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## State of art of RCD dams in Japan

*Estado da Arte do RCD barragens no Japão*

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### Resumo

A construção da primeira barragem do mundo usando concreto compactado a rolo CCR (Concreto Compactado a Rolo) foi iniciada em Outubro de 1978, no Japão. Desde então, em 30 anos, cerca de 50 barragens com esse tipo de concreto foram construídas no Japão. O concreto compactado a rolo é geralmente referenciado pela sigla CCR, e barragens construídas em CCR são diferentes das outras construídas em concreto tradicional tanto em nível de projeto quanto de método de construção. Até agora, a utilização do CCR permitiu através de muitas experiências a construção de barragens de forma segura e econômica. Além disso, como em barragens de concreto convencional, barragens de CCR têm satisfeito requisitos de desempenho como, por exemplo, resistência, massa unitária, permeabilidade e durabilidade. Este trabalho resume a história de barragens de CCR, as características do CCR, e as últimas novidades do método de construção do CCR no Japão.

*Palavras chave: CCR, concreto compactado a rolo, construção racional, transporte*

### Abstract

The world's first roller-compacted concrete in dams was started in October 1978 in Japan. Since then, for just 30 years, about 50 roller compacted concrete dams have been constructed in Japan. This roller-compacted concrete is called RCD (Roller Compacted Dam concrete) and RCD dams are distinguished from the other roller-compacted concrete (RCC) dams because there are some differences in their design and construction philosophies. So far, RCD construction method has realized the smooth, safe and economical dam constructions through many experiences. Further, like conventional concrete dams, RCD dams have satisfied requested performances such as strength, unit weight, water tightness and durability. This paper describes the history of RCD dams, the characteristics of RCD concrete, and the latest situation of RCD construction method in Japan.

*Keywords: RCD, RCC, roller compacted dam-concrete, rationalized construction, transportation*

# 1 Introduction

RCD (Roller Compacted Dam concrete) construction method is a rationalized construction method for concrete dams which was developed by the Ministry of Construction, Japan in 1970's, as the first roller-compacted concrete construction method prior to RCC (Roller Compacted Concrete). Through many RCD dam's experiences, RCD construction method has achieved reduction of the construction period, the labor cost, the environmental issue, and the hazard in safety for the constructor.

## 1.1 Features of RCD concrete and RCD construction method

RCD concrete is extremely dry and lean concrete in order to improve transportability and reduce hydrated heat. The Ministry made up RCD concrete under a new mixture concept to keep the same quality in strength and density as the conventional concrete has.

Further, the Ministry established RCD construction method to manage this RCD concrete. In this method, the concrete is spread in several thin layers over the entire dam surface and is compacted by vibratory rollers (refer to Photo 1, 2). The work cycle by RCD construction method is shown as follows (refer to Figure 1);

- 1) Dry and lean concrete is transported from the concrete plant to the placing site by dump trucks or other developed means of transportation and the concrete is unloaded.
- 2) The concrete is spread out using bulldozers by thin layers.
- 3) Transverse joints are made using vibratory joint cutters in the above time.
- 4) The concrete is compacted using vibratory rollers after all concrete spreading.
- 5) The concrete is then cured for 24 ~48 hours in wet and stable environment.
- 6) Lift surfaces of the concrete should be treated by green cut.
- 7) The mortar is spread out before the next concrete is unloaded in the placing area.

With RCD construction method, many kinds of improved machinery and equipments have been adopted in concrete mixing, transportation, joint cutting, spreading and so on.

Further, the quality control has been systematically performed using the latest measuring equipments such as the RI (Radio Isotope), optics and so on.



Photo 1 - RCD construction in Takizawa dam

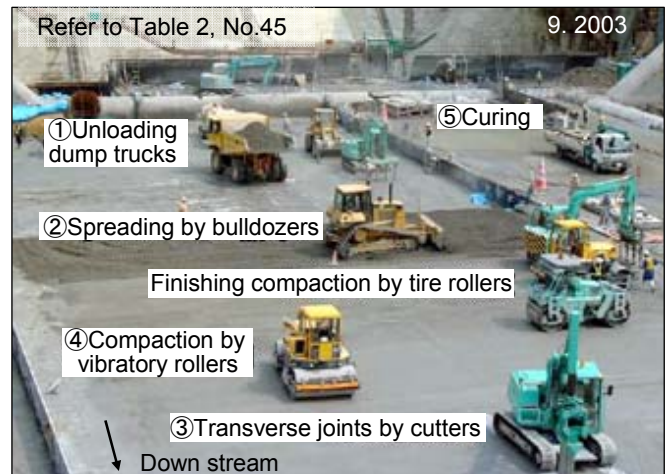


Photo 2 - RCD construction in Nagai dam

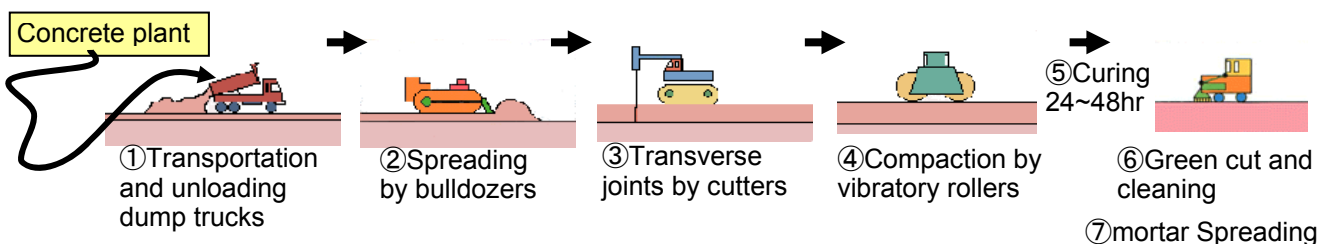


Figure 1 - Concrete work cycle of RCD construction method

## 1.2 Philosophy and background of RCD construction method

The philosophy of RCD construction method is to keep the same performance as concrete dams constructed with the conventional construction method and the former must satisfy the same design criteria as the latter, while to pursue the improvement of economy, safety, and environment.

Therefore, RCD is a construction method to rationalize the dam construction works and the required functions of RCD dams should be completely the same as that of conventional concrete gravity dams. For example;

- 1) Transverse contraction joints are installed every 15 m in order to prevent temperature cracks in the dams.
- 2) Conventional concrete with high quality is placed at the upstream and the downstream surfaces of the dams in order to obtain water-tightness and high durability.
- 3) Lift joints (horizontal surfaces) are treated in the same way as the conventional concrete dams in order to assure good bond and water-tightness between the lifts.

There are two key points as the background of the RCD development in 1970's.

Firstly, in the conventional methods of concrete dam, in order to prevent the concrete cracking, the dam concrete is placed in blocks with contraction joints like as block layer placing of Photo 3. So, the conventional method involves complying with many restrictions. Secondly, the economical benefit of rock-fill dams was rapidly improved by using the common and large scale machinery like as Photo 4.

Eventually, conquering the above concrete problem and adopting the mechanization in fill dams, RCD construction method enables more advantages to construct dams than the other dam construction methods. However, the conventional method like as Photo 3 is still advantageous in a small scale dam because the internal concrete volume is too small to use RCD, and a rock-fill type dam is still advantageous in a case that the foundation is weak or soft.

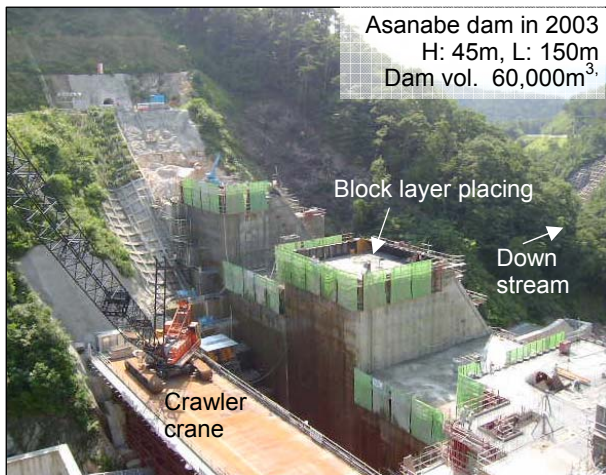


Photo 3 – Block layer placing in a small scale dam

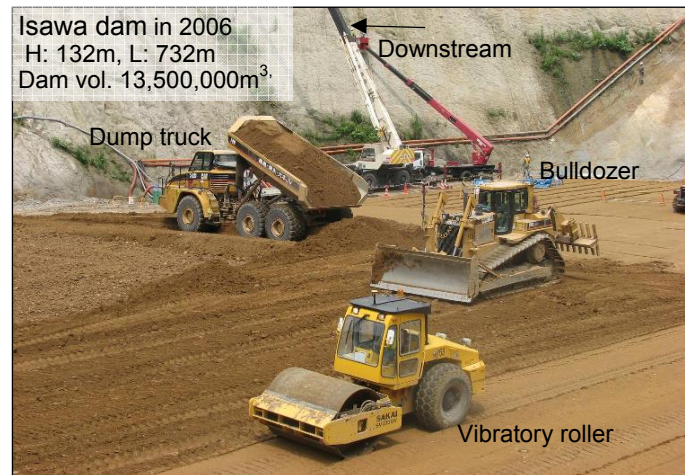


Photo 4 - Mechanized latest rock-fill dam

## 1.3 Comparison between RCD and RCC

The definition according to ACI 116 is that RCC is the concrete compacted by a roller, and from this point, we can say RCD is a kind of RCC. Actually, the both have many common concept, technical know-how, machinery and procedure.

