Implementing Innovative Ideas in Structural Engineering and Project Management
Edited by Saha, S., Zhang, Y., Yazdani, S., and Singh, A.

ISBN: 978-0-9960437-1-7

STRUCTURAL DESIGN OF NEW LINING FOR DIVERSION TUNNELS: ROGUN DAM AND HPP PROJECT

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Rogun dam is a 335m high clay core rockfill dam which will be constructed on Vakhsh River in Tajikistan. Originally, two diversion tunnels with similar geometry were designed for discharging the seasonal floods, up to 3290m^3/s. River diversion was carried out in November 1987 and a 45m high rockfill cofferdam was constructed. However, because of two collapses in the diversion tunnels, the cofferdam was overtopped in May 1993. Reconstruction of these tunnels started in 2009 and the collapsed areas were repaired. Nowadays, the design of complementary rehabilitation including new concrete lining for those parts of the tunnels will be used as tailrace tunnels are underway. The present paper describes the present conditions of diversion tunnels No. 1 and 2, explains the procedure used for the structural design of these tunnels, and presents the results of such design.

Keywords: Vakhsh River, Rock mass, Load combination, Concrete, Reinforcement, Seismic.

1 INTRODUCTION

Rogun dam is a rockfill dam with clay core which will be constructed on Vakhsh River in the Republic of Tajikistan. In its final stage, with crest elevation of 1,300 above mean sea level, it will be 335 m high and therefore, the highest dam in the world under construction. The powerhouse is of underground type and with its 6 turbines it will have a total installed capacity of 3,200 MW.

Originally, two diversion tunnels with similar geometrical characteristics were designed for discharging the seasonal floods during construction period of the project, up to 3,290 m^3/s. Each tunnel is of D shape section with various sizes along its length, starting with 11(w) x 11(h) m in pressurized section which reaches to a gate chamber and after the radial gates, there is a sloping part with 14(w) x 11.9(h) m section. Finally, cross section of the tunnel converts to 14(w) x 17(h) m which will be used as tailrace tunnel during operation period. Each tunnel is almost 1410 m long and while its inlet portal and almost 950 m of its length is located at left bank, after crossing the river, its outlet portal is situated in right bank. The total length of each tunnel is about 1410 m.

Construction of the project started in 1980's during which excavation and construction of the two diversion tunnels were carried out. River diversion was carried out in November 1987 followed by construction of a 45 m high rockfill cofferdam.

However, because of two main collapses in the diversion tunnels the cofferdam was overtopped in May 1993. Reconstruction of these tunnels started in 2009 and the collapsed areas were repaired. Nowadays, the design studies of complementary rehabilitation works including new concrete lining for those parts of the tunnels which will be used as tailrace tunnels are underway.

Considering the unique technical features of Rogun project and due to the fact that it will be constructed on a bi-national river, World Bank has authorized a Joint Venture of two international consulting engineers to review the technical characteristics of the project and re-evaluate the reliability of its main structures. In this regard, technical and constructional aspects of diversion tunnels No. 1 & 2 were examined as the key elements of the diversion system. This paper describes the present conditions of diversion tunnels No. 1 and 2, explains the procedure used for evaluating the existing lining and for the design of new lining, which have to guarantee the long-term performance of these tunnels.

2 PRESENT CONDITIONS OF DIVERSION TUNNELS NO. 1 & 2

Diversion tunnels No. 1 and 2 (CT1 & CT2) are D shape, concrete lined tunnels with various cross sections in pressurized and free flow parts. Figure 1 shows the plan view of Rogun dam site including, CT1 & CT2 tunnels with inlet portal at the left bank and outlet portal at the right bank and CT3 tunnel which is located totally at the right bank. The upstream parts of CT1 and CT2 are located at left bank, before crossing Vakhsh River, are 960 m and 880 m long, respectively. Then, they cross the river with approximate lengths of 110-120m and afterward they pass through the right bank with the length of about 340 m and 408 m, respectively. Total lengths of CT1 and CT2 are 1,415 m and 1,408 m, respectively.

