# Hydrological Stability Analysis of the Existing Soyanggang Multipurpose Dam

**Ko, Seok Ku* · Shin, Yong Lo****

**ABSTRACT :** This study aims at suggesting an alternative to improve flood controlling capacity according to the current design criteria for the existing Soyanggang Multi-purpose Dam which was constructed 20 years ago as the largest dam in Korea. The peak inflow of the adopted probable maximum flood (PMF) at the time of construction was 13,500 $m^3/s$. However, the newly estimated peak inflow of the PMF is 18,100 $m^3/s$ which is 1.34 times bigger than the original one. This is considered to be due to the accumulation of the reliable flood and storm event records after construction, and due to the increasing tendency of the local flood peaks according to the influence of world-wide weather change. The new estimation of the probable maximum precipitation (PMP) was based on the hydro-meteorological method suggested by the guideline of the World Meteorological Organization (WMO). The unit hydrograph which was applied for the estimation of PMF was derived through linear programming algorithm by minimizing the sum of absolute deviations of the calculated and recorded flood hydrographs. In order to adopt the newly estimated PMF as a design flood, following four alternatives were compared : (1) allocation of more flood control space by lowering the normal high water level, (2) construction of a new spillway in addition to the existing spillway, (3) construction of a new dam which has relevant flood control storage at the upstream of the Soyanggang dam, (4) raising the existing dam crest. The preliminary evaluation of these alternatives resulted in that the second alternative is most economic and feasible. So as to stably cope with the newly estimated PMF by meeting all the current functions of the multipurpose dam, a detailed study of an additional spillway tunnel has to be followed.

* General Manager, Develop. Management Dept., Spec. Works Div., KOWACO

** Researcher, Water Resources Research Institute, KOWACO

# 1. Introduction

## 1.1 The Soyanggang Multipurpose Dam

The Soyanggang project, which is the largest rockfill type dam in the Republic of Korea, was completed in 1973 after its commencement of the construction works in 1967 by the Korea Water Resources Corporation (KOWACO). The Soyanggang dam whose dimensions are 123 meters in height, 530 meters in length provides flood control, hydropower generation, and low flow augmentation for water supply, recreation and water quality enhancement of the downstream area including the Seoul metropolitan city. The dam which has the gross storage of 2.90 $km^3$ with a flood control space of 500 $hm^3$ generates 353.0 GWh annually form the installed two units of 100 MW hydropower generator.

The dam is located above 188 km upstream form the estuary of the Han River which is the largest river in the republic of Korea. The Soyanggang dam has the drainage area of 2,703 $km^2$, and the length of the river above the dam is approximately 160 km. The climate of South Korea including the Soyanggang dam basin is a monsoon type, and it varies with geographical location and time of year.

Because the Korea peninsula is somewhat isolated form the vast oceanic bodies, the climate is a compromise between a marine climate and continental climate. Annual precipitation at the Soyanggang dam basin has varied from a minimum of 775 mm to a high of 2,018 mm in the past with the annual average precipitation of 1,146 mm.

## 1.2 Object of Study

The flood discharge spillway was designed according the peak inflow of 10,500 $m^3/s$ which was equivalent to a 200-year returning period flood, and the designed spillway discharge capacity was based on the regulated peak outflow of 5,500 $m^3/s$. However two extraordinary floods (11,995 $m^3/s$, Sept. 2, 1984; 10,653 $m^3/s$ Sept. 11, 1990) which were bigger than the spillway design flood occurred after completion of the project.

Moreover the possible failure of the dam can result in disaster of calamity in loss of civil lives and property damages because heavily populated residential cities and highly developed industrial and commercial areas including the city of Seoul are located in the downstream area of the dam. The configuration of cascade dams along the lower reaches of the river may cause more miserable damages from a possible dam break.

This study aims at suggesting the best alternative to improve flood controlling capacity of the existing Soyanggang Multi-purpose Dam which was constructed 20 years ago as the largest dam in Korea. For the development of the best alternative, extensive hydrological analyses have been performed according to the current design concepts and design philosophy.

