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Performance Prediction of Tunnel-Type Small Hydro Power Plants with Diversion Dam

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Abstract

This study represents the methodology of performance prediction for small hydro power(SHP) sites. Nine tunnel type SHP sites with diversion dam were selected and the performance characteristics were analyzed by using a developed model. Also, primary design specifications such as design flowrate, plant capacity, and operational rate were suggested and feasibility for tunnel-type SHP sites were estimated. It was found that the design flowrate was most important parameter to exploit SHP plant and the methodology developed in this study was useful tool to analyze the performance of SHP sites.

Nomenclatures

A : drainage area(km^2)
C : Capacity of SHP plant(kW)
D(Q) : Function of flow duration
E_a : Annual electricity production(MWh)
F(q),F(Q) : Cumulative distribution function
g : Gravitational acceleration(m/sec^2)
H : Effective Head(m)
k : Discharge coefficient
L_f : Operational rate(%)
P_i : Ideal hydro energy(kWh)
P : Electricity production(kWh)
P_1 : Part electricity production(kWh)
P_2 : Rated electricity production(kWh)
P(q),P(Q) : Probability density 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 drainage area(m^3/sec)
R_m : Monthly amount of rainfall(mm)
R_t : Annual amount of rainfall(mm)

T : Percent of time flow is exeeded(%)
W : Weight of drainage area
α : Shape parameter of Weibull distribution
β : Scale parameter of Weibull distribution (m^3/sec)
ρ : Density of water(=1,000kg/m^3)
η : Efficiency of SHP plant

Subscript

i : i_{th} weather station

1. Introduction

Small hydro power(SHP) offers numerous advantages compared to other alternatives as an important source of renewable energy and it is receives more and more attention due to social, environmental and economic advantages.

The SHP is known as clean energy but it needs more initial investment per unit capacity comparing with other generation sources such as large hydro, oil and nuclear power plant. The economics of SHP, however, can be improved by performing exact analysis for natural geological characteristics and capacity of SHP power sites. The capacity of SHP plant is determined by natural geological conditions and flow duration characteristics of SHP sites.

This paper briefly presents a concept of the performance prediction for SHP sites and its application. Based on the surveyed data of tunnel-type SHP sites, the performance characteristics were analyzed by using a developed model. Also, the optimum design flowrate, optimum capacity and primary design specification were presented.

2. Flow duration prediction model

Hydrological data is not enough to decide flow duration characteristic of SHP sites because most sites locate at upstream of rivers. The flow rate passing SHP sites can be calculated by analyzing the rainfall data measured by weather station in drainage area associated with the sites.

Annual average flow rate of the river is related to the annual total amount of rainfall in drainage area and estimated as follows.

$$Q_a = \frac{R_t \times 10^{-3} \times A \times 10^6 \times k}{365 \times 24 \times 60 \times 60} \qquad (1)$$

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

$$Q_m = \frac{R_m \times 10^{-3} \times A \times 10^6 \times k}{30.42 \times 24 \times 60 \times 60} \qquad (2)$$

Monthly amount of rainfall measured at weather station can be converted to monthly specific drainage per 1 km^2 of unit drainage area by using Equation (2). Also, flow duration curve for unit drainage area can be decided by using monthly specific drainage. Flow duration curve can be expressed to the type of cumulative distribution function.

Probability density function and cumulative distribution function of the Weibull distribution are expressed as follows[1].

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

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

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

$$\ell n\,[-\ell n\{1-F(q)\}] = \alpha\,\ell n\,q - \ell n\,\beta \quad (5)$$

where,

$$Y = \ell n\,[-\ell n\,\{1-F(q)\}]$$
$$X = \ell n\,q$$
$$a = \alpha$$
$$b = -\alpha\,\ell n\,\beta \quad (6)$$

In Equation (6), a and b can be calculated by using (X, Y) data, i.e. data of cumulative probability distribution and monthly average flowrate.

