A Study on the Optimum Design Flowrate for Tunnel—Type Small Hydro Power Plants

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ABSTRACT / This study represents the methodology for feasibility analysis of small hydro power SHP plant. Cumulative density function of Weibull distribution and Thiessen method were adopted to decide flow duration curve at SHP candidate site. The perfomance prediction model and construction cost estimation model for tunnel—type SHP plant were developed. Eight tunnel—type SHP candidate sites existing on Han—river were selected and surveyed for actual site reconnaissance. The performance characteristics and economical feasibility for these sites were analyzed by using developed models.

As a result, it was found that the optimum design flowrate with the lowest unit generation cost for tunnel—type SHP candidate site were the flowrate concerning with between 20 % and 30 % of time ratio on the flow duration curve. Additionally, primary design specifications such as design flowrate, effective head, capacity, annual average load factor, annual electricity production were estimated and discussed for eight surveyed SHP candidate sites.

1. Introduction

SHP offers numerous advantages compared to other alternatives as an important source of energy. Recently, SHP has been received more and more attention in social, environmental and economic aspects.

First estimation of SHP resources has been carried out by map survey to develop as an alternative energy source after the 1st oil crisis (I.Y.Park et al,1974). Also, the design work was performed in 1975, and applying these results, the demonstration SHP plant was constructed at Anheung in Kangwon province (I.Y.Park et al,1975). The 2nd estimation of SHP resources for SHP candidate sites was carried out through actual site reconnaissance after the 2nd oil crisis (B.C.Shon et al, 1982; B.C.Shon et al,1983; D.R.Shin et al,1984). And pre-

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sently, twelve SHP plants are constructed and operated by individuals or private companies.

It is well-known that SHP generation is clean energy but need more initial investment per unit capacity comparing with other generation sources such as large scale hydro power, oil and neucleare power plant. The economy of SHP plants, however, can be improved by performing exact analysis for natural geological characteristics and capacity of candidate sites.

Nomenclature

A ; Catch rain area (km^2)
C ; Capacity of SHP plant (kW)
C_c ; Total investment of SHP (Won)
C_d ; Dam construction cost (Won)
C_e ; Electricity saling price (Won / kWh)
C_g ; Total benefit of SHP plant (Won)
C_i ; Initial investment of SHP (Won)
C_l ; Transmission equipment cost (Won)
C_m ; Hydro generator cost (Won)
C_t ; Tunnel construction cost (Won)
C_{tr}; Transformer equipment cost (Won)
C_u ; Unit generation cost (Won / kWh)
D_h ; Hydralic diameter of tunnel (m)
$D(Q)$; Function of flow duration curve
E_a ; Annual electricity production (MWh)
$F(q)$,$F(Q)$; Cumulative density function of Weibull distribution
f ; Friction coefficient
g ; Gravitational acceleration (m / sec^2)
H ; Head (m),Maximum usable head (m)
H_d ; Dam height (m)
H_e ; Effective head (m)
H_l ; Canal loss (m)
H_r ; Rated head (m)
i_r ; Interest rate (%)
k ; Discharge coefficient
L ; Tunnel length (m)
L_d ; Dam length (m)
L_f ; Annual average load factor (%)
N ; Life of SHP plant (year)

O_m ; Maintenance rate (%)
P_a ; Power characteristic of SHP plant (kWh)
P_i ; Ideal hydro power (kWh)
P_e ; Average electricity production per unit time (kWh)
P(q),P(Q) ; Weibull distribution function
Q ; Flowrate (m^3/sec)
Q_a ; Annual average flowrate (m^3/sec)
Q_m ; Monthly average flowrate (m^3/sec)
Q_r ; Design flowrate (m^3/sec)
q ; Monthly average flowrate per unit catch rain area (m^3/sec)
R ; Rainfall amount (mm)
R_e ; Reynolds number
R_m ; Monthly rainfall amount (mm)
R_t ; Annual rainfall amount (mm)
T ; Time ratio (%)
V ; Fluid velocity (m / sec)
W ; Weight of catch rain area
W_d ; Dam width (m)
α ; Shape parameter of Weibull distribution
β ; Scale parameter of Weibull distribution (m^3/ sec)
ρ ; Density of water (kg / m^3)
η ; Efficiency of SHP plant

Subscript i ; Effect of ith weather station

The capacity is determined by natural geological conditions and flow duration characteristics of SHP candidate sites. Especially, the capacity affects economy and performance characteristics of SHP plant such as initial investment, unit generation cost, and annual average electricity production. This paper presents the methodology to analyze flow duration characteristics, performance prediction, and pre–feasibility model. Based on the actual survey of eight tunnel–type SHP candidate sites existing on Han–river, the performance characteristics and economical pre–feasibility were analyzed by using the developed models. Also, the optimum design flowrate,optimum capacity and primary design specification which lead to minimum unit generation cost were presented.

