LONG-TERM RESERVOIR SEDIMENT MANAGEMENT CONSIDERING OTHER OPERATIONAL OBJECTIVES(*)

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1. INTRODUCTION

It is one of the most important factors in water resources management and operation to predict the impact due to potential sedimentation in dam. The improper design related to sediment may impede to achieve the objectives of dam and cause malfunctions in management stage. The problems due to sedimentation in water resources involve the reduction of effective storage of dam, the effect on water quality and ecosystem, and the increasing of flood level. Especially, the reduction of effective storage can reduce the control ability of dam inflow to fail water supply. In sluicing process, sedimentation can cause malfunction of hydraulic structures involving water turbine, sluicing tunnel and spillway inlet.

The storage facilities built in river cannot be free from of sediment inflow. As the facilities become larger, the amount of sedimentation deposited in reservoir will be more serious because the lag time of sediment becomes longer. In planning, design or operation of reservoirs, engineers should consider the preventive measures which can be taken to reduce the amount of deposited sediment in reservoirs and to estimate their long-term capacity to be kept in the future for various purposes.

Generally, there are three kinds of measures to manage sedimentation; 1) the method of minimizing sediment deposition in reservoir; 2) the method of maximizing sediment discharge through tunnel, or other outlets; 3) the recovery of storage capacity by sluicing.

The sedimentation in dam has relationship with dam operation pattern. In particular, according to the operation of dam in summer season the sedimentation can be varied

(*)Gestion à long terme des alluvions dans la retenue tenant compte d'autres objectifs opérationnels.

dramatically. As sedimentation situation is closely related to dam operation, it is possible to consider sedimentation as evaluation variable of water resources system. Lee etc. (1995) introduced information variable dynamic programming that defines the sedimentation as dependent variable. This dependent variable was treated as information variable of storage in routing storage. Fontane etc. (1989) used dynamic programming to optimally establish the salinity reduction plan, in which cost was regarded as state variable and salinity as constraints.

The purpose of this paper is to address a sediment management methodology that is based on optimal dam operation and used to predict sedimentation in reservoir. This prediction of sedimentation was performed in long-term prediction with monthly dam operation.

2. FENHE RIVER BASIN SYSTEM IN CHINA

Because of the high urbanization and large-scale industrialization since 1960s, the demand on the domestic and industrial water consumption in Taiyuan City of Shanxi province, located in Northern part of China, has been rapidly increasing.

Reservoir operating policies of the Fenhe No. 1 Reservoir, which is currently the only major reservoir existing upstream of the city of Taiyuan, are very complex because of reservoir sedimentation problem. The Fenhe No.1 Reservoir began operation in 1961 to provide for flood control, irrigation water supply and hydropower production

The reservoir has a total storage of 720 MCM

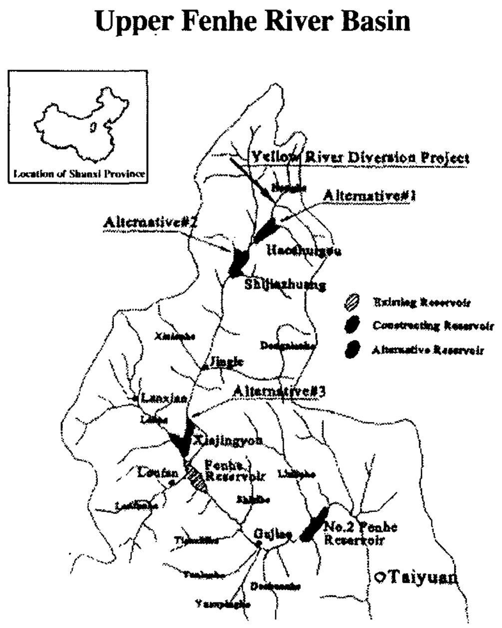

Fig 1. Fenhe River Basin of Yellow River - Bassin du fleuve Fenhe.

with 350 MCM allocated to sediment storage. The Fenhe River Basin is part of the loess plateau in China, and therefore, the river is heavily sediment laden. By the end of 1992, the 350 MCM sediment storage in the Fenhe No. 1 Reservoir is almost filled up. A sediment discharge tunnel is under construction at the reservoir to directly sluice sediment inflow in flood season and restore the active storage by scouring or eroding the deposited sediment during dry season.

Besides the existing No. 1 Fenhe Reservoir, the Yellow River Diversion and a new reservoir are brought on line in 1998 to meet increasing water demand in this area as shown in Fig. 1. It can be easily understood that the function of these water resources systems also be deteriorated by sedimentation. To reduce the sedimentation by proper dam operation, several factors must be considered. The original purpose of water supply may be the one.

