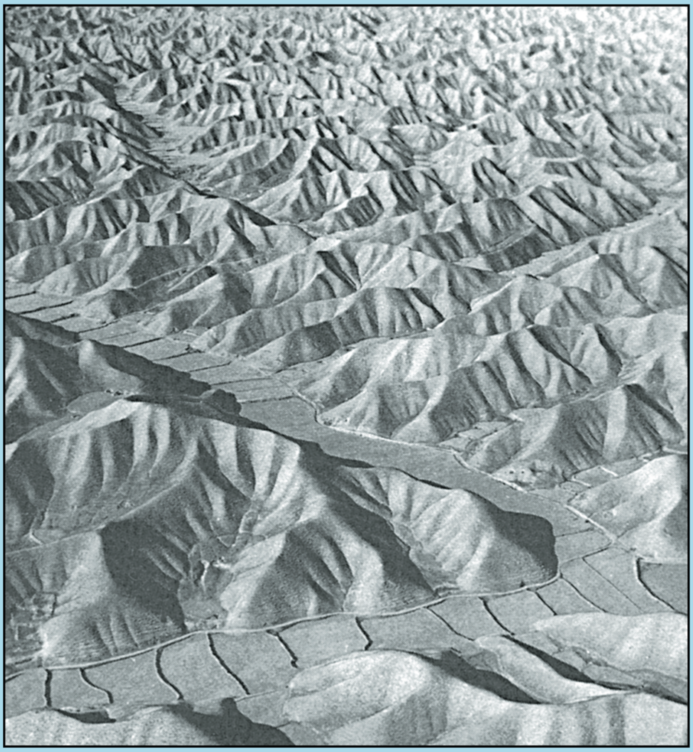
IAHR
AIRH MONOGRAPH

Hyperconcentrated Flow



Zhaohui Wan
Zhaoyin Wang

HYPERCONCENTRATED FLOW

INTERNATIONAL ASSOCIATION FOR HYDRAULIC RESEARCH
ASSOCIATION INTERNATIONALE DE RECHERCHES HYDRAULIQUES

IAHR AIRH

MONOGRAPH SERIES

This monograph was effected under the auspices of the IAHR Section on Fluvial Hydraulics

In the same series:
T. Takahashi, 1991. *Debris flow.*
M. Bouvard, 1992. *Mobile barrages and intakes on sediment transporting rivers.*
I. Nezu & H. Nakagawa, 1993. *Turbulence in open-channel flows.*
W. Rodi, 1993. *Turbulence models and their application in hydraulics – A state-of-the-art review* (3rd edition).

Hyperconcentrated Flow

ZHAOHUI WAN & ZHAOYIN WANG
Institute of Water Conservancy and Hydroelectric Power Research, Beijing, People's Republic of China

Taylor & Francis
Taylor & Francis Group
LONDON AND NEW YORK

Published by Taylor & Francis
2 Park Square, Milton Park, Abingdon, Oxon, OX14 4RN
52 Vanderbilt Avenue, New York, NY 10017

Transferred to Digital Printing 2007

ISBN 90 5410 166 0

Contents

Preface

Hyperconcentrated flow is a peculiar phenomenon in the Yellow River Basin. Significant erosion and siltation associated with hyperconcentrated flood give rise to many problems. On the other hand, irrigation in conjunction with warping by utilizing turbid water at hyperconcentrations greatly enhances agriculture in arid and semi-arid areas. The demand for profound understanding of the mechanism of such flow encourages the study of it. In the past two decades, fruitful results in the study of hyperconcentrated flow were achieved. A feasibility study on utilizing the great potential of sediment-carrying capacity of hyperconcentrated flow in the Yellow River is going on in China. The theory of hyperconcentrated flow can also be applied to hydrotransport, debris flow, sediment release from reservoirs, etc. Furthermore, the development of the theory of hyperconcentrated flow is enriching the knowledge of mechanics of sediment transport.

