Dam construction traces back to thousands of years ago. Although the history is very interesting, a very brief introduction to concrete and masonry dams is presented herein to help readers better understand the innovative technologies used to construct dams. Readers who are interested in ancient dams are encouraged to read the references listed in the ICOLD bulletin on rock-filled concrete dams (ICOLD, 2022).

1.1 Brief History of Masonry and Concrete Dams

In the third or fourth millennium BC, masonry was firstly used in dam construction. Some of the earliest masonry or masonry-like dams include the Saddel-Kafara dam in Egypt and the Jawa dam in Jordan. Many masonry dams have been constructed in Europe during Roman times and in central Asia since the thirteenth century. The 91-m high New Croton masonry gravity dam in US was completed in 1906, which was the highest masonry dam when it was constructed. More than 70 years later, the highest masonry dam in the world became the 125 m high Nagarjuna Sagar dam in India.

Since the invention of Portland cement in the nineteenth century, dam engineers have developed technologies to build concrete dams. The first important achievement is the massive concrete technology employed in the Hoover dam across the Colorado River in US in the 1930s, and it was the world's tallest dam when it was built. Conventional vibrated concrete (CVC) technology employs an immerse vibrator to compact the concrete and construct a dam by blocks. A cooling system is implemented to remove the hydration heat of concrete by embedding steel or PVC pipes in concrete blocks during casting. The construction process of conventional concrete dams is somewhat complicated, posing a significant impact on the overall cost of dams. As a mainstream type of dam, the CVC dam is most mature in construction technology. The highest CVC dam and the highest of all dam types is now the Jinping-I double curvature arch dam in China as it has a height of 305 m.

F. Jin and D. Huang, *Rock-Filled Concrete Dam*, Hydroscience and Engineering,
https://doi.org/10.1007/978-981-16-8298-8_1

The second widespread mass concrete technology in dam engineering is roller-compacted concrete (RCC), where slump concrete is placed in thin layers and compacted by vibration roller compactors. Known as the first large dam constructed using roller-compacted concrete, the Willow Creek Dam in US was completed in 1983. Over the past decades, trends have been towards increasing the dam size, providing several notable RCC dams at heights over 200 m, such as the Huangdeng RCC gravity dam in China. One of the essential advantages of RCC is the rapid placement of concrete, and thus a shortened construction period and reduced cost. In the initial period of the RCC dam, no cooling pipe is employed. Due to increasing cracking in RCC dams, temperature control measures for RCC are becoming increasingly similar to CVC and significantly rely on buried cooling pipes and even digital control automatic cooling systems.

In addition to the CVC and RCC dams mentioned above, engineers worldwide have made unremitting efforts to develop new construction technologies in dam engineering. Several dam construction methods have been developed in recent decades, including prepacked concrete or Prepakt concrete (USACE, 1951, 1954), Colcrete or colloidal concrete (Dempster & Findlay, 2004), Colgrout masonry (BIS, 2017; MERI, 2018), Preplaced Aggregate Concrete (PAC) (Vieira et al., 2010) and Rubble Masonry Concrete (RMC). These dam construction technologies intend to combine concrete and masonry technologies. Most of them use high fluidity mortar or place rocks using labour. Their complicated procedures and labour consumption decrease their efficiency and economy.

1.2 Invention of Rock-Filled Concrete

As introduced above, the dam engineering community has been looking forward to innovative materials and technology that probably revolutionize the conventional engineering practice of concrete dams. The author thinks the development goals for concrete dam construction technology include (1) simple placement and compaction, (2) less consumption of cementitious materials, (3) easy temperature control and cracking prevention and thus (4) cost and construction period savings and environmental friendliness. The development of an innovative concrete dam construction technology has been the focused research field of the author in the last two decades. The initial spark of the author's idea came from the self-compacting concrete (SCC) originating in Japan.