2. Rainfall Data Analysis and Flow Duration Curve

In our country,hydrological data is not enough to decide flow duration characteristics of

SHP candidate sites because the most of candidate sites are located at upstream of rivers. But the flowrate of candidate sites can be calculated by analyzing the rainfall data measured by weather station in catch rain area concerning with candidate sites.

Annual average flowrate of the river is related to the annual total amount of rainfall in catch rain area and estimated as follows.

$$Qa = \frac{R_t \times 10^{-3} \times A \times 10^6 \times k}{365 \times 24 \times 60 \times 60} \tag{1}$$

If the discharge coefficient k does not vary during 1 year,the monthly average flowrate of the river can be described as follows.

$$Qm = \frac{R_m \times 10^{-3} \times A \times 10^6 \times k}{30.42 \times 24 \times 60 \times 60} \tag{2}$$

Total amount of monthly rainfall measured at weather station can be converted to monthly average flowrate per 1㎢ of unit catch rain area by using equation (2). Also, flow duration curve for unit catch rain area can be decided by using monthly average flowrate per unit catch rain area.Flow duration curve can be expressed to certain type of cumulative density function because the concept of flow duration curve is equal to the cumulative density function of probability function.

In this paper,flow duration curve for unit catch rain area is characterized by using the cumulative density function of Weibull distribution function.

Probability distribution and cumulative density function of Weibull distribution are expressed as follows.

$$P(q) = (\alpha / \beta)(q/\beta)^{\alpha-1} \exp(-(q/\beta)^{\alpha}) \tag{3}$$

$$F(q) = \int_0^q P(q)\, dq = 1 - \exp(-(q/\beta)^{\alpha}) \tag{4}$$

Two constants α and β in equation (2) and (3) can be found by using ln least square method. If the both side of equation (4) take twice of natural logarithm, the equation is expressed to the type of $Y = aX + b$ as follows.

$$\ln(-\ln(1 - F(q))) = \alpha \ln q - \ln \beta \tag{5}$$

where,

$$Y = \ln(-\ln(1 - F(q)))$$

$$X = \ln q \tag{6}$$

$$a = \alpha$$

$$b = -\alpha \ln \beta$$

In equation (6),a and b can be calculated by using the nth (X,Y) data, i.e. the nth data of cumulative density and monthly average flowrate. Then,

$$a = \frac{\Sigma XY - \Sigma X \ \Sigma Y/n}{\Sigma X^2 - (\Sigma X)^2/n} \tag{7}$$

$$b = \Sigma Y/n - a \ \Sigma X \ / \ n$$

Actually, flowrate and flow duration curve of SHP candidate site are decided by organizing the data measured at several weather stations because total catch rain area always contains several weather stations. If the ith weather station exist in total catch rain area as shown in Fig.1, average rainfall amount of total catch rain area can be expressed as follows by Thiessen method (J.H.Shunwoo;1989).

$$R = \Sigma W_i R_i \ , \ W_i = A_i \ / \ A \tag{8}$$

where Ai and Ri mean the small catch rain area devided by ith weather station and rainfall amount measured at the ith station, respectively.

Flowrate at SHP candidate site can be expressed as follows.

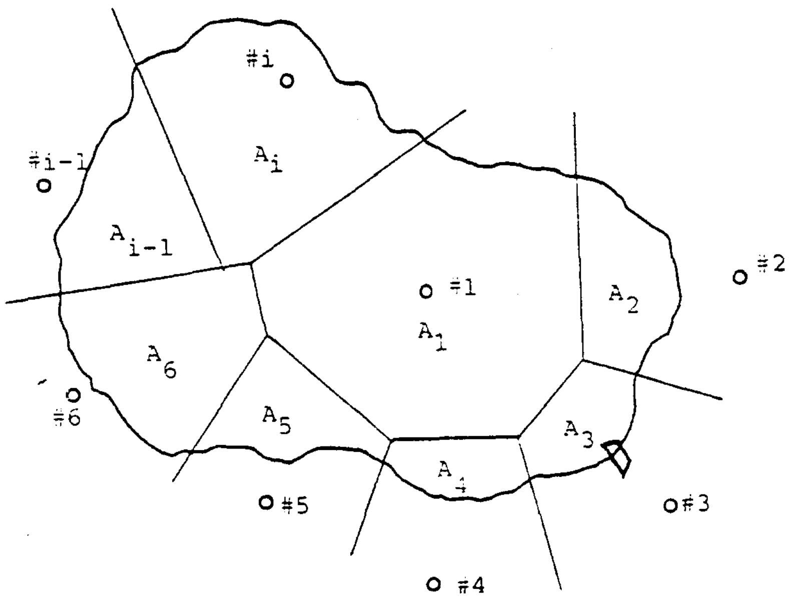

Fig.1. Devided catch rain area by several weather stations

$$Q = A \Sigma W_i q_i \quad (9)$$

Then, the cumulative density function and probability density function at SHP candidate site is expressed as follows.