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

$$b = \Sigma Y/n - a\Sigma X/n \quad (7)$$

Actually, flowrate and flow duration curves of SHP sites are decided by evaluating the

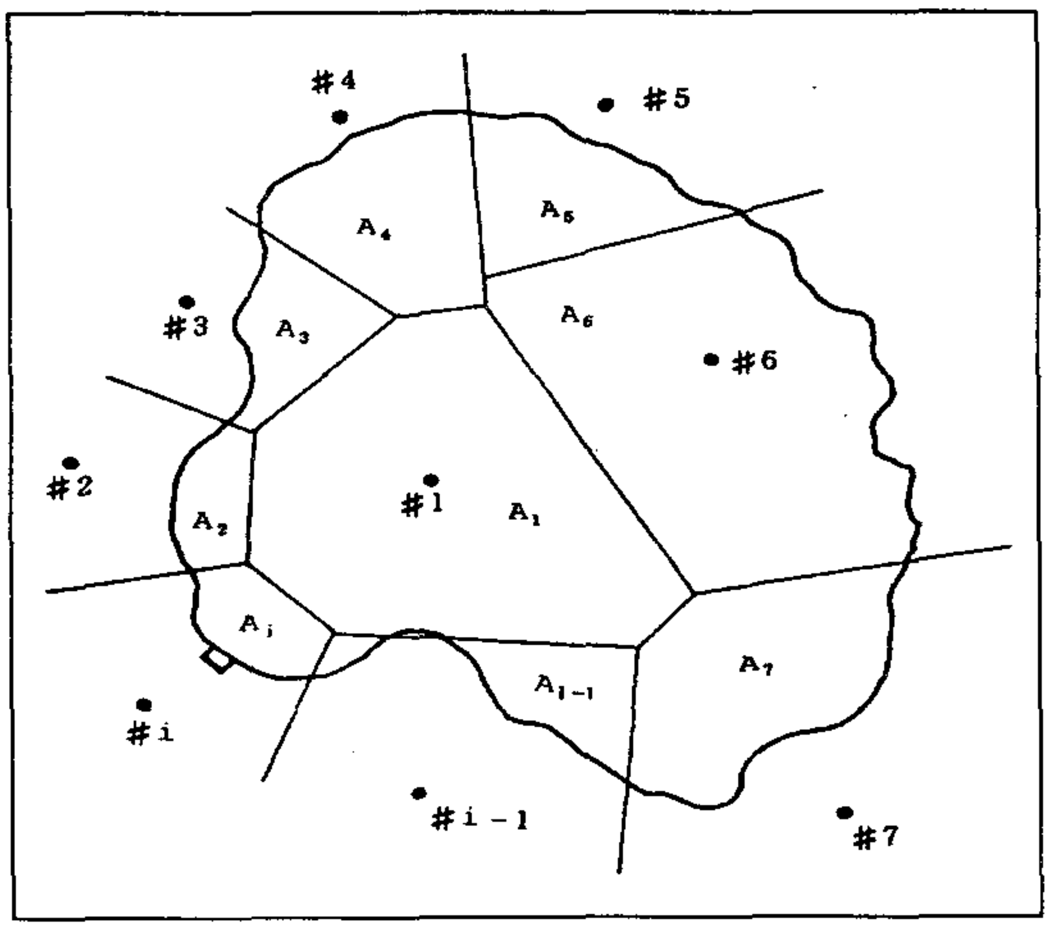

Fig 1. Divided drainage area by weather stations

data measured at several weather stations because total drainage area always contains several weather stations. If weather stations exist in total drainage area as shown in Fig. 1, the average rainfall of total drainage area can be expressed as follows by the Thiessen method.

$$R = \Sigma W_i R_i, \quad W_i = A_i/A \quad (8)$$

where A_i and R_i mean the small drainage area divided by i_{th} weather station and the amount of rainfall measured at i_{th} station, respectively.

Flowrate at a SHP site can be expressed as follows.

