PRACTICAL ASPECTS OF SHOTCRETE FOR UNDERGROUND SUPPORT

Kuenga Gyeltshen, Executive Engineer, Punatsangchhu–II Hydroelectric Project Authority (PHPA)

(This paper is peer reviewed by Mr. N.V. Mahure, Chief Research Officer, PHPA-II on deputation from Central Soil and Materials Research Station (CSMRS), GoI, New Delhi).

Abstract

Shotcrete is one of the main support systems used in underground excavations. Steel arches and/or rock anchoring/bolting are also used as support system. But these arrangements take time for installation. In case of poor quality rock mass, instant support is needed so as to protect man and machinery from rock spalling. Shotcrete has emerged as one of the best solution for providing instant support. Since there is no need of formworks and it can be easily applied on to irregular excavation surfaces, it can thereby also reduce time and cost. In Dagachhu Hydropower Project, shotcrete of different strength grades had been used as rock support for all underground excavations. Shotcrete had also been used as the permanent inner lining for a large portion of the HRT. This paper aims to highlight some practical aspects of the shotcrete works for underground support based on the field experiences and available data.

Key Words: *shotcrete, gunite, testing, quality, standards, specifications, admixtures, aggregates, set-accelerator.*

1. Introduction

The history of shotcrete is as interesting as any other industrial product from invention to production and patenting, development and marketing successes, decline and resurrection to the shotcrete of the modern day age of globalization. To briefly highlight it, an American naturalist Carl Akeley invented the cement-gun and gunite material which was a mixture of cement and fine aggregate mortar applied pneumatically[1]. This was patented in 1910. The term gunite was a trademark of the first gunite equipment manufacturer. Due to patenting and trademarking, the use of similar term by other developers was restricted. Therefore, the other terms such as pneumatically applied mortar or concrete, spray concrete, spraycrete, guncrete, etc. were emerged in markets. The actual term shotcrete was defined by the American Railway Engineers Association in 1930[1]. Only the dry-mix process was used in guniting and the technology gained wide popularity in Northern America and spread to UK and the Europe as well, during the period of about half a century until 1950s. After the World War II, with the development of new machines in '60s and '70s, most important changes took place with the shotcrete technology. It is reported that with the invention of rotor-type continuous feed gun for dry-mix application paved the way for higher production and use of large aggregates in concrete. Since then, wet-mix process of shotcrete application also developed in the process. The confusion in the use of terms was cleared by the American Concrete Institute (ACI) by defining shotcrete as concrete or mortar applied pneumatically, whether it may be dry-mix or wet-mix [8]. Shotcrete is basically a concrete which has poor tensile and ductile property and for this with technological developments have introduced reinforcement elements to enhance its tensile property. Shotcrete which contains elements of steel fiber is called steel fiber reinforced shotcrete (SFRS) and that which contains elements of poly-fiber is termed as poly-fiber reinforced shotcrete (PFRS). This paper is not a fully scientific research paper but a sharing of practical experiences in field on shotcreting in underground works of hydropower projects.

2. Standard Practices and Guidelines

At the time when shotcrete/gunite was developed, clear standards and specifications of the materials and production of gunite were also developed. But with the technological developments over the period, those standards and practices which were in vogue at the time got obsolete and some even forgotten even though they had produced structures that stand to date. From ‘70s and ‘80s onwards, different countries and industrial associations have developed their own standards of practice and guidelines for materials and production of shotcrete. The International Tunneling Association (ITA) in a meeting in Toronto, Canada formed a Working Group in 1989 with the task to implement the status report on shotcreting technology in different countries [6]. The report which came out after two years has reported the general status of the technology in some fifteen countries. The Indian Standard IS: 9102 was published in 1978 as the Recommended Practice for Shotcreting, which got reaffirmed in 1997. The US Army Corps of Engineers have the Engineer Manual for Standard Practice for Shotcrete dated 31st January 1993; ACI 506.2-95 Specifications for Shotcrete was effective from 1st October 1995. EFNARC Technical Committee on Sprayed concrete has produced European Specification for Sprayed Concrete in 1993 and now the latest version available is of 1996. The author wish to state that while most standards, specifications and manuals are not readily available in the open source, the EFNARC guidelines and specifications are available openly for engineers involved in shotcrete works.

