Design and Construction of Pumped-storage Power Plant Upper Reservoir Fully Surfaced with Asphalt Concrete

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ABSTRACT: The Omarugawa Pumped-storage Power Plant has been equipped with an upper reservoir fully surfaced with asphalt concrete. Its asphalt pavement area is approximately 300,000m^2, the largest scale for this type of reservoir in Japan. The upper reservoir, which is located at the top of a mountain, has asphalt facing with four curves as well as joint areas between asphalt facing and concrete structures. Several technical schemes, which were employed at every stage from design through construction and its management, contributed significantly to cutting-edge, superior cost-performance construction of the upper reservoir. This paper focuses particularly on: 1) establishment of an asphalt facing mechanical stability assessment index incorporating a seismic design against large-scale earthquakes and a limit state design; 2) introduction of an advanced testing method to select the optimal proportion of constituents for asphalt mixtures and evaluate their material properties; 3) establishment of unprecedented construction management criteria associated with all-year-round construction in Japan; and 4) efficient construction and its management through the application of ICT and Japan's first thick-layer asphalt pavement.

KEY WORDS: Cutoff performance of dam, ensuring of water tightness, reservoir

1 INTRODUCTION

The Omarugawa Pumped-storage Power Plant, with a maximum output of 1.2 MW, was constructed by Kyushu Electric Power Co., Inc. in Kijo Town, Koyu-gun, Miyazaki Prefecture. The upper reservoir, which is equipped with two dams: main dam and sub dam, is fully surfaced with asphalt concrete. (See Figure 1) The asphalt facing technique, which has been used since the 1960's, is widely employed in dam construction. However, although technical standards for road pavements are relevant to some extent, a broad range of standards covering areas from design to construction of asphalt faced dams and reservoirs have not been established yet in Japan. Therefore, procedures for design and construction have been carried out based on empirical knowledge derived from past performance. In such circumstances, we successfully constructed the upper reservoir fully surfaced with asphalt concrete by applying cutting-edge technologies which were unproven in Japan.

Figure 1: Aerial view of upper reservoir.

Initially, the upper reservoir was designed with two rockfill dams with central earth cores by applying the grouting technique for the foundation and thin ridge area. However, since it was found that permeable zones were spread in the area surrounding the foundation ground of this reservoir, the initial design was changed to make the upper reservoir fully surfaced with asphalt concrete, to ensure impervious work. From the viewpoint of reliability, serviceability, cost-performance and past achievement, asphalt was selected over concrete and rubber sheeting.

Table 1 shows the main specifications of the upper reservoir, and Figure 2 shows the asphalt facing structure. This reservoir was designed with four curves, with the aim of increasing thickness of thin ridges on the right and left sides, reducing pavement area, and eliminating convexities in paving foundation. A large curvature was adopted to avoid stress being concentrated at these curves, as well as to enhance workability. The paving foundation was formed with a bottom area of about 110,000m^2 and a slope area of about 187,000m^2 with a gradient pitch of 1:2.5, using about 6.7 million m^3 of cut earth and about 4.5 million m^3 of earth fill. As for the asphalt facing structure, we determined a 5-layer structure for the slope area and a 3-layer structure for the bottom area, in light of the site characteristics, recent advancements in construction technology, and laboratory material tests and transition layer tests.

Table 1: Main specifications of upper reservoir.

Item	Main dam	Sub dam
Catchment area	1.7km^2	
Dam type	Rockfill dam fully surfaced with asphalt concrete	
Dam height x length	65.5m×173.0m	42.5m×140.0m
H.W.L.	EL. 810.0m	
Available water depth	28.0m	
Total storage capacity	6,200 × 10^{3}m^3	
Water filling area	0.27km^2	

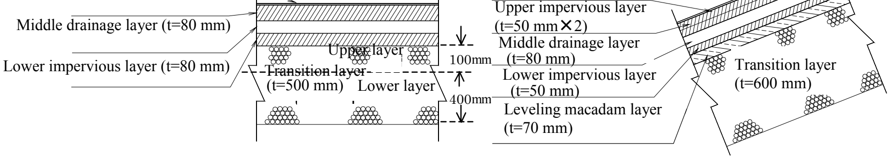

Figure 2: Asphalt facing structure.