The analyses include; hydrological review of the original design by introducing current design concepts; statistical comparison of flood frequencies between before and after construction of the Soyanggang dam project; new estimation of the probable maximum precipitation (PMP) and probable maximum flood (PMF) using the reliable flood and storm event records based on the representative unit hydrograph; and generation and preliminary evaluation of alternatives for the derivation of the best one in order to stably cope with the newly adopted design flood.

## 2. Hydrological Review of the Original Design

### 2.1 Hydrological Features of the Original Design

In order to maximize the utilization of the limited water resources, the Korean government promulgated a special law on the multipurpose dam in 1964. In this regards KOWACO was established for the integrated national water resources planning and development in 1966. The Soyanggang Multipurpose Dam was commenced its development as the first commissioning water resources project from the government to the KOWACO.

Although this dam was considered as the most attracting water project in multipurpose utilization of water resources, there was no enough hydrological data at that time for the project development. Even though the hydrological investigations in the major river systems were begun prior to 1920 when a moderate network of stream gaging stations was completed, the available stream gaging data of the Soyanggang dam site were limited to just 10 years record for the only one station from 1959 to 1968. However, the precipitation data from 6 stations were moderately long with gaging periods of ranging from 19 to 40 years.

According to the final construction report (1974) prepared by KOWACO and its consultants, the flood control scale of the main dam was designed by the inflow with a return period of 1,000 years which had a peak discharge of 13,300 $m^3/s$. However, flood spillway was designed by the peak inflow of 10,500 $m^3/s$ which was equivalent to a flood of 200 years return period. The followings are the principal features of the hydrological design result:

*Main Dam and Reservoir*

| | |
|---|---|
| Designed Flood | : 13,300 $m^3/s$ (1,000-yr.-freq.) |
| Dam Crest Elevation | : El. 203.0 m |
| Flood Water Level | : El. 198.0 m (200-yr.-freq.) |
| Surcharge Water Level | : El. 200.5 m (1,000-yr.-freq.) |

Normal High Water Level : El. 190.3 m (summer season)
Flood Controlling Space : 500 $hm^3$

*Spillway*

Designed Flood : 10,500 $m^3/s$ (200-yr.-freq.)
Regulated Peak Discharge : 5,500 $m^3/s$
Spillway Crest Level : El. 185.5m
Spillway Gates : 5 Tainter Gates of 13m × 13m

*Power House and Outdoor Switchyard*

Designed Tail Water Level : El. 87.2 m
Designed Flood Discharge : 5,500 $m^3/s$ (200-yr.-freq.)

### 2.2 Designed Unit Hydrograph

Because the flood records for this project design were very limited as afore described, the floods were simulated using the derived unit hydrograph and the precipitation records from 1917 to 1941 and from 1957 to 1967. For the unit hydrograph derivation, precipitation and flood records of 9 storm events from the year of 1966 were utilized. The peak discharges of the utilized flood events were ranged from 956 to 5,051 $m^3/s$ which are considered rather small for the design flood estimation.

Because the applied technique for the unit hydrograph derivation was "the Method of Principal Equations", it was necessary to estimate one by one from the recorded each storm event rather to estimate a single one from the multi-storm events. Table 1 shows the result of the unit hydrograph derivation. As shown in this table, even if the variations of the time to peak ($t_p$) and peak discharge ($q_q$) are rather big, these values were adopted by averaging the values from seven events by excluding two outlying events.

Annual flood peaks of 39 years were estimated using the derived unit hydrograph and recorded precipitation data including the 10 recorded annual floods from 1959 to 1968. The frequency analysis using these annual peak floods is shown in Table 2.

### 2.3 Statistics and Trend Analysis of the Floods Events

Statistical analysis was applied in deriving frequency curves using annual peak events including the floods occurred after the construction of the dam. As a result of fitness test, the analysis was made according to the Gumbel distribution. In the analysis, twenty eight annual peak inflows were considered including the data spanning from 1958 to 1968 and from 1974 to 1990.

