kg/cm²

Classification	Symbol	FRP Pipe	
		Circumferential Direction	Axial Direction
Allowable Tensile Stress	σt	630	273
Allowable Compression Stress	σc	555	231
Allowable Shearing Strength	τ	91	

iii) Circumferential Tensile Stress by Internal Pressure

$$\sigma_{1t} = \frac{P \cdot D}{2 \cdot t}$$

Where: P: design water pressure at the positions for calculation
The positions for calculation are the exposed part and the buried part where the maximum design water pressure works.

D: pipe inside diameter
t: pipe wall thickness

Position		P	D	t	σ_{1t}
		kg/cm²	cm	cm	kg/cm²
ϕ 900	Exposed Part	11.652	90	1.8	291
	Buried Part	17.941			449
ϕ1100	Exposed Part	11.661	110	2.2	292
	Buried Part	17.944			449

iv) Circumferential Bending Force Due to Successive Saddle Supports at Exposed Section

$$\sigma_{1B} = \frac{M}{Z}$$

Where: M: circumferential bending moment at saddle support shoulder

$M = K \cdot Q \cdot R \cdot \cos\alpha$

K: coefficient of bending moment created by supporting angle

Q: reaction force from supporting pedestal

R: pipe radius

α: angle of penstock in reference to horizontal line

Z: cross section coefficient of pipe wall

Position		K	Q kg	R cm	α ° ' "	M kg•cm	Z cm^3	σ_{1B} kg/cm^2
φ 900	Exposed Part	0.0528	7.49	45	38 37 32	13.903	0.540	±26
φ1100	Exposed Part	0.0528	11.20	55	38 23 37	25.490	0.807	±32

v) Circumferential Bending Stress due to Earth Pressure and Surface Load at Buried Section

Earth pressure

The earth pressure is calculated by vertical formula as the earth cover is small

$W_v = \gamma H$

W_V: earth pressure

γ : weigh per unit volume of filled back earth (= 0.0018 kg/cm^2)

H: earth cover above pipe top

	H cm	Wv kg/cm²
φ 900	100	0.180
φ1100	120	0.216

v-1 Bulldozer Load

The bulldozer to be taken into account is one, 3-ton class bulldozer.

$$W_B = n\ q_B(1+i)\left(\frac{b}{b+2H\tan\theta}\right)$$
$$= 2\times0.33\times(1)\times\left(\frac{30}{30+2\times100\times\tan45^\circ}\right) = 0.086$$

W_B: bulldozer load

n: number of caterpillars = 2

q_B: unit ground pressure by bulldozer = 0.33 kg/cm²

i: impact coefficient = 0 (for normal ground)

b: caterpillar width = 30 cm

H: earth cover

θ: angle of load transmission into ground = 45°

	H cm	Wv kg/cm²
φ 900	100	0.086

v-2 Total Load

$W = W_V + W_B$

W: total load

W_V: earth pressure

W_B: bulldozer load

	W_v	W_B	W
	kg/cm^2		
ϕ 900	0.180	0.086	0.266
ϕ1100	0.216	--	0.216

v-3 Bending Stress Due to Earth Pressure and Surface Load

The bending stress due to earth pressure and surface load is calculated by the following equation in which the restoring force of internal pressure is taken into account.

$$\sigma_{1B} = M/Z$$

σ_{1B}: bending stress in circumferential direction
M: bending moment created at pipe bottom

$$M = K_1 W Rm_2 + k_2 W_o Rm^3 - 0.083e'\Delta X Rm - k_1 P \Delta X Rm$$

W: strength of vertical load
R_m: radius of the center of thick plate
e': passive earth pressure resistance coefficient of earth
P: maximum water pressure at the position where stress is calculated
ΔX: amount of horizontal displacement
k_1, k_2, k_0: coefficients determined by support angle at pipe bottom
W_0: weight of water per unit volume (= 0.001 kg/cm^2)

$$\Delta X = \frac{2KWRm^4 + 2K_o W_o Rm^5}{EI + 0.061e'Rm^3 + 2KPRm^3}$$

EI: rigidity of pipe against bending
K: coefficient determined by support angle at pipe bottom

Design Support Angle	K	K_1	k_2	K_o
90°	0.096	0.314	0.321	0.085

Postion		P kg/cm^2	D cm	t cm	M kg•cm	Z cm^3	σ_{1B} kg/cm^2
ϕ 900	Buried Part	17.941	90	1.8	45.221	0.540	±84
ϕ1100	Buried Part	17.941	100	2.2	53.529	0.807	±66

vi) Total Stress in Circumferential Direction

$$\sigma_1 = \sigma_{1t} + \sigma_{1B} < \sigma_t$$

Position		σ_{1t}	σ_{1B}	σ_1	σ_t
		kg/cm^2			
ϕ 900	Exposed Part	291	±26	317	630
	Buried Part	449	±84	533	
ϕ1100	Exposed Part	292	±32	324	
	Buried Part	449	±66	515	

As illustrated above, the total stress in the circumferential direction is within the allowable stress for 900 mm diameter (t = 18) and 1100 mm diameter (t = 22)

A.5.6 Calculation of Combined Angle of Penstock

Cos X = Cos A·Cos B·Cos C ± Sin A· Sin B

Where: X: Combined angle in real value (°) in the plane including the upstream and downstream steel pipes

A: longitudinal angle (°) of upstream side steel pipe

B: longitudinal angle (°) of downstream side steel pipe
(for both A and B, positive sign signifies downward direction and negative sign signifies upward direction)

C: horizontal angle of upstream and downstream side steel pipes

No.	A			B			C			X			R	TL	CL	SL
	(°)	(')	(")	(°)	(')	(")	(°)	(')	(")	(°)	(')	(")	(m)	(m)	(m)	(m)
P10	0	3	26	41	28	23	0	0	0	41	24	57	6.000	2.268	4.337	0.414
P12	34	59	51	41	28	23	37	36	40	29	59	46	5.000	1.340	2.618	0.176
P12'	34	59	51	41	6	13	37	36	40	29	59	54	5.000	1.340	2.618	0.176
P13	41	28	23	38	43	32	18	0	0	14	0	47	5.000	0.614	1.223	0.038
P13'	41	6	13	38	23	37	18	0	0	14	4	31	5.000	0.617	1.228	0.038
P14	38	43	32	20	59	34	0	0	0	17	43	58	5.000	0.780	1.547	0.060
P14'	38	23	37	20	59	34	0	0	0	17	24	3	5.000	0.765	1.519	0.058
P15	20	59	34	16	55	39	0	0	0	4	3	55	5.000	0.177	0.355	0.003
P15'	20	59	34	16	55	40	0	0	0	4	3	54	5.000	0.177	0.355	0.003
P16	16	55	39	31	17	40	13	23	41	18	49	43	5.000	0.829	1.643	0.068
P16'	16	55	40	30	28	46	30	30	0	30	53	55	5.000	1.382	2.696	0.187
P17	31	17	40	0	0	0	17	6	19	35	14	35	5.000	1.588	3.076	0.246
P17'	30	28	46	0	0	0	0	0	0	30	28	46	5.000	1.362	2.660	0.182
P18	0	0	0	0	0	0	45	0	0	44	59	60	2.500	1.036	1.963	0.206
018'	0	0	0	0	0	0	45	0	0	44	59	60	2.500	1.036	1.963	0.206