2 ESTABLISHMENT OF AN ASPHALT FACING MECHANICAL STABILITY ASSESSMENT INDEX INCORPORATING A SEISMIC DESIGN AGAINST LARGE-SCALE EARTHQUAKES AND A LIMIT STATE DESIGN [1) & 2)]

Currently, a mechanical stability assessment index for asphalt facing has been not established, although such an assessment based on empirical rules does exist. To respond to this situation, we devised a new streamlined design index to assess the mechanical stability of asphalt facing. This index is characterized by combining a seismic design, taking into account large-scale earthquakes, based on a dynamic analysis of the upper reservoir fully surfaced with asphalt facing, and a limit state design using the results of asphalt concrete material tests.

In developing the index, we studied the behavior of asphalt facing during earthquakes, giving special attention to the facts that: 1) asphalt facing is thin compared to embankment area, and has different characteristics and physical properties from those of paving foundation; 2) the reservoir was to be asymmetrically shaped with curved corners; and 3) asphalt concrete tends to rupture more easily as the strain rate increases or temperature decreases.

As for the concrete used for asphalt facing, its rupture strength largely depends on temperature and strain rate. We assessed the mechanical stability of asphalt facing by comparing the maximum strain obtained by a computer analysis with the tolerable strain obtained by laboratory material tests. In the computer analysis, maximum strain under normal and earthquake conditions was obtained assuming different events in a limit state. While in the laboratory material tests, rupture strain was obtained by changing loading rate and temperature conditions. Figure 3 shows the assessment flow of asphalt facing mechanical stability.

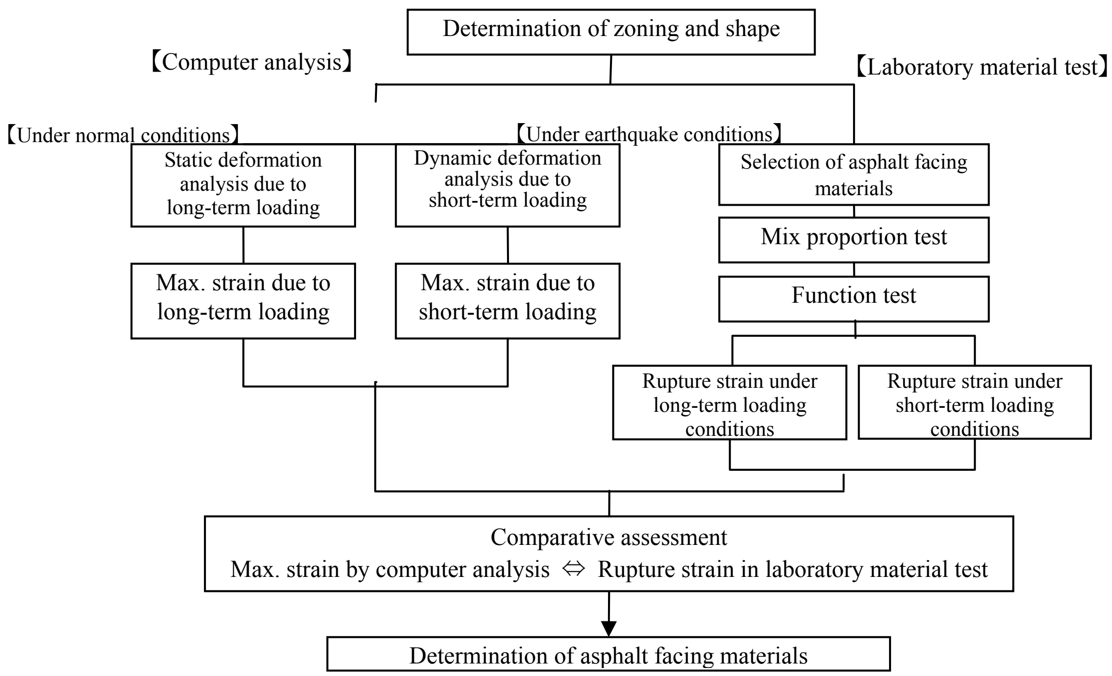

Figure 3: Assessment flow of asphalt facing mechanical stability.

Table 2 shows the assessment result. The maximum strain value obtained by the computer analysis lowered the tolerable strain value. The analysis confirmed that the asphalt facing to be constructed on the site would have sufficient mechanical stability with the appropriate structure and materials, based on our proposed mechanical stability assessment index applied with the seismic design and limit state design.