The result of the statistical analysis is shown in Table 2 and it was compared with the original design result. This result shows that the newly estimated recurring floods are 1.25 to

Table 1. Originally Designed Unit Hydrograph

| Unit Graph Statistics | Time to Peak($t_p$) (hours) | Peak Discharge($q_p$) ($m^3/s$) |
|---|---|---|
| Minimum | 5.0 | 31.7 |
| Maximum | 16.0 | 103.1 |
| Average of 7 Events | 7.7 | 46.1 |
| Standard Deviation | 1.6 | 8.1 |

Table 2. Comparison of Statistical Analysis Results

| Recurring Interval (year) | Original Design($m^3/s$) (A) | Updated Statistical Results | |
|---|---|---|---|
| | | New Estimate ($m^3/s$) (B) | Increased Ratio (B/A) |
| 5 | 4,130 | 5,490 | 1.329 |
| 10 | 5,270 | 7,030 | 1.334 |
| 50 | 8,240 | 10,430 | 1.266 |
| 100 | 9,360 | 11,870 | 1.268 |
| 200 | 10,500 | 13,300 | 1.267 |
| 500 | 12,090 | 15,200 | 1.257 |
| 1,000 | 13,340* | 16,600 | 1.244 |

1.33 times bigger than the designed ones which were estimated at the planning stage.

Judging from the trend analysis, the annual flood peaks have the significant ascending tendency, and it is noted that the annual peak inflows above 10,000 $m^3/s$ took place twice during recent ten years. This is considered to be due to the increasing tendency of the local flood peaks according to the influence of world-wide weather change.

### 2.4 Identified Hydrological Problems

On the bases of Selection of design flood (1992), published by ICOLD (International Commission on large Dams) and current Korean design concept, the principal problems in this design can be outlined as follows ;

(1) According to the category of dam on the basis of a method of Floods and reservoir safety-An engineering guide (1978), developed by the Institution of Civil Engineers the Soyanggang dam can be categorized as a dam where a breach will endanger lives in a community. Hence the general standard of the dam design flood must be probable maximum flood (PMF) because no overtopping is allowed for the dam. Therefore, PMF has to be used for the design flood of the main dam instead of 1,000 years return period flood from the frequency analysis. However, the 1,000 years return period flood was considered as the PMF at the time of design stage, moreover the available hydrological datum were very limited at that time.

(2) The unit hydrograph for the flood analysis of the basin has to be re-derived using the recorded reliable big storm events instead of small ones.

(3) The flood controlling system has to be re-evaluated in order to control the newly estimated

design flood of PMF and the capacity of the spillway system has to be expanded according to the considering flood.

## 3. New Estimation of Design Floods

### 3.1 Unit Hydrograph Derivation from Multiple Storm Events

The unit hydrograph which is usually based on the principle assumptions of time-invariant-linearity and superposition is useful tool for extrapolating the available data. In real problems, however these assumptions are not always true because of the different hydrological conditions and measurement errors. Especially for the multiple storm events the unit hydrographs of the respective rainfall storms are sometimes quite different from each other. In this regards, optimization techniques or least square methods are usually applied to minimize the possible errors due to the afore mentioned assumptions or measurements.

Based on the optimization technique of linear programming (LP) suggested by Mays and Coles (1980), the objective function of Eq. (1) was selected so as to minimize the sum of the absolute values of errors. If it is assumed that a given watershed becomes like a lumped time-invariant-linear system, then the observed direct runoff rate for the ith storm event and for the time period n is expressed as Eq. (2). In this equation, if the system is conservative, the unit hydrograph ordinates add up one as expressed by the Eq. (3). Also to avoid the oscillation of unit hydrograph, Eqs. (5)(Kwon et al., 1993) and (4) are added.