A5.7 Calculation of Water Hammer

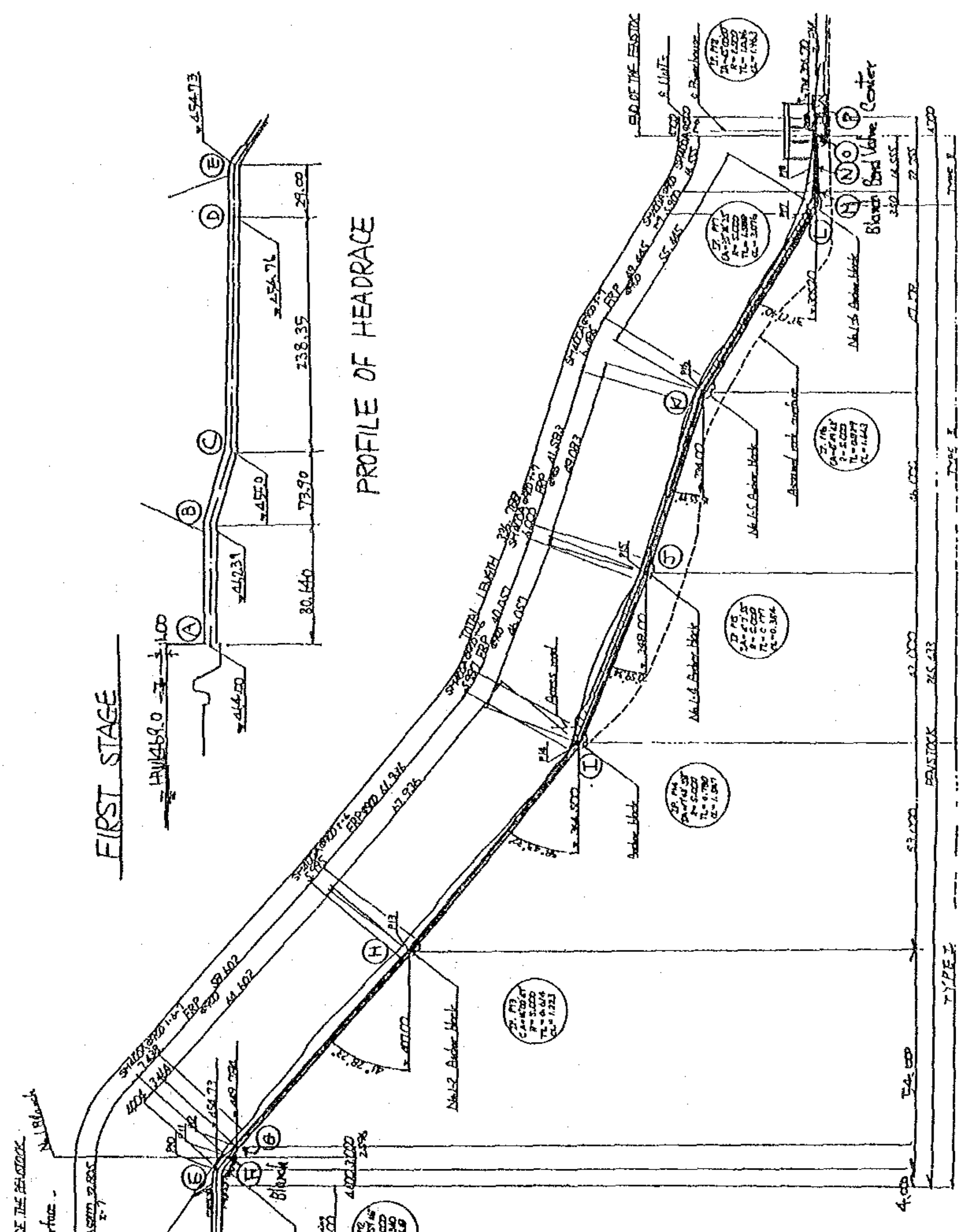
(a) First Stage

i) Calculation Conditions

F.W.L.	470.00 (m)	Closing Time	12.0 (sec)
H.W.L.	469.00 (m)	Propagation Velocity	950 (m/s)
Turbine Center	305.20 (m)		
Discharge	4.80, 1.60, 0.80 (m^3/s)		
Pipe Diameter	2.00 - 0.90 - 0.50 (m)		
Pipe Total Length	734.77 (m)		

ii) Measurement Point

Measurement Point	Elevation EL. (m)	Pipe Diameter D (m)	Pipe Length L (m)	Cross Sectional Area A (m^2)	Flow Rate Q (m^3/s)	Water Velocity V (m/s)	L・V
(A)	464.00	2.00		3.142	4.80	1.528	
(B)	462.39	2.00	80.640	3.142	4.80	1.528	123.209
(C)	455.00	2.00	73.900	3.142	4.80	1.528	112.911
(D)	454.76	2.00	238.350	3.142	4.80	1.528	364.172
(E)	454.73	2.00	29.000	3.142	4.80	1.528	44.309
(F)	452.08	2.00	4.004	3.142	4.80	1.528	6.118
(G)	449.78	0.90	4.000	0.636	1.60	2.515	10.060
(H)	407.00	0.90	64.602	0.636	1.60	2.515	162.477
(I)	364.50	0.90	67.936	0.636	1.60	2.515	170.862
(J)	348.00	0.90	46.057	0.636	1.60	2.515	115.835
(K)	334.00	0.90	48.083	0.636	1.60	2.515	120.931
(L)	305.20	0.90	55.445	0.636	1.60	2.515	139.446
(M)	305.20	0.90	3.500	0.636	1.60	2.515	8.803
(N)	305.20	0.50	6.310	0.196	0.80	4.074	25.709
(O)	305.20	0.50	8.245	0.196	0.80	4.074	33.593
(P)	305.20	0.50	4.700	0.196	0.80	4.074	19.150
Total			734.772				1,457.584


FIRST STAGE
PROFILE OF HEADRACE
PENSTOCK
TYPE I
START OF THE PENSTOCK
END OF THE PENSTOCK
Original ground surface
TOTAL LENGTH
Blow-off
Bend Valve Center

iii) Average Velocity

Average velocity $V_0 = L_i \cdot V_i \ / \ L_0$

$= 1,457.584/734.772$

$= 1.984$ (m/s)

iv) Water Hammer

The calculation equation of water hammer is classified to the following Equation (A) and Equation (B) according to the pipe constant ρ of Allievi.

α ; propagation velocity of pressure wave 950 (m/s)

H_o ; static head at the turbine end = 164.80 (m)

g ; acceleration by gravity = 9.8 (m/s^2)

<1> Pipe Constant of Allievi

$\rho = \alpha \cdot V_o/(2 \cdot g \cdot Ho)$

$= 950 \times 1.984/(2 \times 9.8 \times 164.80)$

$= 0.583$

<2> Closing Time Constant of Closing Device

T; closing time = 12.0 (sec)

$\theta = \alpha \cdot T/2 \cdot Lo$

$= 950 \times 12.0/2 \times 734.77$

$= 7.785$

$n = \rho/\theta$

$= 0.583/7.758$

$= 0.075$

<3> Water Hammer

When $\rho > 1$

$$ho/Ho = n/2 \cdot \{n + \sqrt{(n2+4)}\} \qquad \text{Equation (A)}$$

When $\rho < 1$

$$ho/Ho = 2 \cdot n/\{1 + n(\theta - 1)\} \qquad \text{Equation (B)}$$

Here, ho is the water pressure rise at turbine end due to water hammer.