$$F(Q) = A \Sigma W_i (1-\exp (-(qi/\beta i)^{\alpha -1})) \quad (10)$$

$$P(Q) = A \Sigma W_i (\alpha i/\beta i) (qi/\beta i) \exp (-(qi/\beta i))^{\alpha -1} \quad (11)$$

Also, flow duration function at SHP candidate site which can express flow duration curve is obtained as follows.

$$D(Q) = A \Sigma W_i \exp (-(qi/\beta i)^{\alpha -1}) \quad (12)$$

3. Analyzing the Performance Characteristics of SHP Plant and Investment Estimation

SHP plant extracts energy from flowrate and head.Ideal hydro energy extracted from SHP plant can be calculated as follows.

$$Pi = \rho g Q H \quad (13)$$

The power variation of SHP plant with the flowrate variation per unit head and unit time

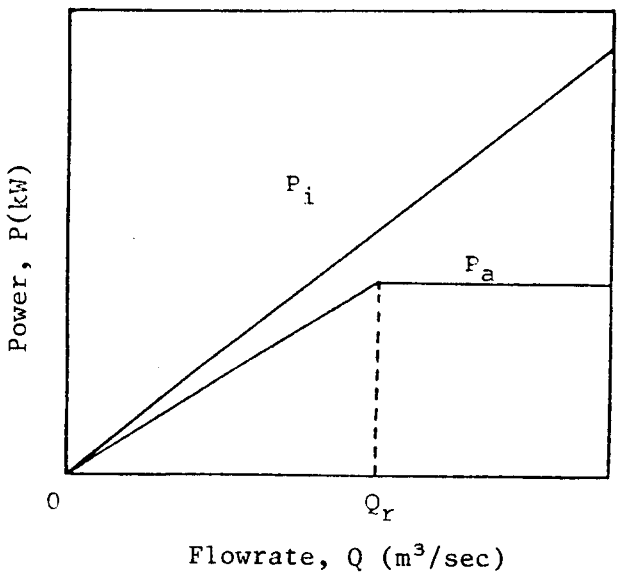

Fig.2. Power characteristics of SHP plant

is shown in Fig.2. Ideal hydro energy Pi vary linearly with flowrate variation, but actual power characteristics Pa obtained from SHP plant is not esual to Pi due to existance of design flowrate Qr.

The power extracted from SHP plant is varied linearly with flowrate variation ur to design flowrate, but the power is always less than the ideal hydro energy because of its efficiency. Also, the power is maintained constant from the design flowrate because SHP plant always use only the design flowrate and extra flowrate is discharged over diversion dam.

Then, amount of average electricity Pe produced from SHP plant per unit time is obtained as follows.

$$Pe = \rho\ g\ He\ \eta\ \int_0^{Qr} P(Q)\,dQ + \rho\ g\ He\ \eta\ Qr\ \int_{Qr}^{\infty} P(Q)\,dQ\ ) \qquad (14)$$

η of the 1st term in equation (14) is varied with flowrate variation. Assuming that has little variation, then equation(14) can be expressed as follows.

$$Pe = \rho\ g\ He\ \eta\ \int_0^{Qr} P(Q)\,dQ + Qr = \int_{Qr}^{\infty} P(Q)\,dQ\ ) = \rho\ g\ He\ \eta\,(S_1+S_2) \qquad (15)$$

The capacity C of SHP plant, annual average load factor L_f and annual electricity production Ea can be calculated as follows.

$$C = \rho\ g\ He\ Qr \qquad (16)$$

$$L_f = (\ S_1 + S_2\ )\ /\ Qr \qquad (17)$$

$$Ea = 8{,}760\ C\ L_f \qquad (18)$$

The capacity of SHP plant is decided by the design flowrate and head. The head means vertical distance from upper water surface to water turbine. Also, the head which can supply the effective energy to water turbine is called the effective head.

