THE STUDY ON INTRODUCTION OF RENEWABLE ENERGIES IN RURAL AREAS IN MYANMAR

FINAL REPORT

Volume 6 Supporting Report
Appendices to Manuals

Part 6-1	Appendices to O&M Manual-Small Hydros
Part 6-2	**Appendices to Design Manual-Small Hydros**
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Appendix 1   Nomograms

Appendix 1-1[*1]: Layout of Powerhouse for Small Hydroelectric Power Generation

The space of powerhouse of small hydroelectric power generation is determined according to each size of hydroelectric power plants and also is subject to the penstock and the conditions of powerhouse.

1. Fundamental Rules of Powerhouse Layout

Fundamental rules (guideline) to determine the powerhouse layout of small hydroelectric power generation are as follows:

(i) Such rooms as operation rooms, office rooms, etc. of operators are not necessary to be provided for hydroelectric power facilities under unmanned regular services, which are covered by this Technical Guideline.

(ii) Also, tool rooms, rooms of machine tool, storage rooms of spare parts , etc. are not necessary to be particularly provided due to utilisation of unused space of floor.

Those fundamental rules are aimed to reduce spaces for hydroelectric power facilities for improvement in economy.

- It is noted that the powerhouse does not need to include temporary spaces for assembling and dismantling of hydroelectric power plants due to utilisation of space outside the powerhouse.

2. Layout Plan

2.1 Basic Items of Layout Plan

(1) Locations of Facilities in Waterway

The layout plan is to be studied in due consideration to the locations and dimensions of the penstock and the tailrace. Even in the case when such locations and dimensions are not decided, temporary decisions for those locations and dimensions are indispensable for implementation of the layout plan and the temporary decisions which are to be reviewed according to the progress of layout plan.

A centerline of hydraulic turbine is determined based on the centerline of penstock line. In addition, such a layout as plan the powerhouse above the tailrace has to be avoided.

(2) Transportation Plan

The layout plans is to be studied in due considerations to the entrance of powerhouse and the transportation route of power plants as well, in particulars its width and its height. In the study, it is a principle that each of a turbine and a generator will be transported in assembled conditions.

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*1: Source from "Technical Guideline for Plan and Design of Steel Structures (Part of Small Hydroelectric Power Generation), Ministry of Agriculture, Forestry and Fisheries"

In the case of small hydroelectric power generation, allmost all hydraulic turbines and generators will not have so much different sizes for the both cases in assemling and disassembling conditions. Also, it is advised to avoid their transportation under the conditions of disassembling in view of quality control and economical procurement. The minimum disassembling unit of control equipment is at a board of equilment.

2.2 Arrangement Plan of Equipment

The procedure to arrange the equipment based on this guideline is to be in reference to Figure 1: Procedure to Proceed Layout Plan.

(1) Notes of Layout Plan

(i) It is desireable to take an allowance until the final determination of specifications.

(ii) It is necessary to implement the layout plan, taking into account the working space required for assembling, and maintenance and inspection. Even in the case of no specific descriptions in this guideline, it is indispensable to secure the space more than 800 – 1000 mm surounding hydroelectric equipment.

(iii) It is necessary to plan the plumbing (for oil, water, etc.) and the electrical wiring so as not intermingle the pipes and the electrical cables.

(iv) It is necessary to include the study of arrangement of exhaust ducts in the case when the cooling system of generators is based on the exit pipe ventilation system.

(2) Procedure to Proceed Layout Plan

Refer to Figure 1.

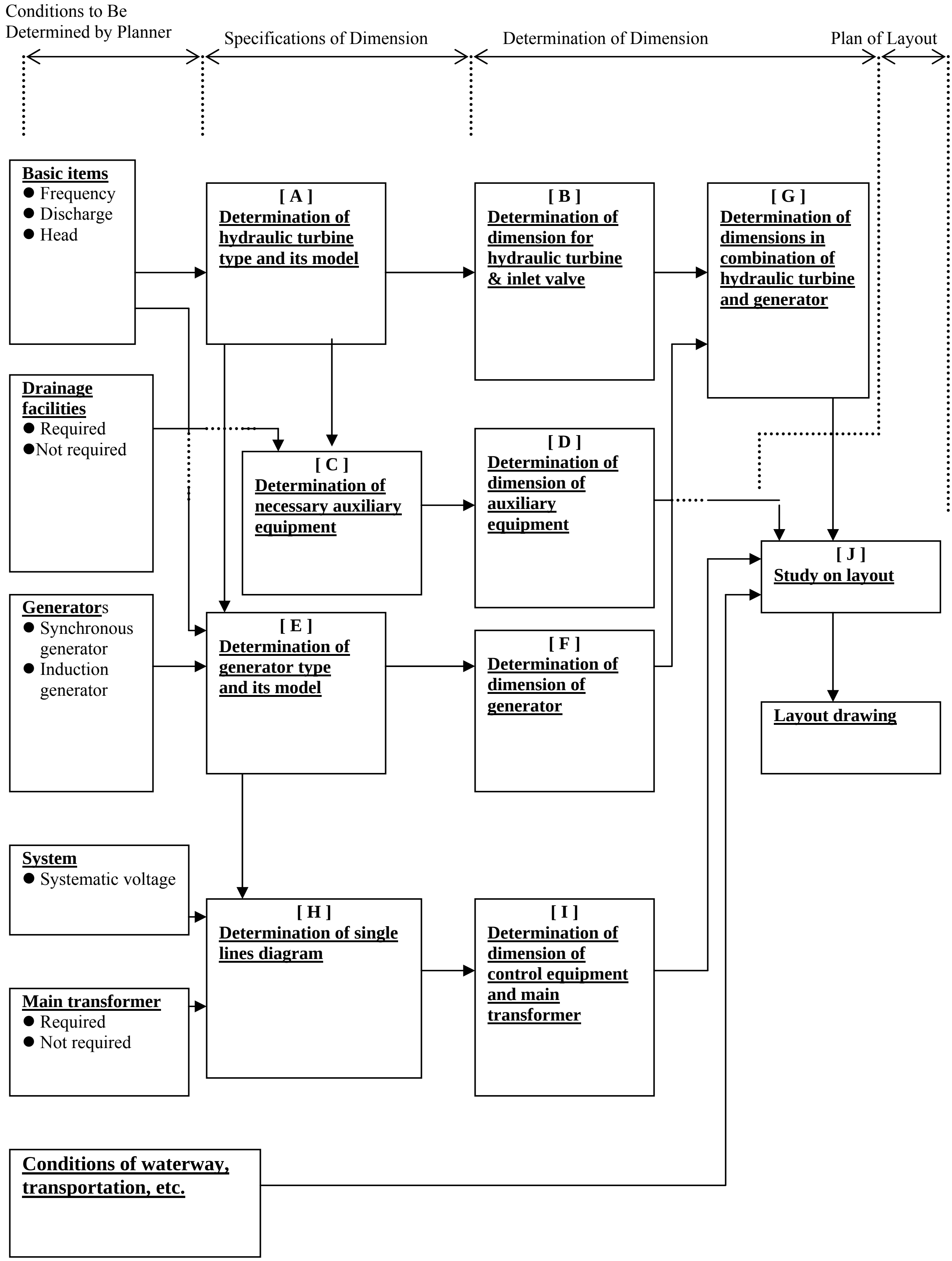


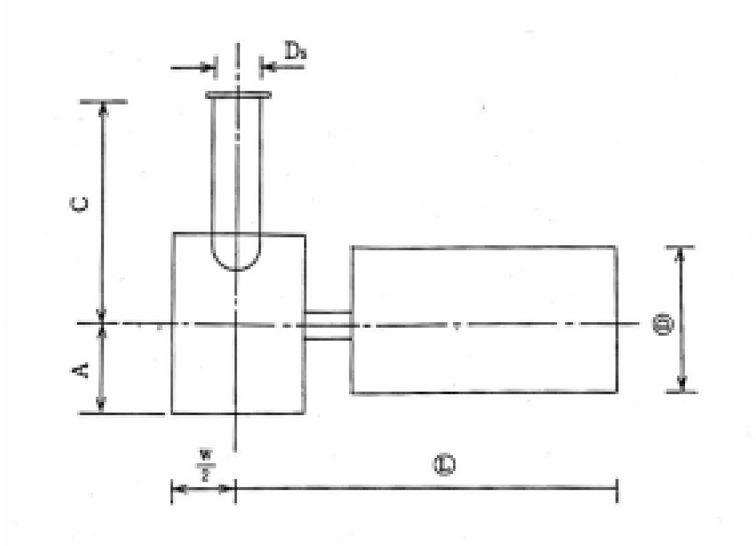
Figure 1 Procedure of Layout Planning

(3) Dimension of External Form in Combination of Hydraulic Turbine and Generator

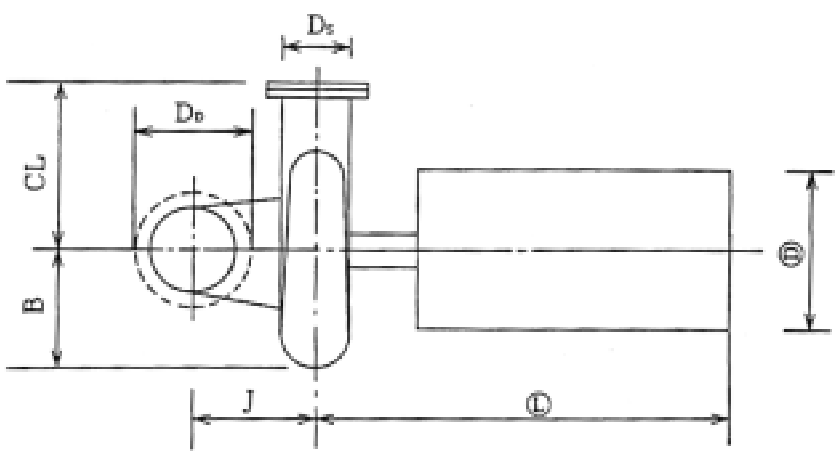
The dimension of the external form in combination of hydraulic turbines and generators is determined as follows, depending on the type of hydraulic turbines:

(Note: The marks of ❍ and △mean each dimension of a generator and a speed increaser respectively.)

(i) Pelton Turbine

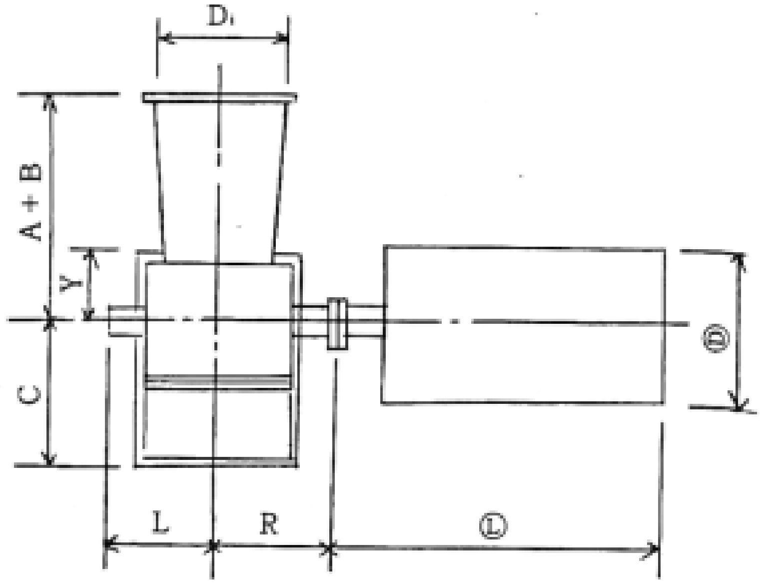


(ii) Francis Turbine

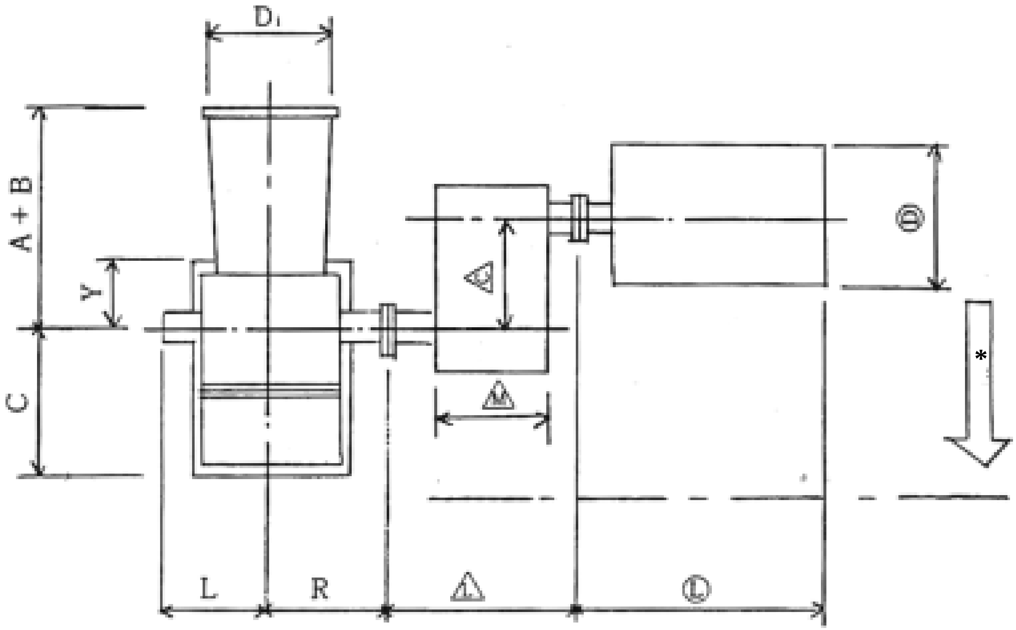


(iii) Crossflow Turbine

(iii-1) Direct Coupling of Turbine and Generator



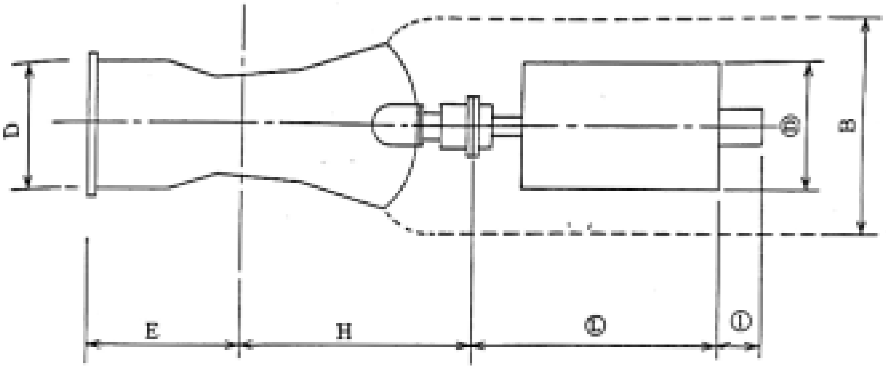
(iii-2) Gear Coupling to Increase Revolution Speed