1.2.1 Self-compacting Concrete

Concrete is a composite material composed of aggregates bonded with hydraulic cement that hardens over time. Pore systems are thus inherent in concrete resulting from cement hydraulic reactions, which govern the most important properties of concrete, notably its strength and durability. In conventional engineering practice of concrete placement, immersed vibration, roller compaction or other compaction measures have to be used to remove air bubbles, which is costly and requires a significant amount of skilled labour. Note that inadequate compaction also results in pores in concrete, while pores larger than 20–50 nm are considered undesired and significantly weaken the strength. To address the key challenge of the skilled labour shortage in Japan, Professor H. Okamura from the University of Tokyo developed a new type of concrete in the late 1980s. This new concrete, which has high fluidity in casting and is viscous to prevent segregation or bleeding and thus can be placed without compaction measures, is named self-compacting concrete or self-consolidating concrete (Okamura & Ouchi, 2003; Okamura & Ozawa, 1995). Note that the capability of compacting wells without vibration during placement is called *self-compacting*. In general, SCC features highly flowable, non-segregating concrete that can spread into place and fill the formwork and space between reinforcements due to its own weight without vibration. Special attention on the mix of SCC should be focused on several key issues: a limited aggregate content, a low water/binder ratio and high-quality superplasticizer, as suggested by Okumura and Ozawa (1995). The higher the flowability of SCC, the further it can flow. On the other hand, in the case of low segregation resistance, difficulty in filling formwork may be experienced, and/or uneven distribution of coarse aggregates may occur. Improvement of the viscosity is beneficial to the segregation resistance of SCC. However, excessive viscosity may affect the flowability of SCC and reduce the filling ability. After hardening, SCC performs similar to that of CVC, although the performance of fresh SCC is quite different.

The advantages of using SCC in construction primarily include labour savings, improved concrete pump ability, and ease of filling hard-to-reach areas in a structure. Therefore, immediately after its invention, SCC technology was applied to a significant number of civil engineering construction projects in Japan, North America and Europe. A notable example in early time is the application in anchorages of the Akashi-Kaikyo Suspension Bridge, which opened in 1998; this bridge is a suspension bridge with the longest span (1991 m) in the world at the time it was built. The entire construction process made best use of the advantages of SCC: concrete was mixed in a batch plant and was transported over 200 m to the casting site, while a total of more than 290,000 m^3 SCC was cast in the bridge anchorages. It was estimated that the use of SCC significantly shortened the concrete period by 6 months. Other well-known large skyscraper projects include the Canton Tower in Guangzhou, China, with a height of 454 m and Burj Khalifa in Dubai, UAE, with a height of 828 m.

Field and laboratory test methods for the performance of SCC, including flowability, passing ability, viscosity and segregation resistance, have been developed over the past decades. For example, flowability is measured with the slump flow test, which has been standardized as ASTM C 1611 *Slump Flow of Self-Consolidating Concrete* (ASTM, 2021b). The V-funnel test, U-flow test, L-box test, and J-ring test can be referred to related standards in Japan (JSCE, 2012), Europe (EFNARC, 2002; SCCEPG, 2005), the USA (ASTM, 2017, 2021a, b) and China (CECS, 2006; MOHURD, 2012).