However, it is a fact that RCD has regarded high quality as important in rationalization of concrete dam construction. For example;

A typical feature of RCD construction method is that the concrete is spread into thin layers by bulldozers by several times, and then they are compacted by vibratory rollers. Thin layer spreading of concrete is the key factor that makes thick lift placement possible.

While, in RCC, the concrete is spread into thin layers by bulldozers, and then every layer is compacted by vibratory rollers one by one.

The reason of higher lift compaction in RCD is to reduce the number of weak planes between successive lifts, considering rare possibilities of serious damages caused by earthquakes and other disasters.

Table 1 shows the feature among some types of concrete for dams and it can be seen the difference of these concrete. Further, Figure 2 shows the relationship between RCC and RCD concretes from the view of paste contents and density or strength of concrete.

As a whole, it is easy to realize that RCD occupies an important position in RCC technology, because the high quality of RCD is based on the starting origin that concrete should be mixed politely and be compacted as possible as firmly not too relying on easy materials. Thus, we might say RCD is a high grade version of RCC.

On the other hand, it is a fact that the design of RCD is on a safer and more durable side, because Japan is a representative natural disaster country of earthquakes or floods, and many lower areas of dams are urbanized areas where much of industries and properties are accumulated. As a whole of infrastructures, design standards in Japan persist in higher quality and safer facilities.

Further, as for the cost, RCD has pursued the economy by various rationalizations and many efforts for the cost reduction will be continued as a world class technology.

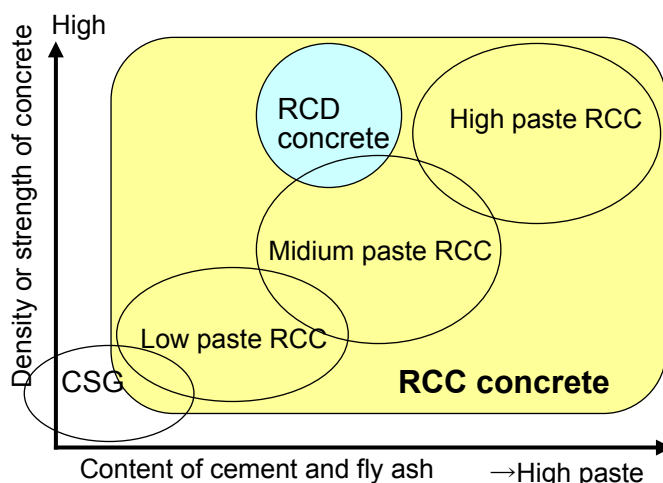


Figure 2 - Conceptual position of RCC & RCD concrete  
CSG: Cemented Sand and Gravel, new material for dams

Table 1 - Comparison between RCD and the other types of concrete (internal zone)

	Conventional dam concrete in ELCM*	RCD concrete	High paste RCC concrete	RCC in Kinta dam**
Property of concrete	dry lean concrete	extremely dry lean	High paste concrete	High paste concrete
Unit content kg/m <sup>3</sup> W: water, C: cement	W=105~115kg/m <sup>3</sup> C+F =130~160kg/m <sup>3</sup>	W=80~105kg/m <sup>3</sup> C+F =110~130kg/m <sup>3</sup>	W=100~150kg/m <sup>3</sup> C+F =150~300kg/m <sup>3</sup>	W=150kg/m <sup>3</sup> C+F =200kg/m <sup>3</sup>
F/C+F, F: fly ash	20~40%	20~40%	□50%	50%
Max size of aggregate	80~150mm	80~150mm	Mostly 40~65mm	63mm
s/a :sand/aggregate	25~30%	28~34%	Higher than RCD	41%
Consistency test	Slump value: 2~4cm	VC value:10~25sec	VB value: 10~17sec	VB value: 12~17sec
Air content ratio	3~4 ±1%	1.5 ±1%	lower than RCD	0%
Compaction machinery	Immersion vibrators	Vibratory rollers	Vibratory rollers	Vibratory rollers
Thickness of a lift	1.0m/1.5m	0.75m/1.0m	0.3m~0.4m	0.3m (slope layer)
Transverse Joint	Block formed by 15m span	Cut by 15m span using joint cutter	Cut by 15~60m span using joint cutter	Cut by 20m span using joint cutter
Lift Joint treatment	Green cut +cleaning + mortar spreading	Green cut + cleaning + mortar spreading	Nothing to do until setting start	Nothing to do in 5hr after placing
External concrete zone	conventional dam concrete	conventional dam concrete	High paste concrete or PVC sheet	High paste concrete (grout enriched RCC)

\*ELCM: Extended Layer Construction Method, ELCM is more popular to middle or small scale dams than RCD in Japan.

\*\*Kinta dam is constructed in Perak state, Malaysia. ( H: 92m, L: 780m, dam vol: 980,000m<sup>3</sup>, RCC term: 1.2003~6.2006)

## 2 History of RCD dams in Japan -30 years since the first RCD dam-

At the beginning of 1970's, the research for the rationalization of the dam construction method was started in Japan. Especially, "Committee for the economical construction of concrete dams" was established in 1974 by Ministry of Construction, and made a comprehensive study. The basic target of the committee was as follows: "Reduction of the unit cost of concrete should be studied, because of the raising labor costs, and because worsening foundation rock conditions had further increased the volumes of concrete gravity dams." After comprehensive research and discussions through the committee, the Ministry established RCD construction method as an effective method used some large-sized and general machines.

RCD construction method was first applied to Shimajigawa dam (Table 2, No.1, Photo 5) and Ohkawa dam (Table 2, No.2). RCD concrete works at both dams were completed in 1980, and the superiority of RCD construction method was proved. Then, RCD construction method was applied to Tamagawa Dam (Table 2, No.4). The construction of these dams confirmed RCD construction method as the superior method.

In the latter half of 1980's, RCD construction method was also adopted at many dams (Table 2, No.5-14). The development of RCD progressed with the improvement of vibratory roller, and it extended to various new concrete transportation systems. Other related studies such as temperature control, quality control, and peripheral technologies such as precast galleries and joint cutting machines have also been improved.

In 1990's, RCD construction method raised technical completeness by the large-scale dam execution such as Ryumon dam (Table 2, No.15), Miyagase dam (Table 2, No.21, Photo 6), Urayama dam (Table 2, No.25), Gassan dam (Table 2, No.30), Origawa dam (Table 2, No.35, Photo 7) and Chubetsu dam (Table 2, No.36). At the same time, RCD construction method was adopted in many middle-scale dams and it was ensured to be advantageous in concrete dams from middle to large-scale. After 2000, Takizawa dam (Table 2, No.44) and Nagai dam (Table 2, No.45) achieved some important developments.

Today in Japan, Kasegawa dam (Table 2, No.48) and other several dams are challenging to progress to a new stage of dam technology for the sustainable future. Table 2 shows the outline of 50 RCD dams in Japan for these 30 years since the first RCD concrete placement in 1978. The performances of these dams are still maintained well.

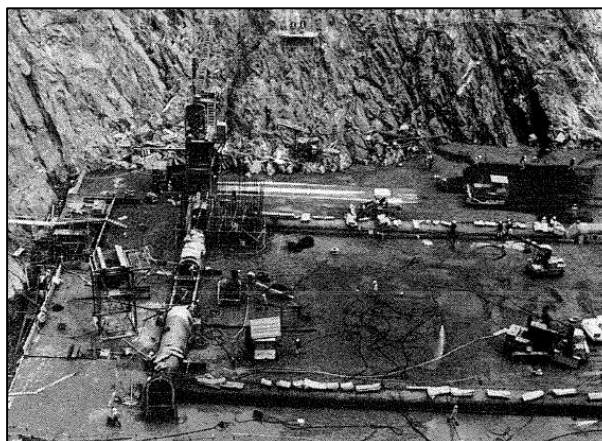


Photo 5 - Shimajigawa dam (first RCD in 1978)



Photo 6 - Miyagase dam (biggest RCD, completed in 2000) Photo 7 - Origawa dam (completed in 2004)

Table 2 - List of RCD dams in Japan (Mainly described on concretes, Numbers are allotted by RCD works starts)

