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Model experiments on bed load transport in the variable backwater zone of a reservoir

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Abstract Systematic model test observations of bed load transport in a lowhead reservoir with a 58-year long-term hydrological series, have been used to investigate the bed-load transport, the characteristics of fluvial processes in the variable backwater zone and its effects on the navigation canal, the possibility of an increase in both the water elevation and the depth of sediment deposition at the upper end of the reservoir's backwater, and potential measures for controlling scour and deposition in the variable backwater zone by making use of river training works. Relevant conclusions have been proposed.

Essai sur modèle du transport de fond dans la zone variable du remous d'un réservoir

Résumé Les données d'observations longues et systématiques avec un essai sur modèle du transport des sables pendant 58 années hydrologiques ont permis de procéder à l'analyse du mouvement des apports solides charriés sur le fond, des caractéristiques de l'évolution fluviale ainsi que de leurs effets sur la navigation dans la zone variable du remous d'un réservoir, de la possibilité de l'extension du dépôt de limons à l'extêmité amont de cette zone de remous et des processus du contrôle du déblaiement des sédiments et des limons par les manoeuvres d'exploitation du réservoir dans la zone variable de remous et on a tiré les conclusions correspondantes.

INTRODUCTION

The study reservoir, Wen-Feng Reservoir, is situated on the Fujiang River which is one of the tributaries of the Yangze River in China. It is a lowhead project comprising a 19 gate regulation sluice for flood discharge and sediment exclusion, a hydroelectric power station and navigation lock. The annual runoff regime is far from uniform and the runoff volume associated with the high-flow season (May to October) accounts for nearly 80% of the annual total.

During the low-flow season (November to April) the minimum monthly mean discharge is 56.2 $m^3 s^{-1}$. The design flood, for a 2% probability, estimated for the project is 19 600 $m^3\ s^{-1}$. According to the available long-term data, this reach of the river has a mean annual suspended load and sediment concentration of 15.4 million tonnes and 1.33 kg m^{-3} respectively. The bed material is rather coarse. Its distribution shown in Table 1 evidences a D_{max} of 350 mm and a D_{50} of 78 mm.

Table 1 *Size distribution of bed material in the test reach*

Particle size (mm)	*350*	*300*	*250*	*200*	*150*
% finer	*100.0*	*98.2*	*96.0*	*86.0*	*76.0*
Particle size (mm)	*100*	*80*	*50*	*30*	*10*
% finer	*59.4*	*50.5*	*41.5*	*34.9*	*19.6*
Particle size (mm)	*5*	*1*	*0.5*	*0.25*	*0.15*
% finer	*14.5*	*10.3*	*9.1*	*4.1*	*1.3*

The annual bed load transport through the test reached during a high, medium and low flow year is 409 00, 280 000 and 96 000 t respectively. On the basis of the results of the model experiment, a discharge of 4000 $m^3\ s^{-1}$ has been selected as a threshold discharge for the project's operation. Thus when the inflow is less than this threshold discharge, the operational water level of the reservoir is maintained at the design normal high water level (365.5 m) by manipulating the sluice, and when the inflow exceeds 4000 $m^3\ s^{-1}$, the sluice will be opened to discharge sediment.

The duration of the total series involved in the sediment transport test is equivalent to 58 years for the prototype and is composed of three kinds of typical hydrological year, namely, high-water, medium-water, and low-water, in different combinations.

The horizontal model scale R_h and vertical model scale R_c are 140 and 100 respectively. The gravel bed load is simulated by natural sand. The verification experiment based on the observed prototype data indicated that the pattern of erosion and deposition in the test river reach was similar (Chen & Chen, 1986).

CHARACTERISTICS OF WATER AND SEDIMENT MOVEMENT IN THE EXPERIMENTAL RIVER REACH BEFORE THE CONSTRUCTION OF THE RESERVOIR

The length of the reservoir's backwater is 12 km when it is impounded to its normal high water level. It consists of a deep narrow river reach located upstream of the headwork, and three wide and shallow bend sections. The water surface widths varied over a range from about 200 m for the main channel to more than 800 m for the flood plain (Fig. 1). The average longitudinal slope of the test reach is 1.25°/₀₀, but the profile changes abruptly along the reach and exhibits a sawtooth form along the thalweg (Fig. 2).