1.2.2 Conception of Rock-Filled Concrete

Although developing rapidly since the 1980s, SCC technology is not suitable for the construction of dams and is limited by a high hydration temperature rise, large shrinkage and high material cost due to the large amount of cement consumption. A team jointly led by Prof. F. Jin and Prof. X.H. An in Tsinghua University, China made much progress for massive SCC to save cement and mineral admixtures, but the cost and hydration heat were still high for practice. In 2003, an idea to combine SCC, masonry and prepacked concrete to break through the limitation of SCC was proposed after discussions with Prof. H. Okamura and Prof. C. H. Zhang; this technology was thereafter named *rock-filled concrete*. The initial concept of rock-filled concrete is grouting SCC via pipes into prelaid large rocks, which is called *rockfill*, to form compact concrete. A pilot study in the lab revealed that SCC can fill the voids among large rocks by pouring on the surface of the rockfill if the workability requirement is met. The SCC in RFC that meets the requirement of filling and with low cement consumption is later called *high-performance self-compacting concrete* (HSCC). Rock-filled concrete leverages many salient features of HSCC, such as segregation resistance and particularly the filling ability of flowing a long distance in a tortuous interspace to fill in voids among prelaid rocks, as shown in Fig. 1.1. The use of rocks considerably reduces cement consumption, thereby substantially lowering the temperature rise caused by hydration heat and reducing the shrinkage of concrete. The presence of a large proportion of rock also notably improves crack resistance and eliminates the requirements for cooling in the dam body. In line with extensive engineering practice since its invention, the concept of rock-filled concrete was brought forward to a standardized and codified construction technology that fulfils the requirements in the design and construction of dams.

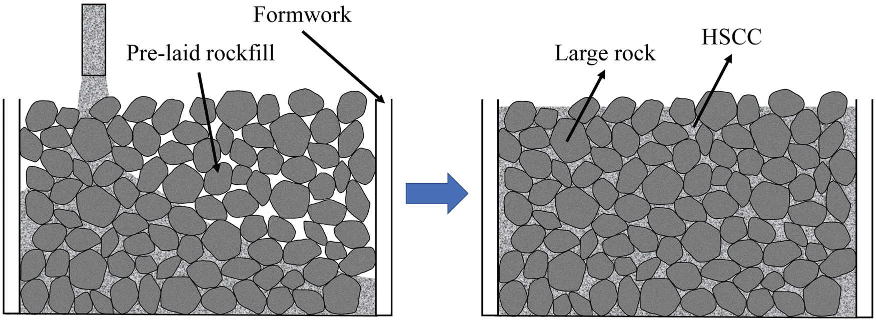

Fig. 1.1 Scheme of rock-filled concrete

To construct a rock-filled concrete dam, large rocks with grain sizes usually larger than 300 mm are laid by machinery or other means as a riprap layer with a certain thickness in a lift formed by the formworks. Then, HSCC is successively poured onto the surface of the rockfill at the pouring point with 3–5 m spacing until HSCC fully filled the voids among the rocks, thereby forming a compact concrete dam body. Some large rocks may be exposed above the surface of HSCC to strengthen the bonding between the lifts. The lift height of a rock-filled concrete dam is usually 1.5–2.0 m and is up to 3.0 m in a recently completed rock-filled concrete dam. From the statistical data in practical rock-filled concrete dams, large rocks occupy a volumetric ratio of approximately 55% in rock-filled concrete. Construction of subsequent dam lifts commences after proper treatment of lift surface by green cutting or other roughening measures.

Due to relatively conservative requirements on large rock size and HSCC workability, the compactness of RFC has been verified by test results in lab, pit sampling and drill core, and monitoring data in normal operation of dozens of RFC dams. Pouring HSCC onto the surface of the rockfill, instead of by grouting pipes for Prepakt concrete, Colgrout masonry or Preplaced Aggregate Concrete, eliminates any requirement for immersed vibration in CVC and masonry or roller compaction in RCC. Employment of HSCC, instead of flowable mortar for Colcrete, Colgrout masonry and PAC, ensures good performance of rock-filled concrete after hardening. Note that the cemented block used to rehabilitate the discharge channel in Morocco in 2010 was the closest form to rock-filled concrete regarding concrete placement. However, the compactness of cemented blocks cannot be guaranteed due to a shortage of high workability requirements for pumped concrete. Therefore, cemented blocks have not been employed to construct any main structures. Based on the advanced mix design for SCC, high-performance superplasticizers and experiences learned from practice, the quality control method for the workability of HSCC is effective and robust. The water dosage per cubic metre of HSCC is usually approximately 170–200 kg. The shrinkage and autogenous strain of rock-filled concrete are significantly smaller than those of HSCC. When compared with CVC, rock-filled concrete consumes less cement but achieves comparable strength after hardening. Specifically, the presence of a large amount of rocks not only considerably decreases cement consumption and hydration temperature rise but also functionally limits crack propagation in concrete and reduces the cost of construction materials. Large rocks and HSCC can all be placed by machinery, and no cooling pipes are needed, which facilitates the rapid construction of large dams. Above all, the use of a large proportion of rocks eliminates complicated cooling systems in the dam body, making rock-filled concrete a promising new material that revolutionizes conventional mass concrete construction.