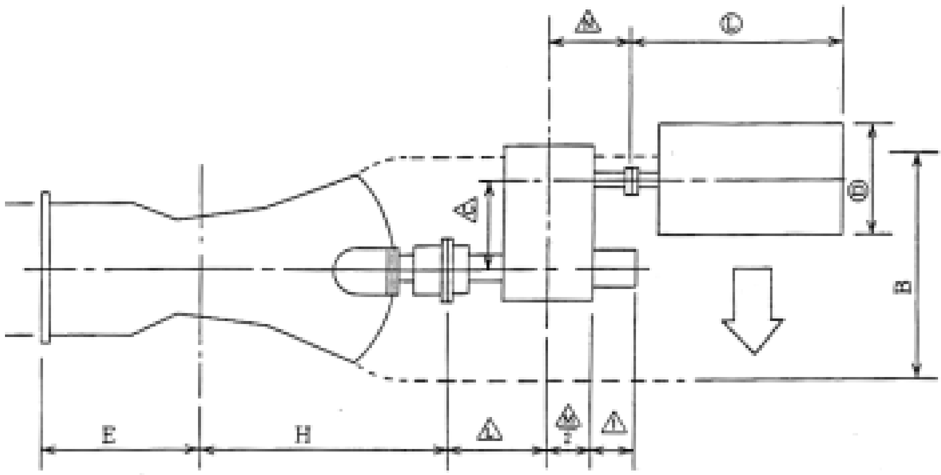
Note: ***** It is possible to arrange the generator on the opposite side.

(iv) S-type Unit

(iv-1) Direct Coupling of Turbine and Generator



(iv-2) Gear Coupling to Increase Revolution Speed



2.3 Example of Layout Plan

In the case of the following conditions, the layout plan is determined as follows based on the procedure shown in Figure 1:

[Assumed Conditions]

(a) Basic items:
Frequency: 50Hz, Maximum plant discharge: 1.0 m3/s, Effective head: 70.0 m(which is also for the maximum head and the rated head)

(b) Drainage facilities:
It is a condition that the drainage water in the powerhouse is able to be drained directly to the tailrace and consequently there is no need to provide pumping drainage facilities after the result of study on the water level conditions of hydraulic facilities and the flood water lecels.

(c) Generator type:
The powerhouse is located at the end point of the transmission line system and the synchronous generator is adopted based on the conditions of the transmission line system.

(d) Voltage of transmission:
To be connected to the 11 kV distributioon line.

(e) Main transformer:
To be provided with the main transformer in due consideration to its connection conditions with the transmission line system.

(f) Waterway/ transportation:
The powerhouse branches off from the facilities of water utilisation and the tailrace is connected with the river to return the used water to the river.

(g) Other condotions:
The powerhouse has an independent building with a surface type powerhouse and it has no externally restricted conditions.

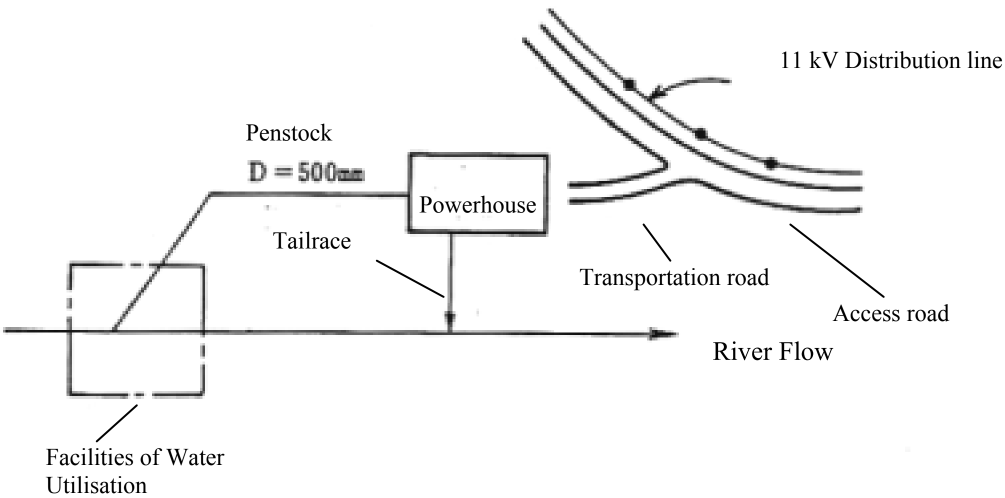
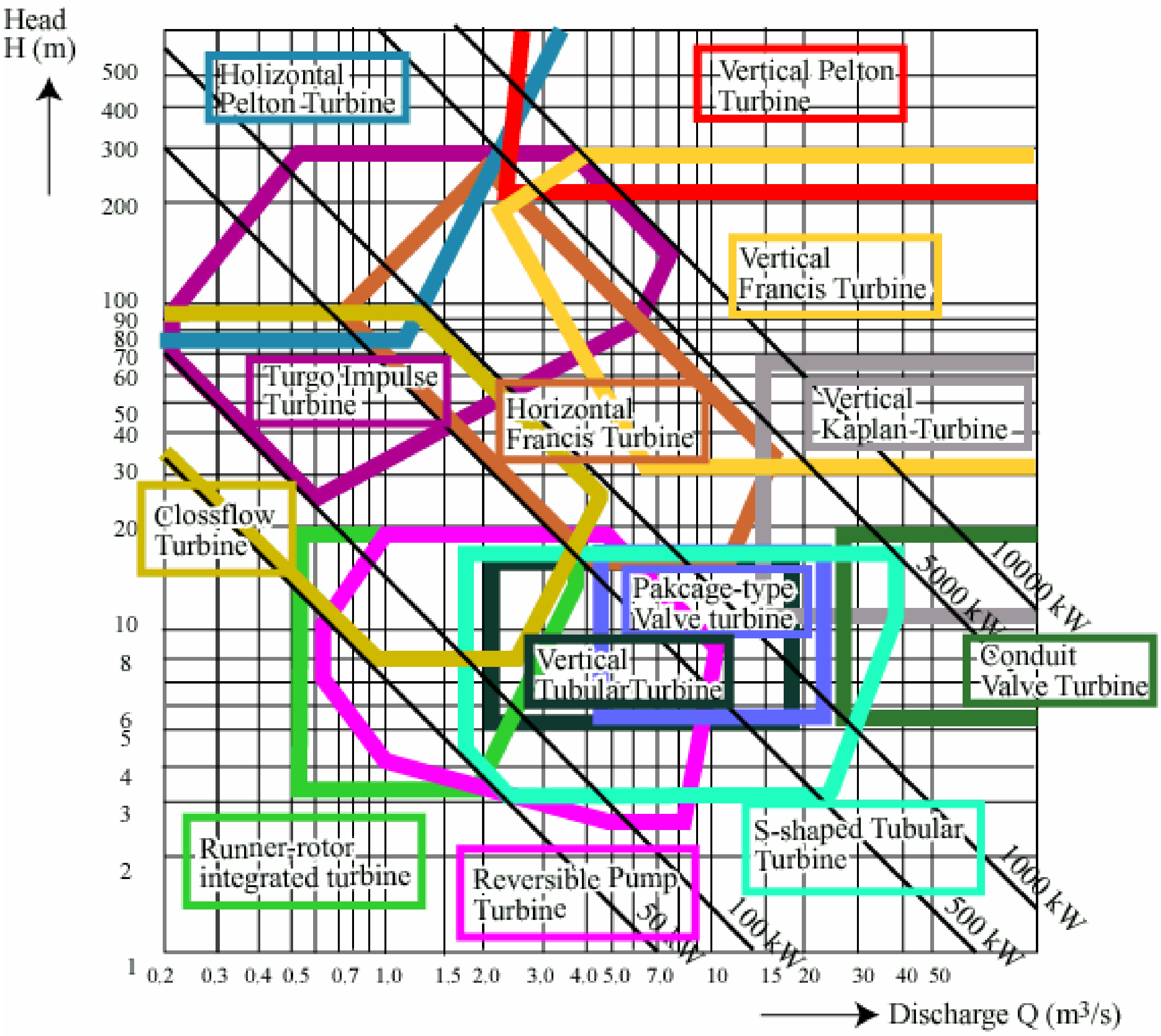


Figure 2 Concept for Location of Powerhouse

The layout is planned as follows in accordance with the descriptins in this guideline:

[A] Determination of Type and Model of Hydraulic Turbines

In reference to Figure 3 Selection of Hydraulic Turbine, it is clear that the applicable turbine is a horizontal Francis turbine or a cross flow turbine. In this example, the layout plan is prepared in application of a horizontal Francis turbine.

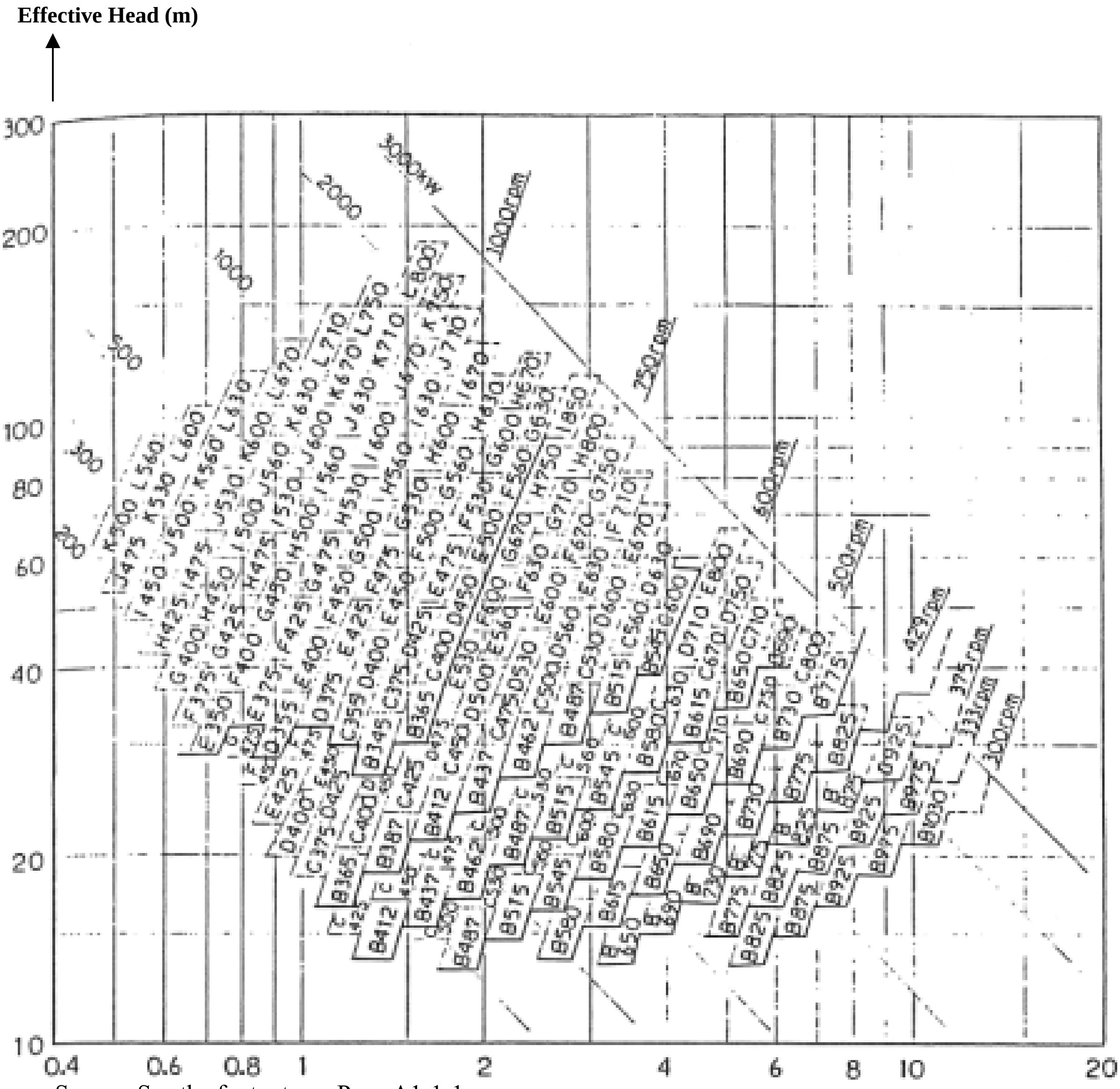


Source: JICA Study Team

Figure 3 Selection of Hydraulic Turbine

In reference to Figure 4: Selection of Horizontal Francis Turbine (50 Hz), the model of horizontal Francis turbine is decided to be ‘H500’ where is at the cross point of Q (= 1.0 m^3/s) and H (= 70.0 m).

Also, in reference to the same figure it is read that the turbine output is at about 550 kW and the rotation speed is at 1000 rpm.