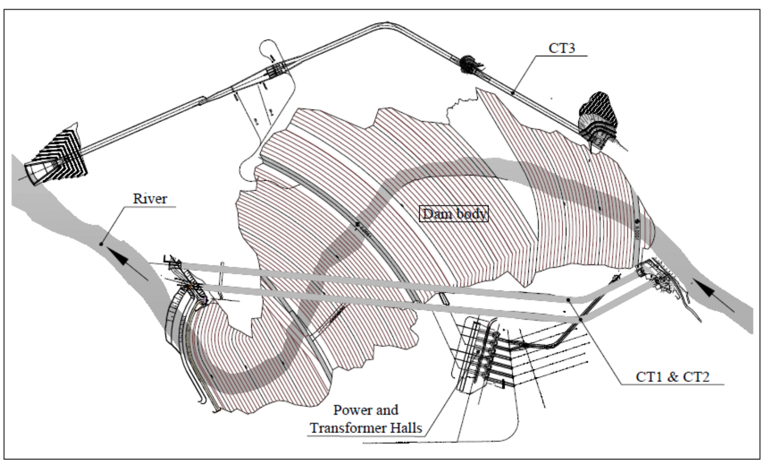

Figure 1. Plan view of diversion tunnels No. 1 and 2 at left bank and diversion tunnel No. 3 at right bank.

Based on the original design of Hydroproject Institute, Tashkent in 1980's, CT1 and CT2 will be used as tailrace tunnels of the powerhouse. In this regard, collector tunnel of draft tubes No. 1-3 connects to CT1 at km 6+78.37, while collector tunnel of powerhouse draft tubes No. 4-6 connects to CT2 at km 6+09.44. According to this design, few meters before these intersections the cross section of these tunnels reaches to its maximum dimensions i.e, 14(w) × 17(h) m. Therefore, CT1 and CT2 at downstream of these junctions were analyzed as permanent structures. Preliminary analysis of the permanent parts of CT1 and CT2 showed that the existing concrete lining cannot withstand against the structural loads considering the well-known long term service requirements for hydraulic tunnels and new concrete lining plus systematic fully grouted rock anchors have to be implemented in these tunnels. In Figure 2, the existing lining (a) and the new lining (b) systems are shown.

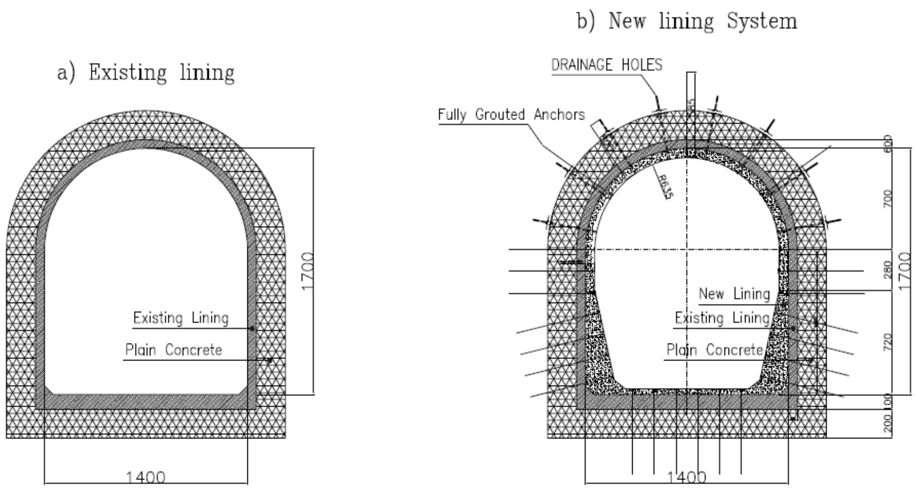

Figure 2. a) Existing lining and b) new lining systems in diversion tunnels CT1 & CT 2 after junction of powerhouse draft tubes (dimensions are in cm).

3 STRESS ANALYSIS OF TAILRACE TUNNEL NO. 1 USING *PHASE*^{2}

A set of FEM models considering various scenarios and load cases has been carried out for diversion Tunnel No. 1 (CT1), D-shape section, 17 m high by 14 m wide at chainage 7+02 m, using *Phase*^{2} Program, developed by Rocscience Inc. The rock mass around CT1 at this change is Sandstone of geological unit of Upper Obigarm (k1ob2).