Early in the fifties, Professor Ning Chien started the study on rheological properties of turbid water. In the sixties, he organized large-scale field surveys of hyperconcentrated flow in rivers. In the following years, he continued active research and organizing hyperconcentrated flow studies. Particularly in the late seventies and in the eighties, he and his research group revealed a series of basic laws of hyperconcentrated flow through a thoughtful arrangement of systematic experiments and field surveys.

As students of Professor Ning Chien, both of us started study on hyperconcentrated flow under his supervision. Thanks to his guidance, remarkable progress has been achieved. Professor Chien passed away in 1986. Now we would like to dedicate this book to him as his memorial.

Prof. P.N. Lin (Lin Bingnan) gave us many valuable instructions during preparation of the manuscript. Prof. H.W. Shen carefully reviewed the draft, gave substantial enlightening advice, and also polished manuscripts. Prof. G. Di Silvio and Prof. M.S. Yalin reviewed the draft. We deeply appreciate their help. Prof. G. Di Silvio, chairman of the IAHR Fluvial Hydraulics Section, recommended to have this monograph published under the auspices of this section. We also acknowledge the help provided by our Chinese colleagues in examining different chapters and giving advice.

Zhaohui Wan & Zhaoyin Wang
Dec. 4, 1992.

CHAPTER 1

Hyperconcentrated flow in nature and in practical application

As a discipline of mechanics of sediment motion, theory of hyperconcentrated flow develops rapidly in the latest two decades, particularly in China. Study on hyperconcentrated flow was started with researches on natural phenomena and engineering problems on the Yellow River. Later on it was found that debris flow, hydrotransport of solid material, etc. are also related to the hyperconcentrated flow.

In an ordinary sediment-laden flow sediment is carried by the flow and sediment has little effect on flow behavior. Therefore such effect can be neglected. In hyperconcentrated flow, however, the existence of large amount of solid particles remarkably influences or changes the fluid properties and flow behavior. In such case the above mentioned influence or change must be considered. In many cases of hyperconcentrated flow sediment together with water, forming a pseudo-one-phase fluid, moves in its entirety and sediment can no longer be considered as material carried by the water.

Whether it is a hyperconcentrated flow can not be simply judged by concentration only. It will be discusssed later that the grain size composition and the mineral content of sediment play very important role. As to the Yellow River where the incoming sediment has similar mineral content and grain size composition, flow with concentration higher than 200 kg/m^3 (or volumetric concentration about 8%) can be considered as a hyperconcentrated one.

1.1 HYPERCONCENTRATED FLOW IN THE MAIN STEM AND TRIBUTARIES OF THE YELLOW RIVER

The Yellow River is notorious for its tremendous amount of sediment. The average annual load is 1.6 billion tons, 80% of which comes from a vast loess plateau in its middle reach. There the land surface, consisting of a chain of undulating hills criss-crossed by thousands upon thousands of gullies (Figure 1.1), is broken up into numerous small watersheds. The erosion- resistance