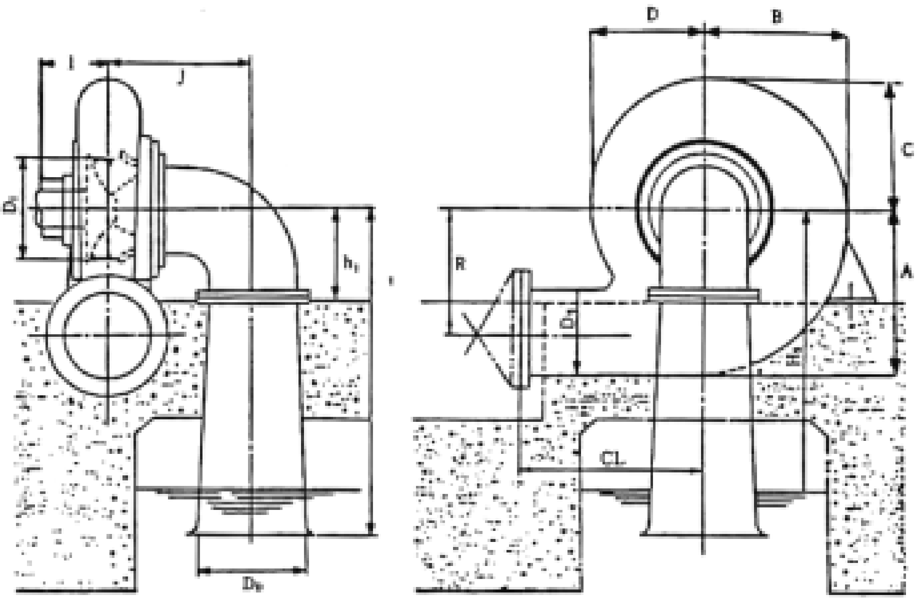
Source: See the footnote on Page A1-1-1.

Discharge Q (m^3/s)

Figure 4 Selection of Horizontal Francis Turbine

[B]	Determination of Dimensions of Hydraulic Turbine and Inlet Valve

The model of ‘H500’ means the diameter at 500 mm and accordingly each dimension of turbine is determined as follows in reference to Table A2.1.1-1:



$$D_1 = 1000 \times \frac{500}{1000} = 500 \qquad A = 1820 \times \frac{500}{1000} = 910$$

$$B = 1710 \times \frac{500}{1000} = 855 \qquad C = 1560 \times \frac{500}{1000} = 780$$

$$D = 1380 \times \frac{500}{1000} = 690 \qquad R = 1390 \times \frac{500}{1000} = 695$$

$$D_S = 930 \times \frac{500}{1000} = 465 \qquad h_1 = 1310 \times \frac{500}{1000} = 655$$

$$H = 4810 \times \frac{500}{1000} = 2405 \qquad J = 2160 \times \frac{500}{1000} = 1080$$

$$CL = 3250 \times \frac{500}{1000} = 1625 \qquad D_D = 1870 \times \frac{500}{1000} = 935$$

Figure 5 Approximate Dimension of Each Portion

Table 1 Coefficients*1 for Approximate Dimension of Horizontal Turbine

Symbol / n_s / Dimension	B	C	D	E	F	G	H	I	J	K	L
	266	236	209	186	165	146	130	115	102	90	80
D_1	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000
A	2880	2620	2420	2220	2060	1960	1820	1710	1640	1560	1450
B	2600	2390	2210	2040	1920	1830	1710	1600	1540	1470	1430
C	2320	2160	2010	1850	1740	1670	1560	1470	1420	1360	1320
D	2000	1860	1730	1610	1520	1470	1380	1300	1270	1220	1190
R	2090	1880	1730	1630	1530	1460	1390	1290	1250	1200	1180
Ds	1630	1500	1350	1230	1110	1010	930	840	770	720	700
h_1	1800	1630	1550	1490	1410	1360	1310	1260	1230	1200	1180
H	7100	6800	6480	5970	5540	5140	4810	4520	4350	4040	3830
J	3280	3130	2910	2600	2540	2440	2160	2030	1850	1740	1640
CL	3600	3500	3460	3390	3340	3290	3250	3200	3180	3160	3160
D_D	2730	2640	2510	2320	2150	1990	1870	1750	1690	1570	1360
ℓ*2	0.93 ~ 1.39	1.07 ~ 1.36	1.03 ~1.36	1.06 ~ 1.36	1.02 ~ 1.27	1.00 ~1.27	0.97 ~0.18	0.99 ~1.18	0.95 ~1.11	0.90 ~1.05	0.90 ~ 1.00

Source: See the footnote on Page A1-1-1.

Note: *1: The coefficient means a coefficient relevant to determination on the dimension of each portion of turbine in the case of the diameter of inlet of Runner = 1000 mm.

*2: The dimension of ‘ℓ’ is shown with a proportion to the diameter of runner: D_1 inclusive of the min. one and the max. one in due consideration to some range of rotation speed.

The butterfly valve is selected in this case in reference to Table 2. Following the precedents, the diameter of inlet valve (Dv) is in $1.1D_s$ ~ $1.2D_s$.

Accordingly, it is calculated as follows: Dv = 1.1 x 465 ~ 1.2 x 465 = 510 ~ 560 mm. However, taking into account the condition that the diameter of penstock is 500 mm in reference to Figure 2, Dv is selected at 500 mm and the inlet valve is determined as shown in Figure 4.

Table 2 Type of Inlet Valve

Type of Valve	Applicable Head	Seal Method	Head Loss
(i) Butterfly valve	Less than 150 m	Rubber seal is generally applied for the valve body.	Slightly large
(ii) Double leaves valve	Less than 200 m	Rubber seal is generally applied for the valve body.	Middle
(iii) Partition valve	Less than 200 m	Metal seal is applied for the valve body.	Small

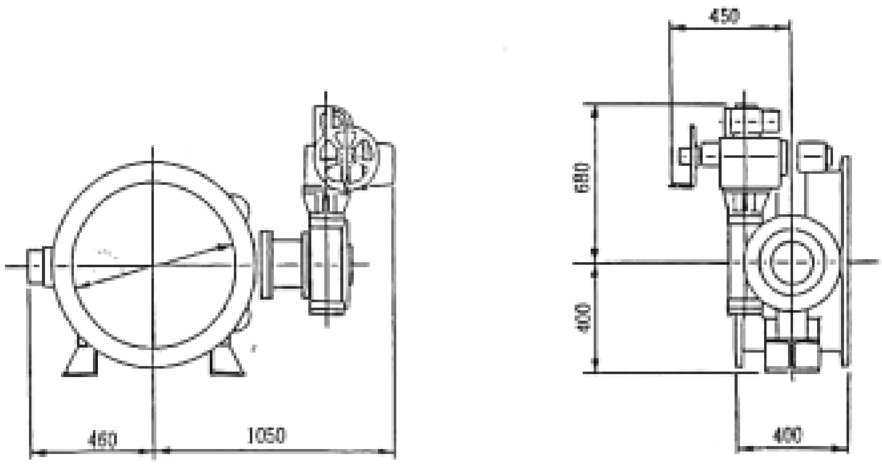


Figure 6 Dimension of Inlet Valve (unit: mm)

[C] Determination of Necessary Auxiliary Equipment

There are oil pressure supply systems, lubricating oil system, plumbing equipment, etc. as auxiliary equipment of hydraulic turbines and generators and such necessary auxiliary equipment are determined as follows:

(i) In respect of the oil pressure supply system, it is a principle to use an electric motor-driven type servomotor and an electric motor-driven type inlet valve except S-type units, accordingly it is not necessary to use auxiliary equipment.

(ii) As to the lubricating oil system, it is a principle to use a self-feeding system as much as possible. In the case of the location for this example, it is considered possible to apply a self-feeding thrust bearing, and accordingly the layout plan is proceeded under the condition of no need of lubricating oil systems.

It is noted that the application of self-feeding thrust bearing is not always general and therefore it will be necessary to re-consider the application of self-feeding thrust bearing according to the progress of the layout plan.

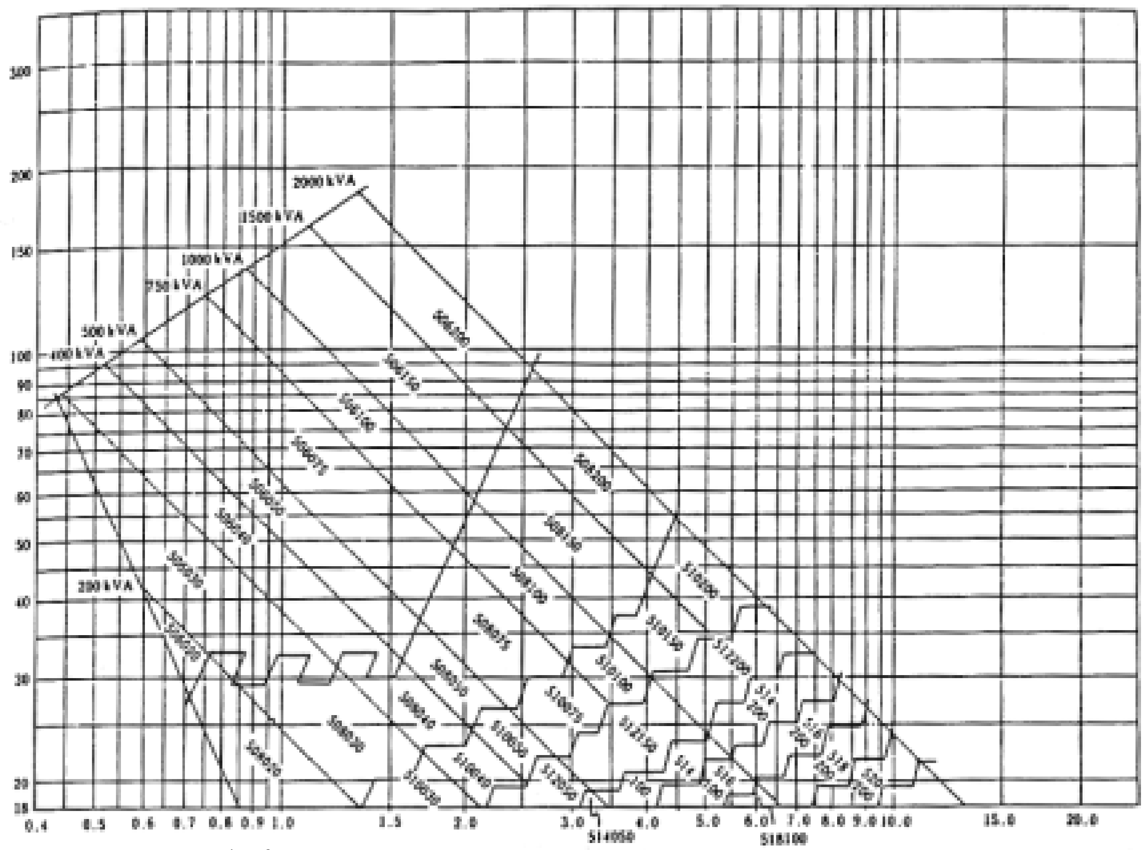
(iii) As to the drainage system of plumbing equipment, the application of the drainage system is not necessary as decided in [Assumed Conditions]. On the other hand, the water supply system is necessary for sealing of spindle units and cooling for lubricating oil of bearing as well in the case of the horizontal Francis turbines. In the case of the location for this example, assuming that the head is rather high and the water quality is good, it is determined to apply the direct water intake from penstock.

[D] Determination of Dimension for Necessary Auxiliary Equipment

Based on the result of the study above in [C] Determination of Necessary Auxiliary Equipment, it is concluded that only the water supply system is required as an auxiliary equipment and its method is the direct water intake from penstock. Acoordingly, such an auxiliary equipment of water supply system is provided in the pit of inlet valve. In this case, it is necessary to proceed the layout plan in consideration of such conditions as application of a manual atraner or a slf-feeding strainer, etc. and consequently the necessary space is subject to the conditions. However, an appropriate space is prepared for the overall layout plan as it is too hard to study such conditions in this example.

[E] Determination of Generator Type and Its Model

As assumed in [Assumed Conditions], the generator is a synchronous generator. In reference to Figure 7: Selection of Synchronous Generator for Horizontal Francis Turbine (50 Hz), the generator model is decided to be 'model 506075' from the cross point by H = 70 m and Q = 1.0 m^3/s. It is noted that in the case of the horizontal turbine, the turbine is directly connected with the generator and therefore it is not necessary to study the necessity of auxiliary equipment. Also, it is clear that the capacity of generator is at about 560 kVA.

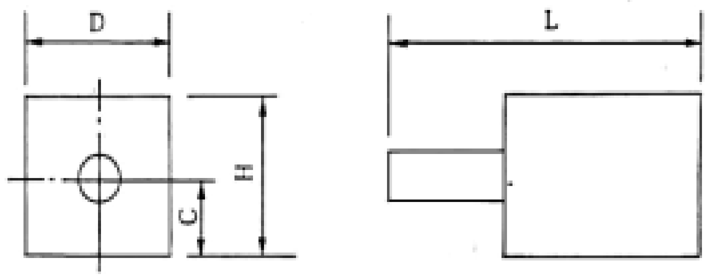


Source: See the footnote on Page A1-1-1.