3. METHODOLOGY

3.1 Reservoir Sediment Management Model

The dynamic programming algorithm, FENHEDP, modified CSUDP for sediment information variable, is used to find the optimal solution of multi-purpose reservoir problems. A weighting method is used to find non-dominated solutions between reservoir sediment and water shortage. Sediment inflow term should be included in a variable of reservoir operation rules and some tradeoff relationship among objectives will be analyzed for decision making.

In real water resources systems, several objectives have to be considered simultaneously. The proposed objectives for this study are the water supply stability, which can be evaluated by minimizing water deficit, and the extension of reservoir life time, which can be estimated by minimizing reservoir sediment or maximizing sediment sluicing. However, these two objectives are in conflict with each other. If a reservoir is to be operated to minimize water shortage, the reservoir sediment will increase. Otherwise the water shortage increases. So this problem has to be analyzed as a multi-objective optimization problem which has more than two objectives, and for decision making to choose the best answer, a set of non-dominated solutions are to be generated which are composed of various optimal alternatives.

The objective function to achieve the goals can be formulated as follows

$$Minimize\ F = \sum_{i=1}^{N} w_1 F_{1i} + w_2 F_{2i} \quad (1)$$

$$F_{1i} = D_i \quad (2)$$

$$F_{2i} = \sum_{k=1}^{L} (DWS_{i,k} + IWS_{i,k} + AWS_{i,k})^2 \quad (3)$$

$$U_i = X_{i-1} - X_i + I_i - T_i - E_i - R_i \quad (4)$$

$$D_i = D_{i-1} + S_i \mu_i \quad (5)$$

$$\mu_i = f(X_{1-i}, X_i, I_i, U_i) \quad (6)$$

$$X_i \geq D_i \quad (7)$$

$$X_{imin} \leq X_i \leq X_{i\,max} \quad (8)$$

$$U_{i\,min} \leq U_i \leq U_{i\,max} \quad (9)$$

where, F is the performance index, F_1 is the objective function for sediment during stage i, F_2 is the objective function for domestic, industrial and agricultural water shortage during stage i, w_1 , and w_2 are the weighting factors for controlling each objective function return value with regard to being a preferred or dominated solution, D_i is the deposited sediment during stage i, $DWS_{i,k}$, $IWS_{i,k}$, and $AWS_{i,k}$ are the domestic, industrial and agricultural water deficit during stage i, and N is the number of the operating stage.

3.2 The Sluicing Efficiency Curve

The trap efficiency, which is the ratio between sediment trapped in the reservoir and the total inflowing sediment, can be a function of the falling velocity of sediment and the allowable time for sedimentation. Brune (1950) developed empirical trap efficiency curve according to the reservoir capacity and total annual inflow.

The sluicing efficiency curve for short-term lag time, which is shown in Fig. 2, has been developed for Yellow River Basin in China. This sediment sluicing efficiency curve predicts the amount of sediment discharge as a function of reservoir volume and discharge rates of inflow and outflow. The long-term sedimentation according to dam operation can be predicted on the basis of sluicing curve that relates sluicing efficiency to lag time of sediment (Brune, 1950; IRTCES, 1985).

It could be decided through empirical flood detention time versus sluicing efficiency curve

$$\mu = f(\frac{XI}{U^2}, d_{50}, S) \qquad (10)$$

where, is the sluicing efficiency at stage i, X is the average storage capacity below the highest water level during the passage of the flood, U is the average inflow rate (m^3/sec), and I is the average outflow rate (m^3/sec), d50 is the median diameter of the suspended load carried

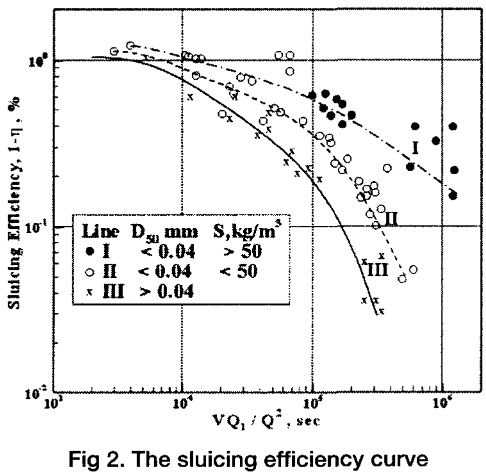

Fig 2. The sluicing efficiency curve - Courbe d'efficacité

by the flood (mm), S is the sediment specific weight of average concentration of the flood flow (kg/m^3).