The maximum head is calculated from the difference between the top of dam and discharging water surface because tunnel–type SHP plants always adopt diversion dam. Generlly, the total loss except tunnel is assumed 5% of maximum head, then the effective head can be expressed as follows (Y.P.Choi,1977).

$$He = H \times 0.95 - H_l \qquad (19)$$

Tunnel loss H_l is expressed as follows (A.J.Stepanoff,1957).

$$H_l = f(L / D_h)(V / 2g) \qquad (20)$$

where the friction factor f is calculated as follows, and Re means Reynold's number in tunnel (H.Schlichting,1979).

$$f = 64 / Re, \ Re < 2,300$$
$$(21)$$
$$f = 0.3164 / R_e^{0.25}, \ Re > 2,300$$

To estimate initial investment of SHP plant,direct investment and indirect investment are considered.Direct investment includes several parameters such as dam construction cost Cd, tunnel construction cost Ct,hydro generator cost Cm, transformer cost Ctr and transmission cost Cl. Control house construction cost and indirect investment are assumed to be 10% and 20% of the total direct investment, respectively. The direct investment is calculated as follows (C.H.Lee et al,1989).

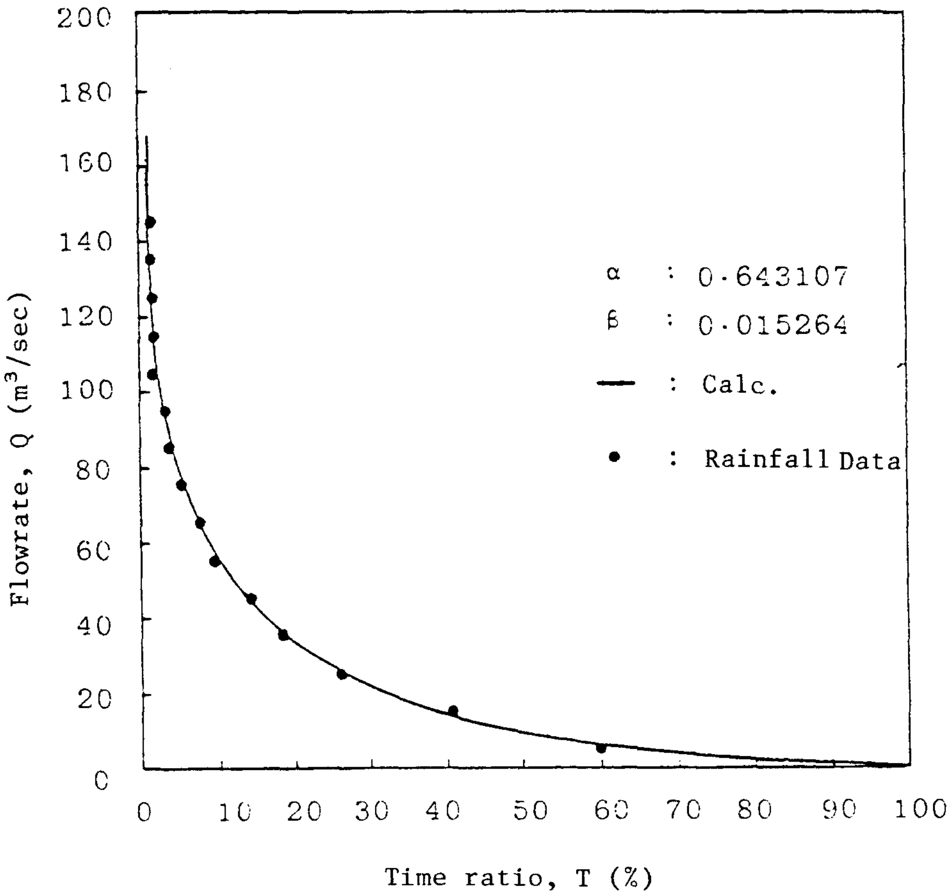

Fig.3. Flow duration curve per unit catch rain area affected by Jinboo weather station

$$C_d = (42,600\ H_d^2 + 111,560\ H_d + 111,560) \times W_d \times L_d \tag{22}$$

$$C_t = (54,320\ Q^{0.75} + 127,430\ Q^{0.375} + 28,630) \times L \tag{23}$$

$$C_m = 9,450,000\ C^{0.7}\ Hr^{-0.35} \tag{24}$$

$$C_{tr} = 0.36\ C^2 + 8,529\ C + 40,584,150 \tag{25}$$

$$C_l = 27,000,000 \times l \tag{26}$$

Then, initial investment for constructing SHP plant Ci is estimated as follows.

$$C_i = ((C_d + C_t + C_m + C_{tr} + + C_l) \times 1.1) \times 1.2 \tag{27}$$

Also, unit generation cost Cu is calculated as follows.

$$C_u = (\frac{i_r\ (1+i_r)^N}{(1+i_r)^N-1} + Om) \times \frac{Cc}{C \times 8,760 \times Lf} \tag{28}$$

5. Results and Discussion

Prior to analyze this results using the cumulative density function of Weibull distribution, the methodology to decide the flow duration curve per unit catch rain area was discussed. And, it was proved that the methodology presented in this study is suitable to predict flow duration curve at SHP candidate site through comparing the hydrological data measured at the river.