Figure7 Selection of Synchronous Generator for Horizontal Francis Turbine (50 Hz)

[F] Determination of Dimension of Generator

In reference to Table 3, the dimension of generator for the model: 506075 is determined as follows:



D = 1300 C = 400 H = 950 L = 3120

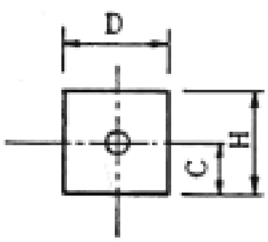
Figure 8 Dimension of Generator

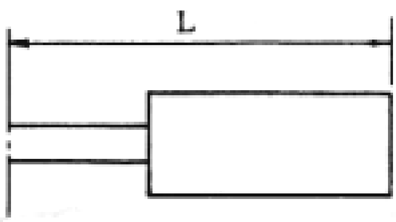
Table 3 Determination of Approximate Dimension and Approximate Weight for Synchronous Generator (50 Hz) in The Case of Francis Turbine Use

	Model Number	Weight (kg)	D	H	C	L	Pull-out Dimension*
1	506020	1700	770	1010	375	2250	
2	506030	2100	850	1010	425	2530	
3	506040	2550	900	1080	425	2800	
4	506050	3400	1150	1080	450	2930	
5	506075	4100	1300	950	400	3120	
6	506100	5100	1300	1200	450	3660	
7	506150	5670	1140	1130	450	3860	
8	506200	7080	1350	1200	450	3990	
9	508020	2700	850	1010	425	2530	
10	508030	3400	1060	1010	490	2680	
11	508040	4100	1150	1130	540	2970	
12	508050	4300	1140	1130	540	3510	
13	508075	5000	1300	1200	450	3730	
14	508100	6240	1500	1270	450	3940	
15	508150	7600	1650	1510	560	4030	
16	508200	8240	1650	1510	560	4180	
17	510020	2800	900	1010	450	2600	
18	510030	3400	1150	1010	490	2780	
19	510040	4500	1140	1130	540	3530	
20	510050	5400	1350	1240	600	3710	
21	510075	5900	1500	1270	450	3840	
22	510100	7280	1650	1510	560	3960	
23	510150	8270	1700	1450	560	4060	2350
24	510200	9570	2000	1610	560	4110	2400
25	510250	6100	1500	1370	560	3880	
26	512100	8320	2200	1770	560	4110	2250
27	512200	11250	2500	1720	560	4430	2400
28	514050	5800	1700	1450	500	3650	1950
29	514100	9050	2200	1770	560	3980	2350
30	514200	13100	2500	1720	560	4530	2550
31	516100	9830	2200	1770	560	4060	2400
32	516200	13750	2500	1720	560	4600	2600
33	518100	10950	2500	1720	560	4360	2400
34	518200	15400	2590	1800	560	4660	2600
35	520200	16050	2590	1800	560	4720	2650

Note:
* : The type of generator is a pedestal type in the case of provision of figures in this column. In the case of no provision of figures in this column the type of generator is a bracket type.

Source: See the footnote on Page A1-1-1.





Center Line of Turbine

[G] Determination of Dimension of Unit in Combination of Both of Hydraulic Turbine and Generator

In reference to [B] and [F], the dimension in combination of both of the hydraulic turbine and the generator is determined as follows:

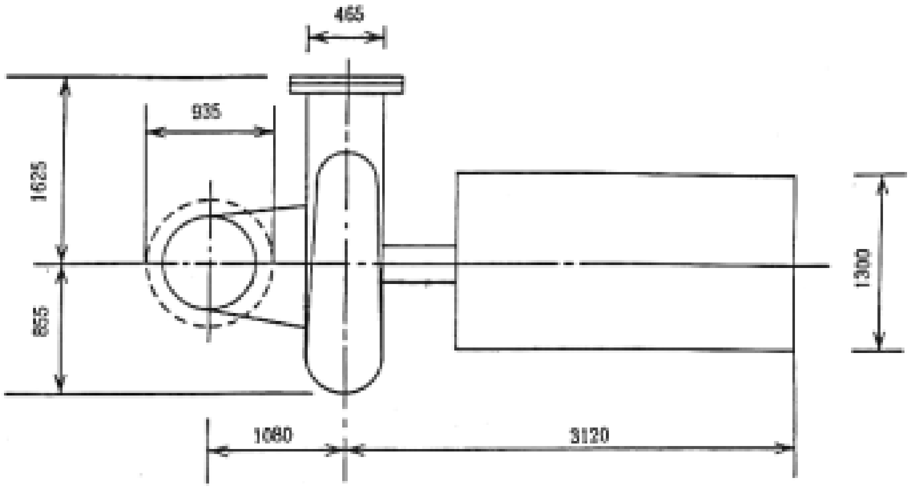


Figure 9 Dimension of Unit in Combination of Both of Hydraulic Turbine and Generator

[H] Determination of Single Line Diagram

According to [Assumed Conditions] described in the above, the generator is a synchronous generator and it is decided to apply a main transformer. Consequently, the single line diagram is as shown in Figure 10.

[I] Determination of Dimension of Control Equipment and Main Transformer

The dimension of control equipment panel and main transformer is determined as shown in Figure 11 by use of the standard control equipment panel. It is noted that the direct current power source is to be provided and its dimension is $^{W}900$ x $^{H}2350$ x $^{D}1200$ (mm).

As the provision of electric motor-driven type servomotor is decided, the size of speed governor is $^{W}700$ x $^{H}1950$ x $^{D}700$ (mm). As to the remote monitoring control device, following the use of cyclic method, its dimension is determined as shown in Figure 12.

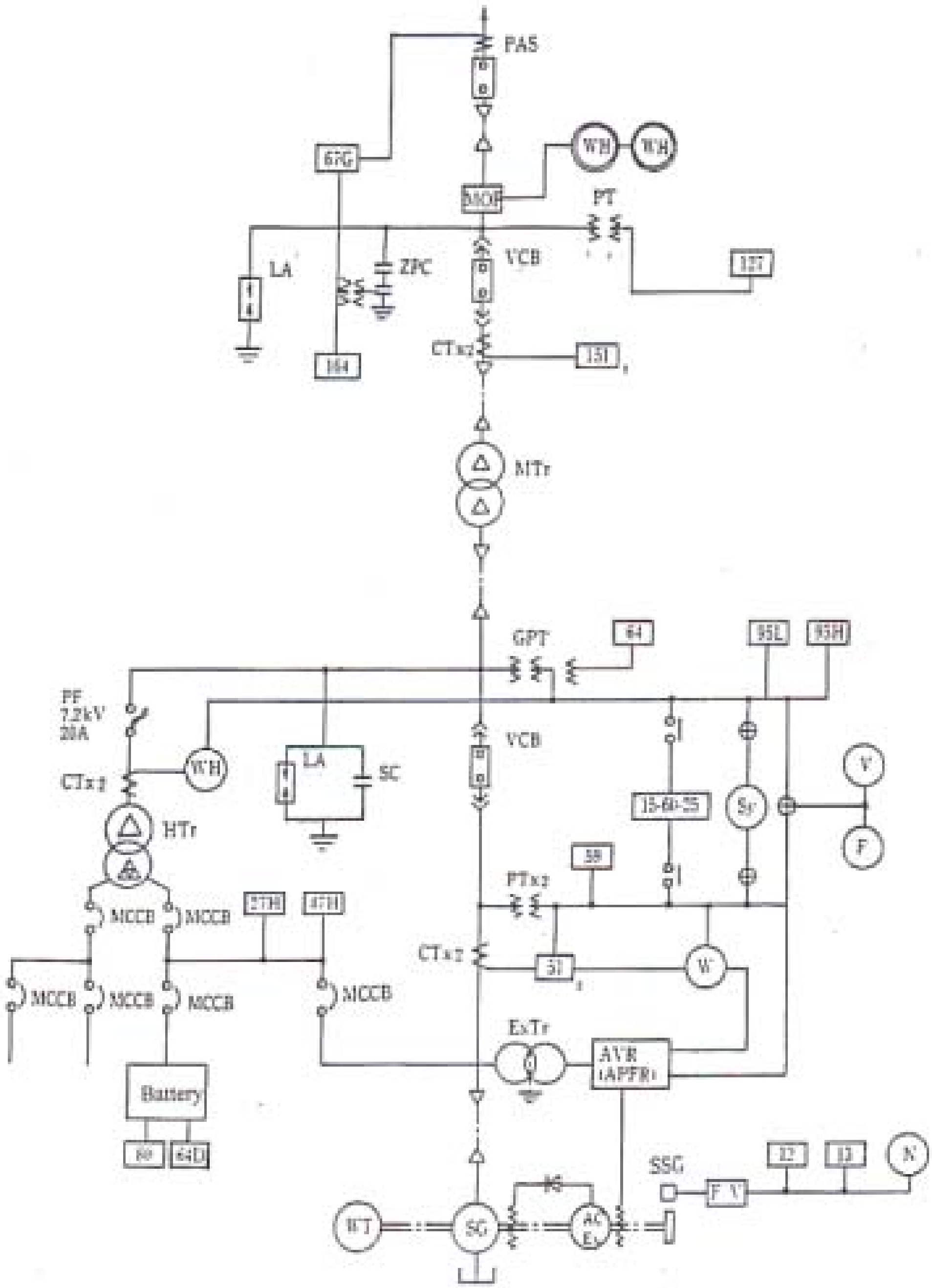
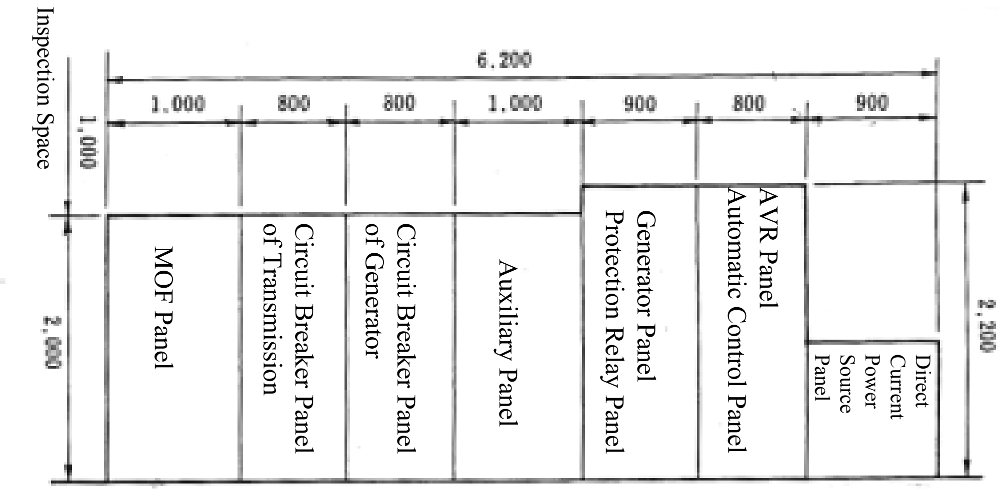
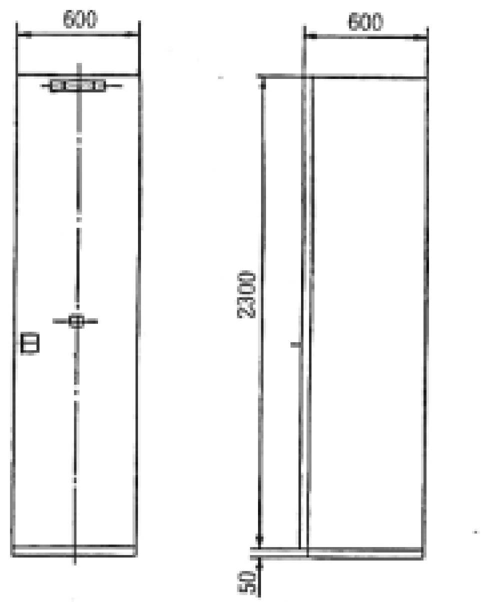


Figure 10 Single Line Diagram



Note: Panel height: 2,350 mm
Unit: mm

Figure 11 Dimension of Control Panel



Mobile Unit

Figure 12 Remote Monitoring Control Device

The power output of generator is estimated at about 560 kVA and accordingly it need the main transformer having capacity at 750 kVA (50 Hz) as shown in Figure 13, in reference to Table 4.

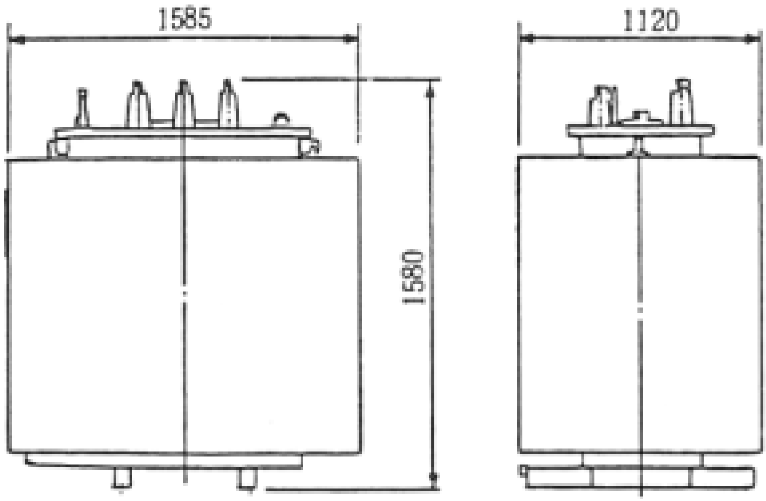


Figure 13 Dimension of Main Transformer

Table 4 Approximate Dimension and Approximate Weight of Oil Type Transformer (For 3 Phase 11 kV Class Transmission)

Capacity (kVA)	Frequency (Hz)	Approximate Dimension X	Approximate Dimension Y	Approximate Dimension Z	Appr. Weight (kg)
300	50	1325	850	1240	1250
	60				1250
500	50	1460	970	1410	1700
	60				1600
750	50	1585	1120	1580	2400
	60	1585	1075		2300
1000	50	1730	1270	1680	2850
	60	1770	1210		2700
1500	50	1975	1670	1855	4550
	60	1975	1610		4100
2000	50	2410	1680	1855	5500
	60				5400
2500	50	2410	2550	2550	5900
	60				5600

Source: See the footnote on Page A1-1-1.

[J] Determination of Layout Plan of Equipment

The layout plan of each equipment is determined, taking into account the results of study carried out in [A]~[I]. In this case, it is necessary to consider the basic items of layout plan described in 2.2 and the location relationship in Figure 2 as well, for the purpose of setting up the layout plan of equipment.

The following Figure 14 is a layout plan of equipment such a study as carried in the precedent sections. Each dimension of the layout plan for equipment is necessary for its finalization after considerations of the arrangement of auxiliary equipment, the dimension of powerhouse, etc.