As ρ = 0.583, ho/Ho = 0.100

∴ ho = 164.80 x 0.100

= 16.48 (m)

(b) Latter Stage

i) Calculation Conditions

F.W.L.	470.00 (m)	Closing Time	13.0 (sec)
H.W.L.	469.00 (m)	Propagation Velocity	950 (m/s)
Turbine Center	305.20 (m)		
Discharge	4.80, 3.60, 1.60 (m^3/s)		
Pipe Diameter	2.00 - 1.10 - 0.75 (m)		
Pipe Total Length	730.05 (m)		

ii) Measurement Point

Measurement Point	Elevation	Pipe Diameter	Pipe Length	Cross Sectional Area	Flow Rate	Water Velocity	L・V
	EL.	D	L	A	Q	V	
	(m)	(m)	(m)	(m²)	(m³/s)	(m/s)	
(A)	464.00	2.00		3.142	4.80	1.528	
(B)	462.39	2.00	80.640	3.142	4.80	1.528	123.209
(C)	455.00	2.00	73.900	3.142	4.80	1.528	112.911
(D)	454.76	2.00	238.350	3.142	4.80	1.528	364.172
(E)	454.73	2.00	29.000	3.142	4.80	1.528	44.309
(F)	452.08	2.00	4.004	3.142	4.80	1.528	6.118
(G)	449.78	1.10	4.000	0.950	3.20	3.367	13.469
(H)	407.00	1.10	65.079	0.950	3.20	3.367	219.137
(I)	364.50	1.10	68.431	0.950	3.20	3.367	230.424
(J)	348.00	1.10	46.057	0.950	3.20	3.367	155.085
(K)	33900	1.10	30.849	0.950	3.20	3.367	103.876
(L)	305.20	1.10	66.672	0.950	3.20	3.367	224.501
(M)	305.20	1.10	3.750	0.950	3.20	3.367	12.627
(N)	305.20	0.75	7.371	0.442	1.60	3.622	26.695
(O)	305.20	0.75	5.945	0.442	1.60	3.622	21.531
(P)	305.20	0.75	6.000	0.442	1.60	3.622	21.730
Total			730.048				1,679.793

iii Average Velocity

Average velocity $V_0 = L_i \cdot V_i \ / \ L_0$

$= 1{,}679.793/730.048$

$= 2.310$ (m/s)

iv) Water Hammer

The calculation equation of water hammer is classified to the following Equation (A) and Equation (B) according to the pipe constant ρ of Allievi.

α ; propagation velocity of pressure wave 950 (m/s)

H_o ; static head at the turbine end = 164.80 (m)

g ; acceleration by gravity = 9.8 (m/s^2)

<1> Pipe Constant of Allievi

$\rho = \alpha \cdot V_o / (2 \cdot g \cdot Ho)$

$= 950 \times 2.301/(2 \times 9.8 \times 164.80)$

$= 0.677$

<2> Closing Time Constant of Closing Device

T; closing time = 13.0 (sec)

$\theta = \alpha \cdot t / (2/L_0)$

$= 950 \times 13.0/2 \times 730.05$

$= 8.458$

$n = \rho/\theta$

$= 0.677/8.453$

$= 0.080$

<3> Water Hammer

When $\rho > 1$

$$ho/Ho = n/2 \cdot \{n + \sqrt{(n2+4)}\} \qquad \text{Equation (A)}$$

When $\rho < 1$

$$ho/Ho = 2 \cdot n / \{1 + n(\theta - 1)\} \qquad \text{Equation (B)}$$

Here, ho is the water pressure rise at turbine end due to water hammer.

As $\rho = 0.677$, $ho/Ho = 0.100$

$\therefore ho = 164.80 \times 0.100$

$= 16.48$ (m)

A5.8 Calculation of Wall Thickness of Penstock Steel Pipe

(a) First Stage

i) Designed Internal Pressure

The internal pressure head at each point is defined as the static head plus the water hammer pressure.

The pressure rise due to water hammer along the head race channel is assumed to have the maximum value at the turbine center, 0 m at the sand stilling basin, and the pressure values in the headrace is proportional to the length of the headrace.

Measurement Point	Elevation	Length	Static Head	Water Hammer	Design Water Pressure		Note
	EL.	L	H	h	Hp	P	
	(m)	(m)	(m)	(m)	(m)	(kg/cm²)	
(A)	464.00				6.00	0.600	
(B)	462.39	80.64	6.000	1.809	9.72	0.942	
(C)	455.00	154.54	76.10	3.466	18.47	1.847	
(D)	454.76	392.89	15.000	8.812	24.05	2.405	
(E)	454.73	421.89	15.240	9.462	24.73	2.473	
(F)	452.08	425.89	17.922	9.522	27.47	2.747	
(G)	449.78	429.89	20.216	9.642	29.86	2.986	
(H)	407.00	494.56	63.000	11.091	74.09	7.409	
(I)	364.50	562.43	105.500	12.615	118.11	11.811	
(J)	348.00	608.49	122.000	13.648	135.65	13.565	
(K)	334.00	656.57	136.000	14.726	150.73	15.073	
(L)	305.20	712.02	164.800	15.970	180.77	18.077	
(M)	305.20	715.52	164.800	16.048	180.85	18.085	
(N)	305.20	721.83	164.800	16.190	180.99	18.099	
(O)	305.20	730.07	164.800	16.375	181.17	18.117	
(P)	305.20	734.77	164.800	16.480	181.28	18.128	
Total		734.77					

ii) Pipe Thickness

The pipe wall thickness was calculated by the formula for pipe wall thickness and the formula for the minimum pipe wall thickness given below, and the larger value obtained was selected. However, the minimum pipe wall thickness is 6.0 mm in any case.

Formula for pipe wall thickness; $t_1 = \frac{P \cdot D}{2 \cdot \sigma_a \cdot \eta} + \varepsilon$

Where: t_1 = pipe wall thickness (cm)

p = design water pressure (kg/cm^2)

D = pipe diameter (cm)

σa = allowable unit tensile stress, 1,300 (kg/cm^2)(SM400A)

η = welding efficiency, 0.95

ϵ = marginal thickness, 0.15 (cm)

Formula for minimum pipe wall thickness; $t_{min} = \frac{D + 800}{400}$

Where, t_{min} = pipe wall thickness including margin (mm)

Measurement Point	Pipe Diameter	Design Water Pressure	Calculated Pipe Thickness	Minimum Pipe Thickness	Pipe Thickness	Selected Pipe Thickness	Note
	D	P	t_1	tmin	t_1, tmin	t	
	(m)	(kg/cm²)	(mm)	(mm)	(mm)	(mm)	
(D)	2.00	2.405	3.45	7.00	7.00	7.0	
	2.00	2.405	3.45	7.00	7.00	7.0	
(E)	2.00	2.473	3.50	7.00	7.00	7.0	
	2.00	2.473	3.50	7.00	7.00	7.0	
(F)	2.00	2.747	3.73	7.00	7.00	7.0	
	0.90	2.747	2.50	4.25	4.25	6.0	
(G)	0.90	2.986	2.59	4.25	4.25	6.0	
	0.90	2.986	2.59	4.25	4.25	6.0	
(H)	0.90	7.409	4.20	4.25	4.25	6.0	
	0.90	7.409	4.20	4.25	4.25	6.0	
(I)	0.90	11.811	5.81	4.25	5.81	7.0	by external pressure
	0.90	11.811	5.81	4.25	5.81	7.0	〃
(J)	0.90	13.565	6.45	4.25	6.45	8.0	〃
	0.90	13.565	6.45	4.25	6.45	8.0	〃
(K)	0.90	15.073	7.00	4.25	7.00	8.0	〃
	0.90	15.073	7.00	4.25	7.00	8.0	〃
(L)	0.90	18.077	8.10	4.25	8.10	9.0	
	0.90	18.077	8.10	4.25	8.10	9.0	
(M)	0.90	18.085	8.10	4.25	8.10	9.0	
	0.50	18.085	5.17	3.25	5.17	6.0	
(N)	0.50	18.099	5.17	3.25	5.17	6.0	
	0.50	18.099	5.17	3.25	5.17	6.0	
(O)	0.50	18.117	5.18	3.25	5.18	6.0	
	0.50	18.117	5.18	3.25	5.18	6.0	
(P)	0.50	18.128	5.18	3.25	5.18	6.0	