In the low flow season, the discharge is mostly below 350 m^3 s^{-1}, the average velocity in the various cross sections is not more than 0.2 m s^{-1}, and

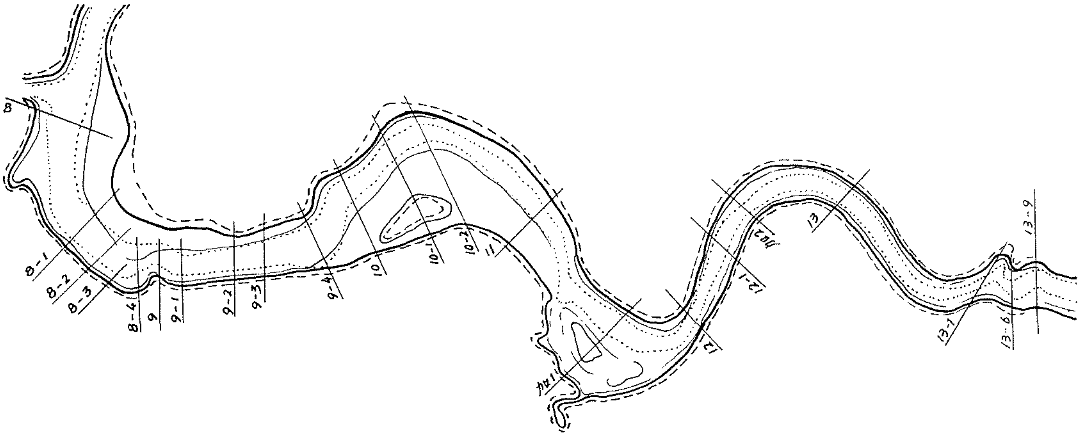

Fig. 1 Plan of the layout of the observation sections along the test reach.

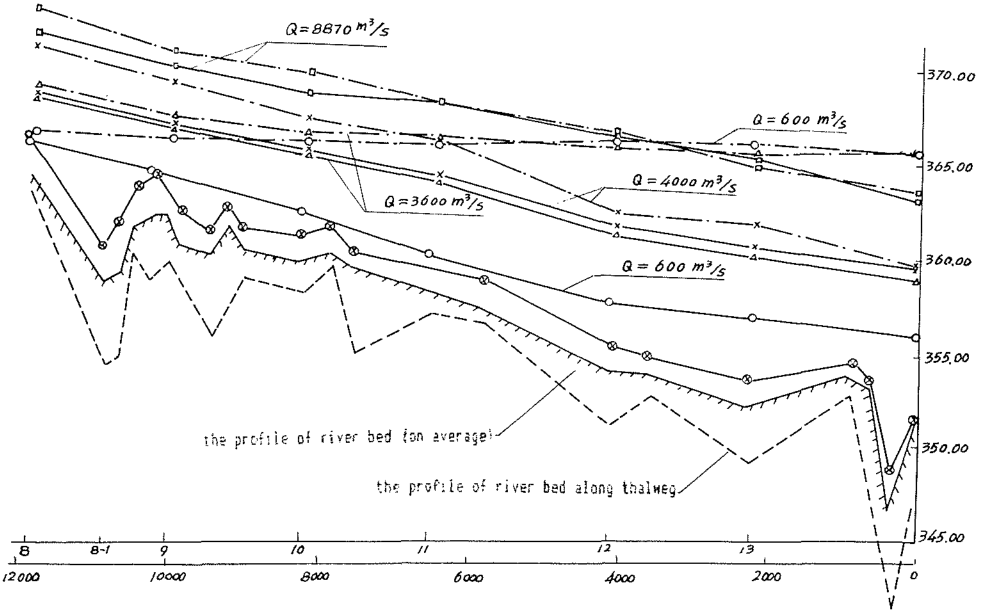

Fig. 2 Water levels associated with different discharges before and after the construction of the project (the solid line and dashed lines denote conditions before and after the construction of the project respectively).

there is no bed load movement within the entire reach. In the flood season, the average velocity in the river cross section is in the range 0.3–1.8 m s^{-1}. Bed load transport exhibits the characteristic pattern of intermittent motion associated with gravel bed rivers, in which, during high flows, the pools are scoured and riffles are filled. Conversely, during low flows, the riffles are scoured and the pools are filled (Emmett *et al.*, 1983).