3. Shotcrete

The term shotcrete now is defined generally by almost all standards as mortar or concrete pneumatically projected on to a surface at high velocity, whether dry or wet-mix processes [7]. European countries tend to use the term sprayed concrete for shotcrete. It is used as one of the main support elements for stabilization of underground excavation of tunnels and caverns. It is also used for various other works in slope stabilization, rock surface protection, repair works, and for some permanent structural members as well. Since there is no need of formworks and it can be easily applied on to any irregular excavation surfaces very rapidly, it could thereby reduce time and cost of projects. For instance, in 126 MW Dagachhu Hydropower Project (DHPP) in south-western Bhutan, plain shotcrete of different strength grades had been used along with welded wire mesh reinforcement as the main rock support system for underground caverns, HRT and in open cut-slope stabilization[9]. Shotcrete had also been used as the permanent final inner lining for a large portion (1264 m of 7800 m) of the pressurized HRT. Use of shotcrete as the permanent inner lining instead of the normal cast-in-place concrete is generally not accepted worldwide except in few advanced countries in Europe and others [9]. However, with the gaining of experiences and skills of shotcreting, there is great opportunity for planners, designers and engineers in Bhutan to make use of the advantages of the material for civil engineering works in hydropower projects, road construction and other miscellaneous repair and rehabilitation works.

4. Practical Aspects

4.1 Materials Testing

Before a shotcrete work is taken up, it is necessary to make appropriate choice of input materials and conduct several tests on physical and chemical properties in line with the provisions in the contract technical specifications and standards. While drafting the specifications for shotcrete, usually specify the requirements for all the ingredient materials and also the test regime. These testing generally include the following:

- Physical properties of aggregates such as specific gravity, water absorption, density, soundness, etc.
- Gradation of individual coarse and fine aggregates and fulfilment of the requirement of combined grading limits.
- Mechanical properties of aggregates.
- Physical properties of cement and cementitious materials.
- Physical and chemical properties of admixtures viz. superplasticizer and set-accelerator.
- Cement-admixture compatibility test or the setting and strength development test.

While most of the above required tests are usually conducted in the routine quality control testing in a project, the cement-admixture compatibility test is the one which is not easily understood by people at project sites and often not conducted at all. In fact, it is one of the important tests especially in the production of shotcrete since chemical admixtures are invariably used in the modern day shotcrete production. In addition, mineral additives such as silica fume and pozzolans are also used in order to improve the performance of shotcrete. Therefore, it is imperative that the compatibility of different materials added for shotcrete production is checked at the very beginning rather than having to tackle some mysterious problems that will pop up in the process of actual shotcrete application.

Cement-admixture compatibility test is a very simple test done using the normal vicat apparatus that is used for testing of cement. Basically, it is a check on the setting properties of the mixture of cement, mineral additives, admixture and set-accelerator with equivalent quantities of materials and water-cement ratio finalized for the shotcrete mix design. Performance is checked with varying dosages of set-accelerator by weight of cementitious content. Most of the technical specifications followed in hydropower projects in Bhutan prescribe the maximum allowable initial setting time of 3 minutes and final setting time of 12 minutes which is as per some standards. Some specifications tend to be very stringent with prescription of maximum initial and final setting times limit of 1.25 minutes and 2.5 minutes respectively [2]. Figure 1 shows the setting times from the compatibility test with set-accelerator for varying dosages. The graph describes that as the dosage of set-accelerator increases, there is corresponding decrease in the setting times.

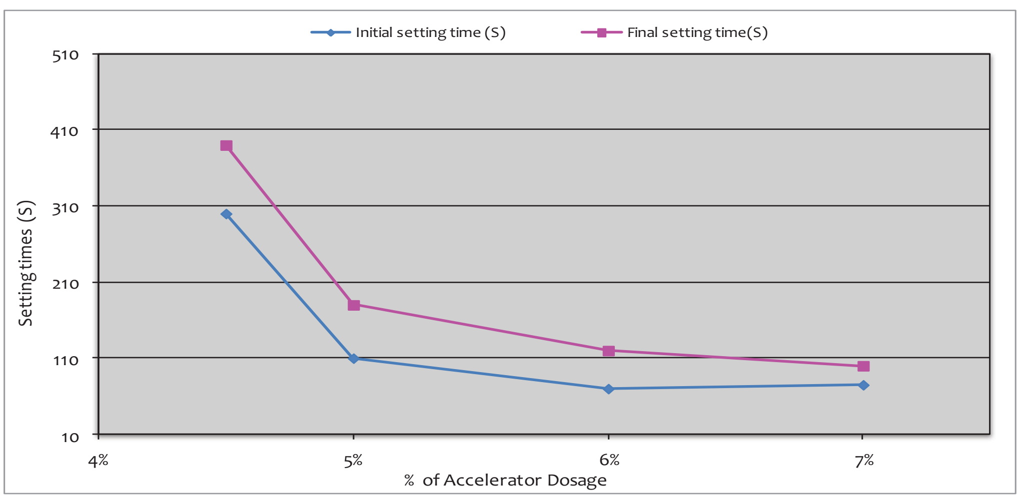

Figure 1: Setting times for different dosages of set-accelerators tested at DHPP (Source: Author).