1.2.3 Key Issues on Rock-Filled Concrete

Although promising, concern persists about the performance of rock-filled concrete, since it is distinctive from conventional concrete. Fundamental questions were raised relating to the inherent nature and characteristics of the rock-filled concrete, such as the presence of rocks, filling ability of HSCC, and in what way they influence the overall performance of rock-filled concrete. Before practising a real project, these questions were put forth to the Tsinghua team:

(1) ***Compactness***: Can voids between rocks be fully filled by HSCC? Or what requirements for HSCC or rockfill must be met to achieve complete filling?
(2) ***Mechanical and physical properties***: Do the properties of rock-filled concrete, such as strength, impermeability, and density support the stability and integrity of a rock-filled concrete dam? How is the shear resistance and impermeability of joints between the lifts in a rock-filled concrete dam? Can the durability of rock-filled concrete support the service life of a dam?
(3) ***Design method***: How can a rock-filled concrete dam be designed? Should it be treated as a concrete or masonry dam when designing an RFC dam? How is the seismic resistance of a rock-filled concrete dam?
(4) ***Construction method***: How can a rock-filled concrete dam be reliably constructed and the quality of the dam be controlled during the construction process?
(5) ***Economics and efficiency***: is the cost of a rock-filled concrete dam cheaper than that of a CVC, RCC or masonry dam? Does a rock-filled concrete dam construct more rapidly than a CVC or RCC dam?

1.3 Advantages of Rock-Filled Concrete Dams

Based on pioneering research by the Tsinghua team, the first rock-filled concrete dam was completed in 2005. Since then, more than 120 rock-filled concrete gravity and arch dams have been completed or are under construction in China. These rock-filled concrete dams range from 30 to 90 m in height with typical rockfill ratios of approximately 55% and average cement contents of 130–220 kg/m^3 of HSCC, or less than 60–100 kg/m^3 of RFC.

In line with the development in dam construction, researchers and practitioners nationwide spent fifteen years thinking critically about key issues raised in the previous subsection and keeping finding perfect ways to address the key challenges. The success of RFC technology vividly demonstrates how in-depth experimental and theoretical research can be rigorously incorporated into engineering practice. Much was leant over the long way, from concept to maturity, and these advantages eventually become the signatures of rock-filled concrete:

(1) ***Less machinery and less labour needed***: The use of HSCC eliminates any requirement for mechanical compaction or vibration, which in turn reduces

the requirements for labour and equipment. The machinery during rock-filled concrete construction is much less than that in CVC and RCC dams. Note that the volume of HSCC is only approximately 45% of the total volume of RFC, and the requirement for the capacity of mixer plants in rock-filled concrete dams is only half of that in CVC and RCC dams. Fully machined construction has been realized and matured in rock and HSCC placement.

(2) ***Low cement consumption and simplified temperature control measures***: A large proportion of rocks used in rock-filled concrete decreases the overall consumption of cement, lowers the thermal rise of hydration and eliminates the requirements for cooling. Temperature control measures are significantly simplified. As per the statistics of practical engineering projects, the consumption of cement per 1 m^3 $C_{90}15$ rock-filled concrete is only 67.5–85.5 kg, since only 0.45 m^3 of HSCC is needed in 1 m^3 rock-filled concrete, where the subscript 90 indicates that the age of concrete is 90 days. The adiabatic thermal rise of rock-filled concrete is much smaller than that of conventional concrete.