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

The cumulative distribution function and the probability density function are expressed as follows.

$$F(Q) = A\Sigma W_i[1-\exp\{-(q_i/\beta_i)^{\alpha i-1}\}] \quad (10)$$

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

The flow duration prediction model at SHP site which can indicate flow duration characteristics is obtained as follows.[2)]

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

3. Performance prediction model of SHP plant

Energy extracted from a SHP plant is affected by flowrate and head. Ideal hydro energy can be calculated as follows.

$$P_i = \rho gQH \quad (13)$$

Power extracted from a tunnel-type SHP plant per unit head is shown in Fig. 2. Power from the plant differs from ideal hydro energy, because of design flowrate and efficiency of hydro generator. Up to design flowrate, the power is varied linearly with flowrate, however, it is always less than the ideal hydro energy. From design flowrate, the power is maintained constant because the exceeding flowrate is discharged over diversion dam.

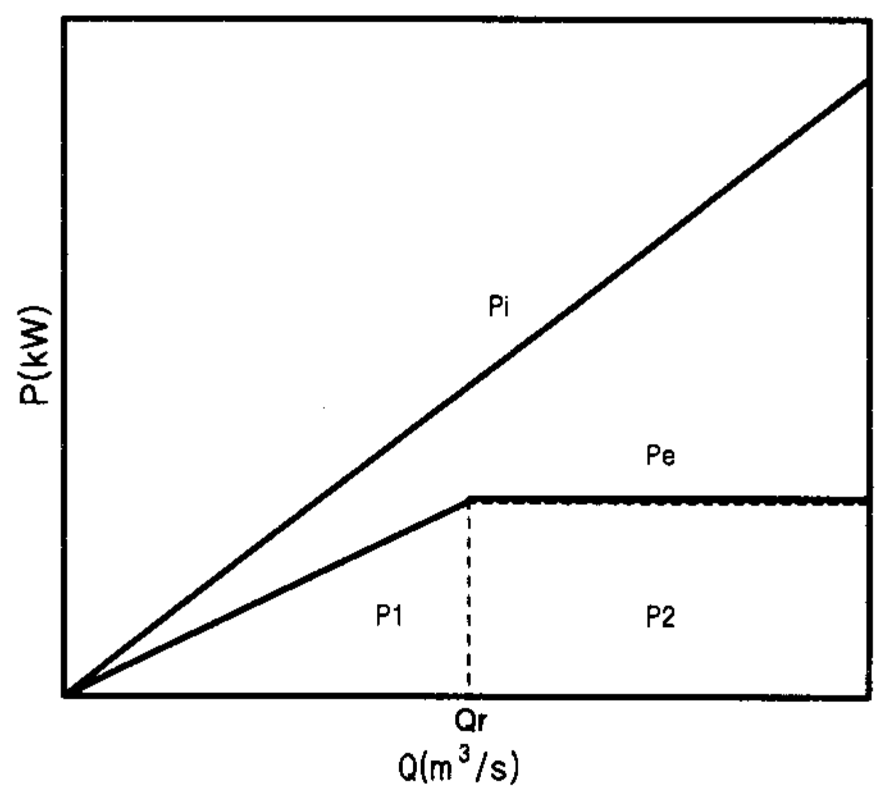

Fig. 2. Power characteristics of SHP

Electricity produced from SHP plant per unit time is obtained as follows.[3)]

$$P = \rho gH\eta\int_0^{Q_r} P(Q)dQ + \rho gH\eta Q_r\int_{Q_r}^{\infty} P(Q)dQ \quad (14)$$

Performance prediction model of SHP having diversion dam can be expressed as follows, assuming plant efficiency maintains a constant value during operation.

$$\begin{aligned} P &= \rho gH\eta\{\int_0^{Q_r} P(Q)dQ + Q_r\int_{Q_r}^{\infty} P(Q)dQ\} \\ &= \rho gH\eta(S_1+S_2) \\ &= P_1+P_2 \end{aligned} \quad (15)$$