However, the maximum dosage of set-accelerator is generally limited in the specification which varies from 5% to 10%. This is due to the fact that there is some reduction in strength of the final product as a result of the acidic nature of the alkali-free accelerator. The maximum dosage to be used in field have to be decided based on the performance of the chemical for imparting immediate setting property, which will enable application in overhead regions in cavern and tunnels as well as to act as immediate support for the freshly excavated openings and the final strength requirement for the shotcrete.

Manufacturer's statements of the product for final strength reduction will have to be verified through actual testing. Some standards and specifications prescribe that the maximum allowable strength reduction due to use of set-accelerator should not be more than 40% from the control mix.

4.2 Mix Design

There are no separate standards or guidelines for performing mix design for shotcrete. It is because shotcrete is no different from the conventional concrete except that it is sprayed using pneumatic spraying equipment at high pressure and makes use of set-accelerator at the nozzle.

As such, mix design is conducted similar to the conventional concrete with few extra cares. This extra cares are required for ensuring the proper spray-ability of the concrete, which is normally related to the workability of the concrete and strength reduction due to use of accelerating chemicals. For this, the target mean strength of the concrete ($_{ftms}$) pre-determined as usual as per IS:456 is enhanced by a certain percentage for the expected strength reduction in order to ensure that the final target strength is achieved even after strength reduction.

As mentioned above, chemicals that produce strength reduction of more than 40% have to be rejected. Another extra care required is for the use of maximum nominal size for coarse aggregate, which is normally limited in the range of 8-16 mm.

In general, 10 mm aggregate is used along with proper gradation of the combined aggregates (i.e. coarse and fine aggregates) to have most cohesive mix for optimum spray-ability. The finalized mix design proportions of different grades of shotcrete implemented at DHPP is shown in Table 1 [9].

Table 1: Mix design proportions of shotcrete implemented at DHPP.

Details	M35A10	M25A10	M20A10	Remarks
Water	150 kg	192 kg	191 kg	
Cement	540 g	480 kg	425 kg	OPC 43
Silica fume	60 kg	20 kg	-	
w/(c+p)	0.25	0.38	0.45	
10 mm	883 kg	850 kg	844 kg	
Sand	815 kg	875 kg	849 kg	
HRWR	1.2 %	0.6 %	0.4%	
Accelerator	5-7%	5-7%	5-7%	
3 day strength	-	22.5 MPa	-	
7 day strength	40.33 MPa	31.5 MPa	18.2 MPa	
28 day strength	56.08 MPa	39.85 MPa	27.22 MPa	
Avg. field strength	37	28	23	
Strength reduction	34%	29.7%	15.5%	

4.3 Execution

Before the actual start of shotcrete work execution, it is of paramount importance to ensure the proper functionality of all equipment involved such as the compressor, concrete pump, pipe lines, air lines, nozzle, pressure gauges, etc. The proper sprayability of shotcrete is contingent up on the capacity of the compressor to deliver the required air pressure at the spray nozzle, which is usually specified by the equipment manufacturer. The performance of shotcrete output is dependent on all lines of aspects from quality of shotcrete materials, mix design, production of shotcrete, surface preparation for application, and equipment and workmanship altogether. Shotcrete is assessed in the fresh state with visual observations for consistency, bleeding and segregation and with measurements of slump and slump-flow with traditional slump cone. This measurement can be done at batching and mixing plant (B&MP) as well as at site of application before pumping into the shotcrete machine. The slump of shotcrete needs to be kept in the range of 180-200 mm and slump flow in the range of 500-550 mm before spraying.