CHARACTERISTICS OF WATER AND SEDIMENT MOVEMENT IN THE VARIABLE BACKWATER ZONE AFTER THE CONSTRUCTION OF THE RESERVOIR

The regulation sluice can raise the upstream water level by a height of 10 m and may be classified as a runoff reservoir. When the inflow is greater than 4000 m^3 s^{-1}, the sluice will be fully opened to discharge sediment. In this case, the discharge capacity is slightly larger than that of the flow cross section of the original river, and the backwater effect upstream of the sluice is completely removed and the water surface slope is restored to the natural condition existing before the construction of the reservoir. In the following paragraphs, the characteristics of bed load mobilization and deposition in the reservoir will be discussed in relation to a number of different factors.

The range and height of the backwater during the initial stages of operation

The normal operation high water level for the project is set at 365.5 m. During the flood season, when Q < 4000 m^3 s^{-1}, the backwater extends to cross section 8-1. The water surface elevation at each of the cross sections in the backwater zone under different discharges is shown in Fig. 2. When $Q \geqslant$ 4000 m^3 s^{-1}, the gates are fully opened to discharge both floodwater and sediment, in order to approach an annual equilibrium of scour and deposition in the reservoir, to prevent the headward extension of the deposits and to ensure the safety of the flood control measure. In this case, the backwater effect is removed from the whole reach.

Water surface elevation and sediment deposition during the later stage

The experiments, indicate that after 25 years of operation of the reservoir the bed load will be reduced to 33.8% of that existing before the construction of the reservoir. After continuous operation for 50 years, unidirectional deposition ceases, and the interchange between scour and deposition in any one year approaches a relative equilibrium (Table 2). Along with the increase of bed load deposition, the water level at the head of the reservoir also increases.

During the flood season, when $Q \geqslant$ 4000 m^3 s^{-1}, the reservoir is operated at full discharge capacity, and the elevation of the water surface in the reservoir recovers to its natural condition. However, because of the

Table 2 Amount of deposition in the reservoir at the end of flood season

Year order of sediment test	*35*	*36*	*37*	*39*
Volume of deposition ($10^4 m^3$)	*375.75*	*385.97*	*389.09*	*468.26*
Year order of sediment test	*50*	*51*	*52*	*53*
Volume of deposition ($10^4 m^3$)	*477.35*	*477.60*	*479.55*	*483.49*
Year order of sediment test	*55*	*56*	*57*	*58*
Volume of deposition ($10^4 m^3$)	*469.61*	*477.58*	*479.55*	*481.22*

deposition concentrated in the reach near the head of the reservoir (the reach above cross section no.11), the water level in this reach showed a general rise.

Table 3 Stage changes in the backwater zone when $Q \geqslant 4000\ m^3 s^{-1}$

Year of operation	*Observation*		*Section*	*no.*
	8	*10*	*12*	*14*
Start	*369.34*	*365.88*	*361.92*	*359.92*
10–12	*370.08*	*365.98*	*362.07*	*359.80*
20–22	*370.29*	*366.74*	*362.55*	*359.32*
30–32	*370.82*	*367.12*	*362.73*	*358.70*
40–42	*371.35*	*367.55*	*1*	*359.36*
50–52	*371.42*	*368.01*	*362.75*	*359.10*
56–58	*371.50*	*368.53*	*362.44*	*359.86*

The degree of stage increase in the reservoir zone when $Q \geqslant 4000\ \mathrm{m^3\,s^{-1}}$ can be seen from Table 3. Table 2 and Table 3 also indicate that, after 50 year's operation, the deposition in the reservoir approaches a relative equilibrium.

Characteristics of bed load scour and deposition in different reaches

Characteristics of bed load scour and deposition in the wide and shallow bend sections As mentioned above, the reservoir consists of three wide and shallow river bend sections. Although these bend sections are affected by the backwater, the movement of water and sediment still evidences the characteristics of that in bends. The locus of bed load movement travels along the convex margin and there is still a belt of flow free from bed load deposition along the concave bank. Fig. 3 shows the distribution of deposition in the cross section.