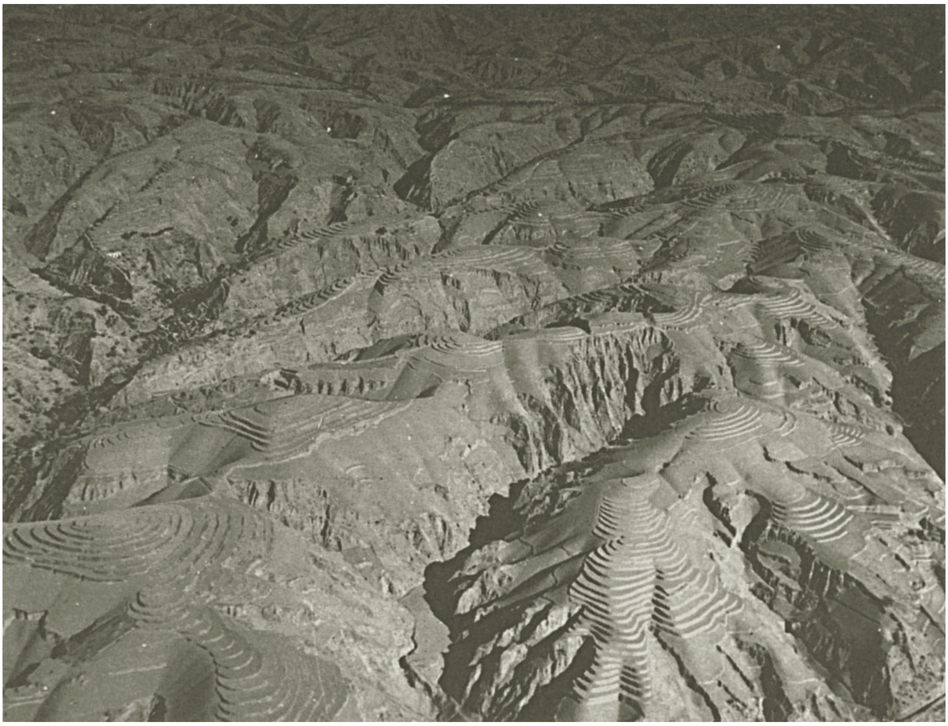


Figure 1.1. A birds' eye view of the loess plateau (after Yin Hexian).

capacity of the loess area is extremely low because of the loamy texture of the soil and the poor vegetative cover. The loess plateau is an arid/semi-arid area, but there in summer rainstorms may be rather heavy. After saturation, the loose loess deposits with columnar voids readily disintegrate. As a result, summer rainstorms cause severe erosion and hyperconcentrated floods frequently in this area.

In Table 1.1 the maximum and average monthly sediment concentrations of ten main tributaries in the middle reach of the Yellow River are listed (Qi, 1987).

The annual sediment load from these ten tributaries (1.024 billion tons) constitutes 64% of the total load of the Yellow River (1.6 billion tons). Most sediment is transported by hyperconcentrated floods.

Usually the flash hyperconcentrated flood caused by heavy rainstorm lasts a short time, but it always conveys huge amounts of sediment. At some gauging stations concentration higher than 1500 kg/m^3 has been recorded. Table 1.2 shows two hyperconcentrated floods recorded at Longmen Gauging Station on the Middle Reach of the Yellow River (Wan & Sheng, 1978). The maximum concentration measured at Longmen Gauging Station is 933 kg/m^3 (in 1966).

Sediment carried by hyperconcentrated floods lasting 2-3 days constitutes one-quarter to one-third of the corresponding annual load. Not only large amounts

Table 1.1. Average monthly sediment concentration and maximum recorded sediment concentration of ten main tributaries of the Yellow River.

River	Gauging station	Period of statistics		June	July	August	September	Annual load (10^6t)
Huangfuchuan	Huangfu	1953-1979	S_{av}	411	523	369	216	64.1
			S_{max}	1370	1570	1480	1240	
Gushanchuan	Gaoshiya	1953-1979	S_{av}	327	410	373	178	27.8
			S_{max}	1300	1190	1090	829	
Kuyehe	Wenjiachuan	1953-1979	S_{av}	162	405	319	90.6	135
			S_{max}	1400	1700	1500	970	
Wudinghe	Baijiachuan	1956-1979	S_{av}	12.5	352	323	90.8	106
			S_{max}	1290	1270	1180	958	
Qingjianhe	Yanchuan	1954-1979	S_{av}	384	503	448	105	45.3
			S_{max}	1150	1080	970	881	
Yanshui	Ganguyi	1952-1979	S_{av}	287	454	368	119	54.6
			S_{max}	1200	1190	1033	1070	
Fenhe	Hejin	1943-1979	S_{av}	19	43	59.4	37.6	43.8
			S_{max}	174	386	227	143	
Weihe	Xianyang	1934-1976	S_{av}	37.1	71.4	80.2	28.5	168
			S_{max}	654	588	729	662	
Jinghe	Zhangjiashan	1931-1979	S_{av}	168	349	329	110	286
			S_{max}	906	1430	984	946	
North Luohe	Zhuangtou	1933-1979	S_{av}	121	337	287	58.1	96.8
			S_{max}	987	1150	1190	1340	

S_{av} = average monthly sediment concentration in kg/m^3; S_{max} = maximum recorded sediment concentration in that month in kg/m^3.