Table 2: Mechanical stability assessment results.

Conditions		Limit state	Seismic wave input	Tensile strain (%)				$\frac{\gamma_i \bullet \varepsilon_{max}}{\varepsilon_y}$
				ε_a	ε_k	ε_{max}	ε_y	
Under normal conditions		Serviceability limit state	—	0.780	1.286	0.780	0.990	0.79
Under earthquake conditions	Level 1 120gal	Serviceability limit state	Simulated seismic wave	0.019	0.031	0.021	0.024	0.88
	Level 2 170gal	Ultimate limit state	Simulated seismic wave	0.030	0.031	0.033	0.046	0.79

3 INTRODUCTION OF AN ADVANCED TESTING METHOD TO SELECT OPTIMAL PROPORTION OF ASPHALT MIXTURES AND EVALUATE THEIR MATERIAL PROPERTIES

Asphalt mixtures used for hydraulic structures are required to have sufficient performance in terms of service tightness, slope stability, following behavior for deformed foundation, and durability. We conducted a mix proportion test to decide the proportions of constituents for asphalt mixtures so that the required on-site performance would be satisfied.

Coarse aggregate, a constituent of the mixture, was recycled from rocks dug up at the time of the reservoir excavation; and it had a water absorption rate of 2% or less, which meant the blistering phenomenon in impervious layers could be prevented. Ferronickel slag generated by a nearby refinery was used as fine aggregate, for reasons of cost-performance, stable quality and effective use of waste. Limestone powder and hydrated lime were used as a filler, as in road pavements. Additive agents, used with the aim of enhancing slope stability and preventing material segregation, were also expected to act as a viscosity improver to reduce material segregation of the mixtures during transportation. In particular, harmless additive agents made of plant fiber, which had a past record for road pavements, were selected.

We conducted quality tests for straight-asphalt products with identical specifications (JIS standard, penetration: 60/80), made by several manufacturers capable of supplying to the site. The series of quality tests included a penetration test, softening point test, elongation test (JIS K 2207), high temperature viscosity test (AASHTO/SHRP standard), dynamic torsional loading test (DSR), rolling thin film oven test (RTFOT), and accelerated weathering test (PAV). As a result, since no specific quality difference was observed, the manufacturer who could most easily provide the products was finally selected.

Next, we made a special study in applying the Marshal test, which is useful for deciding the proportions of basic constituents for asphalt mixtures. Concerning dense-grain asphalt mixtures, porosity (Reference: 3% or less) and flow rate (Reference: 40 to 80 x 1/100cm), were determined as indices for evaluation. Composite grains were determined by referring to experimental grain data from sites in Japan where such grain had been used. In the performance test, we decided the laboratory mix design based on a basic formulation, through the definition of the individual performance required for each kind of asphalt facing.

In addition, we also conducted different tests to identify the strength of materials used in asphalt facing, with the aim of evaluating the following behavior of the materials against deformation as well as rupture strain. Since the deformation and strength of asphalt facing foundation largely depends on temperature and strain rate, the test conditions were set up under the assumption of possible events which might occur on the site. We tested by setting the strain rate in the case of two conditions: deformation resulting from water storage (long-term loading, under normal conditions); and that resulting from earthquake (short-term loading, under earthquake conditions). The minimum temperatures envisioned under individual conditions were set because rupture strain decreases as temperature lowers.

We first fabricated a specimen with dimensions 40 x 40 x 250 mm to obtain tensile strain during rupture, and then conducted an improved three-point bend test using an Instron universal testing machine (bend span length: 200 mm). To evaluate the tensile strain during low temperature earthquake conditions causing a vulnerable rupture, we compared the strain conventionally obtained by calculating the displacement during rupture at the center of the specimen upper surface (crosshead displacement at the loaded area) with the bend theoretical formula used for an elastic beam, with a strain gauge developed by us for the purpose. As a result of using this newly developed strain gauge, we were able to precisely and efficiently measure tensile strain during rupture.