$$\text{Min } Z = \sum_{i=1}^{I} \sum_{n=1}^{N_i} [Z_i(n) + V_i(n)] \tag{1}$$

subjected to:

$$Q_i(n) = \sum_{m=1}^{M} [p_i(n-m+1) \cdot u(m)] + Z_i(n) - V_i(n) \tag{2}$$

$$\sum_{m=1}^{M} u(m) = 1.0 \tag{3}$$

$$2\,u(m) \geq u(m-1) + u(m+1) \quad (2 \leq m < m_p) \tag{4}$$

$$2\,u(m) \leq u(m-1) + u(m+1) \quad (m > m_p) \tag{5}$$

where:

$Q_i(n)$ = Observed direct runoff rate for the $i^{th}$ storm event and for the time period n; $p_i(n-m+1)$ = mean excess rainfall for the time period [if $(n-m+1) \leq 0.0$, $p_i(n-m+1) = 0.0$]; $u(m)$ = $m^{th}$ ordinate of the unit hydrograph; $Z_i(n) - V_i(n)$ = difference between observed value and predicted value($Z_i(n)$

and $V_i(n)$) are non-negative variables); M=the memory of the system defined by the period number of the last non-zero unit hydrograph ordinate; I=number of storm events; $N_i$=number of time periods for the ith storm; and $m_p$=time to peak.

Because the model is expressed as a set of linear equations, the linear programming(LP) package of LINDO program (Schrage, 1991) was applied to obtain a representative unit hydrograph of the Soyanggang dam. For the LP application, all the variables of the above model should be non-negative.

$$
\begin{aligned}
& u(m) \geq 0.0 \text{ for } m=1,\cdots\cdots, M \\
& Z_i(n) \geq 0.0 \text{ for } i=1,\cdots\cdots,I;n=1,\cdots\cdots,N \\
& V_i(n) \geq 0.0 \text{ for } i=1,\cdots\cdots,I;n=1,\cdots\cdots,N
\end{aligned} \tag{6}
$$

Three observed big storm events which were occurred after the completion of the Soyanggang dam were applied. They are June flood of 1990 with peak inflow of 2,773 $m^3/s$; July flood of 1990 with peak inflow of 4,791 $m^3/s$; and September flood of 1990 with peak inflow of 10,653 $m^3/s$.

The derived unit hydrograph and comparison of the designed hydrograph are shown in Table 3 and Fig. 1 It is noted that the unit hydrograph was also re-estimated during the construction in 1972 after experiencing the 100-year flood in the August of 1972 (peak discharge was 9,175 $m^3/s$). However the design flood was not revised at that time.

### 3.2 New Estimation of Probable Maximum Flood (PMF)

#### 3.2.1 Probable Maximum Precipitation (PMP)

Probable maximum precipitation (PMP) is currently defined as the greatest depth of precipitation for a given duration meteorologically possible for a given size storm area at a particular geographical location at a certain time of year with no allowance made for long-term climatic trends (WMO, 1986). The storm-centered PMP values cannot be applied directly to a drainage, but must be modified to develop a drainage-averaged PMP estimate. This is defined (Hansen et al., 1982) as the average PMP depth over the drainage after the storm-centered PMP value has been distributed across the drainage in accordance with the PMP storm pattern and appropriate computational procedures.

At the planning stage of the original design in 1967, 3 days duration PMP of 789㎜ was estimated by using the recorded 3 days maximum precipitation of 457.1㎜ which had arisen in the basin from Jul. 13 to Jul. 15, 1925.