(3) ***High density and compressive strength***: From statistics of pit digging test and testing of core drill samples in practical engineering projects, the density of most rock-filled concrete dams reaches 2500 kg/m^3. A higher density is beneficial to the safety of mass concrete structures such as gravity dams. Rock-filled concrete also has good performance in shrinkage restriction and crack resistance in engineering applications due to its large rocks. Due to the effects of rockfill skeleton, the compressive strength of rock-filled concrete is higher than that of the HSCC.

(4) ***Cost savings and high efficiency***: Under the same condition, the construction cost of building a rock-filled concrete dam can be 10–30% lower than that of the conventional concrete dam or roller-compacted concrete dam. Such a considerable reduction in construction cost is mainly due to the fact that rock-filled concrete technology substantially reduces cement consumption, temperature control measures and labour for construction.

(5) ***Energy savings, low carbon and environmental friendliness***: Rock-filled concrete uses a large amount of rock as a building material, which can make full use of natural rocks. For dikes (levees) and other situations where the requirements for concrete performance are not very strict, construction waste, solid waste from old dams, and river pebbles can be used. Tailings and other solid wastes can be used as coarse aggregate and inert powder materials for producing HSCC directly. Rock-filled concrete decreases the amount of cementitious materials needed and conserves energy in several aspects of construction, such as crushing of aggregates and production and placement of concrete, which reduces carbon dioxide emissions, turns waste into assets, achieves cyclic utilization, and promotes energy conservation. From calculations using actual engineering data, we know that using 1 m^3 rock-filled concrete can reduce CO_2 emissions by 90.1 kg and save 30 kg coal equivalent (Huang et al., 2006; Liu et al., 2013).

1.4 Organization of the Book

The topics covered in this book fall into ten chapters. Current chapter presents basic idea of the rock-filled concrete dam. The development and current state of the practice of rock-filled concrete dams are introduced in Chap. 2. Essential concepts of filling capacity and compactness and in what way they influence strength and other major material properties are developed in Chap. 3. Chapter 4 covers the fundamental physical and mechanical behaviours, beginning with compressive strength, tensile strength and durability, extending to thermal properties and creep behaviour. In-depth analyses of experimental data from laboratory experiments are given as well.

Applications of these principles to the design and construction of rock-filled concrete dams as well as related engineering work are presented in later chapters. Chapters 5 and 6 introduce principles of the design for rock-filled concrete gravity dams and arch dams. Case histories and project-oriented insightful comments are provided, which is intended for practitioners, researchers and students to form a more complete understanding of the design principles. The construction techniques, procedures and equipment are covered in Chap. 7. Chapter 8 presents the quality control and instrumentation of rock-filled concrete dams. Chapter 9 provides a timely review of related technologies that address the newly encountered engineering challenges, including riprap rock-filled concrete, vibrated rock-filled concrete, self-protected underwater concrete and controlled self-compacting grouting. Applications of these technologies are also given, which can be referred by engineers from academia and professional practice. Chapter 10 concludes with a sketch of the future of rock-filled concrete dams from the viewpoint of the authors. Successful insights are developed through extensive engineering practice of rock-filled concrete dams and will guide the development of innovative technology in the years to come.

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Chapter 2
The History of Rock-Filled Concrete Dams

This chapter reviews the history of rock-filled concrete dams. This history explores the story of continuing efforts from conceiving rock-filled concrete, setting engineering practices, and improving knowledge to advancing design and construction techniques, and dams particularly crucial to the story are selected. In early development, the first rock-filled concrete dam was built in 2005. Baoquan Auxiliary Dam with fully mechanized construction and the Qingyu Reservoir are presented as solid examples, providing a full set of technical documents for the first time. Without question, these projects were stepping stones for us, forming a major platform for advancing to other greater rock-filled concrete projects. The development of rock-filled concrete gravity and arch dams is also introduced.