Fig.3 shows the comparison of flow duration curve per unit catch rain area affected by Jinboo weather station.As shown in Fig.3, it is indicated that the cumulative density function of Weibull distribution is suitable to characterize the flow duration curve per unit catch rain area.

Fig.4 shows the comparison of flow duration curves enabled at Pyungchang river in Kangwon province (KEPCO;1982). Robert Noyes'method (1980) was selected to decide real flow duration curve, and the discharge coefficient k is assumed to 0.7 for prediction model presented in this paper (J.H.Cha;1982).

As shown in Fig.4, it is proved that the method presented in this study is suitable to express the flow duration curve measured from real river. And from this result, it is proved that the present methodology can be applied to SHP sites having no real hydrological data.

Eight tunnel−type SHP candidate sites existing on Han river were selected and analyzed. The geological data for each site is summarized in Table 1. Natural head and river width of

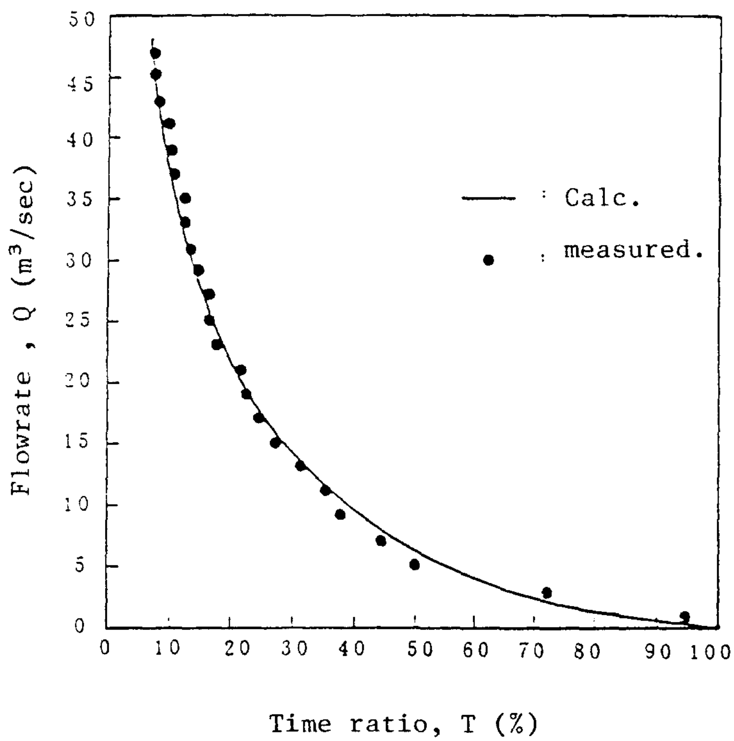

Fig.4. Flow duration curve for the Pyungchang river

Table 1. The characteristics of SHP candidate sites

candidate sites	catch rain area (km²)	natural head (m)	river width (m)	dam height (m)	tunnel length (m)	trans-mission line(km)
Daeki–Ri	215	25.8	73	5	125	0.2
Magdong–Ri	305	7.4	75	6	325	0.4
Duckchun–Ri	2,025	14.1	200	5	500	0.4
Kujeul–Ri	233	21.6	80	6	375	0.2
Dodon–Ri	733	8.1	110	5	350	0.7
Whaeu–Ri	298	11.1	75	5	225	0.3
Misan–Ri	349	12.1	60	6	125	0.5
Yeuljeun–Ri	299	19.6	110	5	675	0.4

candidate sites were decided by actual site reconnaissance, and dam heights were limited to avoid submerging of the houses in upstream.

From the eight tunnel–type SHP candidate sites in Table 1,Dodon–Ri site was selected to analyze the performance characteristics and economical feasibility for construction.