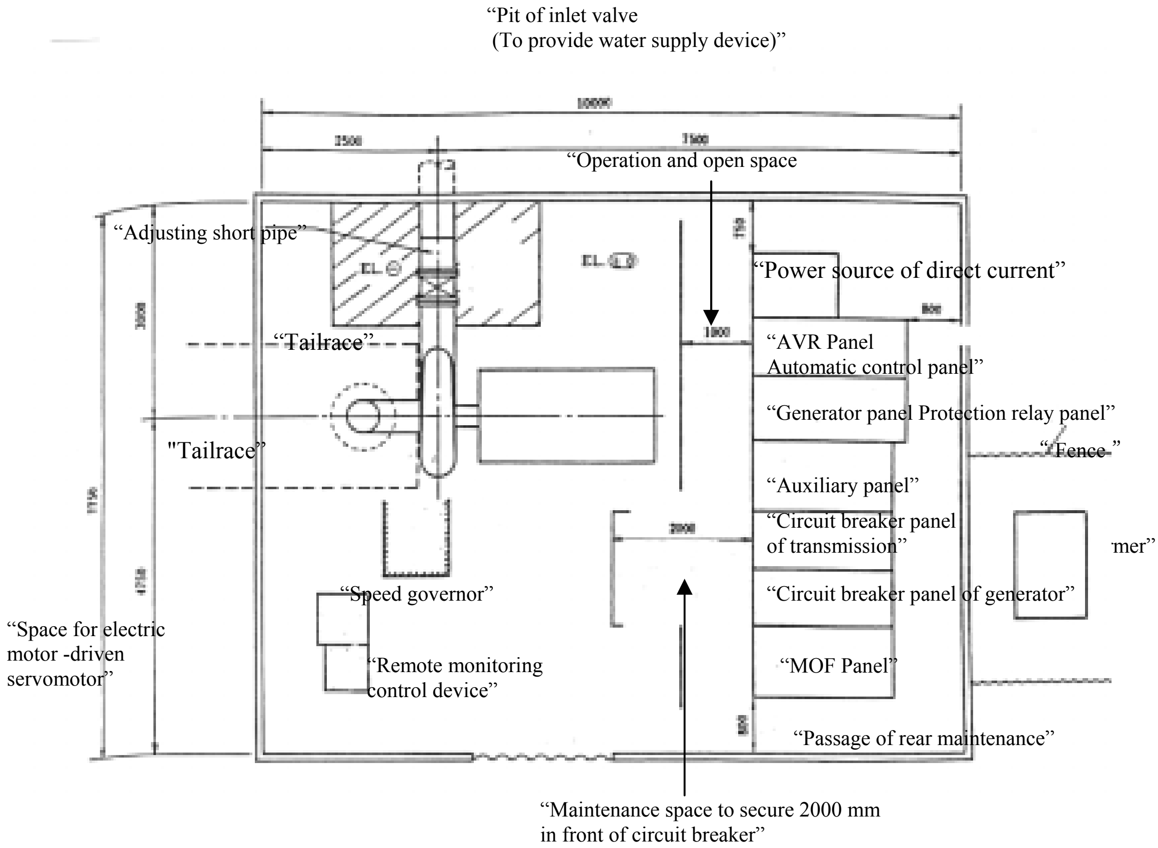


Figure 14 A Layout Plan of Equipment

In respect to the above figure, it is noted that;

(i) in the upstream of inlet valve, it is necessary to secure the space of welding between the penstock and the adjusting short pipe,

(ii) the length of adjusting short pipe is to be longer than the diameter of inlet valve,

(iii) the space of welding is to be more than 300 mm long, and

(iv) the adjusting short pipe is provided to adjust the installation errors which may occur in between the penstock and the inlet valve.

Appendix 1-2 Nomograms: Structural Analysis for Concrete Slabs

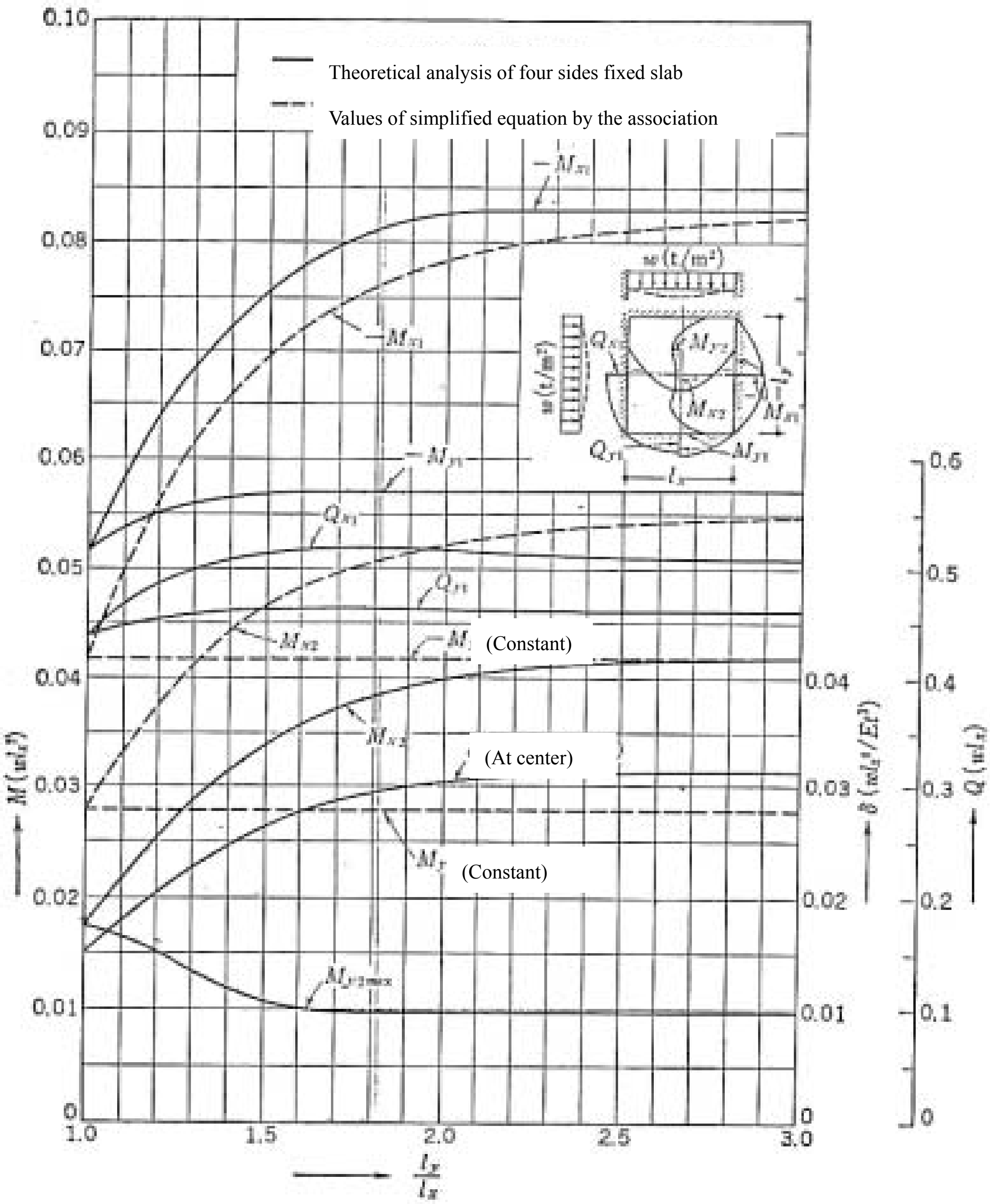


Figure 1 Stress Distribution of Slab Fixed along 4-Sides & Displacement δ[1]（v＝０） at Center of Slab against Uniformly Distributed Loads

Source: 1) Youich Azuma & Seiji Komori: Slab Structure, Vol.11 of 'Outline of Architectural Structure' Published by Shoukokusha, Nov.1970

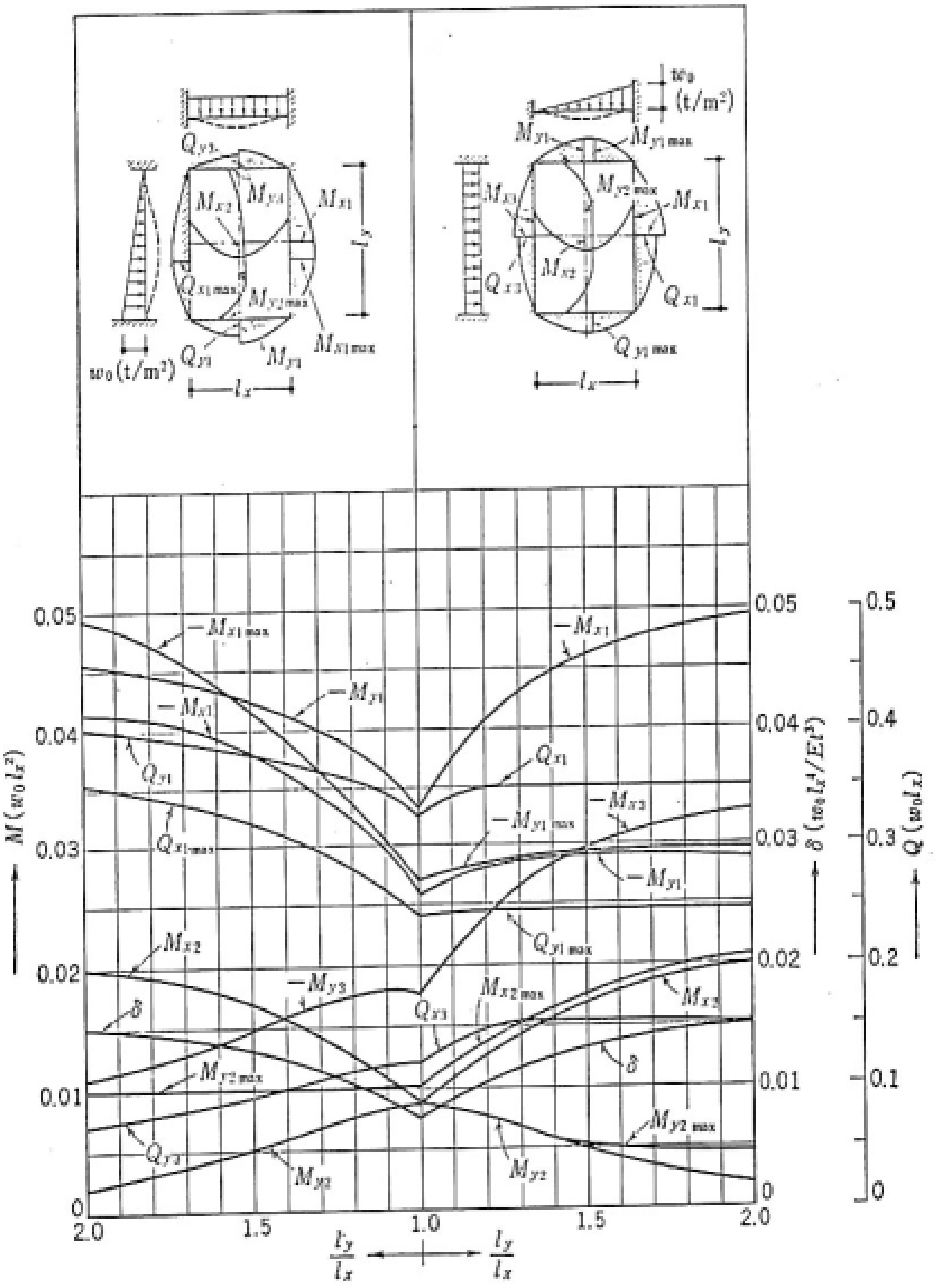


Figure 2 Stress Distribution of Slab Fixed along 4-Sides & Displacement δ[1] (ν= 0) at Center against Uniformly Distributed Loads

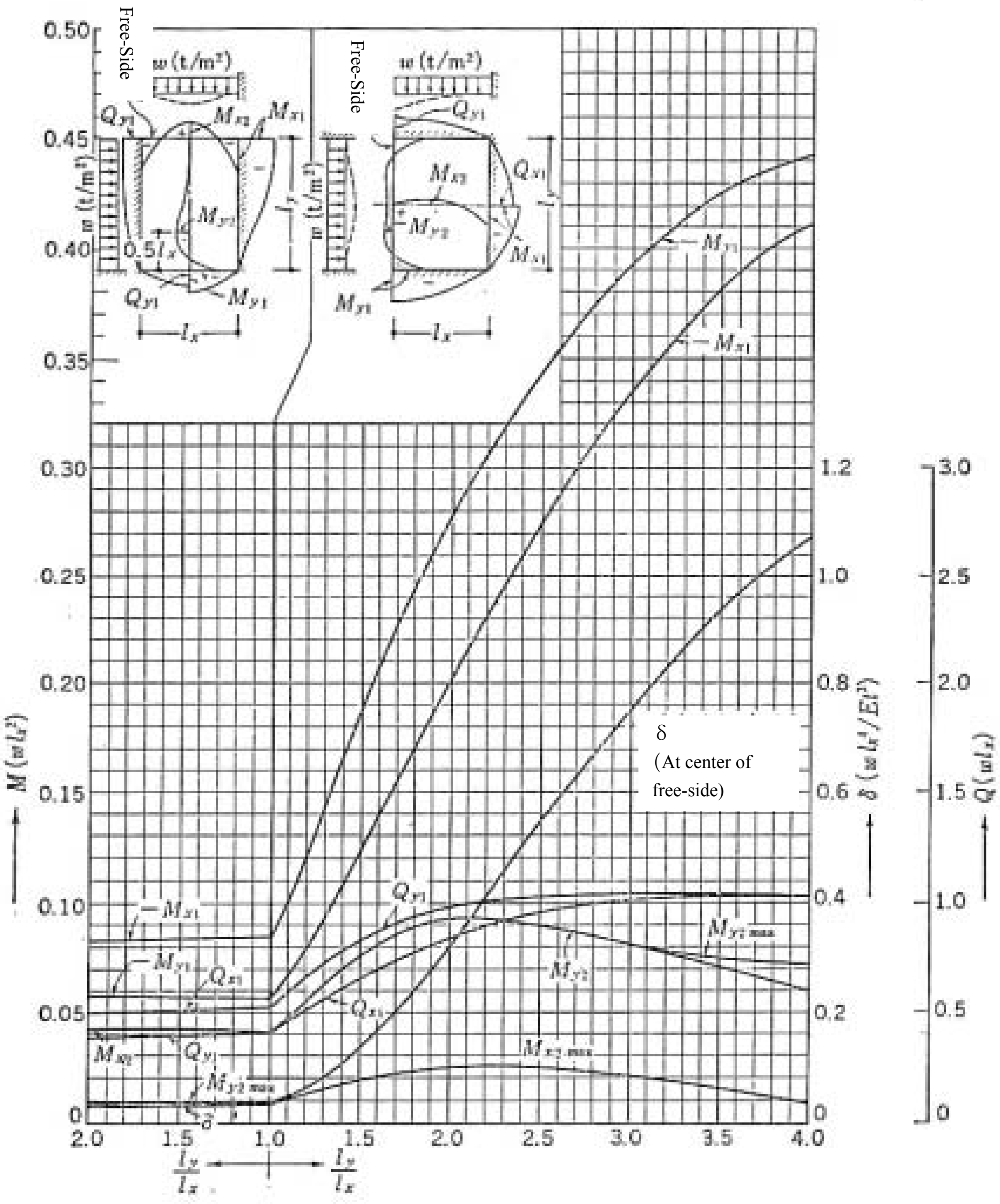


Figure 3 Stress Distribution of Slab Fixed along 3-Sides and Supported Freely along 1-Side & Displacement δ [1)]（v＝０） at Center of Slab against Uniformly Distributed Loads