(b) Latter Stage

i) Designed Internal Pressure

Measurement Point	Elevation	Length	Static Head	Water Hammer	Design Water Pressure		Note
	EL.	L	H	h	Hp	P	
	(m)	(m)	(m)	(m)	(m)	(kg/cm²)	
(A)	464.00				6.00	0.600	
(B)	462.39	80.64	6.000	1.820	9.43	0.943	
(C)	455.00	154.54	76.10	3.489	18.49	1.849	
(D)	454.76	392.89	15.000	8.869	24.11	2.411	
(E)	454.73	421.89	15.240	9.524	24.79	2.479	
(F)	452.08	425.89	15.270	9.614	27.54	2.754	
(G)	449.78	429.89	17.922	9.704	29.92	2.992	
(H)	407.00	494.97	20.216	11.173	74.17	7.417	
(I)	364.50	563.40	63.000	12.718	118.22	11.822	
(J)	348.00	609.46	105.500	13.758	135.76	13.576	
(K)	339.02	640.31	122.000	14.454	145.44	14.544	
(L)	305.20	706.98	130.982	15.959	180.76	18.076	
(M)	305.20	710.73	164.800	16.044	180.84	18.084	
(N)	305.20	718.10	164.800	16.210	181.01	18.101	
(O)	305.20	724.05	164.800	16.345	181.14	18.114	
(P)	305.20	730.05	164.800	16.480	181.28	18.128	
Total		730.05					

ii) Pipe Wall Thickness

Measurement Point	Pipe Diameter D (m)	Design Water Pressure P (kg/cm²)	Calculated Pipe Thickness t_1 (mm)	Minimum Pipe Thickness tmin (mm)	Pipe Thickness t_1, tmin (mm)	Selected Pipe Thickness t (mm)	Note
(D)	2.00	2.411	3.45	7.00	7.00	7.0	
	2.00	2.411	3.45	7.00	7.00	7.0	
(E)	2.00	2.479	3.51	7.00	7.00	7.0	
	2.00	2.479	3.51	7.00	7.00	7.0	
(F)	2.00	2.754	3.73	7.00	7.00	7.0	
	1.10	2.754	2.73	4.75	4.75	6.0	
(G)	1.10	2.992	2.83	4.75	4.75	6.0	
	1.10	2.992	2.83	4.75	4.75	6.0	
(H)	1.10	7.417	4.81	4.75	4.81	6.0	
	1.10	7.417	4.81	4.75	4.81	6.0	
(I)	1.10	11.822	6.77	4.75	6.77	8.0	by external pressure
	1.10	11.822	6.77	4.75	6.77	8.0	〃
(J)	1.10	13.576	7.55	4.75	7.55	8.0	
	1.10	13.576	7.55	4.75	7.55	8.0	
(K)	1.10	15.544	7.99	4.75	7.99	9.0	by external pressure
	1.10	15.544	7.99	4.75	7.99	9.0	〃
(L)	1.10	18.076	9.56	4.75	9.56	10.0	
	1.10	18.076	9.56	4.75	9.56	10.0	
(M)	1.10	18.084	9.56	4.75	9.56	10.0	
	0.75	18.084	7.00	3.88	7.00	8.0	
(N)	0.75	18.101	7.01	3.88	7.01	8.0	
	0.75	18.101	7.01	3.88	7.01	8.0	
(O)	0.75	18.114	7.01	3.88	7.01	8.0	
	0.75	18.114	7.01	3.88	7.01	8.0	
(P)	0.75	18.128	7.02	3.88	7.02	8.0	

A5.9 Stability Calculation of Anchor Block

(a) Calculation of External Forces

i) Dead Load of Pipe and Weight of Water

Thrust (direction of pipe axis)

$P_1 = S \times L \times \sin \alpha$

S ; weight of penstock per meter of length
$= \pi \cdot (D + t) \cdot t \cdot \rho$ (t/m)

D ; internal diameter of penstock (m)

t ; wall thickness of penstock (m)

ρ ; unit weight of steel material = 7.85 (t/m^3)

L ; distance from anchor block to expansion joint (m)

α ; The angle with which the center line of penstock crosses the horizontal line, in degrees.
The subscript "U" is for upstream, and "D" for downstream.

Direction Perpendicular to Pipe Axis

$W_1 = (S + \omega) \times \ell/2 \times \cos \alpha$

ω ; weight of water in pipe for 1 meter length of penstock
$= \pi/4 \times D^2$ (t/m)

ℓ ; distance from anchor block to support pedestal (m)

ii) Thrust Due to Friction of Water Flow inside Penstock

Thrust Due to Friction

$$P_2 = \frac{2 \times f_w \times Q^2}{g \times \pi \times D^3} \times L$$

f_w; friction resistance coefficient of water flow inside pipe = 0.02

Q ; discharge (m^3/s)

g ; acceleration by gravity = 9.8 (m/sec^2)

Centrifugal Force Acting on Curved Section of Pipe

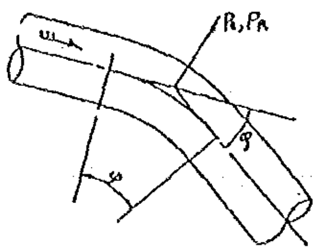
$$P_c = \frac{2 \times V^2}{g} \times A \times \sin\frac{\phi}{2}$$

V ; aveage velocity inside pipe (m/s)

A ; cross sectional area of pipe (m^2)

ϕ ; central angle of curved section of pipe (°)

The force acts outward in the direction of the bisector of angle ϕ.



iii) Thrust Due to Internal Pressure

Thrust in the Pipe Axial Direction Working on Shrinking Section

$P_3 = H_T$ x $(A_u - A_d)$

H_t ; design pressure at the center of shrinking pipe (t/m^2)

under normal condition;	maximum design water pressure
under earthquake;	maximum static water pressure

A_u ; internal cross sectional area of pipe to the upstream of the shrinking pipe (m^2)

A_d ; internal cross sectional area of pipe to the downstream of the shrinking pipe (m^2)

Thrust in Pipe Axial Direction Working on Expansion Joint

$$P_4 = H_E \times \pi \times D_E \times t_E$$

H_E ; water pressure at the center of expansion joint (t/m^2)
under normal condition; maximum design water pressure
under earthquake; maximum static water pressure

D_E ; pipe internal diameter at expansion joint (m)

t_E ; pipe wall thickness at expansion joint (m)

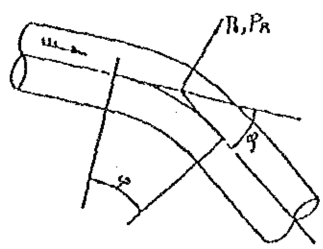
Unbalanced Force Working on Curved Section

$$P_R = 2 \times H \times A \times \sin(\phi/2)$$

H ; water pressure at the center of curved section (t/m^2)
under normal condition; maximum design water pressure
under earthquake; maximum static water pressure

A ; internal cross section of curved pipe (m^2)

The force acts outward in the direction of the bisector of angle ϕ.