Hydro-meteorological method (WMO, 1986) was adopted again for the re-estimation of PMP as did in the original design. As a traditional approach of this method, estimation of PMP includes moisture maximization, transposition of observed storms and marginal evaluation according to the

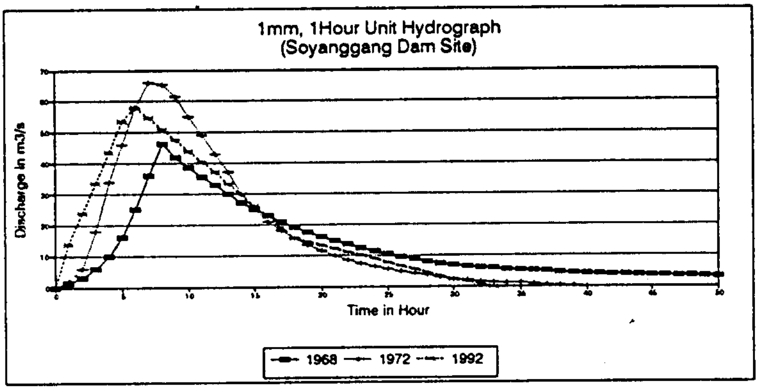


Fig. 1. Comparison of the Unit Hydrographs

Table 3. Original and Newly Derived Unit Hydrograph

| Estimated Year Unit Hydrograph | Current Design 1968 (A) | New Estimation | | | |
|---|---|---|---|---|---|
| | | 1972 (B) | Ratio (B/A) | 1992 (C) | Ratio (C/A) |
| Memory Time(hours) | 55.0 | 40.0 | 0.727 | 32.0 | 0.582 |
| Time to peak(hours) | 8.0 | 7.0 | 0.875 | 6.0 | 0.750 |
| Peak discharge($m^3/s$) | 46.1 . | 66.9 | 1.451 | 58.2 | 1.262 |

drainage size and duration of PMP. For the re–estimation of PMP, three more recorded big storm events which occurred in the Han River basin were considered in order to improve the accuracy, reliability of the PMP.

Through a depth–area–duration (DAD) analysis of the considered storm events, 3 days duration–basin average rainfall depths of the recorded storms are 457.9, 483.0, 538.0 ㎜, respectively, of which values are 0.0 to 17.8 % bigger than the originally adopted 457.1 ㎜ at the planning stage.

PMP values were estimated according to the traditional approach, and these values are shown in Table 4, Estimated 72 hour duration PMP value is 760 ㎜, which is slightly less than the originally estimated value of 789 ㎜.

### 3.2.2 Probable Maximum Flood (PMF)

The flood simulating computer model of HEC–1 program (1987) which was developed by the United States Army Corps of Engineers was utilized to estimate the PMF by using the newly estimated unit hydrograph and PMP.

To apply this model the precipitation loss was estimated by simulating the experienced extreme flood storms. Initial rainfall loss of 4.0 ㎜ and uniform loss rate of 1.1 ㎜/hr were estimated from the simulation, of which are identical to the values of original design. The hyetograph of hourly distribution of the estimated PMP was derived from the rainfall distribution pattern of the 1990 Sep-

Table 4. Estimated PMP and PMF

| PMP | | RMF |
|---|---|---|
| Duration(hr) | Rainfall(mm) | ($m^3$/s) |
| 12 | 420 | 18,100 |
| 18 | 521 | 18,900 |
| 24 | 590 | 19,100 |
| 48 | 690 | 17,400 |
| 72 | 760 | 18,100 |

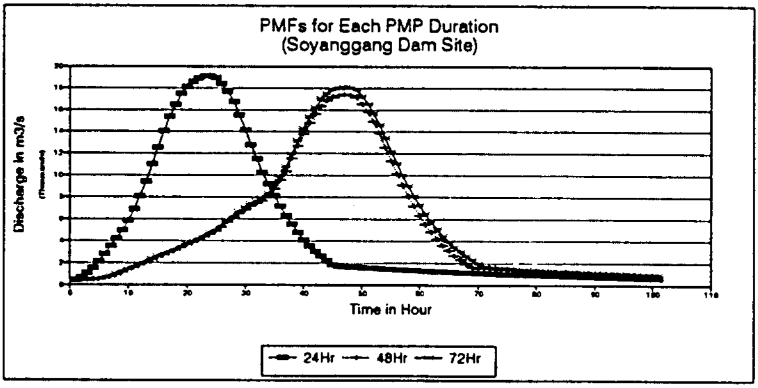


Fig. 2. Newly Estimated PMFs for Each PMP Duration

tember storm.