Table 1.2. Two hyperconcentrated floods recorded at Longmen Gauging Station.

Flood time	Duration (hrs)	Peak discharge (m^3/s)	Maximum concentration (kg/m^3)	Total load carried by the flood		Thickness of bed erosion (m)
				Amount (10^6t)	Ratio to annual load (%)	
1966 July 18, 9:00 to July 20, 19:00	58	7460	933	453	26.5	7.0
1970 Aug. 2, 0:00 to Aug. 4, 24:00	72	13800	826	497	35.3	8.8

of sediment, but also rapid and severe erosion or deposition are asssociated with hyperconcentrated floods. As seen from Table 1.2, the river bed at Longmen Gauging Station was eroded about nine meters in a very short period (72 hours). Such strong erosion takes its own peculiar form, called 'ripping up the bottom' by local habitants. This phenomenon will be later discussed in detail.

However, in most cases hyperconcentrated flow results in severe siltation. At some gauging stations on small tributaries, the entire river stops moving during the recession of a hyperconcentrated flood, when the discharge becomes smaller but the concentration is still high. The river stops moving for a while, then flows

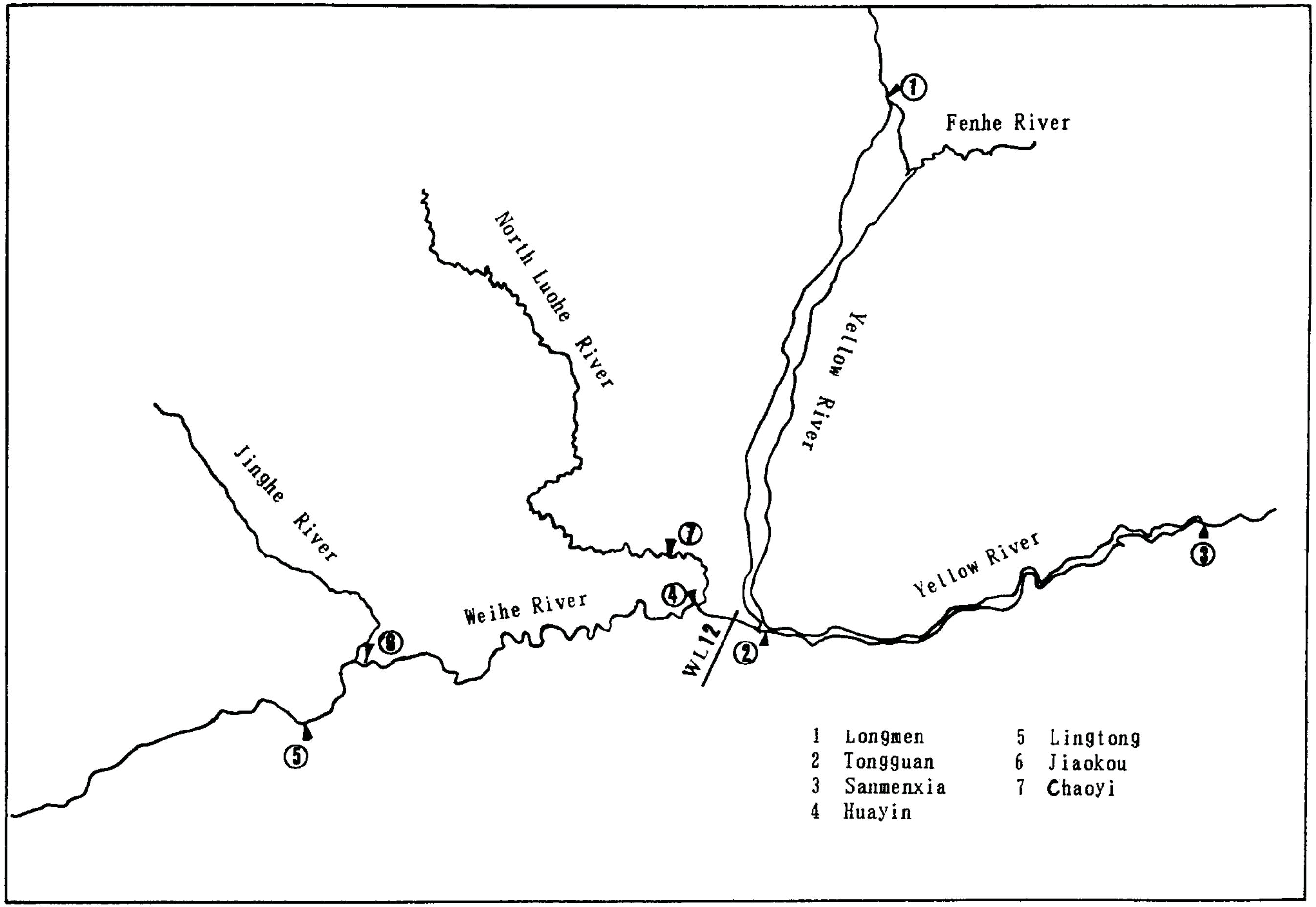


Figure 1.2. Plane view of the middle reach of the Yellow River.

again... Such unstable flow may last for a rather long time and is locally known as 'clogging of the river'. Laboratory studies on such phenomenon (Wan et al., 1979) will be discussed later.

Large amounts of sediment and associated serious erosion and siltation inevitably cause a series of problems in agriculture and industry.

One hundred-three flood events occuring in the Lower Yellow River over a 19-year period have been carefully analysed (Qian et al., 1987). Of these, 13 hyperconcentrated floods contributed to 60% of the total deposition caused by the 103 floods. The average aggradation intensity was as high as 31×10^6 tons per day, much higher than the aggradation intensity caused by other types of floods. Moreover, because such flash floods seldom overflow the flood plain, most of the deposition occurred in the main channel of the river. Consequently, the water surface profile along the river rises rapidly; therefore, floods of this type are most disadvantageous to the flood control of the Lower Yellow River.