iv) Friction Force Due to Temperature Change

Friction at Bearing Part

$$F_1 = C \times (\omega + S) \times (L - \ell/2) \times \cos\alpha$$

C ; friction coefficient of support pedestal

concrete bearing = 0.60

concrete saddle with sliding element = 0.50

slide bearing = 0.25

locker bearing = 0.15

roller bearing = 0.05

Friction Force of Expansion Joint

$$F_2 = F_E \times \pi \times (D_E + 2 \times t_E)$$

F_E; friction coefficient of expansion joint 0 0.7 (t/m)

v) Total of External Forces

* Thrust from upstream part of penstock

$$P = P_1 + P_2 + P_3 + P_4 \pm F_1 \pm F_2$$

(+) is used when temperature is rising

(-) is used when temperature is falling

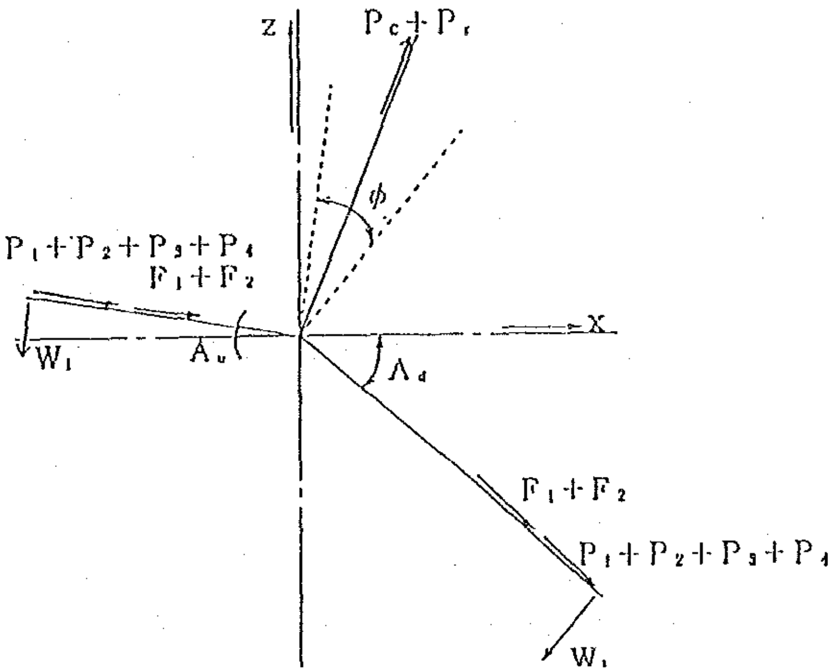
* Thrust from downstream part of penstock

$$P = P_1 + P_2 + P_3 + P_4 - (\pm F_1 \pm F_2)$$

(+) is used when temperature is rising

(-) is used when temperature is falling

Out of the friction forces of F_1 and F_2, the one that gives the severer combination is used.



(b) Conditions for Stability

The following conditions must be satisfied in order that the anchor block is stable.

i) Stability against Turning Over

The loads applied to the anchor back are combined in a manner that the worst condition is realized, and the acting line of that combined force must pass the central 1/3 of the anchor block foundation.

$e \leq 1/6$ (The point on which the combined force acts must be within the middle third.)

ii) Stability against Sliding

The vertical force generated in the bottom of the anchor block must be larger than the value which is the horizontal force divided by the sliding coefficient.

$$\Sigma \frac{H}{\Sigma V} \leq 0.5$$

The following values are used as standards for the sliding coefficient between anchor block and ground foundation, depending on the conditions of the foundation.

Rock foundation of good quality	0.75
Soft rock foundation and gravel layer	0.50
Clay	0.30

iii) Stability against Collapse

The compressive stress generated by the anchor block must be less than the bearing capacity of foundation and the allowable stress of concrete.

Allowable Bearing Capacity of Ground Foundation

Type of Ground		Allowable Bearing Capacity (t/m^2)
Sand or clay		10
Clay containing sand or loam		15
Mixture of gravel and sand		20
Gravel		30
Soft rocks:	shale, mud stone, etc. aqueous rocks such as slate, schist	100 250
Hard rocks:	igneous rocks such as granite, diorite, gneiss and andesite, and hard conglomerate, etc.	400

$$\sigma = \frac{\Sigma V}{\ell \cdot b}\left(1 \pm \frac{6 \cdot e}{\ell}\right) \leq 18.0\, t/m^2$$

Where:

σ ; ground stress (t/m^2)

e ; eccentricity distance (m)

l; length of fixing pedestal (m)

b; width of fixing pedestal (m)

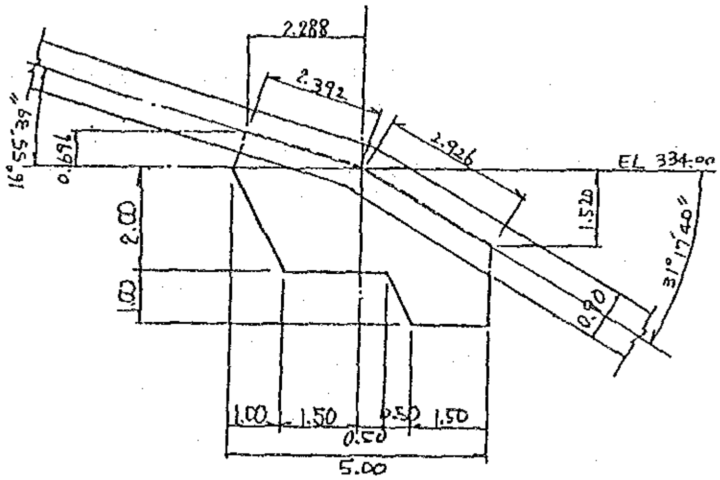
H; working force in horizontal direction (t)

V; working force in vertical direction (t)

(c) Calculation Result

i) No. 1-5 Anchor Block (First Stage)

Width = 2.30 m



Only the weight of steel pipe and water in the pipe directly above the anchor block is considered.

<1> Stability against Turning Over

[Under Normal Condition]

	V (t)	H (t)	X (m)	Y (m)	Z (m)	V·X (tm)	V·Y (tm)	H·Z (tm)
Dead Load	49.595	0.000	0.035	0.000	1.704	1.752	0.000	0.000
External Force	-16.120	7.615	0.000	0.000	3.000	0.000	0.000	22.844
Total	33.474	7.615				1.752	0.000	22.844

$\Sigma M = V \cdot X + H \cdot Z = 24.596$ (t·m)

$X_M = 24.596/33.474 = 0.735$ (m)

$e = 5.000/2 - (2.500 - 0.735) = 0.735$ (m) $< 5.000/6 = 0.833$ (m)

[Under Earthquake]

	V (t)	H (t)	X (m)	Y (m)	Z (m)	V·X (tm)	V·Y (tm)	H·Z (tm)
Dead Load	49.595	0.992	0.035	0.000	1.704	1.752	0.000	1.690
External Force	-16.120	7.615	0.000	0.000	3.000	0.000	0.000	22.844
Total	33.474	8.606				1.752	0.000	24.534

$\Sigma M = V \cdot X + H \cdot Z = 26.286$ (t·m)

$X_M = 26.286/33.474 = 0.785$ (m)

$e = 5.000/2 - (2.500 - 0.785) = 0.785$ (m) $< 5.000/6 = 0.833$ (m)

<2> Stability against Sliding

$H/V \leq 0.5$

f; sliding coefficient between ground and anchor block = 0.50

[Under Normal Condition]

$7.615/33.474 = 0.23 < 0.5$

[Under Earthquake]