For the base flow identification, the initial flow of 400 $m^3$/s (Final construction report, 1974) with recession threshold flow of 9 % of computed peak discharge and recession coefficient of 1.02 after recession threshold flow were derived from observed hydrographs.

Table 4 and Fig. 2 show the results of hydrologic simulation using the computer program HEC-1 with the identified unit hydrograph and various parameters according to the rainfall duration of the estimated PMP.

## 4. Considered Alternatives

In order to adopt the newly estimated PMF which considers to the severe hydro-meteorological conditions as a design flood, following four alternatives were compared; allocation of more flood control space by lowering the existing normal high water level during flood season, construction of an emergency spillway tunnel in addition to the present spillway, raising the existing dam crest, construction of a new dam which has relevant flood control storage and construction of fuse plug as a emergence spillway. Fuse plug structures which are more economical than the other inlet structures are designed by breaching and washing off the structure to release extreme flood for protecting the main embankment (Shen , 1994). But construction of fuse plug was excluded as a alternative in this study because there are no low saddles or depressions along the Soyanggang reservoir rim encircled by high mountains.

When the newly estimated PMF inflows into the Soyanggang reservoir under the existing flood operating rule, the reservoir water level comes up to 3.2 meters above the current surcharge water level according to the PMFs relevant to the PMP durations. Maximum water level was induced by the PMF from the PMP of 72 hours, which might overtop the current dam crest and cause severe damages to the dam safety. Therefore, the PMF produced by the 72 hours duration PMP is tentatively selected as the new design flood for the hydrologic analysis of the existing Soyanggang dam. Also although the flood water level of Soyanggang is 198.0 meters, the elevation of the impervious centered core zone is 202.6 meters according to final construction report on Soyanggang Multi-purpose dam project (Final construction report, 1974). In this study to take into consideration of the settlement of dam body and of the uncertainty of construction work, the design flood level to PMF was adopted as 200.5 meters which was the surcharge water level at the planning and design stage of Soyanggang dam.

### 4.1 Allocation of Extra Flood Control Space

By lowering the current normal high water level of El. 190.3 m to El. 177.6 m, it is possible to regulate the new tentative design flood of PMF by allocating the extra flood control space of 350 $hm^3$. However this alternative brings out reduction in annual hydro-energy production of 53 GWh, and reduction of annual water supply of 292 $hm^3$.

Moreover, considering that current spillway crest elevation is 185.5 m which is much higher than the lowering normal high water level of 177.6 m, it will require much cost in economy and hard efforts in engineering.

### 4.2 Construction of a Spillway Tunnel

Because of the geomorphological constraint, expanding the existing spillway requires extremely large volume of excavation of left abutment. Moreover it might cause severe stability problems due to the fragility of the dam abutment.

In this regards, free overflowing ogee weir with diversion tunnel type spillway was considered as an extra spillway. In this tunnel spillway the flow is free flow at the beginning of flood inflow. However if the reservoir water level exceeds certain amount and the overflowing discharge through the weir exceeds the free flowing tunnel capacity, the flow turns into a pressure flow over the certain transition zone.

The results of the hydraulic calculation with reservoir flood routing are summarized as followings and on Fig. 3.

| *Structural Dimensions:* | | *Flood Routing:* | |
|---|---|---|---|
| Length of Weir | : 85.0 m | Peak Inflow | : 18,100$m^3$/s |

| | | | |
|---|---|---|---|
| Elevation of Weir Crest | : El. 190.3 m | Peak Discharge | : 12,095$m^3/s$ |
| Tunnel Dimension | : Φ15.0 m (circular) | Existing Spillway | : 7,223$m^3/s$ |
| Length of Tunnel | : 900.0 m | Spillway Tunnel | : 4,672$m^3/s$ |
| Elevation of Tunnel Entrance | : El. 170.0 m | Discharge Though Turbine | : 200$m^3/s$ |
| Elevation of Tunnel Exit | : El. 60.0 m | Peak Reservoir Water Level | : El. 200.5m |