The capacity of SHP plant, the operational rate and the annual electricity production can be calculated as follows.

$$C = \rho gHQ_r \quad (16)$$

$$L_f = (S_1+S_2)/Q_r \quad (17)$$

$$E_a = 8{,}760\ CL_f \quad (18)$$

4. Results and discussion

Nine tunnel-type SHP sites with diversion dam were selected and analyzed. The geological data of each site are summarized in Table 1. Natural head and river width of selected sites were decided by actual site

Table 1. Characteristics of SHP sites

sites	drainage area (A, ㎢)	head (H, m)	dam height (m)
Daeki	215.0	25.8	5.0
Duckchon	2,025.0	14.1	5.0
Kujul	233.0	21.6	6.0
Dodon	733.0	8.1	5.0
Misan	349.0	12.1	6.0
Kikok	277.9	20.3	4.0
Hwoiryong	955.8	12.2	5.0
Daiya	170.8	22.0	5.0
Yangchon	1,096.6	5.9	4.0

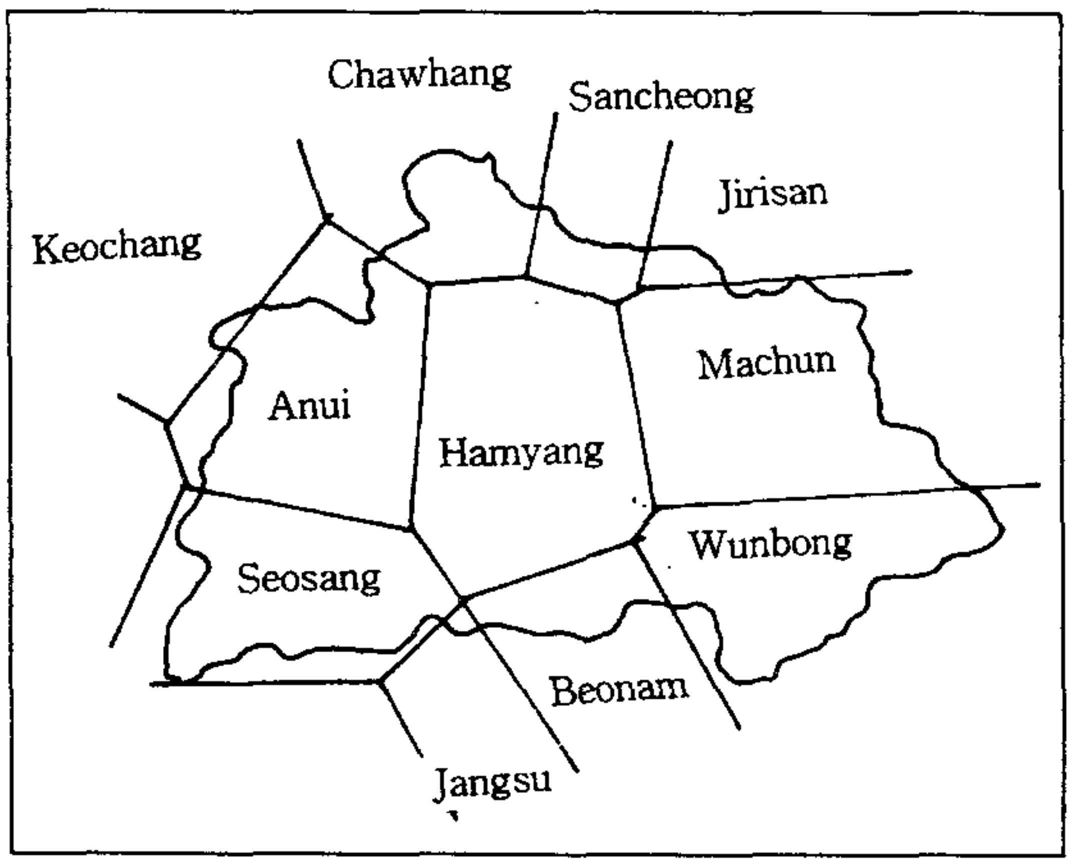

Fig. 3. Divided drainage area of Yangchon site

Table 2. The characteristics of divided drainage area

weather station	drainage area (A_i, ㎢)	weight (W_i,%)	scale parameter (β, m³/sec)	shape parameter (α)
Seosang	153.9	14.1	0.020080	0.767730
Jangsu	3.1	0.3	0.021078	0.802574
Anui	161.9	14.8	0.018355	0.742935
Keochang	3.1	0.3	0.020090	0.752564
Beonam	43.5	4.0	0.019440	0.752963
Hamyang	249.5	22.8	0.022712	0.804387
Chawhang	57.2	5.2	0.020226	0.729155
Wunbong	163.0	14.9	0.023807	0.794683
Machun	223.1	20.4	0.023056	0.753964
Sancheong	25.9	2.4	0.024057	0.759215
Jirisan	12.4	1.1	0.028511	0.796184
Total	1,096.6	100.0		

survey and dam heights were restricted to avoid submerging of the residential areas in upstream.[4)]

Out of nine tunnel-type SHP sites in Table 1, Yangchon site was selected for performance prediction. Drainage area of Yangchon site shown in Fig. 3 is measured 1,096.6km^2 and is divided by small areas affected from eleven weather stations. The characteristics of divided areas are shown in Table 2.

Fig. 4 shows the flow duration curve of Yangchon site enabled by combining the characteristics of small drainage areas in Table 2.