Shotcrete is sprayed through nozzle using shotcrete spraying machine and the set-accelerator is incorporated at the spray nozzle and intimately mixed with concrete. Proper functioning and adjustments in the spraying equipment is important to achieve good performance of shotcrete. Sometimes a mere inadequate knowledge of handling and operation of machine often leads to a blame-game, pointing doubts at concrete mix design, quality of cement, aggregates, chemical, weather condition, etc. which also lead to wastage of resources. Sometimes a good shotcrete produced from B&MP is spoilt at the shotcrete machine pump due to unnecessary overuse of vibration in the pump. Sometimes, there is simply no adequate pumping capacity due to wear and tear; and sometimes there is inadequate delivery of air pressure from the compressor. Other important things which have to be taken into consideration are to set limits for setting times, rate of concrete pumping, cementitious content of the mix, approved dosages of accelerator in the computer panel of the shotcrete machine. Unnecessary use of high pumping rate leads to high rebound loss and use of higher accelerator dosage lead to damage of shotcrete due to its acidic nature. Therefore, it is very important to check all gauges and parts before starting to spray. Worn-out spray nozzle also leads to poor shotcrete application. Figure 2 shows the computer screenshot available in the shotcrete machine showing details required for the set-up. In order to prevent excessive use of accelerator in the field by operator without knowledge of supervisors just to complete the work faster, screen pass-word protection should be used to lock the set-up.

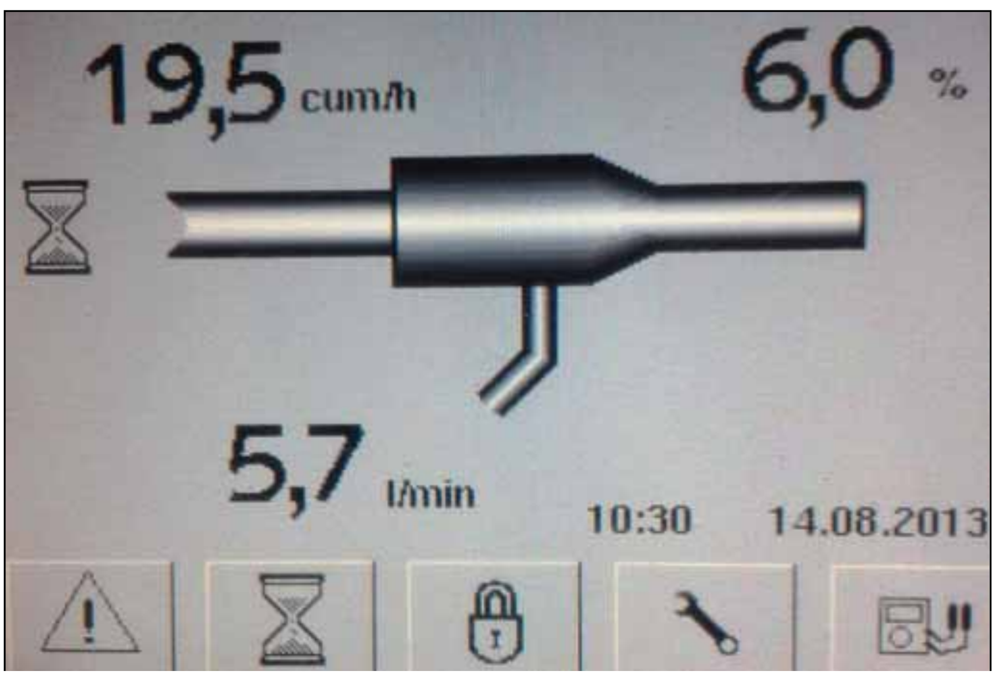

Figure 2: Screen-shot of computer set-up required in Shotcrete Machine (Source: Author).

Once all the equipment accessories have been inspected and checked for proper functionality, the first lot of shotcrete is to be subjected for suitability test.

4.3.1 Suitability Test

Subsequent to a successful laboratory tests for compatibility of the cement and admixtures, a suitability tests for the shotcrete mix have to be conducted to determine setting and initial strength development and also to establish the suitable range of accelerator dosages. For this, a full-scale application of shotcrete have to be arranged without any problem or errors in the equipment functionality so that any problem arising during the test could be purely due to some deficiency in the property of shotcrete materials only. This test could also be performed to assess the nozzle-man proficiency. Depending on the number of samples required to be made for assessment, test panel boxes of size 500 mm x 500mm x200 mm (lxbxd), preferably made of steel need to be prepared and taken to the site of shotcrete application. Nozzle-man whose proficiency is to be assessed will have to be made to operate the shotcrete application at the actual site and in the same process of shotcreting test panels shall be filled. Different accelerator dosages will have to be used in the samples to assess the effect of the chemicals.