No.	Dam name	Area**	Term of RCD placing	Dam height :m	Dam volume :m <sup>3</sup>	One lift		G <sub>max</sub> mm***	RCD Unit content: kg/m <sup>3</sup>				s/a***** :%	Transportation
						Layers	Lift :cm		Water	C+F****	F/C+F: %	Sand		
1	<b>Simajigawa</b>	7	1978-80	89.0	317,000	4	70	80	105	120	30	752	34	CC
2	<b>Ohkawa*</b>	4	1979-80	75.0	900,000	3	50	80	102	120	20	686	32	DT
3	Shinnakano*	1	1980	74.9	202,000	4	70	80	95	120	30	689	32	DT
4	<b>Tamagawa</b>	2	1983-86	100.0	1,150,000	4	100	150	95	130	30	657	30	IC
5	Mano	2	1985-87	69.0	218,700	3	50	80	103	120	20	735	33	IC
6	Siromizugawa	2	1985-88	54.5	315,333	3	50	80	102	120	20	673	31	DT
7	Asahiogawa	4	1986-88	84.0	361,000	3	50	80	94	120	20	711	32	DT
8	Asari	1	1987-90	73.9	514,006	3	50	80	103	120	20	659	30	DT
9	Sakaigawa	4	1987-91	115.0	713,000	4	75	150	103	120	30	707	32	IC
10	Pirika	1	1988-89	40.0	870,000	3	75	80	90	120	30	661	30	DT
11	Dodairagawa	3	1988-90	70.0	374,630	3	50	80	102	120	20	725	30	IC
12	Nunome	6	1988	72.0	303,000	3	75	150	95	120	35	608	27	DT
13	Kamuro	2	1988-90	60.6	306,600	3	50	80	103	120	20	729	32	IC
14	Hattabara	7	1989-92	84.9	500,000	3	75	150	90	120	30	617	28	DT
15	<b>Ryumon</b>	9	1990-92	99.5	1,074,000	4	100	150	83	130	30	621	28	DT
16	Sabigawa	3	1990-91	104.0	590,000	3	75	150	95	130	30	655	30	TC
17	Miyatoko	2	1990-93	48.0	286,852	3	50	80	98	120	20	673	30	DT
18	Kodama	2	1991-93	102.0	571,890	3	75	80	102	130	30	668	30	IC
19	Satsunaigawa	1	1991-95	114.0	761,780	3	75	150	83	120	35	641	28	DT/TC
20	Tsugawa	7	1991-93	76.0	343,000	3	75	80	100	120	20	692	30	DT/BC
21	<b>Miyagase</b>	3	1991-94	156.0	2,060,000	3	75	150	95	130	30	652	30	IC
22	Chiya	7	1992-95	97.5	697,000	3	75	80	103	130	30	724	33	CC
23	Ohmatsugawa	2	1992-95	65.0	294,000	3	75	80	105	130	30	659	30	DT
24	Hinata	2	1992-94	56.5	231,560	3	75	80	100	120	30	727	32	DT
25	<b>Urayama</b>	3	1992-95	156.0	1,750,000	3	75	150	85	130	30	679	30	BC
26	Takisato	1	1993-97	50.0	455,000	3	75	80	88	120	30	734	32	BC
27	Yoshida	8	1993-95	74.5	304,437	3	75	80	95	120	30	656	30	IC
28	Shiokawa	3	1993-95	79.0	388,600	3	75	80	100	120	20	711	32	DT
29	Shimagawa	3	1994-96	89.5	494,300	3	75	80	100	120	20	732	32	DT
30	<b>Gassan</b>	2	1994-98	123.0	1,160,000	4	100	150	87	130	30	664	30	BC
31	Hiyoshi	6	1994-96	67.4	674,300	4	100	80	83	120	30	100	30	DT
32	Tomisato	8	1995-97	106.0	507,619	4	100	80	90	120	30	746	30	CC
33	Hayachine	2	1995-98	73.5	334,602	3	75	80	97	120	30	715	32	DT
34	Kazunogawa	3	1995-97	105.2	622,000	4	100	120	90	120	30	632	28	TC
35	Origawa	5	1996-00	114.0	742,069	3	75	150	93	130	30	635	29	CC
36	<b>Chubetsu</b>	1	1997-01	86.0	1,007,000	4	100	150	76	120	30	632	28	DT
37	Shinmiyagawa	4	1997-00	69.0	480,000	3	75	80	95	130	30	710	32	DT
38	Kubusugawa	4	1998-99	95.0	468,500	3	75	80	97	120	30	703	31	DT
39	Ohnagami	7	1998-00	71.5	362,000	3	75	80	103	120	30	710	32	CC
40	Ueno	3	1998-01	120.0	720,000	4	100	150	89	110	30	658	29	TC
41	Kutani	4	2000-02	75.8	359,449	3	75	80	105	120	30	675	30	DT
42	Fukuchiyama	9	1999-01	64.5	202,000	3	75	80	90	120	30	764	32	DT
43	Koyama	3	2000-02	65.0	531,000	3	75	80	100	120	30	662	30	DT
44	<b>Takizawa</b>	1	2001-05	140.0	1,616,808	4	100	150	85	120	30/40	708	32	CC
45	<b>Nagai</b>	2	2002-07	125.5	1,200,000	4	100	80	100	130	30	662	30	TC
46	Kido	2	2003-05	93.5	501,150	4	100	150	103	120	30	630	28	CC
47	Toppu	1	2005-08	78.4	520,269	3	75	80	86	120	30	729	32	DT
48	<b>Kasegawa</b>	9	2007-09	97.0	965,000	4	100	80	99	120	30	644	29	DT
49	Obara	7	2008.9-	90.0	573,000	4	100	80	92	120	30	631	28	TC
50	Yubari-shuparo	1	2009.5-	110.6	940,000	4	100	80	85	130	30	668	30	DT

\* RCD concrete was placed in the basement of dam. \*\*Area is shown in Figure 3.

\*\*\*G<sub>max</sub>: max size of aggregate, \*\*\*\*C+F: Cement+Flyash, \*\*\*\*\*s/a: ratio of sand to aggregate

DT: dump truck, IC: incline, CC: cable crane, TC: tower crane, BC: belt conveyor

Figure 3 shows RCD dams in Japan grouped by the transportation method which is one of the most outstanding features of RCD construction method, in fitting for various areas. Additionally, it can be found that RCD dams have been constructed more in north and east areas. The first reason relies on that dams in these areas are more requested to speed up the concrete placing to recover breaks by snow or coldness in winter. The second reason relies on that RCD fits to large size dams and rivers in these areas are mostly bigger.

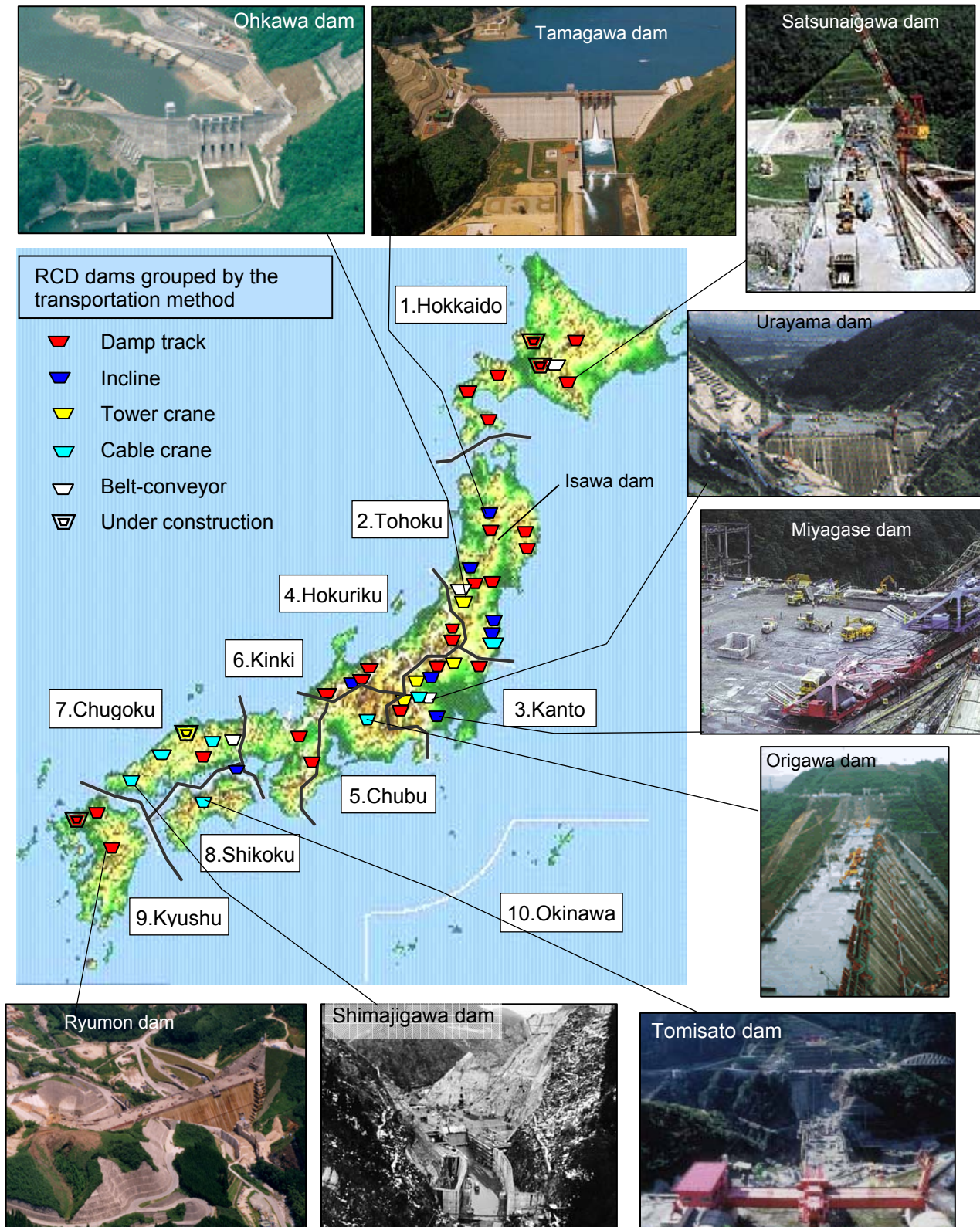


Figure 3 - Map of RCD dams in grouped by the transportation method

### 3 Planning of RCD construction method

The basic plan of RCD construction method is decided by considering the schedule, temperature control, compacting thickness, construction facility capacity, geography, geology, climate and environment. Key points in RCD planning are described below.