2.1 Early Development

The development of rock-filled concrete dams from conception to maturity, consists of a crucial early period during which many fundamental concerns and key challenges had to be addressed. Although the concept was originated in 2003, it was not a ready-to-use technology in dam engineering until the fall of 2004, when a series of pilot tests were conducted by the Tsinghua team to evaluate the feasibility and improve rock-filled concrete technology before implementation in a real engineering project. The focal point in the pilot test was placed on the most essential aspects of rock-filled concrete, including the filling performance of HSCC and compactness of rock-filled concrete. Shortly after the first-phase test, which demonstrated the excellent filling ability and compactness of the material, a historic chance to design and build the first rock-filled concrete dam came over to the Tsinghua team. For the design and construction of the first rock-filled concrete dam, the second phase of the pilot test was conducted in the spring of 2005 to verify the proposed construction procedure.

F. Jin and D. Huang, *Rock-Filled Concrete Dam*, Hydroscience and Engineering,
https://doi.org/10.1007/978-981-16-8298-8_2

2.1.1 *Pilot Testing*

In the embryonic stage of rock-filled concrete, perforated pipes were considered for use in casting HSCC, similar to the Prepakt concrete. On the basis of the study of HSCC at Tsinghua University, the filling ability of HSCC encouraged the research team to propose a revolutionary filling method by casting HSCC on the surface of rockfill without leveraging pipes. To investigate the performance of rock-filled concrete built by the proposed filling method, a series of pilot tests were conducted at Nanhua University in Hunan Province (An et al., 2005; Jin et al., 2005; Shi et al., 2005, 2007; Zhang et al., 2007).

The first-phase experiment was designed and conducted to probe the flow mechanism and filling ability of HSCC, thereby acquiring an understanding of the performance of rock-filled concrete. The Tsinghua-Nanhua joint research team cast three large specimens in dimensions of 500 mm × 500 mm × 2000 mm in the laboratory of Nanhua University (Fig. 2.1). The tested average compressive strength of the standard HSCC specimen is 44.74 MPa, and the workability includes a slump of 275 mm, slump flow of 650 mm and V-funnel flow time (VF) of 20 s.

The filling process was designed such that the HSCC was poured from one end of the form, flowing through pre-laid rocks. The grain size of the rocks was yet another key issue because it had a significant influence on the filling behavior of HSCC. Intuitively, HSCC fills the voids more easily when rockfill has a larger void ratio. Therefore, special consideration was given that rocks with a grain size of 150 mm to 200 mm were used, resulting in a void ratio of approximately 48% in rockfill. In a real dam project, rocks with a larger grain size have a larger void ratio, thereby achieving a better filling ability and compactness of the material.

After the completion of Sample A, another two samples were filled by a similar process. To study the potential interlock between the two lifts of rock-filled concrete, the partial top surface of Sample B was not filled fully. Sample C was intentionally partial finished. During the pouring of Sample C, the HSCC was collected from the far end and cast as a group of standard specimens. The compressive strength of this specimen group is 48.15 MPa, slightly higher than the 44.74 MPa compressive strength of the HSCC standard specimen. Some rocks were exposed at the surfaces, and they fixed within the rock-filled concrete very well. A concrete test hammer was used to test the strength of Samples A and B at the ages of 7 d, 14 d and 28 d. Two rock-filled concrete samples have a roughly uniform distribution of strength from the near to far end at every age. The development of strength at 7 d reached 70–75% of the strength at 28 d. The strength of rock-filled concrete is near that of HSCC. The first-phase test also investigated the strength of the rock-filled concrete specimen by conducting a flexural test of Sample A. Figure 2.1d presents the failure section, clearly showing that HSCC completely filled voids between rocks, and no large void was observed. The section was smooth with a few large rocks fractured, indicating strong bonding between rocks and HSCC. The first-phase experiment demonstrated an overall good performance of rock-filled concrete in terms of filling ability and