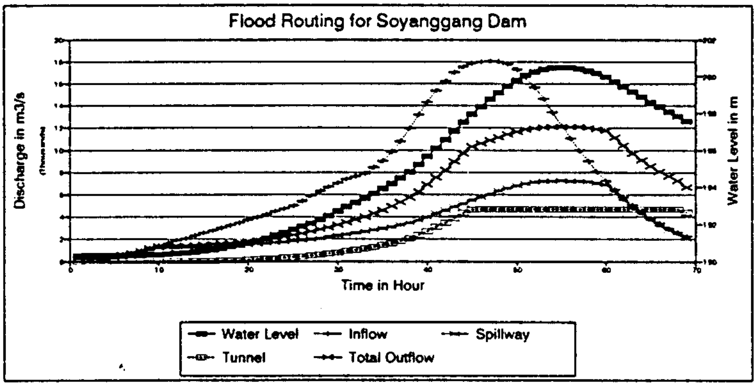


Fig. 3. Flood Routing with Additional Spillway Tunnel

### 4.3 Heightening the Existing Dam

In case the selected PMF inflows into the reservoir under the existing flood operating rule, the maximum water level will reach to the Uelevation of 203.7 meters which is 3.2 meters higher than the originally designed surcharge water level of 200.5 meters.

In order to heighten the existing dam by 3.2 meters, the estimated embankment volume is about 1. 23 $hm^3$ and the compensation of the reservoir area is about 3.70 $km^2$ including residential areas. Moreover it has the structural difficulties of heightening the existing spillway gates and appurtenant facilities.

### 4.4 Construction of a Upstream Flood Control Dam

The total flood control storage of 850 $hm^3$ was required to safely pass the PMF at Soyanggang dam site, therefore the volume which should be added to Soyanggang dam was 350 $hm^3$, considering the present flood control storage (500$hm^3$) of the Soyanggang dam.

As a result of joint operation of Soyanggang and Inje dam (drainage area: 1,059 $km^2$), the required minimum diameter of Inje tunnel spillway was 12.5 meters and the top elevation of Inje dam crest was 317.0 meters so that the PMF could stably passed through the spillway of Soyanggang dam. However this alternative requires long term design and evaluation for the project development and requires too much investment cost (316 billion won).

## 5. Discussions and Concluding Remarks

This study aimed at evaluating the design flood and suggesting an alternative to improve the flood controlling capacity according to the current design criteria for the existing Soyanggang Multi-purpose Dam which was constructed 20 years ago as the largest dam in Korea.

Judging from the trend analysis, the annual flood peaks have the significant ascending tendency and the result of the statistical analysis shows that the newly estimated recurring floods are 1.25 to 1.33 times bigger than the designed ones which were estimated at the planning stage. Estimated 72 hour duration PMP value which was estimated according to the traditional approach is 760 mm. The originally designed peak inflow of 1,000 years recurring interval as the adopted PMF at the time of planning stage was 13,500 $m^3/s$. However the newly estimated peak inflow of the PMF is 18,100 $m^3/s$ which is 1.34 times bigger than the original one. This is considered to be due to the accumulation of the reliable flood and storm event records after construction, and due to the increasing tendency of the local flood peaks according to the influence of world-wide weather change.

So as to stably cope with the newly estimated PMF by meeting all the current functions of the multipurpose dam, four feasible alternatives were generated and evaluated according to the five criteria. The considered evaluation criteria are economic point, constructability, effects on the existing dam stability, reliability of the operation in case of the PMF inflow, and social problems arising from land acquisition and residential area compensation.

The construction cost of a spillway tunnel with free-flowing weir was estimated to be the least in cost as 55.5 billion Won (equivalent to 70 million US dollars). Moreover this alternative was evaluated as the best one in almost all the evaluation criteria. Accordingly a detailed study of an additional spillway tunnel has to be followed.

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