8.606/33.474 = 0.26 < 0.5

<3> Ground Stress

[Under Normal Condition]

$\sigma = V/(\ell \cdot b) \times (1 \pm 6 \cdot e/\ell)$

$= 33.474/(5.000 \times 2.300) \times (1 \pm 6 \times 0.735/5.000)$

$= 5.474\ (t/m^2)$

$\quad 0.344\ (t/m^2) \quad < 18.0\ (t/m^2)$

[Under Earthquake]

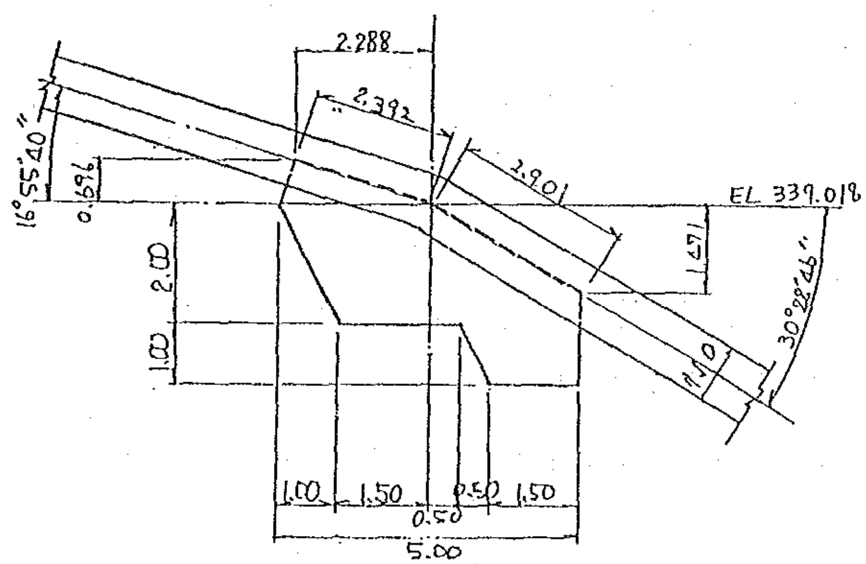
$= 33.474/(5.000 \times 2.300) \times (1 \pm 6 \times 0.785/5.000)$

$= 5.654\ (t/m^2)$

$\quad 0.168\ (t/m^2) \quad < 18.0\ (t/m^2)$

ii) No. 2-5 Anchor Block (Latter Stage)

Width = 3.00 m



Only the weight of steel pipe and water in the pipe directly above the anchor block is considered.

<1> Stability against Turning Over

[Under Normal Condition]

	V (t)	H (t)	X (m)	Y (m)	Z (m)	V·X (tm)	V·Y (tm)	H·Z (tm)
Dead Load	64.389	0.000	0.045	0.000	1.693	2.923	0.000	0.000
External Force	-20.878	9.866	0.000	0.000	3.000	0.000	0.000	29.597
Total	43.510	9.866				2.923	0.000	29.597

$\Sigma M = V \cdot X + H \cdot Z = 32.520$ (t·m)

$X_M = 32.520/43.510 = 0.747$ (m)

$e = 5.000/2 - (2.500 - 0.747) = 0.747$ (m) $< 5.000/6 = 0.833$ (m)

[Under Earthquake]

	V (t)	H (t)	X (m)	Y (m)	Z (m)	V·X (tm)	V·Y (tm)	H·Z (tm)
Dead Load	64.389	1.288	0.045	0.000	1.693	2.923	0.000	2.180
External Force	-20.878	9.866	0.000	0.000	3.000	0.000	0.000	29.597
Total	43.510	11.153				2.923	0.000	31.777

$\Sigma M = V \cdot X + H \cdot Z = 34.700$ (t·m)

$X_M = 34.700/43.510 = 0.798$ (m)

$e = 5.000/2 - (2.500 - 0.798) = 0.798$ (m) $< 5.000/6 = 0.833$ (m)

<2> Stability against Sliding

$H/V \leq 0.5$

[Under Normal Condition]

$9.866/43.510 = 0.23 < 0.5$

[Under Earthquake]

11.153/43.510 = 0.26 < 0.5

<3> Ground Stress

[Under Normal Condition]

$\sigma = V/(\ell \cdot b) \times (1 \pm 6 \cdot e/\ell)$

$= 43.510/(5.000 \times 3.000) \times (1 \pm 6 \times 0.747/5.000)$

$= 5.502\ (t/m^2)$

$0.299\ (t/m^2) \quad < 18.0\ (t/m^2)$

[Under Earthquake]

$= 43.510/(5.000 \times 3.000) \times (1 \pm 6 \times 0.798/5.000)$

$= 5.677\ (t/m^2)$

$0.125\ (t/m^2) \quad < 18.0\ (t/m^2)$

A5.10 Records of FRP (M) Pipe Construction Works in Japan - I

Penstocks

Owner	P. S Name	Year of Const-ruction	Pipe Type	Max. Output (kW)	Max. Discharge (m³/s)	FRP Pipe (mm)		Head		Note
						Dia. (mm)	Length (m)	All Pipe (m)	FRP Pipe (m)	
Hokkaido E.P.C	Hoyaishikawa	S. 62	FRP	170	0.18	300	293	Effe. Head:134.44 Design Head:14.1kg/cm²		Class I
Tohoku E.P.C	Ohfudo	S. 61	FRP	1,400	2.33	1,100	96	82.1	74.3	Class I
Tokyo E.P.C	Tsugane	S. 61	FRP	909	0.695	800	221	130.3	112.8	Class I
Tokyo E.P.C	Kurokawa	S. 61	FRP	800	3.62	1,350	55	30.3	12.7	Class I
Kansai E.P.C	Mannami	S. 62	FRP	12,400	5.00	1,500	168	303.6	61.0	Class I
Tosei Kogyo	Komagome	S. 63	FRP	4,000	8.15	1,800	84	60.6	52.6	Class I
Kanazawa City	Shinnaigawa 2	S. 63	FRP	3,000	3.70	1,350	114	100.6	72.3	Class I
Iwate Pref.	Irihata	H. 1	FRP	2,100	3.50	1,500	207	81.2	79.8	Class I
Akita Pref.	Hachimantai 2	S. 60	FRPM	1,500	1.80	1,200	881	100.5	100.5	Class I
Shin-Hotta City	Uchinokura	H. 1	FRP	2,800	5.00	1,200	230	69.4	56.5	Class I
Nishime City	Nishime	S. 62	FRPM &FRP	740	0.80	600	520	Effe. Head 116.00 m		Class I
Nichinan Town	Shinhinoue	H. 1	FRPM	560	4.00	1,500	780	Effe. Head 30.00 m		Class I
Nichinan Town	Shinhinoue	H. 1	FRPM	560	4.00	1,500	300	Effe. Head 30.00 m		Class II
Tohoku E.P.C	Ozasau	H. 2	FRP	11,400	6.50	1,650 1,500	480	215.2	174.3	Class I