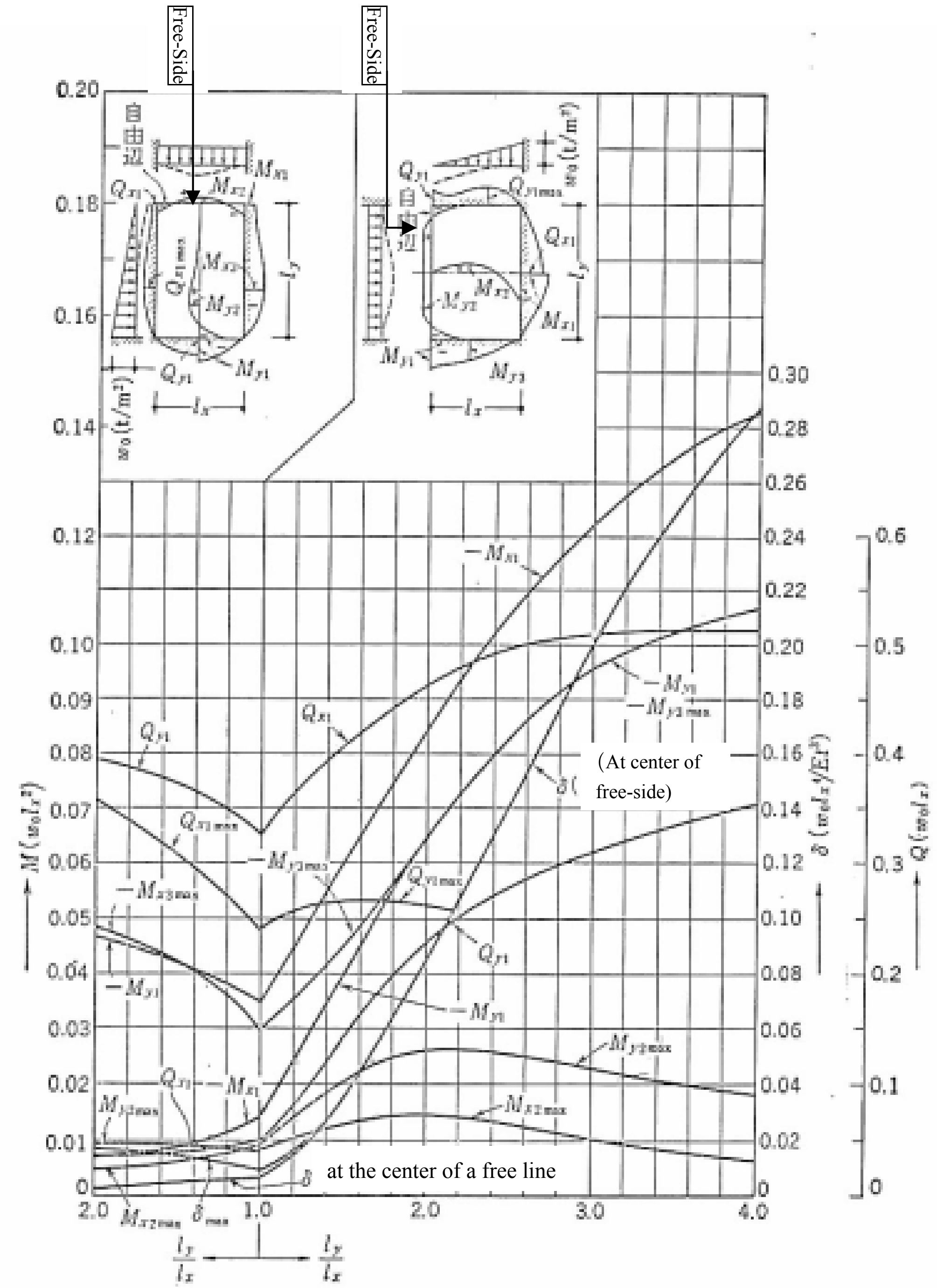


Figure 4 Stress Distribution of Slab Fixed along 3-Sides and Supported Freely along 1-Side against Uniformly Distributed Loads & Displacement δ[1]（v＝０）of Slab at Center of Slab

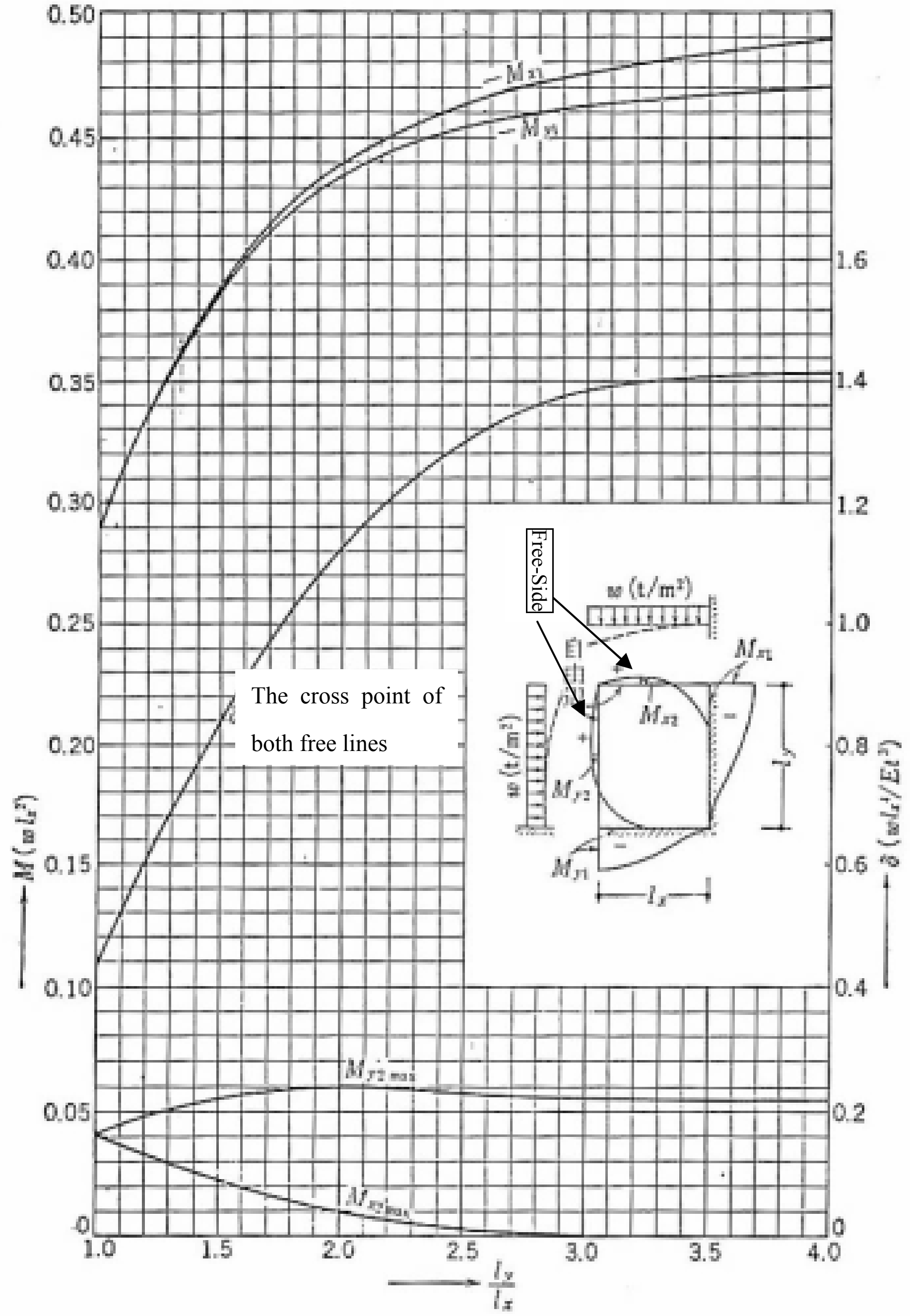


Figure 5 Stress Distribution of Slab Fixed along Neighboring 2-Sides and along Supported Freely along Other 2-Sides & Displacement δ[1)]（v=０） at Cross Point of 2-Sides Free against Uniformly Distributed Loads

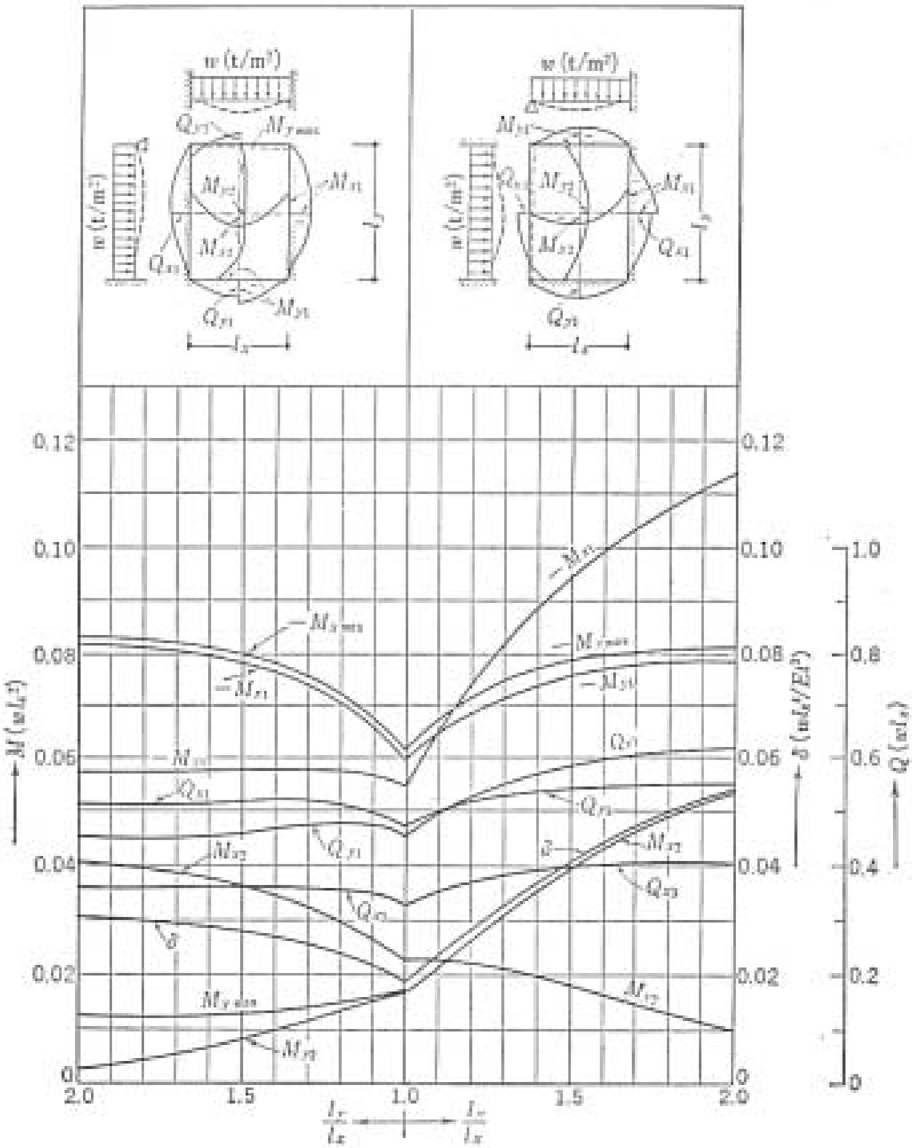


Figure 6 Stress Distribution & Displacement δ [1] (v＝0) at Center of Slab Fixed along 3-Sides and Simply Supported along 1-Side against Uniformly Distributed Loads