In the upper bend near the head of the backwater (Fig. 3(a)), the

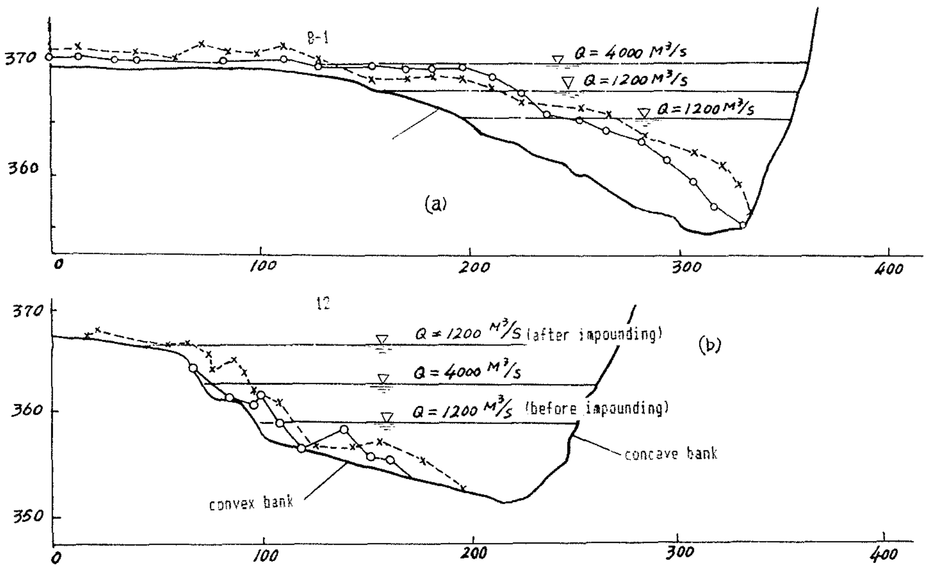

Fig. 3 Distribution of deposition in a river bend (the circle and cross symbols denote the deposition after 49 years and 58 years respectively).

backwater effect is weak, but the deposition is still appreciable because much of the incoming sediment is deposited in this section. When $Q \geqslant 4000$ m^3 s^{-1}, as a result of the reservoir being operated at full discharge capacity, the scouring activity is strong on account of the circulatory flow. Large amounts of the deposited sediment are thus pushed to the convex bank, increasing the difference in elevation between the main channel and the flood plain. Conversely, in the case of the lower bend, very little of the bed load entering the upstream section reaches this point under backwater condition and deposition is therefore much less (see Fig. 3(b)).

Characteristics of bed load scour and deposition in the deep narrow reach The reach between cross sections 13 and 14 is narrow and deep. It was generally a depositional reach during medium and low flow conditions before construction of the reservoir. After impounding, bed load deposition increased due to the backwater effect and most of the inflowing sediment will deposit within this reach. The sediment will not be mobilized unless the discharge increases to produce sufficiently large velocities. When $Q \geqslant 4000$ m^3 s^{-1}, due to the elimination of the backwater effect, the longitudinal slope of the water surface in this reach increases and its sediment transport capacity is increased. Most of the sediment deposited during the period of backwater operation can be transported to the gates and discharged downstream. Although more sediment is deposited during the period of low flow, in the deep narrow reach it will not obstruct navigation because at that time it is located in the deep water zone and the necessary depth for navigation is therefore ensured.

Characteristics of bed load scour and deposition in the transition between bend sections Model experiments show that the path of bed load movement in the transition between two bends is from the convex bank of the upper bend to the convex bank of the lower bend. Once it is influenced by the backwater, the intensity of circulatory flow in the bend is reduced and the bed load transport capacity is decreased, encouraging further deposition. Experimental observations can be used to determine whether the sediment deposited is primarily related to the cross section's geometrical form. When its width B satisfies the hydraulic geometry relationship (Artuning, 1962), $B \geqslant A\ (Q^{0.5}/J^{0.2})$ (where A is taken to be 1.5, Q represents the bankfull discharge before the construction of the reservoir, and J is the water surface slope at discharge Q), there is still a belt of continuous bed load movement from the convex bank of the upper bend to that of the lower bend. During the period when the reservoir is operated at full discharge capacity, most of the deposited sediment can be scoured away. If the cross section width is in the range

$$A(Q^{0.5}/J^{0.2}) < B < 1.5\ A(Q^{0.5}/J^{0.2})$$

when the inflow discharge is less than 4000 $m^3\ s^{-1}$, the width of the water surface will increase rapidly as a result of the backwater effect.