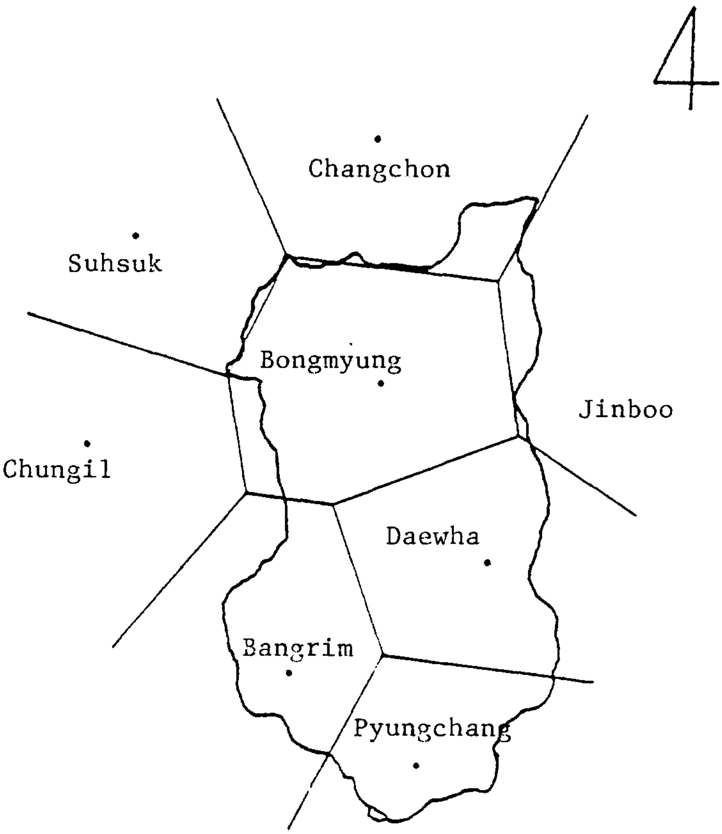

Fig .5. Devided catch rain area of Dodon-Ri site

Table.2 The characteristic of devided catch rain area

weather station	catch rain area (Ai,㎢)	weight value (Wi,%)	shape parameter (α)	scale parameter (β,㎥/sec)
Pyungchang	97	13.2	0.770748	0.019082
Bangrim	127	17.3	0.686524	0.017048
Daewha	189	25.9	0.690516	0.01661
Bongpyung	273	37.2	0.664584	0.016606
Jinboo	16	2.2	0.643107	0.015264
Changchon	31	4.2	0.631996	0.01541
total	733	100.0		

Fig.5 shows the total catch rain area of Dodon-Ri SHP candidate site, and this catch rain area is devided into six small areas which are affected from six weather stations by Thiessen method. Total catch rain area of Dodon-Ri is 733㎢, and the characteristics of devided areas are shown in Table 2.

Fig.6 shows the flow duration curve of Dodon−Ri site enabled by combining the characteristics of several catch rain area in Table 2.

Fig.7 shows the varation of annual average load factor L_f, system capacity C, and annual electricity production Ea with variation of design flowrate. In order to analyze the performance characteristics of candidate sites, system efficiency η was assumed to be 0.8, and effective head to be 12.3 m.

System capacity C varied linearly with the varation of design flowrate,but annual average load factor L_f decreased with increasing design flowrate. Also, load factor was decreased rapidly at the lower region of design flowrate,but decreased gradually at upper region. This is the reason why the average electricity production Pe is relatively larger than system capacity in the case of system with lower design flowrate. Thus, annual average load factor reaches 100 % extremly in case of system with zero of design flowrate.

Annual electricity production increased with increasing design flowrate, and increasing rate decreased gradually at upper region of design flowrate. This phenomenon is due to de-