#### 3.1 Zoning of dam concrete

The upstream and downstream of dam surfaces should be covered by high quality concrete to maintain water-tightness and durability to protect the concrete from freeze-and-thaw attack or other aging.

In RCD dams, like conventional concrete dams, the concrete is classified into external concrete that is used at the surface of the dam, foundation concrete that faces the bedrock, structural concrete that is used in and around structural elements, and internal concrete that is used inside the dam. RCD concrete is placed in internal zone as shown in Figure 4.

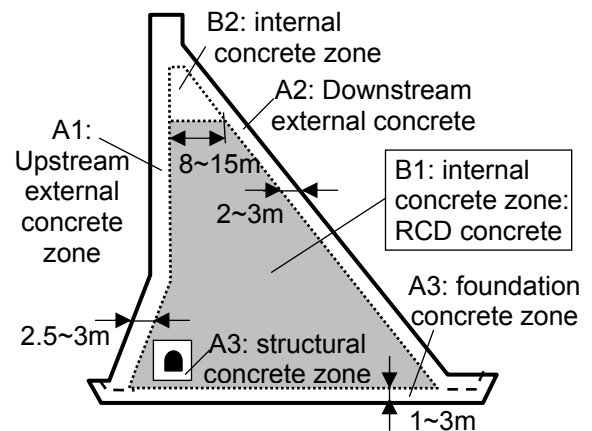


Figure 4 - Cross section of RCD dams classified by concrete mixture

Thus, RCD concrete volume is estimated excluding external, foundation and structural zones, and this volume is a key point on the adoption of RCD construction method.

#### 3.2 Lift schedule

In RCD construction method, much more concrete can be placed within the same period than the conventional construction method.

Therefore it is extremely important to plan an appropriate concrete placement schedule (lift schedule) to obtain construction efficiency and to prevent temperature cracks.

##### 3.2.1 Lift thickness

In order to speed up construction and to reduce the number of lift surface treatments, lift thickness had to be increased. But it was accompanied by a risk of inadequate compaction of RCD. At Tamagawa Dam, 1 m of lift thickness was made possible by thin layer placement. 1 m of lift thickness was divided into four thin layers that were spread by bulldozers. Recently, most of RCD dams have reduced the terms and costs by the 1 m lift.

##### 3.2.2 Rain restriction

Since RCD concrete is dry and lean concrete, it is more sensitive to rainfall than conventional concrete. If the rainfall is stronger than 2~4 mm/hour or if the concrete surface might be disturbed by the rain, the concrete placement is interrupted and a cold joint is provided. This rain restriction is also considered in making the lift schedule.

#### 3.3 Temperature control

Since it is difficult to use embedded pipe cooling in RCD dams, the temperature control plan should be prepared to prevent temperature cracks at the planning stage.

- 1) To suppress the heat of hydration: Moderate-heat Portland cement with fly ash is used and the unit cement content is reduced in RCD concrete.
- 2) Cutting of transverse joints: Experiences have shown that temperature cracks can be prevented mostly when the transverse joints are placed about 15 meters apart.
- 3) Curing RCD concrete: Through the term of concrete placing in most of RCD dams, the concrete is cured by ponding and water sprinkler. Further, in cold winter, the surfaces of concrete dams should be covered by heat insulators like as urethane materials.



- 4) Pre-cooling of materials: In the summer season, most of RCD dams have executed pre-cooling of concrete materials (mainly, water and coarse aggregates).
- 5) Another important step is to start the concrete placing from the more advantageous month. Miyagase dam started the concrete placing from September from this idea.

### 3.4 Choice of concrete plant capacity and mixer type

As RCD construction method enables to place much more concrete, RCD concrete plants should have enough capacity to speed up the concrete placement. Figure 5 shows that concrete plant capacities in RCD dams tend to be bigger and more in accordance with the dam volumes than the others, because RCD dams are more free from the restrictions of temperature control, concrete transportation and concrete placing.

Further, since RCD concrete has low cement content and water, it must be mixed thoroughly to get uniformity. Various types of mixer have been used, like as a compulsory type, a tilting type or a new type using the gravitational power shown in Photo 8.

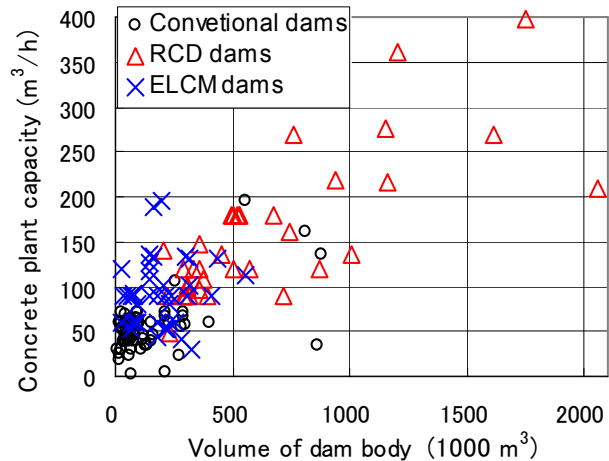


Figure 5 – Concrete plants to dam volumes

### 3.5 Choice of transportation system

Spectacular achievements in RCD construction method has been the improvement and diversification of transportation system. Because the construction surface of a dam built by RCD construction method is flat, dump trucks can transport RCD concrete to every pouring area on the dam. It provides greater freedom of choice of the transportation system from concrete batching and mixing plant to the dam. Accordingly, by selecting the most suitable transportation systems, there is less damage to the natural environment.

### 3.6 Simplification of inside structures of dam body

Inside structures such as inspection galleries, temporary diversion channels, conduits and gates might affect the smooth concrete placing of RCD construction method. So, various simplifications of inside structures have been implemented to speed up the RCD concrete works in Japan. For example, they are adoption of precast members, rearrangement or shortcut of galleries to avoid duplication with concrete works, reposition or bridging of temporary diversion channels, course and elevation change of conduits, and improvement of complicated structural works which is a bottleneck of the rationalization.

Photo 9 shows the precast set for inspection galleries to simplify formworks.

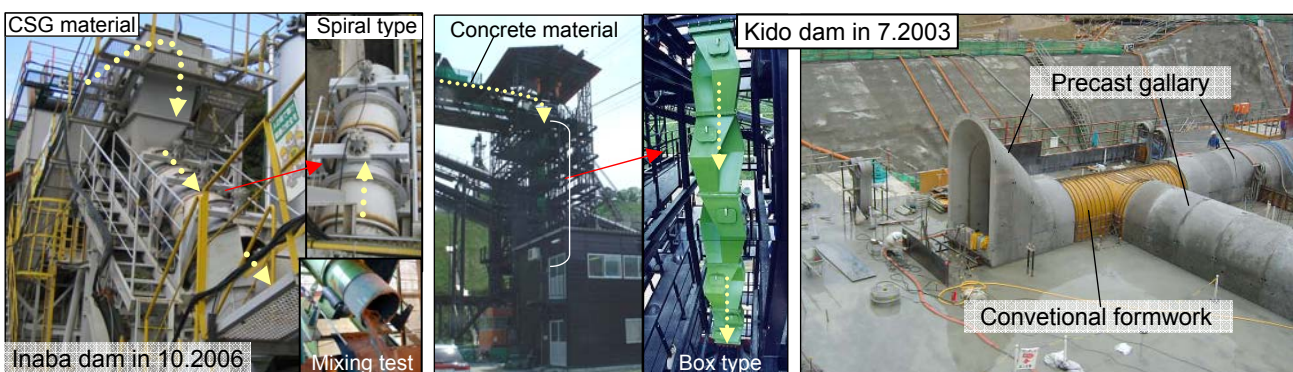


Photo 8 - Spiral type mixer (Left) and Box type mixer (right)

Photo 9 – Setting of precast gallery

## 4 RCD concrete

The requirements of RCD concrete mixes are the same as those of conventional concrete. The mixture design of RCD has been improved throughout the history of RCD construction method.

### 4.1 Requirement to RCD concrete

The mixtures of RCD concrete in table 2 shows that the unit cement content and unit water content in RCD concrete are much less than those in the conventional concrete for dams. It is because RCD concrete should be extremely dry and lean concrete. Extremely dry concrete is required to allow the construction equipment to travel on fresh concrete. Lean concrete is required to minimize temperature rises which may cause temperature cracks. At the same time, hardened RCD concrete should have the same properties as conventional concrete, which is required to construct the safe and watertight concrete dams. Many efforts have been made to ensure that RCD concrete has all these properties. Like conventional concrete, RCD concrete must have strength, unit weight, water tightness and durability to satisfy the requested performance.