The velocity must also evidence a corresponding decrease, and the belt of bed load transport will no longer exist. Furthermore, the sediment is deposited mainly in the main channel and it is more resistant to scour. As a result the main channel is shallow and unstable, resulting in frequent interchange between the main channel and the flood plain. Even when the backwater effect is removed, only a small proportion of the deposited sediment can be scoured. For the wide-shallow reach with a mid-stream island, when the cross-section width $B > 1.5\ A\ (Q^{0.5}/J^{0.2})$, the flow will be dispersed and accompanied by a frequent shifting of the river channel, resulting in a major decrease of the sediment transport capacity. As a result substantial deposition occurs both in the main channel and on the flood plain. The main channel becomes shallow and unstable and the interchange between the main channel and the flood plain becomes more frequent. When the backwater effect ceases, the deposited sediment is resistant to scour.

REALIGNMENT OF THE TRANSITION BETWEEN THE BENDS IN THE RESERVOIR

As described above, the transition between two bends in the variable backwater zone, such as the reach between cross sections, 9-3 and 10-2, is wide and shallow with a branch. Experiments indicate that in this type of reach, the main channel frequently shifts, causing a problem to navigation as a result of the worsening of the condition of the shallow shoal and the unstable nature of the navigation course. Furthermore this problem should also be considered from the viewpoint of preventing the depth of deposition increasing at the upper end of the reservoir. Many examples indicate that it is not only rivers carrying high concentrations of suspended sediment that cause increasing depths of deposition in reservoirs, but that those rivers carrying suspended loads with low concentrations can also cause this type of serious problem. (Chen, 1984; Fang, 1978). In order to ensure that the navigation course remained clear, two plans for realignment of this transition were selected for comparative tests. The first plan made use of a series of submerged longitudinal dikes 4 m high along the right bank of the transition (Fig. 4), and the second used a series of oblique spurs of the same height (Fig. 5). Their purpose is to restrain the river channel, to increase the sediment carrying capacity and to maintain a stable main channel with the necessary navigation depth. The width B of the realigned reach was determined by hydraulic geometry, using the relationship $B = A\ (Q^{0.5}/J^{0.2})$ mentioned above.

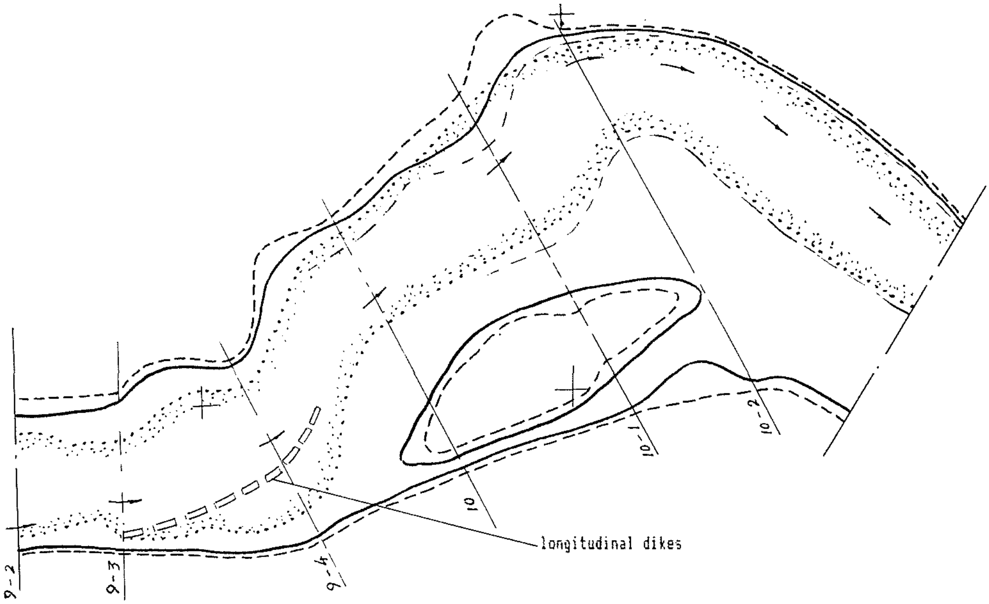

Fig. 4 Layout of the first plan of realignment.