However, the strain gauge cannot be used to measure the tensile strain under ordinary temperature submerged conditions causing ductile rupture, because the magnitude of tensile strain during rupture under such conditions becomes large. Therefore, we defined 50% of the value of the strain, obtained by calculating the displacement during rupture at the center of the specimen upper surface in a bend test under ordinary temperature submerged conditions, as being tensile strain during rupture. Following this, we conducted bend tests for dense-grain asphalt mixtures, which were to be used for conventionally-paved slopes and the thick-layer-paved bottom area, under normal and earthquake conditions (referred to as dense-grain #1 for the upper and lower impervious layers in slope area, dense-grain #2 for the upper impervious layers in the thick bottom area, and dense-grain #3 for the lower impervious layers in the thick bottom area). As a result, the magnitude of tensile strain under both conditions satisfied the maximum strain obtained by the computer analysis, showing a reliability of 95%.

Concerning compressed strain and shearing strain during rupture, values with a sufficient margin under both normal and earthquake conditions, as compared with computer analysis values, were obtained. As for the water tightness of asphalt mixtures used for facing on the site, hydraulic conductivity of $k<10^{-8}$ was obtained through a constant head permeability test (water temp: 5°C, water pressure: 0.1MPa).

To verify delamination resistance due to water immersion of the asphalt mixtures, a bend test was conducted before and after water immersion (water temp: 20 °C, water immersion period: 360 days). As a result, no significant transformation in tensile strain or strength during rupture was observed, thus the asphalt mixtures showed sufficient durability. We had also carried out outdoor exposure tests over a period of about 7 years under this site's weather conditions, aimed at understanding the degradation characteristics of asphalt facing under actual weather conditions on such sites. Optimal proportions of constituents of asphalt mixtures based on comprehensively-evaluated durability, were finally determined.

4 ESTABLISHMENT OF UNPRECEDENTED CONSTRUCTION MANAGEMENT CRITERIA ASSOCIATED WITH ALL-YEAR-ROUND CONSTRUCTION IN JAPAN [3)]

Since this site has relatively mild weather conditions throughout the year, we adopted an all-year-round construction scheme including the seasons of high summer temperatures and low winter temperatures. To prepare our original construction management criteria, we conducted a mix proportion test of asphalt mixtures, as well as a pavement test for which construction work in summer and winter seasons was simulated. Unlike the case of road pavements, specimen sampling to check quality after pavements have been laid in the case of asphalt facing could not be conducted because such sampling activity risks degradation of the impervious quality of pavement. Qualities such as water tightness and following behavior for deformation could not be directly checked either, and no effective non-destructive quality evaluation methods had been established at the time. In this situation, before actual construction, we conducted an outdoor pavement test using actual machinery, as well as laboratory material tests; and based on the results, we prepared the construction management criteria in which material quality items to ensure the necessary standard of asphalt facing, and techniques required for construction were described in a detailed manner. In addition, we prepared streamlined construction management procedures to establish new construction management items taking into account outdoor temperature variations, and to standardize temperature ranges as a gauge to the impact on asphalt facing quality. Table 3 shows our unique construction management and quality items for this site.

Table 3: Unique construction management and quality items for this site.

Category	Subject to be managed	Description	Management items	
Quality control	Plant	Material quality	Asphalt	Penetration, softening point, mass change ratio and residual penetration ratio based on the loss on heating of Bitumen
			Aggregate	Density, water absorption, spindly and flattened schist content rate (coarse aggregate), grain (fine aggregate)
			Filler	Grain size, water content, hydrated lime mixing rate
		Mix proportion	・Asphalt quantity, additive quantity ・Composite grain size	
	Paved site	Foundation quality	Depth of asphalt emulsion penetration	
		Asphalt facing quality	Vacuum	
Construction management	Plant	Material quality	・Asphalt temperature ・Filler temperature	
	Paved site	Asphalt facing quality	Surface compaction	Temperature, compaction frequency
			Finish thickness	

The asphalt mixture materials used for this site were classified into purchased materials (asphalt, fine aggregate, filler) and on-site produced materials (coarse aggregate). To ensure the quality required for asphalt facing, our construction management criteria stressed strict quality control based on JIS Standards. In particular, for asphalt concrete and fine aggregate, we applied not only the concerned criteria but also control target values that manufacturers were required to meet.

The proportions of constituents of asphalt mixtures used for each facing layer were fully determined based on the results of laboratory material tests and pavement tests. Taking into account the characteristics of each material to be used as well as site conditions, the proportions capable of allowing the greatest flexibility during construction at the site were defined. Since asphalt has the property that its volume may increase to some extent at the pavement starting point or during low winter temperatures, the quantity of asphalt was determined within the increase-decrease range possible to ensure the required quality, taking into account workability and weather conditions.