The accumulated sediment deposit volume can be calculated as deposition of each stage through the following equation

$$D_i = D_{i-1} + SI \times \mu \qquad (11)$$

where, D_i is the accumulated sediment volume at the end of the stage i, D_{i-1} is the accumulated sediment volume at the beginning stage i and SI is the unregulated sediment inflow volume into reservoir at stage.

This curve is verified in following way. The observed sediment data are compared with simulated data, which are generated using reservoir simulation model with one empirical curve. The verification result shows that the sluicing efficiency curve adopted for this study can be used in long-term reservoir operation model, especially monthly and 10 days operation.

3.3 The Applications of the Reservoir Sediment Management Model

The storage function of reservoirs is to assure a better supply of water for users and consumers compared to withdrawal directly from natural river reaches.

The design of a reservoir, therefore, depends mainly on the needs to be met and on the water sources available. Since there are many variables to be considered in the Fenhe River Reservoir system, it is not easy to get a correct answer. The analysis strategies of the developed optimization model to cover these goals can be classified as follows in respect of the time horizon decided by the status of available water resources.

In order to get the best solution for the best solution for the No.1 Fenhe Reservoir operation, the optimization model, FENHEDP, was formulated based on the information variable DP (Lee etc., 1995). In model application, the weighting value of the domestic and industrial sectors in Eq. (1), is given the first priority so that the tradeoff relationship will be between agricultural sector and reservoir sedimentation.

The deposited sediment volume was predicted through monthly dam operation using FENHEDP and sediment sluicing curve from 1994 to 2030. Inflow data and sediment data over the past 30 years were used as input data in this model. Water supply was attained primarily, and sediment management was considered secondly to prolong dam life.

As shown in Fig. 3, the operation strategy that considers two objectives simultaneously was preferred to the operation strategy considering only water supply objective in terms of dam sediment control. Whether in latter case 262 MCM sediment was predicted to be deposited for 30 years, in former case 204 MCM sediment was predicted. Therefore, about 22 percent sediment will be expected to reduce.

In terms of long-term water supply, the operation considering sediment was also preferred to the operation not considering sediment as shown in Fig. 4. In same probability level the water deficit magnitude due to latter operation is larger than former operation. This result can be understood more precisely in Fig. 5. As passing the operation periods, the ability of water supply was diminished by the reduction of reservoir sediment.This phenomenon

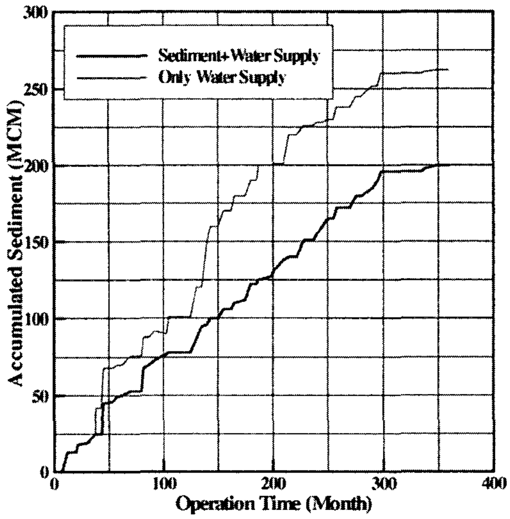

Fig 3. The comparison of deposited sediment for 30 years according to different reservoir operation
Comparaison du dépot des alluvions sur 30 ans selon le fonctionnement différent de la retenue.

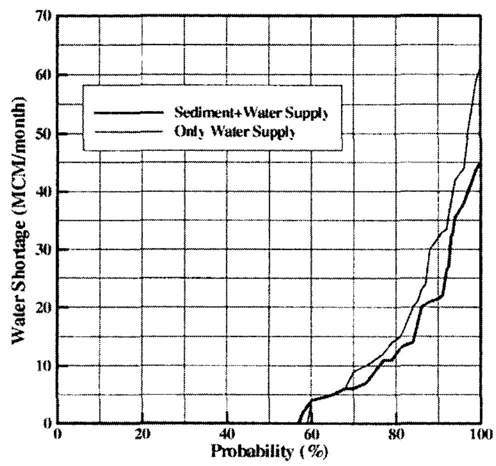

Fig 4. The comparison of long-term water deficit
Comparaison du deficit en eau à long terme.