### 4.2 Material properties used in RCD concrete

In RCD construction method, prescribed strength, unit weight, durability and water-tightness must be secured. In particular, temperature rises due to heat of hydration of cement must be minimized, and the mix must be determined so that it can be well compacted by vibratory rollers. Prior to mix design, materials should be selected like as below.

- 1) Cement: Cement with low heat of hydration is the most ideal to prevent large temperature rises in concrete. Growth in strength over long term is also important. In consideration of these points, moderate-heat Portland cement is generally used, and low hydration heat type cements were also developed. At Hiyoshi dam and Ueno dam, workability was improved by finer particles or admixtures, and the unit cementitious material (cement and fly ash) content was reduced to  $110\text{kg/m}^3$ .
- 2) Aggregates: Aggregates used in RCD concrete must have the same quality as those of conventional concrete. While the maximum size of aggregate 150 mm is sometimes used, in most cases 80 mm is the maximum size of aggregate in RCD concrete.
- 3) Finer particles: Reducing the cement paste content or mortar content may cause the segregation of the aggregates. It is improved by adding finer particles (50 % grain size of about  $50\ \mu\text{m}$ ) to the fine aggregate. At Chiya dam, the rock flour from lime stone was added in order to increase the content of finer particles. Recently at many RCD dams, the finer particles produced during aggregate production that were formerly discarded as industrial waste material, are effectively used to improve the workability of RCD mixture. At Hiyoshi dam and Urayama dam, dry-process-type aggregate production facilities were adopted in order to increase the content of finer particles.
- 4) Admixture: Technological progress has been achieved in the areas of mineral admixture and chemical admixture. Fly ash is generally used as mineral admixture and 20 % to 40 % of cement is replaced by fly ash. The use of fly ash contributes to lowering the heat of hydration, improving consistency, and increasing long term strength. At many RCD dams, cement and fly ash have been mixed at the dam site according to the season and concrete mixture. For example, 40 % of the cement in RCD is replaced by fly ash in the summer season and 30 % in the other seasons, and 35 % of the cement in conventional concrete (external concrete) is replaced by fly ash in the summer season. Special chemical admixtures for RCD and low hydration heat type cements were also developed.

### 4.3 VC (Vibrating Consistency) test

Since RCD concrete is dry and lean, the slump test cannot be used to measure its consistency. Compaction energy is also an important factor in determining the strength of RCD. So, the VC test method was developed to measure the consistency of RCD concrete. There are two kinds of container used in the VC test: the standard-size (diameter 24cm) and the large-size (diameter 48cm) container. In the VC test using a standard-size shown in Photo 10, concrete wet screened up to 40mm or less is used. In the VC test using a large-size container shown in Photo 11, a full-size mix of concrete is applied. Concrete specimens were made using the large specimen compaction device. The methodology is the same for both tests and the standard-size VC meter is also used in quality control.

- 1) First, the concrete is packed into the container. Next, the surface of the concrete layer is leveled out. Then a disk is placed over it, and a weight is placed.
- 2) A vibrating table applies vibration to RCD concrete in the container. During this vibration, paste rises up over the entire surface of the concrete and the time for this paste to adhere to the disk is measured.
- 3) The number of seconds recorded becomes its VC value. The consistency of RCD concrete is denoted by this VC value. When the VC value is less than 10 seconds, the vibratory roller sinks in field operations and compacting becomes difficult. Conversely, when this value is more than 60 seconds, RCD concrete is too stiff to be compacted.
- 4) VC value between 10 and 30 seconds is optimum in compacting RCD concrete. It has been confirmed that when the VC value is set at 20 seconds  $\pm$  10 seconds, about 97% of the theoretical density can be obtained.

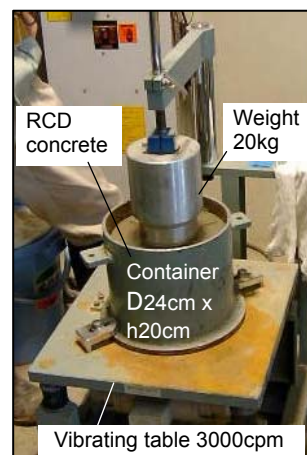


Photo 10- VC test with a standard size container



Photo 11- VC test with a large-size container

### 4.4 Mixture design of RCD concrete

The success of RCD construction depends on the mixture design of RCD. In the development of RCD concrete, some new concepts are adopted.

The mix design of RCD concrete is carried out as shown below.

- 1) Unit cement content: The unit cement content must be kept lowest in order to prevent a high temperature rise, as long as the required workability, strength, and other properties are satisfied. Mostly, the unit cement content of RCD concrete is 110 to 130 kg/m<sup>3</sup>.
- 2) Unit water content: The unit water content is determined so that adequate compacting can be achieved. Concrete mixes with various water contents are subjected to the VC test. In the test, the optimum water content is determined when the prescribed VC value is obtained. Normally, the optimum VC value is 20 seconds and the unit water content is 80 to 105 kg/m<sup>3</sup>. Figure 6 shows the unit water content to the VC value.
- 3) Sand aggregate ratio: The optimum sand aggregate ratio is investigated. Sand aggregate ratio is an important element in RCD concrete mix to obtain uniform quality, as mentioned in next section. The optimum sand aggregate ratio is the ratio where the VC value is at its smallest. The sand aggregate ratio of RCD concrete is about 30% in general. In comparison to conventional concrete, the sand aggregate ratio in RCD concrete is higher. Full size mix of concrete is used in the VC test with a large-size container. In this VC test, the unit cement content and unit water content are held constant, but the sand aggregate ratio is varied. Figure 7 shows the relationship between the sand aggregate ratio and VC value with a large-size container.

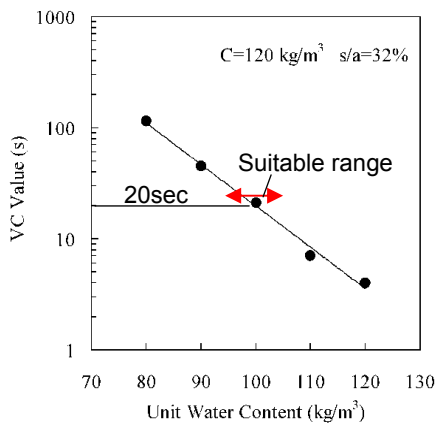


Figure 6- Unit water content to VC value

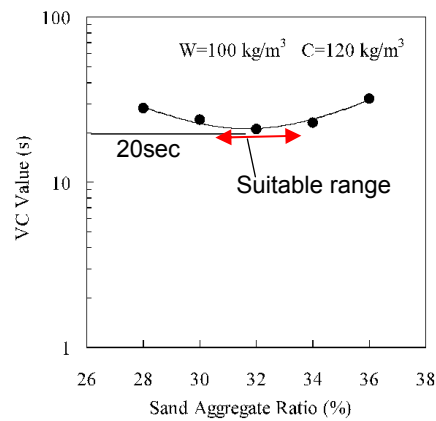


Figure 7- Sand aggregate ratio to VC value

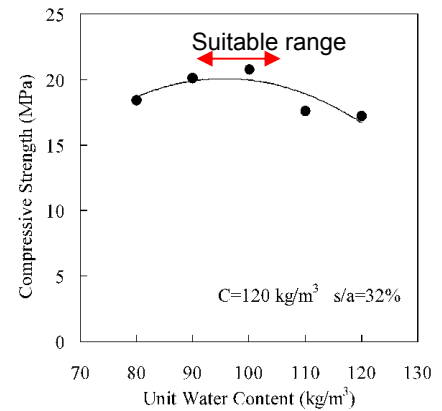


Figure 8 - Unit water content to compressive strength

4) Strength and surface appearance: Strength and surface appearance of RCD concrete are evaluated with diameter 150mm specimens drilled out from the large-size container. Figure 8 shows the unit water content to the compressive strength of specimens. The reason why the strength is dropped down in lower unit water area is that the density of specimens is also dropped down because it is mentioned at chapter 4.5. Thus, the VC value becomes an important element in determining the unit water content and the sand-aggregate ratio of RCD concrete.

#### 4.5 Ratio of volume to void in concrete and mortar

To find the optimum mixture ratio, the concepts of the coefficients  $\alpha$  and  $\beta$  are introduced. The ratio of paste volume to the voids in the sand aggregate is defined as  $\alpha$  and the ratio of mortar volume to the voids in the coarse aggregate is defined as  $\beta$ . In order to fill the voids in coarse aggregate and sand with mortar or cement paste sufficiently, both  $\alpha$  and  $\beta$  should be more than 1. According to this  $\alpha$  and  $\beta$  concept, compared with  $\alpha = 1.5$  to  $1.8$ ,  $\beta = 1.2$  to  $1.5$  of conventional dam concrete, and  $\alpha = 2.1$  to  $2.4$ ,  $\beta = 2.0$  to  $2.3$  of structural concrete,  $\alpha = 1.1$  to  $1.3$ ,  $\beta = 1.2$  to  $1.5$  are suitable values for RCD. It is noted in particular that the volume of cement slurry is close to the volume of voids between fine aggregates. This result shows that unit cementitious material content is in the range of  $110$  to  $130$   $\text{kg/m}^3$  and unit water content is in the range of  $80$  to  $105$   $\text{kg/m}^3$  for RCD.