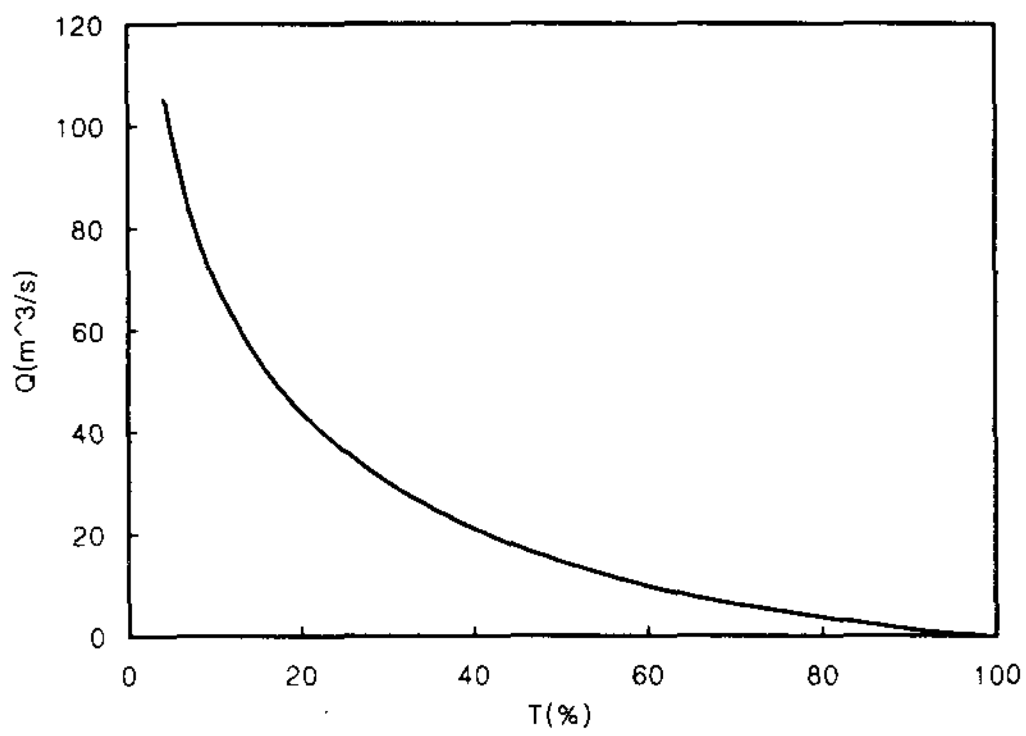

Fig. 4. Flow duration curve of Yangchon site

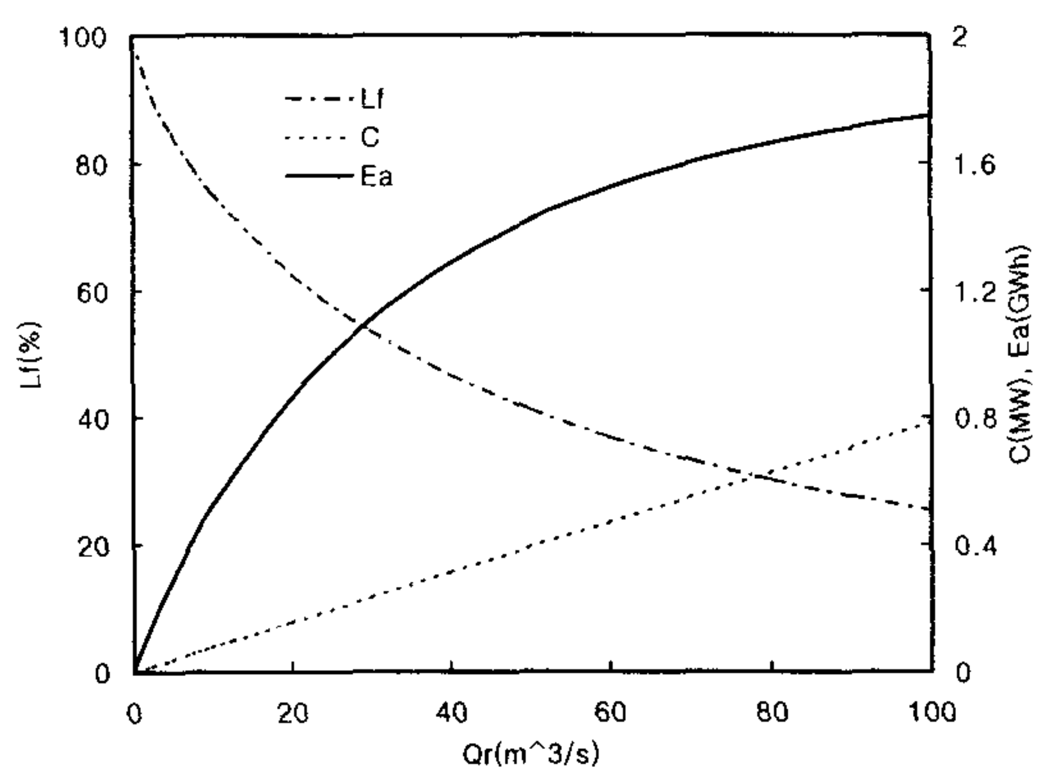

Fig. 5. Capacity operational rate and electricity production with flowrate

Fig. 5 shows the variation of operational rate, plant capacity and annual electricity production with variation of design flowrate. Plant efficiency was assumed to 0.8 and effective head of 9.2m was applied to analyze the performance characteristics of the sites.

Capacity of SHP plant vary linearly with the variation of design flowrate, but operational rate decrease with increase of design flowrate. Also, operational rate is decreased rapidly in the region of lower design flowrate and decrease gradually in higher design flowrate region. Annual electricity production increase gradually in the higher region.

Fig. 6 shows comparison of electricity production with variation of design flowrate. As shown in Fig. 6, the electricity production of tunnel-type SHP plant with diversion dam is consisted of two parts, electricity which is produced at rated power P_2 and at part load condition P_1. In order to design and operate SHP plant effectively, it is important that flowrate to maximize P_2 can be selected as