One of the test panels need to be subjected to penetration test using soil Proctor Penetrometer with needle plunger. The penetration resistance measured gives an indication of the setting and very early strength development of shotcrete, say up to 1 hour. Beyond 1 hour and up to 3 hour, which is also the early strength development stage for shotcrete, Hilti Stud driving method with hand-held gun is used, which can measure from 3-20 MPa strength. However, this type of testing is rarely found used in hydropower projects in our country.

Some technical specifications prescribe the minimum required needle penetration resistance at certain time periods, for instance DHPP as given in Table 2[2].

Table 2: Minimum needle penetration resistance prescribed in technical specification of DHPP.

Time Period	Minimum Penetration Resistance
After 2 Minutes	260 kN
After 5 Minutes	380 kN
After 10 Minutes	450 kN

The diameter of the penetration needle tip should be 3 mm and depth of penetration approximately 15 mm into the shotcrete. With use of such penetration, strength development up to 1.5 MPa is possible to be measured.

Empirical relations are available to convert the penetration resistance into a compressive strength corresponding to core specimen having height-diameter ratio of 1. Table 3 shows the specimen data of the needle penetration test done at DHPP showing the equivalent core compressive strength [9].

There is no specification as such for the minimum compressive strength required to be achieved from the penetration resistance. The experience is that 2-5 minutes time is practically a very short time period to perform penetration test for shotcrete in the field. Practically, it takes at least 10 minutes to get one set of test of at least 10 readings.

The above figures of penetration resistance are also very difficult to be achieved even with chemicals from most reputed manufacturers like BASF Chemicals. The performance is highly dependent on the prevailing ambient condition and quality of shotcrete materials.

It is also the experience that if the shotcrete sets and start to harden rapidly indicating the proper action of the chemical on cement, penetration resistance achieved would be around 250 to 350 N by half an hour. This should yield about 0.5 MPa equivalent core strength.

Such shotcrete have been found to be performing satisfactorily in tunnels and caverns. Upon examining the applied shotcrete, it should look dry and there should be temperature development, but not beyond the maximum.

Freshly applied shotcrete which looks wet and covered with slurry on surfaces is an indication of poor performance and may have to do corrective actions either on mix design or the cement-admixture compatibility have to be reconfirmed.

The test panels have to be taken to laboratory after 24 hours and take out core specimens to be tested at ages of 1 day, 3 day, 7 day and 28 day to determine the strength development and fulfilment of the acceptance criteria.

Table 3: Specimen data of needle penetration resistance test done at DHPP.

Acce. Dosage	Time (Min.)	Penetration Resistance (N)											Strength (MPa)
		1	2	3	4	5	6	7	8	9	10	Avg.	
6%	5	343	353	235	225	323	362	343	313	255	382	313	0.51
	10	294	333	353	431	480	441	441	392	343	323	383	0.64
	30	490	529	529	539	549	568	539	490	539	510	528	0.90
7%	5	343	343	196	294	196	196	245	245	274	245	258	0.42
	10	235	294	362	235	392	343	392	343	431	431	346	0.58
	30	441	431	441	392	490	421	392	392	539	539	448	0.76
8%	5	441	412	421	451	441	353	392	441	421	412	418	0.71
	10	441	539	490	490	539	490	490	490	490	539	500	0.85
	30	510	Difficult for penetration test										

4.3.2 Requirements for Final Product

The common specification found in hydropower projects in Bhutan is plain shotcrete of grade M25A10 and steel fiber reinforced shotcrete (SFRS) of grade M3510. These are specified for use as rock supports in excavation of tunnels and caverns. Mostly SFRS is specified for underground works; while plain shotcrete with wire mesh reinforcements are specified for open slope protections in dam abutments and portals.

Similar to the conventional concrete, the requirements for the final product of shotcrete is specified with the 28 day compressive strength. In addition, compressive strength requirements for shotcrete are specified at early ages such as 1 day, 3 day and 7 day in order to check the early strength development and trends towards the final specified strength. Table 4 shows strength requirements specified for the shotcrete product in the technical specifications of different hydropower projects in Bhutan [2,3,&4].

Table 4: Requirements for shotcrete strength found in technical specifications of hydropower projects in Bhutan.