According to the geophysical studies along CT1 at left bank, three zones around the tunnel have been specified:

- Highly disturbed zone in depth of 0 to 3 m from tunnel boundary;
- Moderately disturbed zone in depth of 3 to 8 m from tunnel boundary; and
- Undisturbed zone in depth of more than 8 m from tunnel boundary.

In the *Phase*^{2} analyses, k1ob2 rock mass around the tunnel was modeled as an elasto-plastic material while its strength parameters were decreased in post failure mode. Rock mass parameters of k1ob2 are presented in Table 1.

In addition, 3 types of concrete lining are considered in the model namely: a) Unreinforced concrete, as primary support; b) Existing reinforced concrete; and New reinforced concrete. Mechanical properties of these concrete linings are also presented in Table 1.

Table 1. Rock mass parameters and mechanical properties of concrete linings used in *Phase²*.

Material Type	Unit Weight (kN/m³)	E (MPa)	Poisson's ratio	Mohr-Coulomb Failure Criterion Parameters				Tensile Strength (MPa)	
				C (kPa)		ϕ [°]			
				Peak	Residual	Peak	Residual	Peak	Residual
k1ob2 - Undisturbed	26.0	15,000	0.3	1,000	500	40	35	0	0
k1ob2 - Moderately Disturbed (zone 3-8m)	26.0	9,000	0.3	500	250	40	35	0	0
k1ob2 - Highly Disturbed (Zone 0-3m)	26.0	3,000	0.3	250	125	40	35	0	0
Primary Support (Unreinforced Concrete, C20)	24.5	20,000	0.2	5,000	5,000	35	35	0	0
Existing Lining (Reinforced Concrete C25)	24.5	25,000	0.2	5,200	5,200	35	35	0	0
New Lining (Reinforced Concrete C25)	24.5	27,000	0.2	6,500	6,500	35	35	2.6	2.6

Firstly, a series of FEM analyses were carried out on a typical section of the permanent part of CT1 with the existing lining in order to prove that it could not comply with the long term service requirements. Afterward, these tunnels were analyzed while a reinforced concrete lining with minimum thickness of 40 cm was included in the model. Finally, Structural design of the new lining of CT1 and CT2 was performed in accordance with ACI 318-2003 Code and USACE Design Guidelines. In this regard, stress values in x and y directions along with shear stresses in xy plane (Sxy) and angle of normal to the plane with horizontal (as the output data of Phase² analysis) were used for reinforcement design of the new concrete lining.

4 STRUCTURAL DESIGN OF NEW LINING IN TAILRACE TUNNEL NO. 1

4.1 Material Properties

4.1.1 *Concrete*

Due to importance of diversion tunnel structures and high velocity flow with hydraulic jump, concrete with 28 day compressive strength of 35MPa (on standard cylindrical sample) is considered. Modulus of elasticity and Poisson's ratio of the new concrete were assumed as 28,250 MPa and 0.2, respectively while its unit weight was taken as 25 kN/m^3.

4.1.2 *Reinforcement*

Steel bars shall comply with the ASTM standard A615 Grade 60 (AIII). Such a steel bar has minimum yield strength of 400 MPa while its elasticity modulus and Poisson's ratio are 2×10^5 MPa and 0.3, respectively.

4.2 Design Method

Strength design method was used for structural design, in which sections are designed taking inelastic strains into account to reach ultimate strength when an ultimate load, equal to the sum of each service load multiplied by its respective load factor, is applied to the structure. Load factors and strength reduction factors were chosen according to US Army and ACI.

Stresses in the structure which are found in Phase^2, are changed into forces and moments on sections, and then considering these forces structures are designed for moment, shear or combined action of moment and axial force.

The minimum temperature and shrinkage reinforcement has been provided wherever the computed reinforcement is less than that. The minimum reinforcement of structural members for temperature and shrinkage stresses has to be 0.0028 times the cross sectional area, distributed equally on both faces. However, this shall not be less than 420 mm^2/m or more than 2100 mm^2/m per face (EM 1110-2-2901).