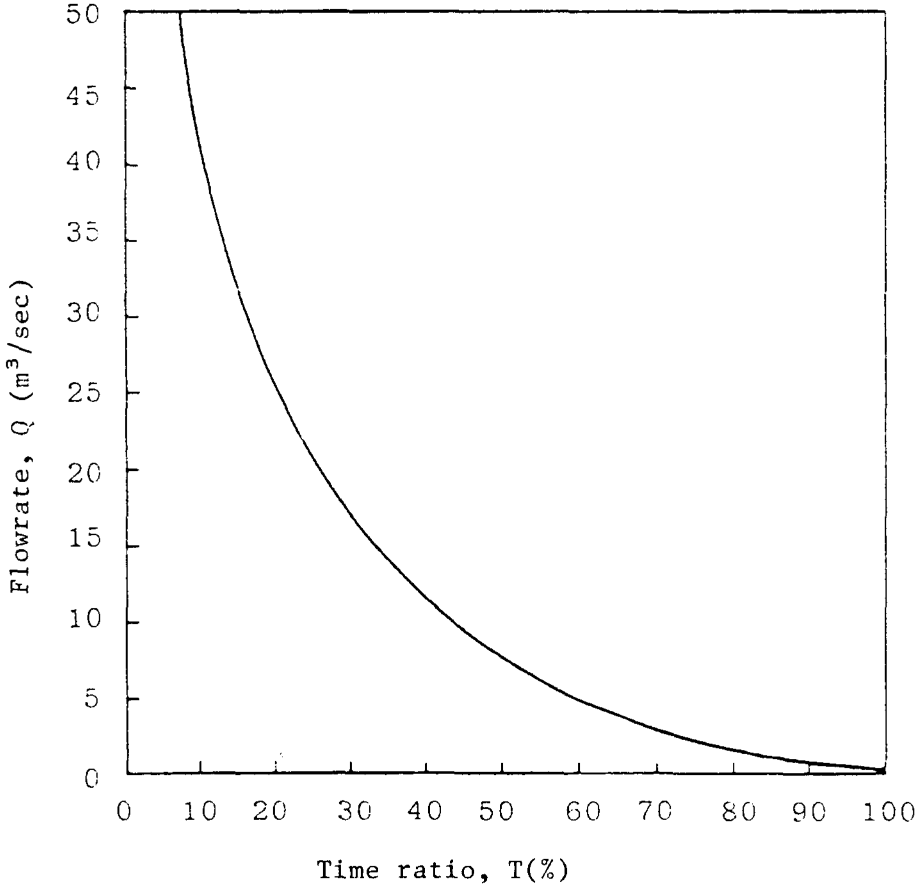

Fig.6. Flow duration curve of Dodon−Ri SHP candidate site

creasing annual average load factor with increasing design flowrate

Fig.8 shows the varation of system capacity C and unit generation cost Cu on the flow duration curve with design flowrate Qr. As shown in Fig.8, the design flowrate with mininum unit generation cost is 18.0 m^3/sec of flowrate. Also, the time ratio on the flow duration curve is 27.5%, and system capacity corresponding to this flowrate is 1,740 kW.

The system characteristics and design flowrate with minimum unit generation cost for the eight SHP candidate sites are summarized in Table.3. As shown in Table.3, design flowrate with minimum unit generation cost is determined as the flowrate nearby corresponding to 25 % of time ratio on the flow duration curve for the most of candidate sites. But the time ratio with optimum design flowrate has maximum 9.3 % of difference according to the geological and hydrological conditions of the candidate sites. Thus, the use of feasibility study method presented in this paper is recommended for determining the optimum design flowrate of tunnel–type SHP candidate sites.

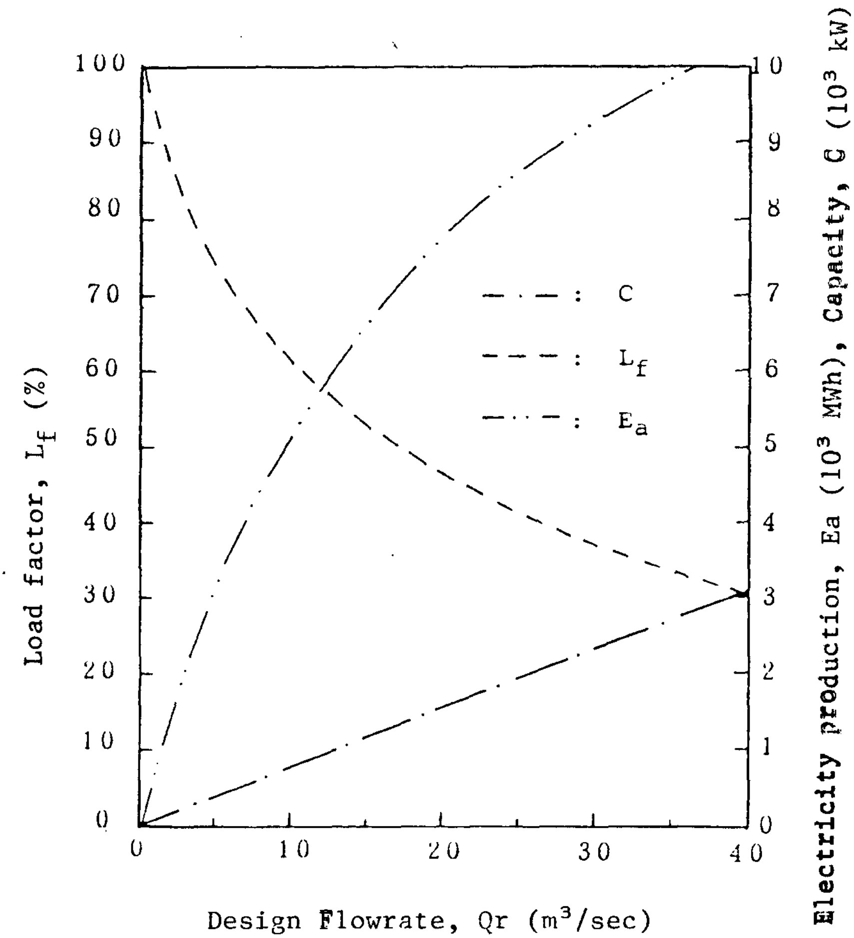

Fig.7 The varation of system capacity,annul average load factor and annual electricity production according to design flowrate