Additive agents were used to curtail liquidity of asphalt mixtures. The quantity of agents used for the upper and lower impervious layers could be decreased as necessary to provide an increase in liquidity, aimed at enhanced workability during low winter temperatures. In contrast, the quantity of agents used for the middle drainage layer could be increased in order to prevent surface deformation resulting from pavement machinery under high summer temperatures.

Since composite grains of aggregate used for asphalt mixtures have a large impact on asphalt facing quality, we decided to define both coarse and fine aggregates as composite grains, and fillers.

It had been a rule that pavement work for asphalt facing should never be conducted at or below a temperature of 5 ^{o}C, or in a rainy weather, since the quality of asphalt mixtures depends significantly on temperature control. Therefore, in our original construction management criteria, we regulated operating temperature range to maintain quality, and created new items to be controlled taking into account asphalt mixture temperature drop resulting from outdoor temperature, making all-year-round construction possible. As for asphalt facing layers, our attention was on controlling their thickness, by calculating an average finish thickness based on the quantity of paved asphalt mixtures in a streamlined manner.

To control temperatures at primary and secondary surface compactions in asphalt facing construction, we set up a standard operating temperature, which made a large impact on asphalt facing quality; and in particular, we also regulated the end temperature after the secondary surface compaction was done. We also established temperatures before shipping and leveling with an appropriate margin, in order that the operating temperature at the final surface compaction could be maintained. Since outdoor temperature affects the paved surface temperature, there was a possibility that integration between layers might be hindered. To resolve this problem, we incorporated new items to be controlled, such as temperature adjustment before asphalt mixture shipping and leveling, paved facing temperature check, and lane joint heating.

Longitudinal joints, which were layer-to-layer connections, were set up in parallel with extended facing lanes. With this, there was a possibility that installation defects might lead to degradation of the following behavior of deformation as well as water leakage. As a solution, we heated already-paved lane joints by using joint heaters, and immediately leveled them. Then, we conducted compactions of both already- and newly-paved lane joints by using compactors. Joint heaters and joint compactors were set up at paved lanes in the front and back of an asphalt finisher. As stipulated in our construction management criteria, we ensured surface compaction by devising a unique method of operating compactors.

Since it was impossible to measure the finish thickness by way of sampling any paved layer specimen, we measured the thickness of a cutting-plane by using a cutter in a pavement test in advance. The average finish thickness, which was calculated from the total quantity of asphalt mixtures, was compared with the actually-measured value. As a result, it was revealed that the management of finish thickness, based on the total quantity of asphalt mixtures, was sufficiently accurate; thus, we could manage finish thickness of individual paved lanes. Further, we managed finish thickness based on height data using indirect leveling at every 10m x 10m grid section, to supplement the method based on the total quantity of asphalt mixtures.

5 JAPAN'S FIRST THICK-LAYER ASPHALT PAVEMENT AND EFFICIENT CONSTRUCTION AND MANAGEMENT THROUGH APPLICATION OF ICT [4) & 5)]

As for the asphalt facing construction, firstly asphalt mixture was made by heat mixing at a temporary asphalt plant built on site. The mixture then was fed into an asphalt finisher by dump truck or damper (for the slope area only) to be paved and smoothed by the finisher. After cooling down to a predefined temperature, the paved asphalt was roller-compacted twice; primary non-vibratory and secondary vibratory. At the slope area, this paving and compaction process was repeated for each layer, using a damper, asphalt finisher and vibratory compactor, which were pulled by winch porter set up at the dam crest. (See Figure 4)

Figure 4: Slope area paving.

5.1 Streamlined Management of Thick-layer Asphalt Paving of Impervious Layer

We conducted the first pavement tests on the bottom and slope areas, using the optimal asphalt mixture previously selected through the mix proportion test. These tests included asphalt workability and functional verification (e.g. permeability test with specimen sampled from paved site, and bend test), and the asphalt's specified mix and construction specification were confirmed. In particular, since it would be Japan's first thick-layer asphalt paving, we focused on the construction specifications and joint part paving method during the pavement test aimed at verifying the application of thick-layer asphalt paving to the bottom of the dam. As a result, it was observed, by employing appropriate methods, that it was possible to achieve thick-layer asphalt paving in lane bodies and joint parts with a quality equal to that of conventional paving (5cm layer thickness). Also, for the slope area, we clarified proper construction specifications and special paving considerations for winter.