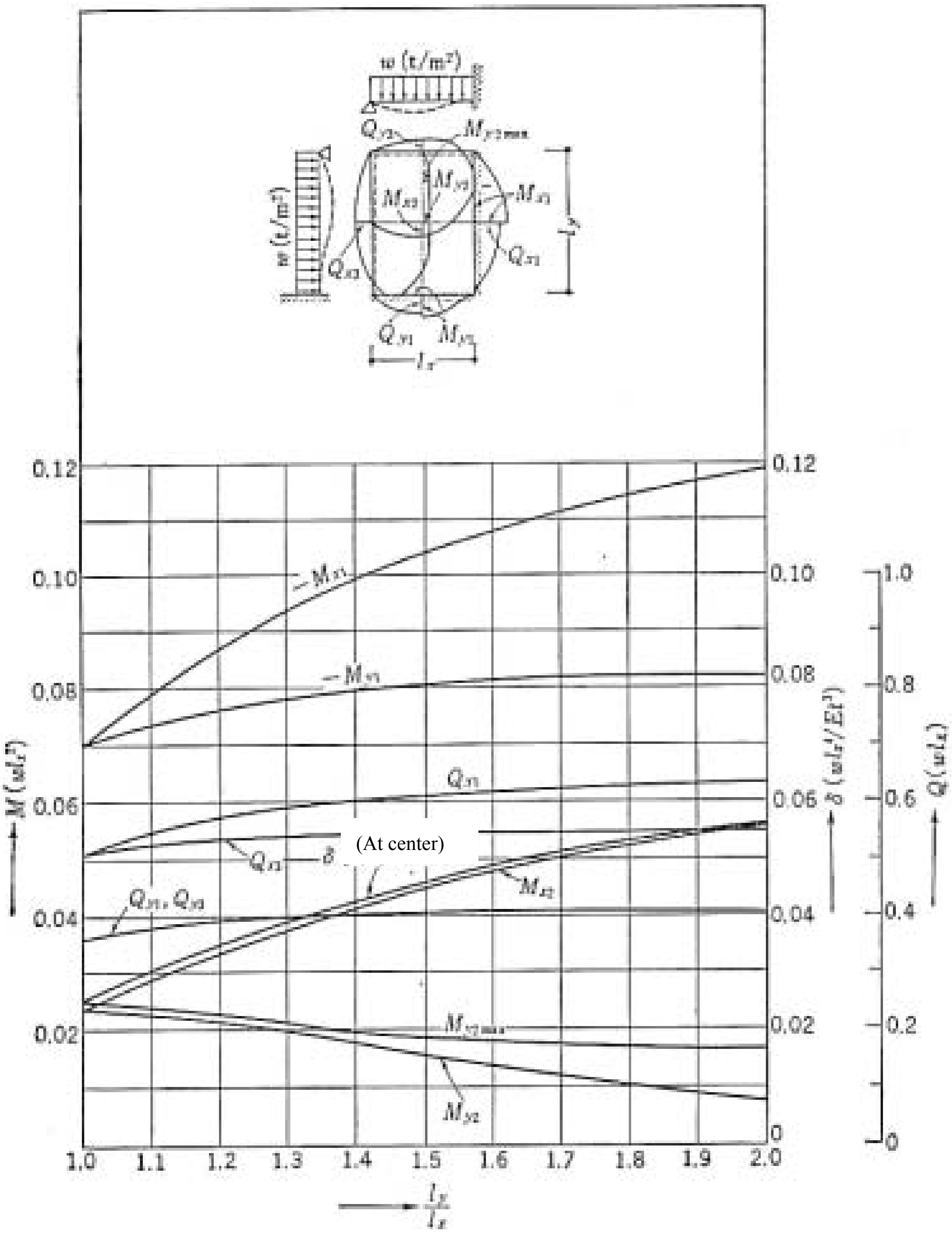


Figure 7 Stress Distribution of Slab Fixed along Neighboring 2-Sides and along Supported Simply along Other 2-Sides & Displacement δ [1] （ν＝０） at Center against Uniformly Distributed Loads

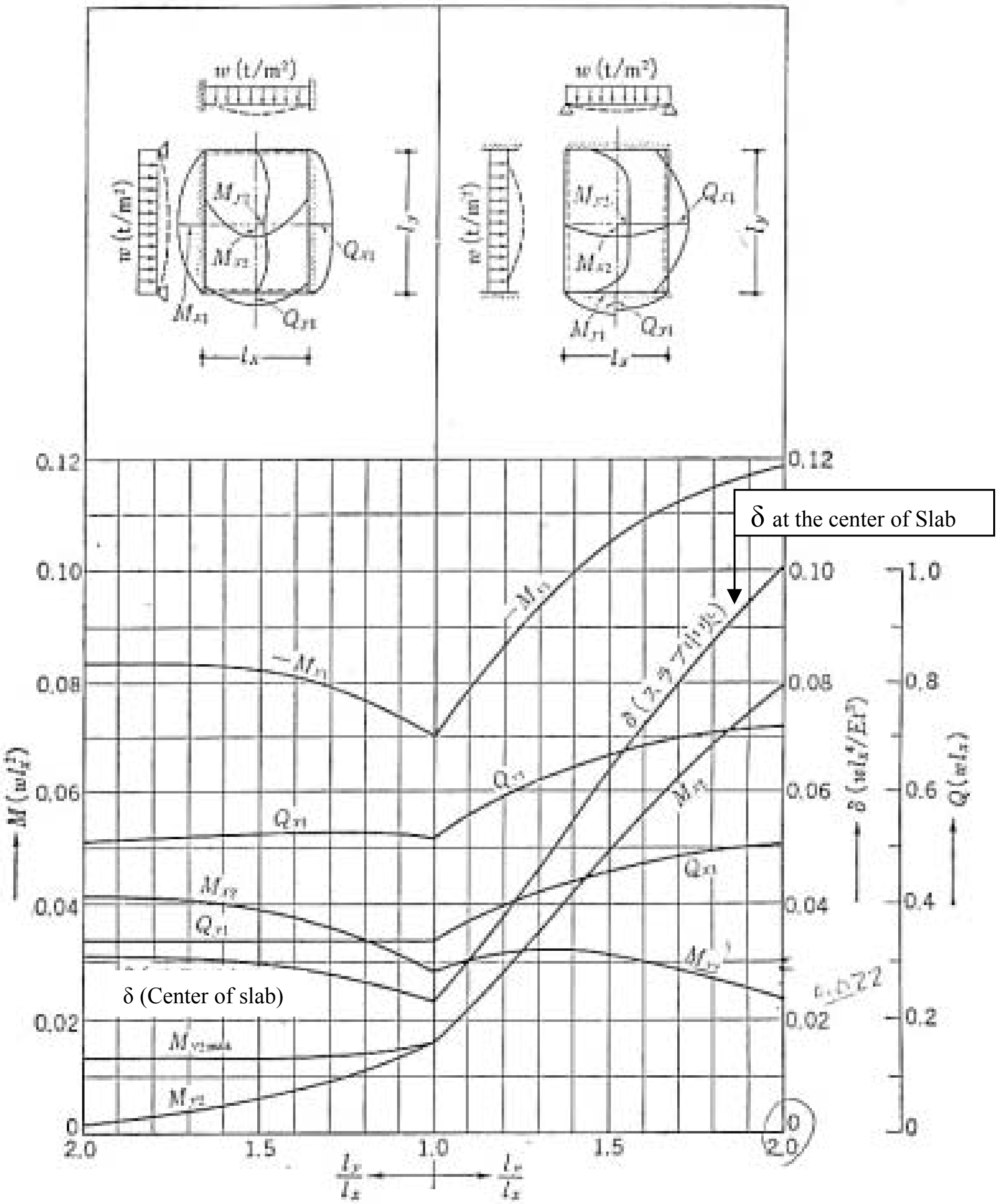


Figure 8 Stress Distribution of Slab Fixed along Facing 2-Sides and along Supported Simply along Other 2-Sides & Displacement δ [1] at Center against Uniformly Distributed Loads

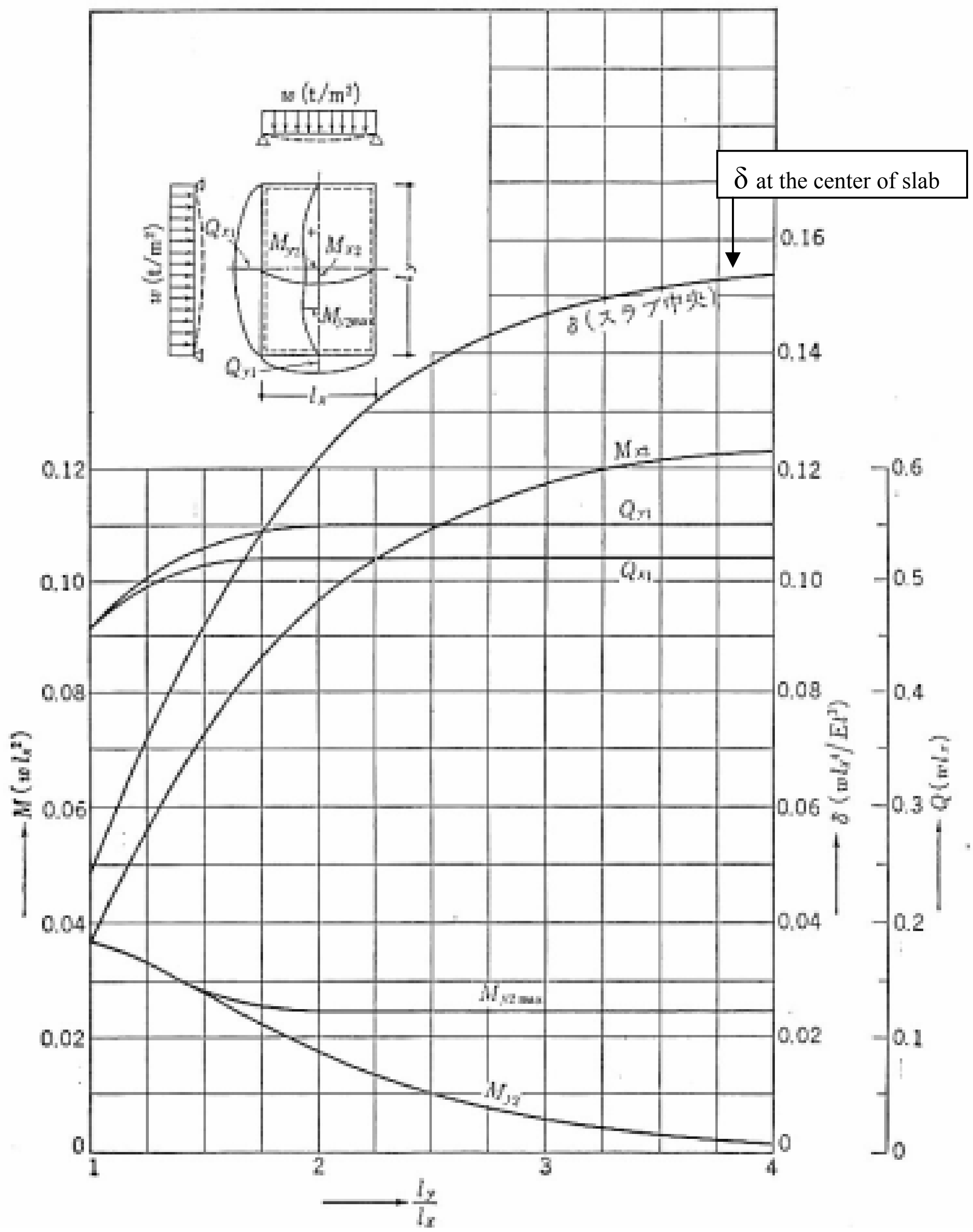


Figure 9 Stress Distribution of Slab Fixed along 4-Sides & Displacement δ [1)]
（ν＝0） at Center against Uniformly Distributed Loads

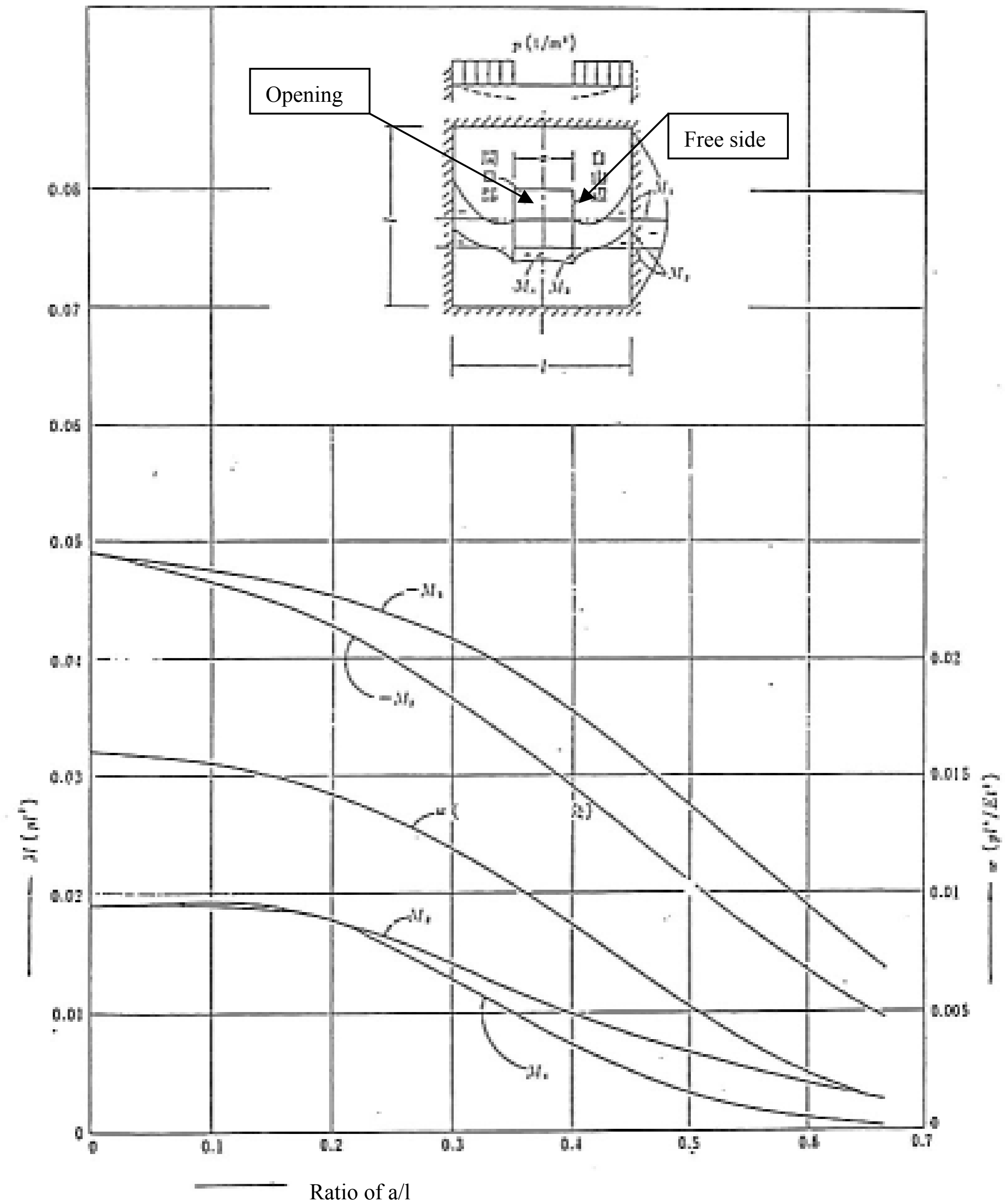


Figure 10 Bending Stress of Square-Shaped Slab with An Opening Fixed along 4-Sides & Displacement at Center of Opening against Uniformly Distributed Loads[1)]

Source:1) Yoshitaka Dobashi: 'Bending Moment of Square-Shaped Slab with Opening, Study Report No.12 of Japan Society of Architecture, Feb. 1958

Appendix 1-3 Penstock Diameter

Power tunnels and penstocks: the economics re-examined

By F. Fahlbusch
Principal Engineer*

The problem of determining the optimum diameter of power tunnels and penstocks for hydro plants is re-examined and a formula derived which circumvents the laborious numerical calculations involved in a detailed analysis.