For the first plan, an experiment based on a three-year series representing high-flow, medium-flow and low-flow conditions, showed that the slope of water surface in this reach was increased to 0.402°/₀₀, as a result of the reduction of deposition (see Table 4), the depth was increased from <4 m, to not less than 4.54 m. In the case of the second realignment plan, the observations indicated that the water surface slope increased to 1.22°/₀₀, that the depths of deposition at the same cross sections were decreased much more than by the first plan, and that the water depths are correspondingly increased with a range from 5.067 to 5.794 m.

The substantial deposition in cross sections 10 and 10-1 indicates that because the river channel in the transition is shallow and wide and affected by

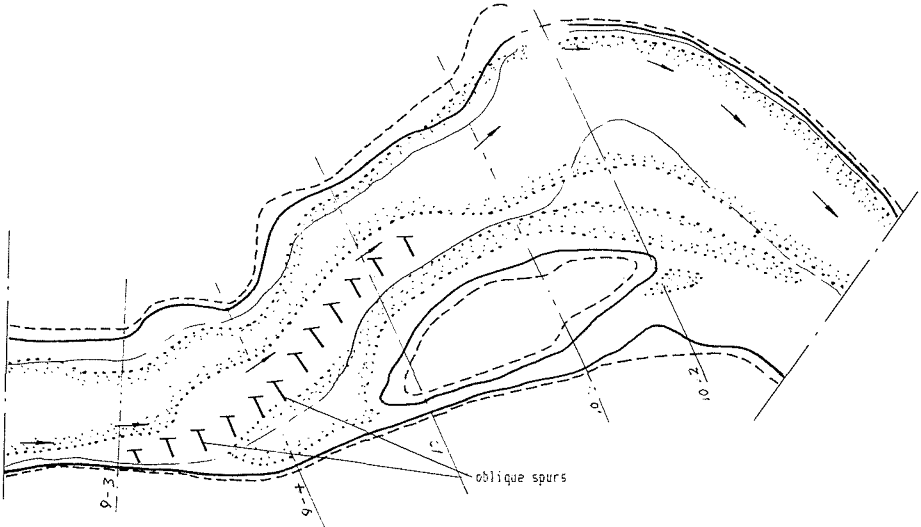

Fig. 5 Layout of the second plan of realignment.

Table 4 Comparison of the average depth (of deposition cm) before and after the realignment

Cross section no.	9-3	9-4	10	10-1	10-2
Before realignment	1.512	1.765	2.683	2.198	2.749
First plan	1.341	1.776	2.619	1.823	1.893
Second plan	1.271	1.406	1.381	1.604	1.491
After a big flood peak	0.800	1.376	2.454	2.684	1.562

affected by a branch as well as the backwater, the transport rate there is low and the sediment is readily deposited. During the flood season, the reservoir is operated at full discharge capacity and even after the backwater disappears both the upward flow in from of the gates and the scouring along the flow path produce little effect (either for the first or the second plan), especially after a large flood peak (see Table 4). The navigation condition in this transition may become worse due to the silting up of the river channel, and problems of interruption of navigation in the changing backwater zone of the reservoir may arise.

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REFERENCES

Artuning, C. T. (1962) *Fluvial Processes* (in Russian). Moscow.

Chen, Y. X. & Chen, J. Y. (1986) Report of the model experiment study on the headworks of Wen-Feng Electric-Navigation Project (in Chinese). Laboratory of Sediment Research, CUST, Chengdu.

Chen, W. B. (1984) Study on the problem of upstream extension of deposition in reservoirs (in Chinese). *J. Sediment Res. no. 4.*

Dou, G. R. *et al.* (1981) Experimental study of sediment problems in the Gezhauba project on the Yangtze River (in Chinese). *J. Sediment Res. no. 2.*

Emmett, W. W., Leopold, L. B. & Myrick, R. M. (1983) Some characteristics of fluvial processes in rivers. In: *Proceedings of the Second International Symposium on River Sedimentation.*

Fang, D. (1978) Problems in the diversion of water and prevention of deposition in the Dujiangyan reconstruction project (in Chinese). *J. Chengdu University of Science and Technology no. 1-2.*