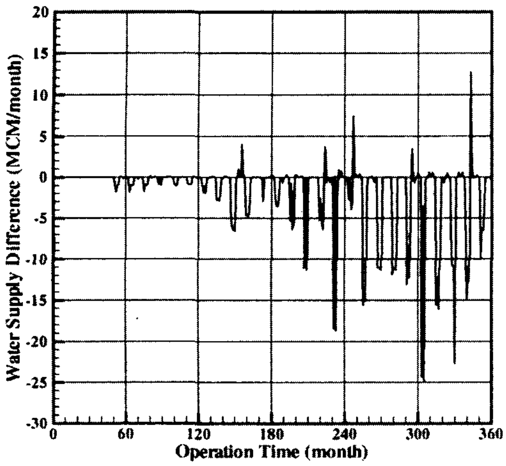

Fig 5. The comparison of water supply ability with/without considering sediment management
Comparaison des capacités d'alimentation en eau selon la gestion des sédiments

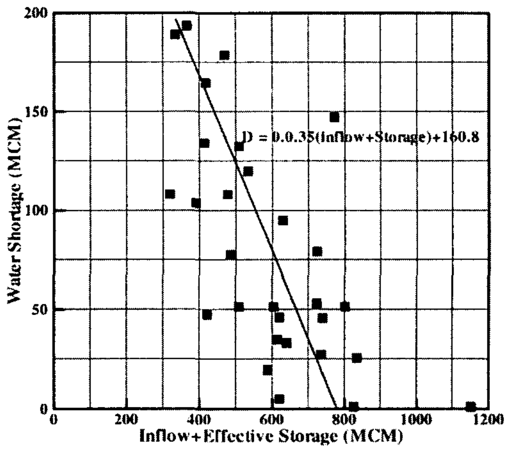

Fig 6. The change of water supply ability due to reduction of reservoir storage
Le changement de capacité d'alimentation en eau dû à la reduction de réserve de la rétenue.

apparently appears in the case of not considering sediment in reservoir operation. The water supply ability depends on reservoir storage as well as hydrologic condition. In Fig. 6, the relationship between water deficit and available water supply quantity, which is defined as sum of reservoir inflow and effective reservoir volume, was plotted. That figure says that water deficit is inversely proportional to as available water supply quantity.

4. CONCLUSIONS

In this study, the reservoir operation technique, one of the various sediment management measures, is applied to reduce sedimentation in Fenhe River Reservoir system. This technique involves sluicing sediment in summer season to lengthen dam life.

The optimization model, FENHEDP, which treats sediment as information variable, was developed and applied. Through this model the reservoir sediment is predicted for 30 years. The predicted results indicate that reservoir operation considering sedimentation will be more efficient in both water supply and sedimentation management than operation not considering sedimentation.

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Summary

The Yellow River Basin located in the Northern part of China is well-known not only as the seriously limited water sources but the greatest sediment-carrying stream in the world. The observed annual average sediment concentration in this area is 37.6kg/m³, and 3.1% of the water volume is occupied by sediments. Due to the reason, water development has been extremely limited and it has been appeared as one of the most difficult problems in reservoir development and management. The major obstacle to surface water uses is reservoir sedimentation so that it has been strongly requested to seek the method managing sediment by optimal fashion. To solve this problem, KOWACO (Korea Water Resources Corporation) has developed various methods on the optimal reservoir management schemes including sediment management for the Upper Fenhe Basin Reservoir System at the cooperation project with Chinese. Information Variable Dynamic Programming, which is one of them, was developed for the reservoir sediment management and a set of non-dominated solutions are generated to choose the best alternative in water supply and reservoir sediment objective problem.

Résumé

Le bassin du fleuve Jaune, situé au nord de la Chine, est bien connu non seulement pour son nombre limité de sources mais aussi pour être le plus grand courant alluvionnaire du monde. La moyenne annuelle observée de concentration de sédiments dans cette zone est de 37.6 kg/m^3 et 3.1 % du volume d'eau est occupé par les alluvions. Pour cette raison, le développement de l'eau a été extrémement limité et il est apparu comme un des plus difficiles problemes pour la gestion et le développement des retenues. L'obstacle majeur aux utilisations de l'eau de surface est l'alluvionnement de la retenue, ce qui a fortement poussé à chercher une méthode optimale de gestion des alluvions. Pour résoudre ce probléme, la KOWACO (Sociéte des ressources en eau de Corée) a développé différentes méthodes de gestion des retenues comprenant la gestion des alluvions de la retenue du bassin du Fenhe supérieur, dans un projet de coopération avec la Chine. La programmations des variables dynamiques, qui est l'une d'entre elles, a été développée pour la gestion des alluvions de la retenue et un ensemble de solutions ont été produites pour choisir la meilleure alternative pour l'alimentation en eau et le probleme objectif des alluvions de la retenue.