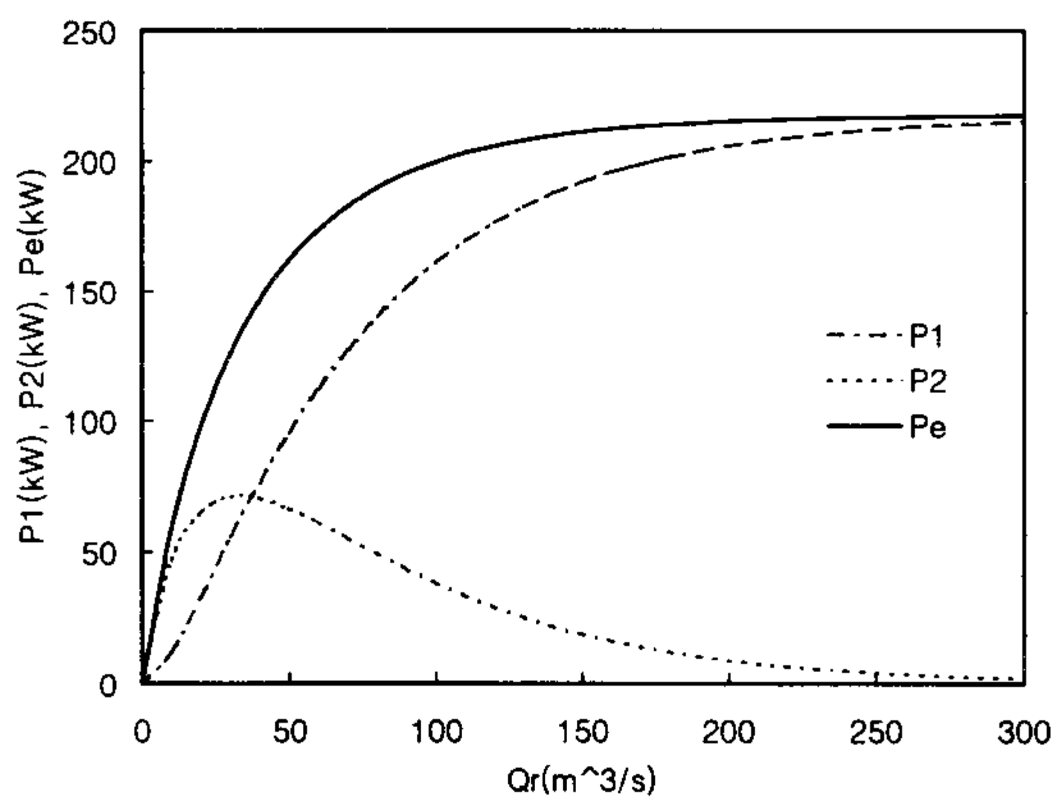

Fig. 6. Comparison of electricity production with variation of design flowrate

Table 3. Summary of performance for SHP sites

Sites	Flowerate (Q_r, m³/sec)	Head (H,m)	Capacity (C,kW)	Operational rate(L_f,%)
Daeki	6.0	29.2	1,370	43.1
Duckchon	38.5	17.8	5,370	51.2
Kujul	7.0	26.1	1,430	41.3
Dodon	21.5	12.2	2,056	45.4
Misan	10.0	17.1	1,340	43.5
Kikok	7.0	22.8	1,250	49.9
Hwoiryong	23.5	16.0	2,940	56.1
Daiya	4.5	25.5	900	48.0
Yangchon	33.5	9.2	2,410	51.1

design flowrate. For the case of Yangchon SHP site, design flowrate and capacity per unit head are decided to be 33.5m³/s and 262.6kW respectively.

The system characteristics and the design flowrates for nine tunnel-type SHP sites are summarized in Table 3. Operational rate ofeach site shows quite different value caused from hydrological and geological conditions. As a result, it is found that the model developed in this study is useful tool to analyze the performance of SHP sites.

5. Conclusions

Performance prediction for tunnel-type SHP sites with diversion dam has been studied, using a developed model. The primary design specifications including capacity and design flowrate for each tunnel-type SHP plant were suggested. It was found that the methodology developed in this study was useful tool to analyze the performance of tunnel-type SHP sites.

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