Records of FRP (M) Pipe Construction Works in Japan - II

Except for Penstocks

Owner Name	P.S Name	Applic.	Diam (mm)	Length (m)	Pipe Type	Note
Hokkaido E.P.C	Akinokawa	Headrace	1200	126	FRPM	Class II
Hokkaido E.P.C	Shibinai	Spillway	900	31	FRP	Class I
Tohoku E.P.C	Sendai T.P.P	Ash Disch Pipe	1200	100	FRPM	Class I
Tohoku E.P.C	Ogawa	Spillway	1000	149	FRP	Class I
Tohoku E.P.C	Kakkonda	Spillway	800	309	FRP	Class I, Conc.Lining
Tohoku E.P.C	Yokokawa	Headrace	1350	315	FRPM	Class I
Tohoku E.P.C	Miyako	Headrace	2200	76	FRPM	Class I
Tohoku E.P.C	Ryozu T.P.P	Cooling Pipe	500	173	FRPM	Class I
Tokyo E.P.C	Onogawa	Spillway	1500, 1650	195	FRPM	Class I
Tokyo E.P.C	Minowa	Spillway	1200	129	FRP	Class I
Tokyo E.P.C	Minowa	Spillway	1200, 1500	46	FRPM	Class I
Tokyo E.P.C	Tsugane	Headrace	900	43	FRP	Class I, Water Pipe Bridge
Tokyo E.P.C	Tsugane	Spillway	450	274	FRPM	Class I
Tokyo E.P.C	Shikazawa	Headrace	1200	835	FRPM	Class I
Tokyo E.P.C	Tanimura	Headrace	3000	380	FRPM	Class I, Tunnel
Tokyo E.P.C	Tōnozawa	Headrace	1800	13	FRP	Class I, Water Pipe Bridge
Tokyo E.P.C	Tōnozawa	Spillway	700, 800	121	FRP	Class I
Tokyo E.P.C	Higashio-ogishimaT.P.P	Cooling Pipe	900, 1100	85	FRPM	Class I
Tokyo E.P.C	Kasumizawa	Sand Flush Pipe	500, 450	725	FRPM	Class I
Chubu E.P.C	Ochiai	Spillway	500	194	FRPM	Class I
Kansai E.P.C	Hashitani	Headrace	900	273	FRPM	Class I, Conc.Lining
Kansai E.P.C	Hashitani	Headrace	900	270	FRPM	Class I, Conc.Lining
Kansai E.P.C	Kusanogawa	Headrace	700	230	FRPM	Class I, Conc.Lining
Chugoku E.P.C	Hikimi	Spillway	600	241	FRPM	Class I
Shikoku E.P.C	Higashi-toyonaga	Headrace	1000	50	FRP	Class I, Tunnel
Shikoku E.P.C	Higashi-toyonaga	Headrace	1100	90	FRPM	Class II
Kyusyu E.P.C	Jikumaru	Headrace	1800	130	FRPM	Class I
Kyusyu E.P.C	Uchinoura	Spillway	800 ~ 1350	329	FRP	Class I, Conc.Lining
Akita Pref.	Hachimantai2	Headrace	1200	1045	FRPM	Class I
Akita Pref.	Hachimantai2	Headrace	1200	500	FRPM	Class II
E.P.D.C	IshikawaT.P.P	Cooling Pipe	2800	564	FRP	Class I
Okayama Pref.	Kuramigawa	Spillway	600	148	FRPM	Class I
Okayama Pref.	Awa	Headrace	900	1200	FRPM	Class I
Okayama Pref.	Awa	Spillway	400	72	FRPM	Class I, Conc.Lining
Tosei Kogyo	Komagome	Spillway	1100	60	FRP	Class I
Nishime Town	Nishime	Spillway	500	523	FRPM &FRP	Class I
Nichinan Town	Shinhinogami	Spillway	2000	126	FRPM	Class II
Tohoku E.P.C	Ōzasau	Spillway	1200, 900	557	FRPM	Class I

A5.11 Comparison of Construction Costs of FRP Pipe and Steel Pipe

The construction cost of a penstock (for 6,000 kW) employing steel pipes having the same diameter as the FRP pipe has been calculated. The result is presented in the table below.

		FRP Pipe	Steel Pipe	Difference
		(1,000$)	(1,000$)	(1,000$)
	Material Cost			
	Steel Pipe	229	601	} 9
	FRP Pipe	363	-	
	Installation Cost	363	369	6
	Transportation Cost	320	294	-26
	Engineering Cost	243	328	85
	Total	1,518	1,592	74
Civil Work Cost		744	772	28
Total		(100%) 2,262	(104.5%) 2,364	(4.5%) 102

A5.12 Calculation of Accommodation Capacity of Spoil Bank

(in m^3)

Location		Excavation Volume	Increase Factor	Increased Volume	Disposal Rate	Disposed Volume	Note
(First Stage)							
Intake Dam	Soil	483	1.3	628	100%	626	Fillback Volume 2
	Rock	1,482	1.3	1,927	30	578	
Intake	Soil	85	1.3	111	100	31	" 80
	Rock	480	1.3	624	30	187	
Sand Stilling Basin	Soil	110	1.3	143	100	-772	" 915
	Rock	844	1.3	1,097	30	329	
Culvert	Soil	6	1.3	8	100	-171	" 179
	Rock	963	1.3	1,252	30	376	
Headrace Tunnel	Rock	1,996	1.5	2,994	20	599	
Sediment Discharge Tunnel	Soil	95	1.3	124	100	124	
	Rock	279	1.5	418	20	84	
Intake Dam Construction Road	Soil	2,000	1.3	2,600	100	2,600	
Sediment Discharge Tunnel Road	Soil	4,250	1.3	5,525	100	5,525	
A-Spoil Bank	Soil	60	1.3	78	100	78	
Sub Total						10,194	Total For A-Spoil Bank Disposed Volume = 10,194 m^3
Penstock	Soil	1,900	1.3	2,470	100	1,320	Fillback Volume 1,150
	Rock	2,105	1.3	2,737	100	2,737	
Powerhouse	Soil	386	1.3	502	100	428	" 74
Tailrace	Soil	268	1.3	348	100	348	
Switchyard	Soil	156	1.3	203	100	91	" 112
Powerhouse Construction Road	Soil	5,600	1.3	7,280	100	7,280	
B-Spoil Bank	Soil	17	1.3	22	100	22	
Sub Total						12,228	Total for B-Spoil Bank Disposed Volume (First Stage) = 12,226 m^3
(Latter Stage)							
Penstock	Soil	2,892	1.3	3,760	100	2,590	Fillback Volume 1,170
	Rock	1,493	1.3	1,941	100	1,941	
Powerhouse	Soil	1,899	1.3	2,469	100	2,469	
Tailrace	Soil	169	1.3	220	100	220	
Sub Total						7,220	Total for B-Spoil Bank Disposed Volume (Latter Stage) = 7,220 m^3

A5.13 Calculation of Head Loss

(a) Cases

Case	(1)	(2)	(3)
Output	2,000 kW Completed	4,000 kW Completed	
Channel Inside Diameter (m)	2.0 → 0.9 → 0.5	2.0 → 0.9 → 0.5	2.0 → 1.1 → 0.75
Maximum Discharge (m^3/s)	1.6 → 1.6 → 0.8	4.8 → 1.6 → 0.8	4.8 → 3.2 → 1.6

(b) Calculation Formula

i) Intake

* Loss of Water Level by Inflow to Intake

$$\Delta he = fe \cdot V_2^2/2g + (V_2^2/2g - V_1^2/2g)$$

Δhe ; loss of water level by inflow (m)

fe ; inflow loss coefficient = 0.20 (rectangle with round corner)

V_1 ; velocity before inflow = 0.00 (m/s)

V_2 ; velocity after inflow = Q/Bh (m/s)

B ; width of inflow port = 6.00

h ; water depth at inflow port = 468.00 -466.50 = 1.50 (m)