4.4 Results of Analysis

Moment, shear and axial forces are computed with the aid of stresses calculated with Phase^2 Finite Element Program. Figure 3 shows section numbers used in the design.

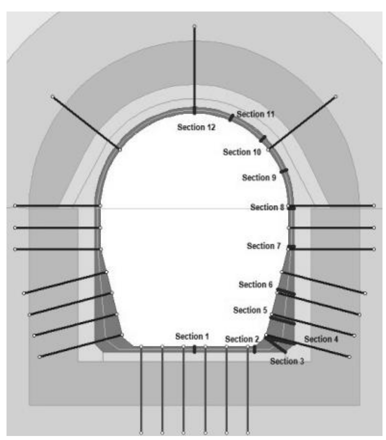

Figure 3. Formwork, location and number of Sections considered for reinforcement design in new lining of CT1 & CT2.

4.5 Reinforced Concrete Design

In order to check the moments and axial forces, interaction diagram was used for each section. Interaction diagrams of all sections under the four load combinations are shown in the next section.

4.5.1 *Interaction diagrams for new lining*

Interaction diagram for Section No. 1 (middle of floor slab) with thickness of 0.4 m is shown in Figure 4. While, interaction diagram for Sections No. 9 to 12 (upper half and roof) with thickness of 0.4 m is shown in Figure 5.

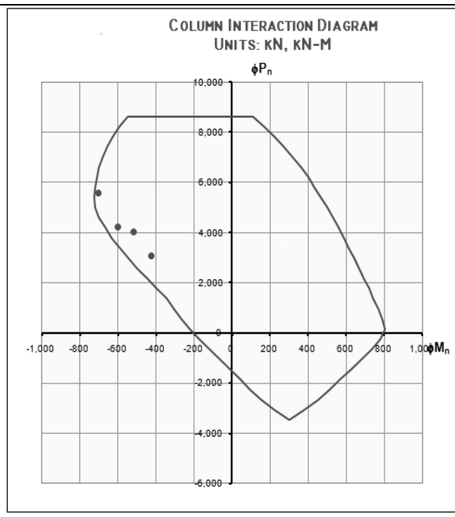

Figure 4. Section 1 (floor slab) Thickness = 0.4m, f'c = 35MPa; one Layer of ϕ32 @ 100 mm (top) + one Layer of ϕ20 @ 200 mm.

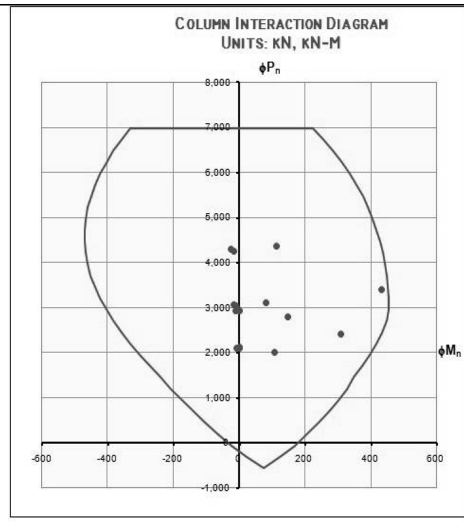

Figure 5. Sections 9 to 12 (tunnel roof) – Thickness = 0.4 m, f'c = 35MPa; one Layer of ϕ20 @2 00 mm.

5 CONCLUSIONS

Structural design of the new lining of diversion tunnels No. 1 and 2 of Rogun dam and HPP has been carried out in a manner that it can withstand against all the short term and long term loads during construction of the project and powerhouse operation, respectively. This design proved that 40 cm thick reinforced concrete lining with compressive strength of (f'c = 35MPa) is adequate and will guarantee the long-term performance of these tunnels.

References

ACI 318-2003, "Building Code Requirements for Reinforced Concrete."
USACE, "Tunnels and Shafts in Rocks (EM 1110-2-2901)".
USACE, "Strength Design for Reinforced Concrete Hydraulic Structures (EM-1110-2-2104)".