In the second pavement test, insufficient density was found in parts of impervious layers within both the slope and bottom areas, and blistering was observed in multiple locations (0.18 blisters per m^2) after compaction. These were considered to be caused by: 1) inadequate asphalt mortar due to insufficient filler in the specified mix proportion of asphalt mixture used for impervious layers; and 2) water for compaction entrapped inside the impervious layers due to large porosity of paving caused by deficient screed compaction of asphalt finisher (paving width: max. 6m per lane). Under these circumstances, we focused on porosity of the impervious layers both before and after compaction and used on-site produced sand and rocks in the asphalt mixture instead of the coarse aggregate to achieve absolute dryness in the mixture and site-mixing with 1 to 2% more 0.075mm screen pass rate. Also, comparisons were made between initial construction specifications with the use of a single tamper and the improved specifications using a double tamper for the screed compaction of the asphalt finisher. As a result, there was a lower occurrence of porosity both before and after compaction, resulting in less blistering (0 blisters per m^2). Furthermore, in order to streamline construction, a paving width extension of the asphalt finisher for thick-layer paving (max. 8.5m per lane), and a reduction in the number of secondary compactions from 4 to 0 were examined. It was confirmed that these modifications satisfied the targeted porosity after compaction (3% or less), and the verification tests (e.g. water permeability and bend tests) were conducted on the lane body and joint parts. As a result, the final on-site mix proportion and compaction specifications were determined (Table 4).

Table 4: On-site asphalt mixing proportion and compaction specifications

Type of asphalt mixture	Usage	Thickness (mm)	Aggregate max. grain size (mm)	Mixture ratio (weight %)				Aggregate grain ratio (%)		Compaction specifications (Roller type: 2.8 ton vibratory roller)			
				Asphalt	Aggregate	Filler	Additive	Screen mesh size (mm) 2.36	Screen mesh size (mm) 0.075	Primary compaction starting temp. (℃)	No. of primary compactions (lower no. is for joint parts)	Secondary compaction ending temp. (℃)	No. of secondary compactions (lower no. is for joint parts)
Dense grain #1	Upper and lower impervious layers in slope area	50	13	7.7	84.2	7.9	0.2	60	13	*2	Non vibratory: 2 times Vibratory: None	80 or over	Vibratory: None
											Non vibratory: 1 time Vibratory: 1 time		Vibratory: 3 times
Dense grain # 2	Upper impervious layers in thick bottom area	100	20	6.8	85.9	7.1	0.2	55	12	*2	Non vibratory: 4 times Vibratory: None	80 or over	Vibratory: None
											Non vibratory: 3 times Vibratory: 1 time		Vibratory: 4 times
Dense grain No.3	Lower impervious layers in thick bottom area	80	20	6.7	86.0	7.1	0.2	55	12	*2	Non vibratory: 2 times Vibratory: None	80 or over	Vibratory: None
											Non vibratory: 1 time Vibratory: 1 time		Vibratory: 4 times
Open grain	Middle drainage layers in slope and bottom areas	80	20	4.1	93.7	2.0	0.2	13	3		Non vibratory: 4 times Vibratory: None	70 or over	Vibratory: None
											Non vibratory: 3 times Vibratory: 1 time		Vibratory: None
Coarse grain	Leveling macadam layer in slope area	70	20	4.8	93.0	2.2	-	28	4		Non vibratory: 2 times Vibratory: None	70 or over	Vibratory: 4 times
											Non vibratory: 1 time Vibratory: 1 time		Vibratory: 4 times

*1: For slope area, vibratory compaction was used as roller moved up slope (non-vibratory when moving down)
*2: Starting temp. for primary compaction of asphalt mixture with dense grain #1 to #3 should be 140℃ or lower to realize secondary compaction ending temp.

5.2 Introduction of Construction Management System through Application of Information and Communication Technology (ICT) and its Effects

For this reservoir construction and its management, ICT "Construction System," "Surveying System" and "Design/Construction Control System" were introduced in order to address the following issues as well as to realize advanced, laborsaving and quality control. Figure 5 shows the overview of ICT construction and control systems.