Projects	Grade of Shotcrete	Compressive Strength (MPa)				
		8 Hour	1 Day	3 Day	7 Day	28 Day
PHEP-I & II	M35A10 SFRS	-	-	12.50	22.5	35.00
	M25A10 Plain	4.41	-	12.26	-	25.00
NHPP	M35A10 SFRS	-	-	15.00	25.00	35.00
	M35A10 Plain	-	-	15.00	25.00	35.00
DHPP	M35A10 Plain	-	8.00	-	-	35.00
	M20A10 Plain	-	8.00	-	-	20.00

The acceptance criteria stipulated by most standards is that the average 28 day compressive strength of three specimens of shotcrete cores should be greater than 85% of the specified compressive strength and that no individual core specimen result should be less than 75% of the specified compressive strength.

In addition to the compressive strength requirements, there are other requirements like flexural strength, toughness and bond strength between intact rock and shotcrete, and shotcrete-shotcrete bond. However, these tests are rarely conducted in project sites due to lack of adequate testing facility.

4.3.3 Quality Control Testing and Evaluation

Collection of samples of construction materials, preparation of test specimens and conducting laboratory tests are the routine quality control (QC) activities in a project. Evaluation and interpretation of test results and making proper documentation and reporting to the project authority or owners constitute quality assurance (QA). QA/QC progamme are framed in line with the provisions in the contract technical specifications and national and international standards for each work.

For shotcrete works, quality control testing is mainly for the input materials viz. cement, aggregates, water, admixtures, fibers and construction chemicals; and testing of the shotcrete work for checking the acceptance criteria for the final product. It is important to know particularly the content of tri-calcium aluminate (C3A) in cement since it has a major influence with admixtures used in concrete. Some manufacturers add small amounts (~ 5%) of mineral additives like pulverised fly ash (PFA) or ground granulated blast furnace slag (GGBS) to OPC as performance improver which also affects the setting times and actual performance of shotcrete.

Other testing include checking the thickness of the in-situ shotcrete for the designed/specified minimum thickness, which is usually done by drilling holes and physically measuring the thickness with gauges.

5. Conclusion

The experience of the author is that shotcreting is a job which requires skill; and skill is developed only through practice. However, even though having the theoretical knowledge, practical knowledge is required to gain proficiency in this field. A person entrusted with the work of shotcrete operation in a project often lacks the required knowledgeable skills. In order to have persons with the required knowledgeable skills for operating shotcrete works, particularly in the execution of prestigious hydropower projects, the relevant agencies in the country need to arrange to impart vocational training to our people. It is in the opinion of the author that it is high time the state utility firms and vocational training institutes cooperate and initiate to conduct trainings for shotcrete operators since opportunities for shotcrete works are increasing day by day in the country. The state department of roads could look at starting to make use of the technology in the construction and repair and maintenance of the roads and structures making use of the advantages of the shotcrete materials to save time and resource in ensuring safety of vehicles and commuters along the national highways.

References

1. George D. Yoggy, The history of shotcrete, Shotcrete Classics online document.
2. Technical Specifications, 126 MW Dagachhu Hydropower Plant (Civil Works).
3. Technical Specification, 1020 MW Punatsangchhu –II Hydroelectric Project.
4. Technical Specification, 118 Nikachhu Hydropower Project.
5. Engineer Manual, Standard Practice for Shotcrete, USACE Publications.
6. ITA Report, Shotcrete for Rock Supports: A summary report on the state of the art in 15 countries, ITA Working Group on Shotcrete use prepared by Swedish Rock Engineering Research.
7. EFNARC 1999, European specifications for sprayed concrete guidelines.
8. ACI-506.2-95, Specification for shotcrete.
9. Gyeltshen, K. Project Completion Report Part III Quality Control and Instrumentation Monitoring during Construction of 126 MW Dagachhu Hydropower Project, June 2015.

Author's Profile

Kuenga Gyeltshen graduated from South Gujarat University, SV Regional Engineering College, Surat in India with Bachelor of Engineering in Civil in 2001 and started his career as Assistance Engineer in Tala Hydroelectric Project Authority. In 2011 he completed his MSc. in Hydropower Development from Norwegian University of Science and Technology, Norway. He has a wide experience in the field of hydropower ranging from underground construction management, quality control, instrumentation and monitoring, tender evaluation of main contract packages, due diligence of DPR documents, planning, project risk management, preparation of project completion reports, etc. He is currently working in PHPA-II on deputation from Druk Green Power Corporation.