### 5 Transportation system of RCD concrete

In the past, the main concrete transportation facility was the cableway which the concrete in a bucket suspended from a cable stretched across the valley. The cable is moved upstream or downstream by shifting a moving tower on a railway on one or both sides of the valley. It can easily cover a wide range of concrete placing areas. However, this cableway does not work as well with wide valleys and its transportation capacity is limited by its long cycle time. In addition, it often requires a large amount of excavation to build the railway; and this is a major disadvantage both economically and environmentally.

Further, other transportation facilities have limits in the length and capacity to carry. For example, as the boom length of a tower crane is limited short, several cranes are needed. Eventually, the biggest subject for the transportation of concrete was how to carry much more concrete covering the entire placement area efficiently.

Then, RCD concrete enabled that dump trucks can be used to carry the concrete on the lift surface, and the main transportation is only necessary to handle concrete from the mixing plant to the lift surface. This makes it possible to utilize inclines, belt conveyors and fixed cableways with a surging hopper to transfer the concrete into dump trucks. It's also possible to use tower cranes easily and dump trucks which bring the concrete directly.

Thus the much wider choice of transportation systems can be available with RCD construction method.

### 5.1 Dump truck (direct transportation system)

The direct transportation from the mixing plant to the lift surface by dump trucks is most advantageous when the topographical conditions are suitable, because there are no other special transportation facilities and no reloading during transportation. The use of the direct transportation by dump trucks is also often applied to the lower part of the dams.

This direct transportation was used at Ohkawa dam, which is one of the first RCD dams. Pirika dam and Ryumon dam (refer to Figure 3) are the combined dam type with a concrete dam and a rock fill dam. Because of their topographical feature, RCD construction method using the direct transportation by dump trucks was adopted for the concrete sections. The roads to the dam body were designed as embankment-type roads, and they were connected by temporary bridges that were 30 m long, 4 m wide and adjustable every 50cm high. This direct transportation system by dump trucks has got a majority among RCD dams (refer to Table 2).

### 5.2 Incline system

Inclines can be adopted at the steep slopes and transport large amounts of concrete per hour. So, inclines have been often used at relatively large scale RCD dams without depending on the dam site topography.

Dams constructed by the incline transportation system include Tamagawa dam (refer to Photo 14), Miyagase dam (refer to Photo 15) and other dams.

### 5.3 Cableway and tower crane

Concrete transportations by buckets such as the tower crane and cableway-type crane methods are also useful, because they permit three-dimensional transportation. This method is not affected by the topography of the river bed, and it's easy to operate.

The fixed cableway was used at Shimajigawa dam, which is one of the first RCD dams.

At Sabigawa dam, change of the environment at the dam site was minimized by installing two 13.7 ton tower cranes on the left and right banks. Two 9 m<sup>3</sup> ground hoppers were installed on the construction surface of the dam and concrete was transported from the ground hoppers to the pouring area by dump trucks.

At Origawa dam (refer to Photo 7), 20 ton both-side-running cableway-type cranes were installed as RCD transportation system like as the cableways in Tomisato dam. This cableway-type crane permitted transportation not only in the dam axis direction but also in the river flow direction by about 15 m.

At Takizawa dam (refer to Photo 1), the automated transportation system was introduced, in which the concrete were automatically supplied to five rotating buckets on a monorail, and three fixed cable cranes automatically carried the buckets to the hoppers near placing areas, choosing the shortest cycle time root.

At Nagai dam (refer to Photo 17), two tower cranes with the short boom were used to carry a larger amount of concrete rapidly and economically.

### 5.4 Belt conveyor

Belt conveyers are another important transporting system performed in high dams.

At Tsugawa dam, Urayama dam (refer to Figure 3) and Gassan dam (refer to Photo 18), belt conveyor systems were used to transport concrete. Concrete transported from the concrete batching and mixing plant by belt conveyers was temporarily stocked in a ground hopper installed on the dam, then was transported by dump trucks to the placing area.

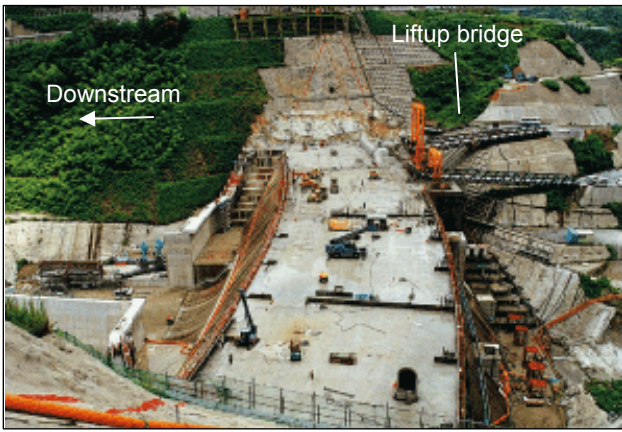


Photo 12 - Dump truck, Kutani dam, 2002



Photo 13 - Dump truck, Toppu dam, 7.2005



Photo 14 - Incline, Tamagawa dam, 1984



Photo 16 - Tower crane, Ueno dam, 11.1998

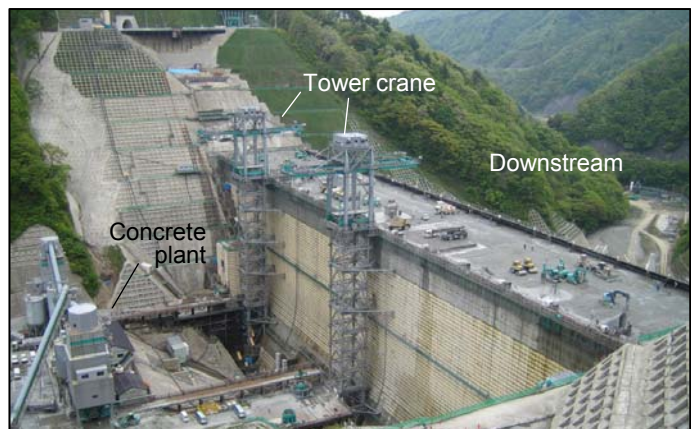


Photo 17 - Tower crane, Nagai dam, 5.2005

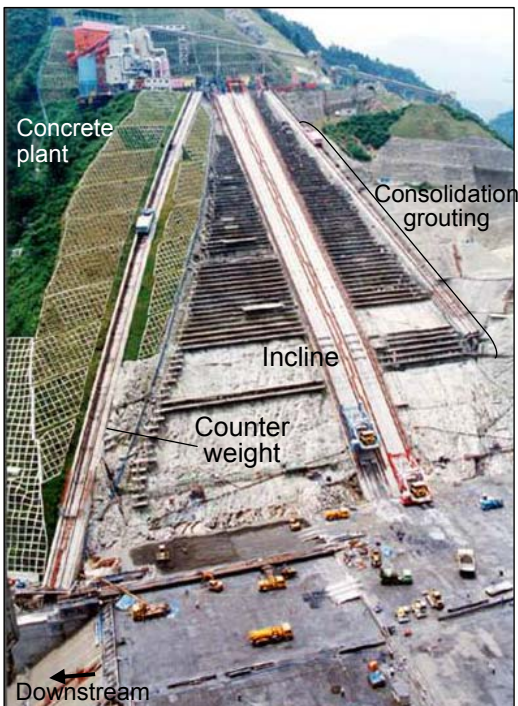


Photo 15 - Incline, Miyagase dam, 1992

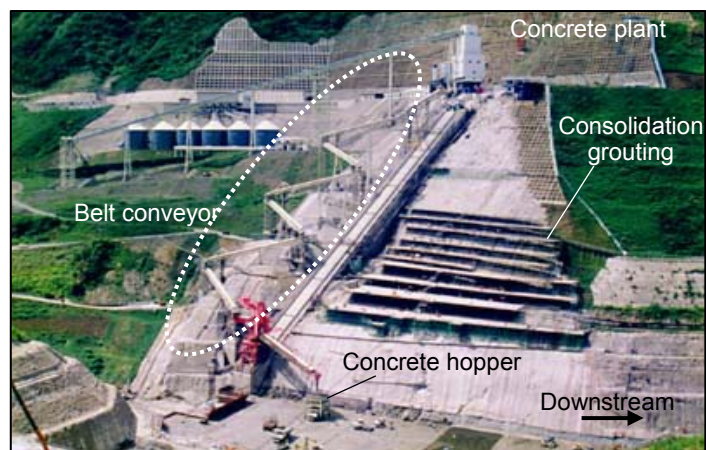


Photo 18 - Belt conveyor, Gassan dam, 1995

## 6 Concrete works in RCD construction method

The concrete works in RCD construction method has been improved through many RCD dam experiences in Japan, because the compaction of RCD dry lean concrete by vibratory rollers need much more experiences and technologies compared to the conventional wet concrete. Some of these technologies are already adopted in a RCC method like as mortar spreading, concrete compaction, joint treatment, connection of different concrete, various machinery and equipments.

The procedure of concrete works in RCD construction method is shown in photo 19.