* Loss of Water Level by Pipe Screen

$$\Delta hr = fr \cdot V_1^2/2g + (V_2^2/2g - V_1^2/2g)$$

Δhr ; loss of water level by screen (m)

fr ; screen loss coefficient = $\beta \sin\theta\,(t/b)^{4/3}$ = 0.424

ß ; coefficient determined by cross sectional shape of screen bar = 1.79

θ ; sloping angle of screen bar = 90(°)

t ; thickness of screen bar = 76 (mm)

b ; net clearance between screen bars = 224 (mm)

V_1 ; velocity before inflow (m/s)

V_2 ; velocity after inflow (m/s)

B ; total width of screen = 6.00 (m)

* Loss of Water Level by Screen Bar

$$\Delta hr = fr \cdot V_1^2/2g + (V_2^2/2g - V_1^2/2g)$$

Δhr ; loss of water level by screen (m)

fr ; screen loss coefficient = $\beta \sin\theta \, (t/b)^{4/3}$ = 0.121

β ; coefficient determined by cross sectional shape of screen bar = 2.34

θ ; sloping angle of screen bar = 75(°)

t ; thickness of screen bar = 10 (mm)

b ; net clearance between screen bars = 90 (mm)

V_1 ; velocity before inflow (m/s)

V_2 ; velocity after inflow (m/s)

B ; total width of screen = 6.00 (m)

ii) Sedimentation Basin

* Loss of Water Level by Screen Bar

$$\Delta hr = fr \cdot V_1^2/2g + (V_2^2/2g - V_1^2/2g)$$

Δhr ; loss of water level by screen (m)

fr ; screen loss coefficient = $\beta \sin\theta \, (t/b)^{4/3}$ = 0.356

β ; coefficient determined by cross sectional shape of screen bar = 2.34

θ; sloping angle of screen bar = 75(°)

t ; thickness of screen bar = 10 (mm)

b ; net clearance between screen bars = 40 (mm)

V_1 ; velocity before inflow (m/s)

V_2 ; velocity after inflow (m/s)

B ; total width of screen = 5.00 (m)

* Loss of Water Level by Sectional Reduction

$$\Delta hc = fc \cdot V_2^2/2g + (V_2^2/2g - V_1^2/2g)$$

Δhc ; loss of water level by Sectional Reduction (m)

fc ; inflow loss coefficient by reduction = 0.001

V_1 ; velocity before reduction (m/s)

V_2 ; velocity after reduction (m/s)

B_1 ; width of the beginning of reduction = 5.00 (m)

B_2 ; width of the end of reduction = 2.00 (m)

θ ; angle of reduction = 46.40°

iii) Headrace

* Head Loss by Inflow to Headrace

$$he = fe \cdot V_2^2/2g$$

he ; inflow head loss (m)

fe ; inflow loss coefficient = 0.10 (circle with round edge)

D ; diameter of headrace = 2.00 (m)

V_2 ; water velocity after inflow (m/s)

* Head Loss by Friction of Headrace

$$hf = f \cdot L/D \cdot V^2/2g$$

hf ; friction head loss (m)

f ; friction loss coefficient = $124.5 \cdot n^2/D^{1/3}$

n ; 0.013 (coefficient of roughness)

L ; length of headrace (m)

D ; diameter of headrace = 2.00 m

V ; water velocity inside headrace (m/s)

iv) Penstock

* Head Loss by Friction of Penstock

$$hf = f \cdot L/D \cdot V^2/2g$$

hf ; friction head loss (m)

f ; friction loss coefficient = $124.5 \cdot n^2/D^{1/3}$

n ; coefficient of roughness

n_1 ; 0.011 (FRP pipe)

n_2 ; 0.012 (steel pipe)

L ; length of penstock (m)

D ; diameter of penstock (m)

V ; water velocity inside penstock (m/s)

* Head Loss by Branching of Penstock

$$h_B = f_B \cdot V^2/2g$$

h_B ; branching head loss (m)

f_B ; branching loss coefficient = 0.50

D ; diameter of penstock before branching (m)

V ; water velocity inside penstock before branching (m/s)

* Head Loss by Curvature of Penstock

$$h_b = f_{b1} \cdot f_{b2} \cdot V^2/2g$$

h_b ; head loss by curvature (m)

f_b ; curvature loss coefficient

$f_{b1} = 0.131 + 0.1632 \times (D/\rho)^{3.5}$

$f_{b2} = (\theta/90°)^{0.5}$

D ; diameter of penstock (m)

ρ ; radius of curvature of penstock (m)

θ ; intersection angle of curve (°)

V ; water velocity inside penstock (m/s)

* Head Loss by a Valve on Penstock

$$h_v = f_v \cdot V^2/2g$$

h_v ; head loss caused by valve (m)

f_B ; valve loss coefficient = t/d = 0.10

D ; diameter of penstock before valve (m)

V ; water velocity inside penstock before valve (m/s)

(c) Total Head Loss

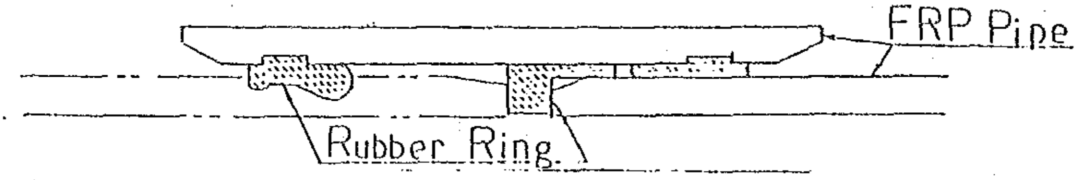
Total Head Loss

(in: m)

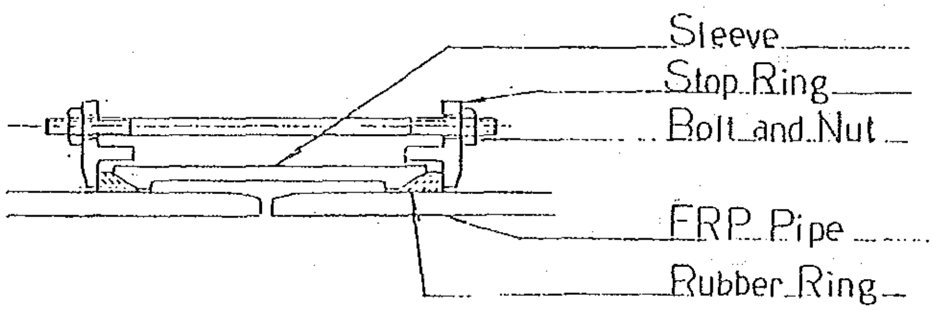
Case	(1)	(2)	(3)
Q (m^3/s)	1.6	4.8	4.8
(Q')	1.6	1.6	3.2
(1) Intake			
Inflow	0.002	0.017	0.017
Pipe Screen	0.001	0.006	0.006
Screen	0.000	0.002	0.002
Sub Total	0.003	0.025	0.025
(2) Sand Stilling Basin			
Screen	0.000	0.004	0.004
Reduction	0.000	0.000	0.000
Sub Total	0.000	0.004	0.004
(3) Headrace			
Inflow	0.001	0.012	0.012
Friction	0.043	0.391	0.391
Sub Total	0.045	0.403	0.403
Others	0.052	0.068	0.068
Total	0.100	0.500	0.500
(4) Penstock			
Friction	2.220	2.244	2.498
Branch	0.161	0.221	0.349
Curvature	0.195	0.205	0.287
Valve	0.085	0.085	0.067
Others	0.439	0.545	0.599
Sub Total	3.100	3.300	3.800
Total	3.200	3.800	4.300

A5.14 Structures of T Type Joint (1 Type) and Sleeve Joint

FPR JOINT (FRP－FRP / FRP－STEEL)



SLEEVE JOINT



JICA