1) Appropriate and laborsaving control of earth volume, raw stone volume and compaction for large-scale civil engineering work,
2) Laborsaving construction of transition layers to cover the longest slope area in this reservoir construction and maintaining accuracy of paved bases, and
3) Expediting and laborsaving surveying on a large site during construction.

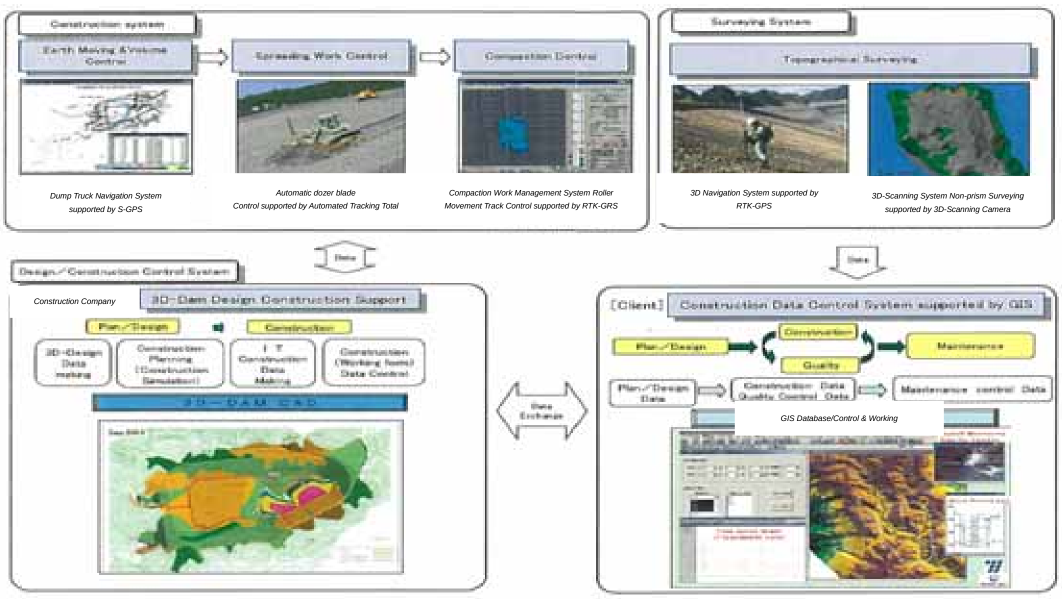

Figure 5: Overview of ICT construction and control systems.

The effects of the ICT construction and control systems used for the reservoir construction were significant in laborsaving, advancement and quality enhancement of construction and control overall. These effects resulted from efficient and organic functioning of multiple systems and easy data exchange between the client and construction company.

Specifically, the approximately 10m x 10m grid plane of the entire transition slope layer (approx. 190,000m^2), which was paved by using a 3D Machine Control System, was completed with outstanding accuracy; average +1mm and 2σ range of ±41.0mm.

The entire surface of the slope leveling macadam layer paved by an automatic paved layer thickness control system fully satisfied the required flatness with a mean accuracy of -4mm and 2σ range of ±31.8mm.

5.3 Recycling of Waste Asphalt Mixture Generated during Construction

During the construction, various waste materials were generated, including materials removed during paved lane end-part shaping and materials left in asphalt finishers. Waste asphalt mixtures were generated from each layer and together accumulated to approximately 20,000 tons. These wastes were crushed to make recycled aggregate to be used for the base course of the soil disposal site road, impervious materials for No. 1 soil diversion channel and surface layer of the road around the reservoir. Almost 100% of the waste materials were recycled, resulting in reduced disposal cost. Through this effort to reduce environmental load, further streamlining of construction was realized.

6 CONCLUSIONS

By making full use of the technical achievements uniquely developed by Kyushu Electric Power and relevant suppliers, the upper reservoir of the Omarugawa Pumped-storage Power Plant could be constructed using cutting-edge, rationalized design and construction techniques. After construction, this reservoir passed an official government test, and was put into operation in July, 2007. The mechanical stability has been soundly maintained without any problems. Currently, we collect data from measurement instruments installed around the upper reservoir, and inspect it through periodical patrol, to verify its integrity. Our future target is the continuous assessment of the stable functioning of the upper reservoir.

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