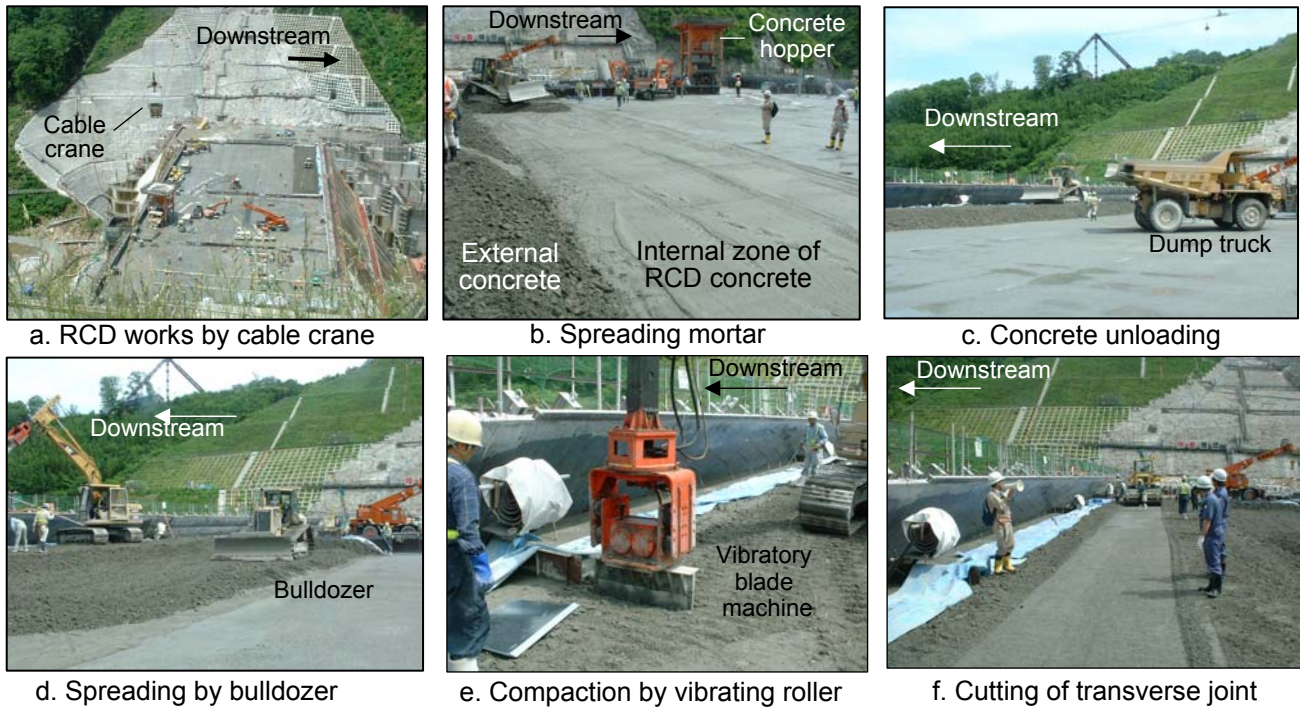


Photo 19- Concrete work cycle of RCD construction method in Kido dam, 8.2005

### 6.1 Test filling of RCD concrete works

Test filling of RCD concrete works is conducted in order to reconfirm the mix design and to determine a compaction method appropriate to the specific site condition. Test filling must be carried out in accordance with actual construction conditions. Upstream coffer dams and basement of downstream apron are used in the test filling.

Especially, RCD concrete must be compacted sufficiently in the deep portions, and numerous test fillings have revealed that adequate compaction can be achieved over 100cm of a lift thickness.

Another important effect of test filling is to master the RCD skill on spreading by bulldozers, compaction by vibrating rollers and so on.

### 6.2 Lift joint treatment by green cut and mortar spreading

On the surface of each lift, green cutting is performed by motorized sweepers so that the lift joints don't become weak layers in the structure. The time to implement green cut of RCD concrete is determined by the hardening



Photo 20- Lift joint treatment: mortar spreading

time of RCD concrete. In the summer, it is usually about 24 to 36 hours after compaction. In the winter, it is about 36 to 48 hours after compaction.

Before the placement of the next lift of RCD concrete, the water is removed and the mortar is spread immediately so that a good bond is secured at the horizontal lift joints.

The standard thickness of the mortar is 15 mm (refer to Photo 19b, 20).

### 6.3 Unloading of concrete by dump trucks

RCD concrete of uniform quality is transported by dump trucks to the placement area. However, when RCD concrete is unloaded from a dump truck, coarse aggregate of a large diameter is easy to segregate (refer to Photo 19c).

So, various techniques have been adopted to prevent this phenomenon, such as providing a hatch on the discharge gate of dump trucks or unloading RCD concrete in two piles.

### 6.4 Spreading of RCD concrete

In RCD construction method, the concrete is spread out thinly and evenly by bulldozers. Each layer is spread about 20~30 cm thick and 3 or 4 layers make one lift (refer to Photo 19d, 21). When the lift thickness is 100 cm, 4 layers make one lift. As a time limit between RCD layers, spread RCD concrete has to be placed by the next layer in 2 hours.

Thin layer spreading by bulldozers is effective to prevent the segregation of RCD concrete. If the spread layer is too thick, RCD concrete will segregate easily, and it will be impossible to compact it sufficiently. Further, spreading by bulldozer is quite effective to compact the concrete prior to the compaction by vibratory rollers.

The thin layer spreading method used in RCD construction method completely differs from compaction in RCC construction which adopted compacting concrete in a single layer. Thick lift placement, as used in conventional concrete dam construction, prevents the formation of a possible weak plane on the lift surface.

### 6.5 Roller compaction of RCD concrete

RCD concrete is compacted by vibratory rollers (refer to Photo 19f, 21).

Compacting should be carried out as soon as possible because if a long period elapses after mixing, adequate compacting is difficult to perform.

A specification example of Obara dam which is the latest RCD dam is shown as below.

- 1) Kinds of vibratory rollers: In the first stage of RCD, 7-ton self-propelled vibratory rollers were generally used, but recently 11-ton type vibratory rollers are popular. Their standard traveling speed is about one kilometer per hour.
- 2) Trips of roller compaction: When the lift thickness is 50 cm, the vibratory rollers make one round trip over the concrete without vibration and then at least three round trips with vibration. When the lift thickness is 100 cm vibratory rollers, make one round trip without vibration and at least six round trips with vibration.

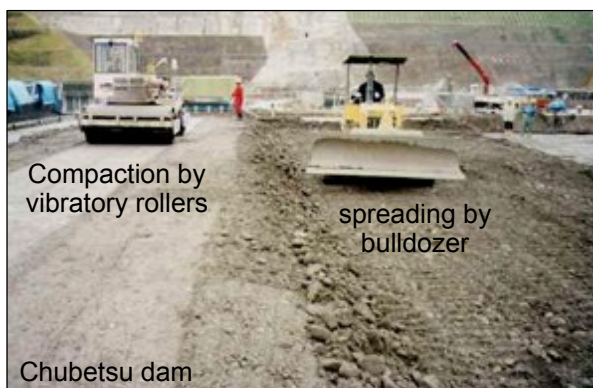


Photo 21- Spreading and compaction in RCD concrete



Photo 22- RCD concrete after compaction



- 3) Trips of finishing compaction: The tire rollers make three round trips with vibration.
- 4) Direction and width of the compaction lane: The spreading and the compacting of the concrete are generally done in the direction parallel to the dam's axis by the lane width of 7m~8m. The lanes of compaction are overlapped by about 20 to 30 cm.
- 5) Time limit until the compaction start: If a long time passes after the concrete is mixed, it will become difficult to compact it sufficiently. So, it must be compacted quickly. So far, generally, the compaction of RCD concrete has been started within 2 to 4 hours after the start of the concrete spreading in the summer, and 3 to 5 hours in other seasons.
- 7) Transportation restriction on the concrete surface: Dump trucks cannot run on the concrete surface in 6 hours after finishing the compaction works.

Photo 22 shows the RCD concrete face after roller compaction is well compacted and laitance and bleeding is very low.

## 6.6 Contraction joint (transverse joints)

At the upstream and downstream edges of the dam, galvanized steel plates were installed in advance as a contraction joint at interval of 15m. Then, water-stop plates and drainage holes were set in the upstream galvanized steel plate (refer to Photo 23).

After RCD concrete is spread, transverse joints are installed to prevent temperature cracks in the concrete. Contraction joints were cut by a vibratory blade machine and galvanized thin plates were installed in the cutting plane to prevent closing (refer to Photo 19e).

Along the end of a RCD placing block by several transverse joints, block forms are set up, and conventional concrete is placed around forms (refer to Photo 24).

## 6.7 Compaction between different concretes

RCD concrete in the internal zone is placed after conventional wet concrete in the external zone. So, the connection zone between RCD concrete and the conventional concrete should be compacted thoroughly by the method like as Figure 9.

## 6.8 Curing

After RCD concrete has been placed, it is cured thoroughly in the specified temperature and wetness conditions. Wet curing by ponding or sprinklers is generally applied. Water is sprayed on RCD concrete by sprinklers.

## 6.9 Quality control

Various quality control measures are executed at RCD dams so that the quality of materials is monitored carefully. Radioisotopes are used to measure concrete density after compacting.