PROCEDURES FOR determining the optimum or the most economical diameter of power tunnels and penstocks are fully discussed in literature and can therefore be regarded as established. Depending on the degree of accuracy required in a particular case, establishing the optimum diameter may be laborious and require numerical techniques in combination with a high-speed computer, but the procedure is generally straightforward. Models have been formulated without difficulty, even incorporating hydraulic transient aspects, turbine governing requirements, and flywheel effects. In contrast to theoretical analysis, the numerical approach, although competent in dealing with a particular case, usually has the shortcoming of not providing information which can be generalized.

A completely different approach to determining the economical diameter, which demands not more than a few elementary calculations, is by application of empirical formulae, such as those proposed for penstocks by Ludin[1], Sarkaria[2], and Fahlbusch[3]. These require knowledge of the rated capacity and head, but, despite their simplicity, performance is generally within an accuracy of 10 to 15 per cent. There are circumstances where the application of an empirical formula is more rational than a detailed study, which is the case when too many arbitrary assumptions are unavoidable. Although the arguments underlying the derivation and structure of these formulae are reasonably valid, occasionally there is doubt as to whether they are applicable. Successful application of the empirical formulae, therefore, requires some deeper understanding of the peculiarities of a problem so that exceptions can be recognized.

Half way between detailed numerical study and empirical formulae is theoretical analysis, which is the premise of this paper, in attempting to combine the advantages of both theoretical rigour and simplicity.

To keep the complexities mathematically tractable, a few expedient assumptions are deliberately made, but these do not seem to diminish the accuracy of the results.

In the following formulation, the effects of hydraulic transient and turbine governing requirements on the diameter are disregarded. To meet these requirements, adjustments might become necessary which will have to be determined on an individual basis.

Formulation

With increasing diameter, the head losses and consequent energy losses in a power tunnel or penstock decrease, while construction costs increase. The objective of the economic analysis is thus to determine the diameter which minimizes the total annual costs, consisting of the annual charges from the investment and the monetary value of the lost energy. The objective can be stated alternatively in terms of the amount of invested capital, and the capitalized value of the lost energy, which will achieve the same result.

Inflow into a reservoir, release, water level, amount of water in storage, and the output from the powerplant are basically continuous time functions or, even more precisely, stochastic processes with deterministic components. For the present purpose, these functions are considered as discrete, with one day being taken as the basic time interval. It is also assumed that the plant has a pulse-shaped output of duration Δt, implying instantaneous step-up to full capability, operation at full capability for the time Δt, and return to complete standstill once the hydro energy available on a particular day is delivered.

The interval Δt, which is a fraction of a day, depends explicitly on the available energy and capability on the specific day and, implicitly, on the rated capacity, rated head, and the actual head under which the plant is momentarily operating.

With these definitions and assumptions, the energy loss during the particular day, i, is given by:

$$\Delta E_i = 0.7(fQ_i^3/D^5)\Delta t_i \quad \ldots \quad (1)$$

where E = energy loss, f = Darcy-Weisbach friction factor, Q_i = discharge through the turbine, Δt_i = time interval specified above, and D = diameter. Underlying

Notations		
i	=	index designating a particular day
Δt_i	=	duration of plant operation in (h/day)
E_i	=	energy loss during a particular day
D	=	diameter
f	=	Darcy-Weisbach friction factor
Q_i	=	discharge through turbines on the particular day during duration Δt, (m³/s)
H_i	=	head on a particular day (m)
e	=	monetary value of one kWh electrical energy
ML	=	average annual monetary loss
J	=	number of years comprising planning horizon
N	=	total number of days of planning horizon
T	=	hours per year = 8760
h	=	hours per day = 24
Q_R	=	rated discharge (m³/s)
H_R	=	rated head (m)
P_R	=	rated capacity (kW)
A	=	dimensionless coefficient
k	=	factor representing the sum on the right-hand side of Eq. (6)
θ	=	average long term plant factor
T'	=	time a plant is actually in operation during planning horizon, in hours
C'	=	cost of a penstock or power tunnel of unit length
CRF	=	capital recovery factor
n	=	economic scaling factor, Eq. (8)
n	=	economic scaling factor for penstocks Eq. (12)
K	=	quantity defined by Eq. (4)
C_v	=	coefficient of variation
$\bar{K}$	=	average of the quantity K
k_s	=	coefficient: Sarkaria formula
k_f	=	coefficient: Fahlbusch formula

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Eq. (1) is the Darcy-Weisbach friction formula and an overall efficiency of the electrical and mechanical equipment of 85 per cent. The monetary loss incurred during the day is obtained by multiplying Eq. (1) by an appropriate unit energy value, e, and the average annual monetary loss (ML) is obtained by summing up the daily losses and dividing the total by the number of years J, comprising the planning horizon.

$$ML = 0.7(ef/D^5J)\sum_{i=1}^{N} Q_i^3 \Delta t_i \quad \dots \quad (2)$$

where N denotes the total number of days. With the relationship of N, the hours per year, T, and the hours per day, h, Eq. (3) can be written:

$$ML = 0.7(efT/D^5)\sum_{i=1}^{N}(Q_i^3 \Delta t_i/Nh) \quad \dots \quad (3)$$

The quotient $\Delta t_i/h$ in Eq. (3) represents the daily plant factor. When the discharge does not vary explicitly with the head, the sum on the right becomes simply the product Q_i^3 multiplied by the average long-term plant factor.

The two relationships:

$$Q_i = \lambda Q_R \quad \dots \quad (4)$$

$$T' = \phi Nh \quad \dots \quad (5)$$

where T' equals the hours a plant is in operation during the planning horizon and ϕ is the average plant factor, transform the sum to the right of Eq. (3) into a pure number smaller than, or equal to, unity:

$$ML = 0.7(efT\phi/D^5)\sum_{i=1}^{N}\lambda_i^3(\Delta t_i/T') \quad \dots \quad (6)$$

The dimensionless quantity, λ, which is also restricted to values smaller than unity, follows from known functions of the ratio between the head, H_i, under which a plant is operating on a specific day and the rated head, H_R. In the special case that λ is constant and unity, implying constant discharge equal to the rated discharge, the sum in Eq. (6) takes on the numerical value 1. The final expression for the average annual monetary losses caused by friction in a power tunnel or penstock of given diameter is obtained by considering the relationship between rated capacity, discharge, and head. Assuming again an overall efficiency of 85 per cent and inserting for T = 8760 h, Eq. (6) then becomes:

$$ML = 10.6\left[(ef\phi k)/D^5\right](P/H)^3 \quad \dots \quad (7)$$

where the subscripts referring to the rated variable are dropped for convenience. The letter k stands for the sum on the right of Eq. (6).

The second term in the objective function is the function relating the annual cost to the diameter. In practice, cost functions are not necessarily continuous, because the most appropriate construction equipment may change at discrete diameter steps. Actual cost estimates, on the other hand, indicate that the quadratic polynomial, Eq. (8), represents a reasonable approximation

$$C = CRFnD^2 \quad \dots \quad (8)$$

where CRF designates the capital recovery factor and the coefficient, n, is an economic scaling factor of a power tunnel or penstock of unit length which has to be determined by fitting Eq. (8) to actual cost estimates.

Mathematically, the problem of determining the optimum diameter can now be stated as an unconstrained optimization problem with the following objective function:

$$\text{Total annual cost} = 10.6ef\phi(P/H)^3D^{-5} + CRFnD^2 \quad \dots \quad (9)$$

and the optimum diameter is obtained by application of standard calculus methods or by geometric programming. Geometric programming applied to the current problem not only results in a statement of the solution simply by inspection, but shows that, at the optimum design, the ratio between the second and first term on the right of Eq. (9) is constant, having the numerical value 2.5, that is:

$$(CRFnD^2)/[10.6ef\phi k(P/H)^3D^{-5}] = 2.5 \quad \dots \quad (10)$$

which eventually yields:

$$D = 1.6(ef\phi k/CRFn)^{1/7}(P/H)^{3/7} \quad \dots \quad (11)$$

Eq. (11) applies to both power tunnels and penstocks, since no specific assumptions were made in the derivation, which would restrict it to either function.

Validation of equation for the optimum diameter

The comparison to be discussed next, though not entirely rigorous can, nevertheless, be regarded as an acceptable proof of the theory. For this purpose, two data sets compiled and published by Sarkaria[1,4] from existing penstocks were used, which cover the whole spectrum of penstocks encountered in practice. The sets encompass penstocks from 1.5 m to 12.2 m-diameter, 20 m to almost 7000 m head and 2 MW to 700 MW capacity.

In comparing the formulae of the optimum diameter with penstock data, it is expedient to modify slightly the cost function to account explicitly for the head which varies within a very wide range. In the case of power tunnels, the variations of the head are usually within narrow limits and not as important as in penstocks. Elementary mechanics and economic considerations suggest a form as indicated by Eq.(12)

$$C = CRFaHD^2 \quad \dots \quad (12)$$

where the rated head, H, is used as the variable representing the internal water pressure and a is again a scaling factor for cost. With Eq. (12) instead of Eq. (8), the formula for the optimum diameter of penstocks takes on the form:

$$D = 1.6(ef\phi k/CRFa)^{1/7}H^{-1/7}(P/H)^{3/7} \quad \dots \quad (13)$$

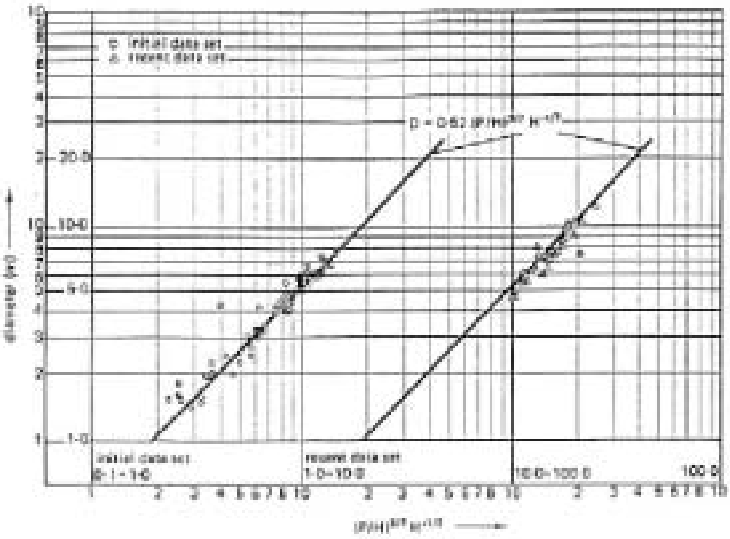
which differs only slightly from Eq. (11)

The test, as used herein, compares the diameter of the existing penstocks against the quantity $H^{-1/7}$ $(P/H)^{3/7}$. Corresponding pairs are plotted on log-log paper on the Figure which show, in accord with Eq. (13), a linear relation.

A statistical analysis of the quantity

$$K = D/(P/H)^{3/7}H^{-1/7} \quad \dots \quad (14)$$

the result of which is summarized in the following table, disclosed an overall average $\bar{K}$ = 0.52 and a coefficient of variation Cv = 0.11. Thus within an accuracy of 11 per cent, Eq. (15) can be used for a quick determination of the most economical diameter.



Diameter of existing penstocks compared with $H^{-1/7}$ $(P/H)^{3/7}$. The log-log paper demonstrates the linearity of the relationship.

$$D = 0.52 H^{-1/7} (P/H)^{3/7} \quad \ldots \quad (15)$$

Relationships of G and $\bar{K}$: see Eq. (14)	$\bar{K}$	Cv
1st data set	0.54	0.11
2nd data set	0.40	0.07
Both sets combined	0.52	0.11

Both Fig. 1 and the values listed in the Notations tend to indicate that the diameter of the more recent penstocks are, on average, 10 per cent smaller than those of the earlier penstocks. Although the difference is significant statistically, this observation is of little practical use, since the cause of the difference cannot be isolated and allowed for in Eq. (15).

The formulae for penstocks suggested by Sarkaria and Fahlbusch stated in the metric system are, respectively:

$$D = k_s H^{-0.22} (P/H)^{0.43} \quad \ldots \quad (16)$$

and:

$$D = k_f H^{-0.17} (P/H)^{0.43} \quad \ldots \quad (17)$$

which are both quite similar to the theoretical expression in Eq. (13) and Eq. (15), for the most economical penstock diameters. While there is a slight difference between the exponents of the variable H, the exponents of the quotient, 0.43, found by curve fitting, agrees fully with the theoretical value 3/7.

Conclusion

As far as penstocks are concerned, a quick estimate of the diameter can be obtained from the empirical formulae of Sarkaria and Fahlbusch as well as from Eq. (15). Their use may also be considered in cases where it is difficult to obtain reasonably reliable estimates of the technical and economic parameters involved in Eq. (13), or where an approximate estimate suffices. In this case, Fig. 1 provides additional guidance for judgment and adjustment.

In general, however, the formula, Eq. (11), for the optimum diameter of both power tunnels and penstocks suggested in this article is recommended. Determination of the parameter values entails a somewhat greater effort, which is acceptable and justifiable considering the investment associated with the construction of power tunnels and penstocks. Since the sensitivity of the diameter with respect to the first term on the right of Eq. (11), is moderate, because of the small exponent, even rough estimates of the parameter values are completely adequate.

Evaluations of operation studies of storage projects tend to indicate a lower value of k of about 0.7, which may be applied without producing errors of more than 5 per cent. Generally, it would seem appropriate to conduct a few simple operation studies to obtain a more accurate estimate of the value k. □

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