Hyperconcentrated floods usually occur in the middle reach of the Yellow River and its tributaries. Weihe River is one of the main tributaries (Figure 1.2 and Table 1.1).

After the completion of Sanmenxia Reservoir in the middle reach of the Yellow River in September, 1960, serious siltation occurred and the backwater deposits extended upstream, seriously endangering the Weihe valley area, which is an important agricultural and industrial base in northwest China. In normal years along the Weihe River the end of the backwater deposits moves upstream. But whenever hyperconcentrated flood with large discharge passes through, the end of the backwater deposits moves downstream due to the intensive erosion along the main channel. Figure 1.3 shows the variation with time of the end of the deposits along the Weihe River. In the figure L is the distance between the end of backwater siltation and Tongguan Guaging Station, the confluence of the Weihe River and the Yellow River (Figure 1.2). In 1964 and 1966 the end moved far downstream, as the result of intensive erosion caused by hyperconcentrated floods. A similar situation also occurs along the stem of the Yellow River upstream from Tongguan. Figure 1.4 shows that after the passage of the second hyperconcentrated flood listed in Table 1.2, the main channel along the upper part of the reach was obviously degraded. In the meantime the flood plain was aggraded.

Intensive erosion causes great trouble for diversion works. In 1977 when a hyperconcentrated flood with large discharge passed through, intensive erosion in the form of 'ripping up the bottom' occurred at Lingtong, where a pumping station with a capacity of 40 m^3/s is located. The local river bed as well as the water level was lowered by 2 m after this event. The bottom of the inlet of the pumping station was above the water surface, so that water could no longer be pumped. An irrigated area of 84 000 hectares suffered from drought for a long time in the summer. A similar situation also occurred in the stem of the Yellow River at Jiamakou, not far upstream from Tongguan.