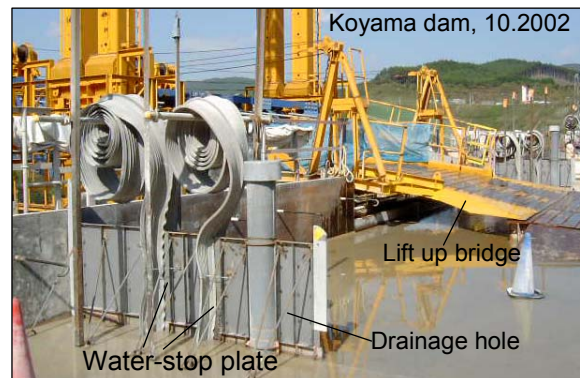


Photo 23- Contraction Joint in upstream side



Photo 24- Block forms along the placing end

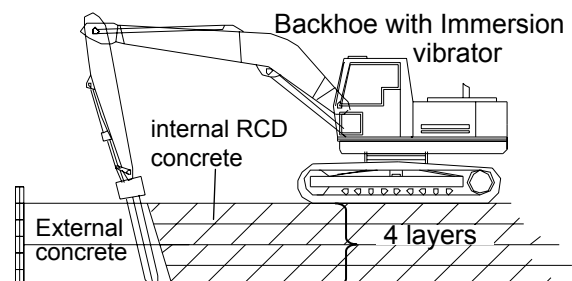


Figure 9 - Compaction between different concretes

- 1) Concrete strength: Once or twice a day, a compressive strength test is conducted to confirm the strength of RCD concrete. The strength of RCD concrete and the other qualities are also confirmed by cores drilled from the dam body.
- 2) Density: There are several methods to check the rate of compacting of RCD concrete: the number of passes of the vibratory rollers, the RI (Radio Isotope) density meter, or the settlement of the lift during compaction. Especially, in order to control the quality of RCD concrete after compaction, density control is executed with the insert-type RI density meter (refer to Photo 25). These measures permitted thick lift placement without inadequate compaction.
- 3) Water content: The surface water content and grading of aggregates must be monitored with special care since they affect the consistency of RCD concrete. If the deviation of the surface water content of the fine aggregate is large, it will be difficult to control the consistency of RCD concrete. Therefore the surface water content of the fine aggregate should be kept as constant as possible using the latest water content meter (refer to Photo 26).
- 4) Consistency: The VC test with the standard container is conducted to monitor the consistency of RCD concrete. The test is conducted once every one to two hours.
- 5) Temperature: The temperature of the mixed concrete is measured periodically to confirm that the concrete is placed according to the temperature restrictions. Thermometers are also embedded in the dam when necessary.



Photo 25- Concrete density measuring by RI meter

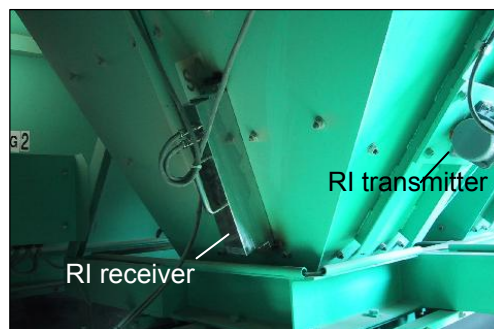


Photo 26- Sand water content measuring by RI meter

## 7 New approaches in RCD construction method

### 7.1 Rationalization of external concrete in Kasegawa dam

Kasegawa dam is one of the latest RCD dams, and the dam is under concrete placing in the basement. At present, an improvement of RCD construction method is progressing in order to place much concrete rapidly above the middle elevation of Kasegawa dam. The essential presupposition of this new technology is as follows.

- 1) The thickness of a layer is from 75cm to 100cm to reduce horizontal joints which are prone to be the weaknesses in earthquakes.
- 2) Green cut and mortar spreading is implemented on every compacted face to attach layers completely, considering seismic characteristics in Japan.

Under the above presupposition, in the conventional method, external conventional concrete has been placed prior to internal RCD concrete placement. However, in the new method, internal RCD concrete is placed prior to external conventional concrete placement. As a result of the above methodological change, the following effects will be gained.

- 1) Internal RCD concrete and the external concrete can be placed independently each other, and the efficiency of concrete works will be greatly increased.
- 2) External concrete will be compacted efficiently because of the firm binding between internal RCD concrete and installed external forms.

Figure 10 and photo 27 shows the above concept (Cruising RCD) and the field situation.

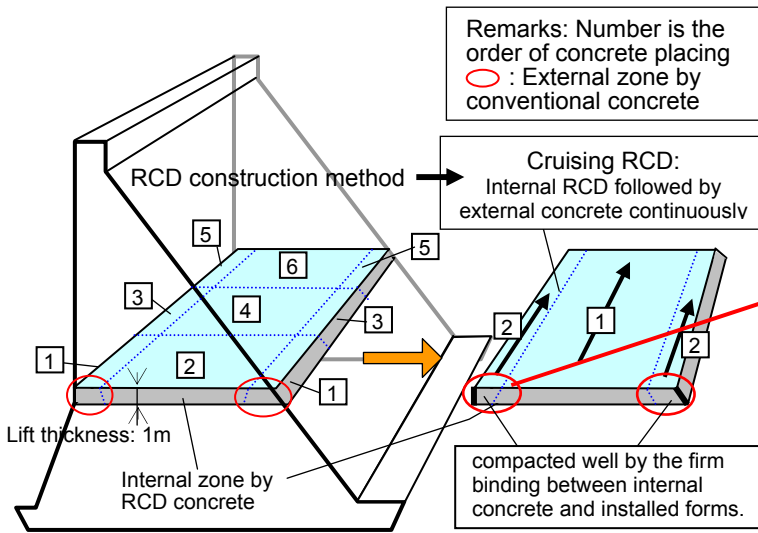


Figure 10- Concept of the rationalization by Cruising RCD

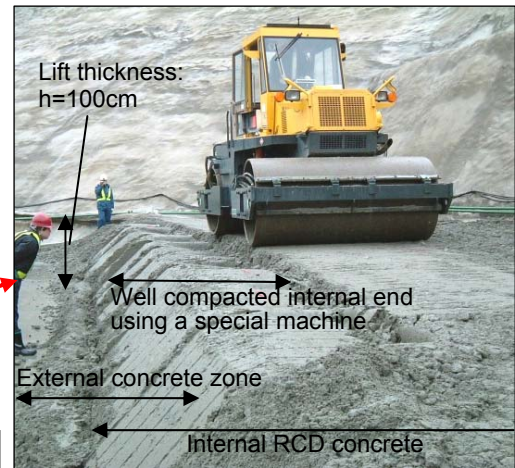


Photo 27- Compaction works at the end of internal concrete for cruising RCD, Kasegawa dam, 6.2008

## 7.2 Facilitation by precast concrete form

In Japan, the precast concrete (the concrete structure of pre-fabricated members) have been developed to increase the safety and efficiency in construction works. So far, it has been improved in light-weighting of members, holding of strength and water-tightness at each segment junction, adhesion to the around concrete and concrete placing under precast floors. Recently, external precast forms for the upstream side and downstream side have been developed, and it was confirmed to be efficient in facilitating the concrete works. Figure 11 and photo 28 shows the example in Taiho dam.

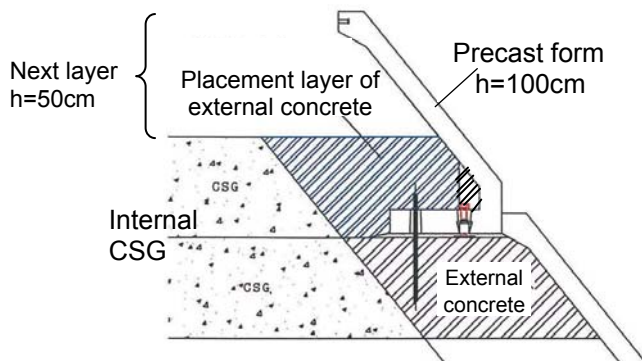


Figure 11- Cross section of precast form



Photo 28- Set up of precast form

## 7.3 Construction management by IT (Information Technology)

In recent years, IT (Information Technology) for the quality management by use of GPS information, latest measuring equipments, and integrated information on design and construction is rapidly progressing. Currently, a full-scale real-time IT system is adopted in Kasegawa dam for quality and quantity management, concrete volume surveying, internal concrete temperature observation, three-dimensional drawings, and labor-saving measures. Photo 29 shows RCD compaction works controlled by IT with GPS positioning and observation of compacted situation by counting.

Now, construction managements by IT for concrete dams are scheduled to be adopted in other RCD dams to increase quality and efficiency in Japan.



Photo 29- Vibratory roller SD451 with IT, Kasegawa dam

## 8 Acknowledgements

RCD construction method have been developed through many concrete works of RCD dams by Ministry of Construction (now, Ministry of Land, Infrastructure, Transport and Tourism), prefectures, Water resources development corporation (now, Japan Water Agency), and others. Further, research organizations (universities, societies and technical centers) and private companies (contractors and consultants) in Japan have been strongly supported to upgrade RCD technology. Eventually, the leading achievements on roller compacted concrete dams by Japan have been greatly contributed for the improvement of RCC technology in the world.

Our authors have been related in RCD technology development, joining technical committees of the Ministry on RCD construction method and activities of Japan Dam Engineering Center for the technical support on concrete dams.

We are grateful for all the organization concerned in RCD construction method for providing precious data and materials.

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