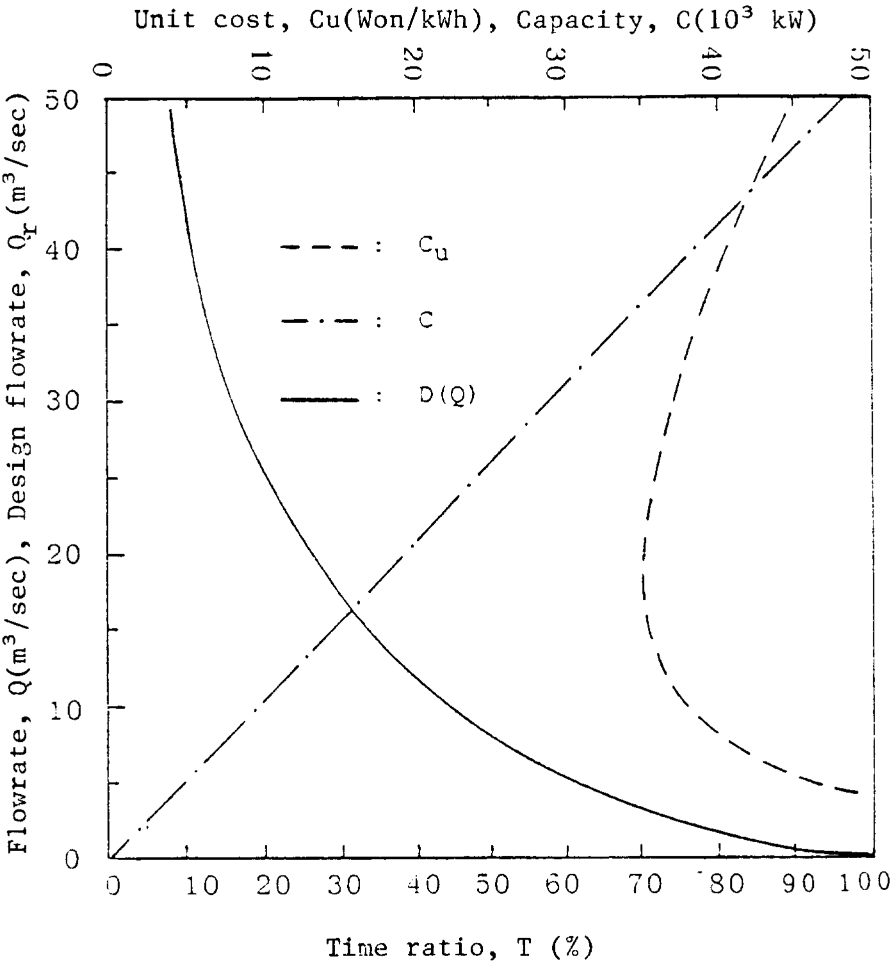

Fig.8 The relation of flow duration curve,system capacity and unit generation cost

Table.3 The characteristics of SHP candidate sites

candidate sites	time ratio (%)	design flowrate (m^3/sec)	effective head (m)	system capacity (kW)	load factor (%)	generation cost (won/kWh)
Daeki−Ri	32.8	5.5	29.2	1,260	43.9	28.09
Makdong−Ri	21.1	9.3	21.3	920	41.1	54.86
Duckchun−Ri	30.4	38.0	17.9	5,340	50.6	21.71
Kujeul−Ri	22.4	6.3	26.1	1,290	42.7	37.32
Dodon−Ri	27.5	18.8	12.3	1,740	48.5	35.79
Whaeu−Ri	24.5	7.8	15.2	930	45.1	41.39
Misan−Ri	24.3	9.3	17.2	1,250	44.1	33.44
yeuljeun−Ri	23.0	8.5	23.1	1,540	42.7	41.84

6. Conclusion

This study presents the methodology to predict performance characteristic and to analyze pre−feasibility of tunnel−type SHP candidate sites through analyzing monthly rainfall data.The results of this study is summarized as follows:

The flow duration curve can be decided by using monthly rainfall data at most of the SHP candidate sites with no useful hydrological data. It was proved that the monthly rainfall data can be characterized by using the cumulative density function of Weibull distribution. Also, applying these results, the method to predict and analyze the performance of SHP plants was presented.

Feasibility study was carried out by using construction cost estimation model for tunnel−type SHP candidate sites. It was found that the design flowrate with minimum unit generation cost was determined as the flowrate nearby corresponding to 25 % of time ratio on the flow duration curve for the most of candidate sites.But the time ratio having optimum design flowrate is varied with geological and hydrological conditions of the candidate sites. Thus, the use of feasibility study method presented in this paper is recommended for determining the optimum design flowrate for tunnel−type SHP candidate sites.

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