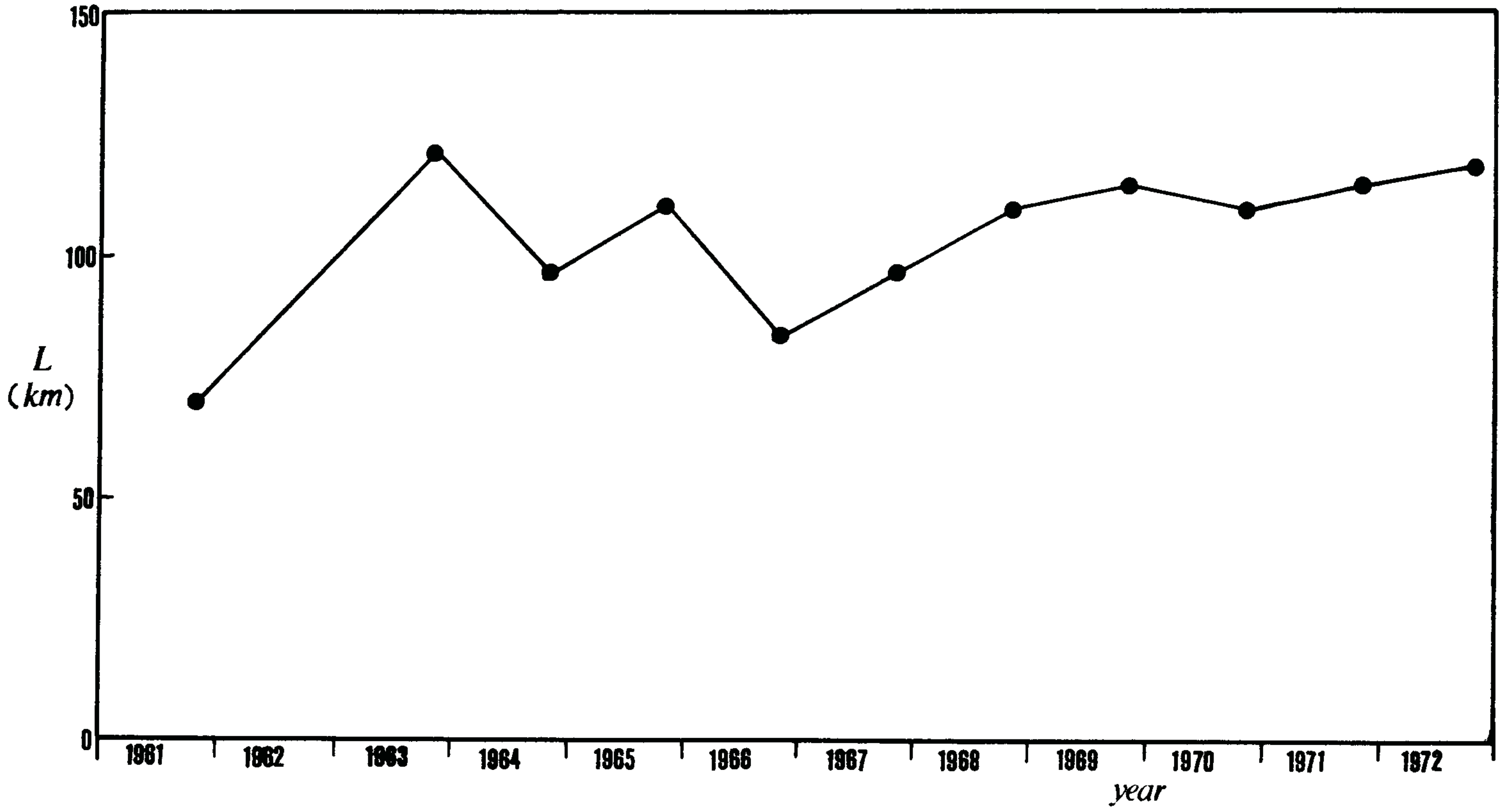
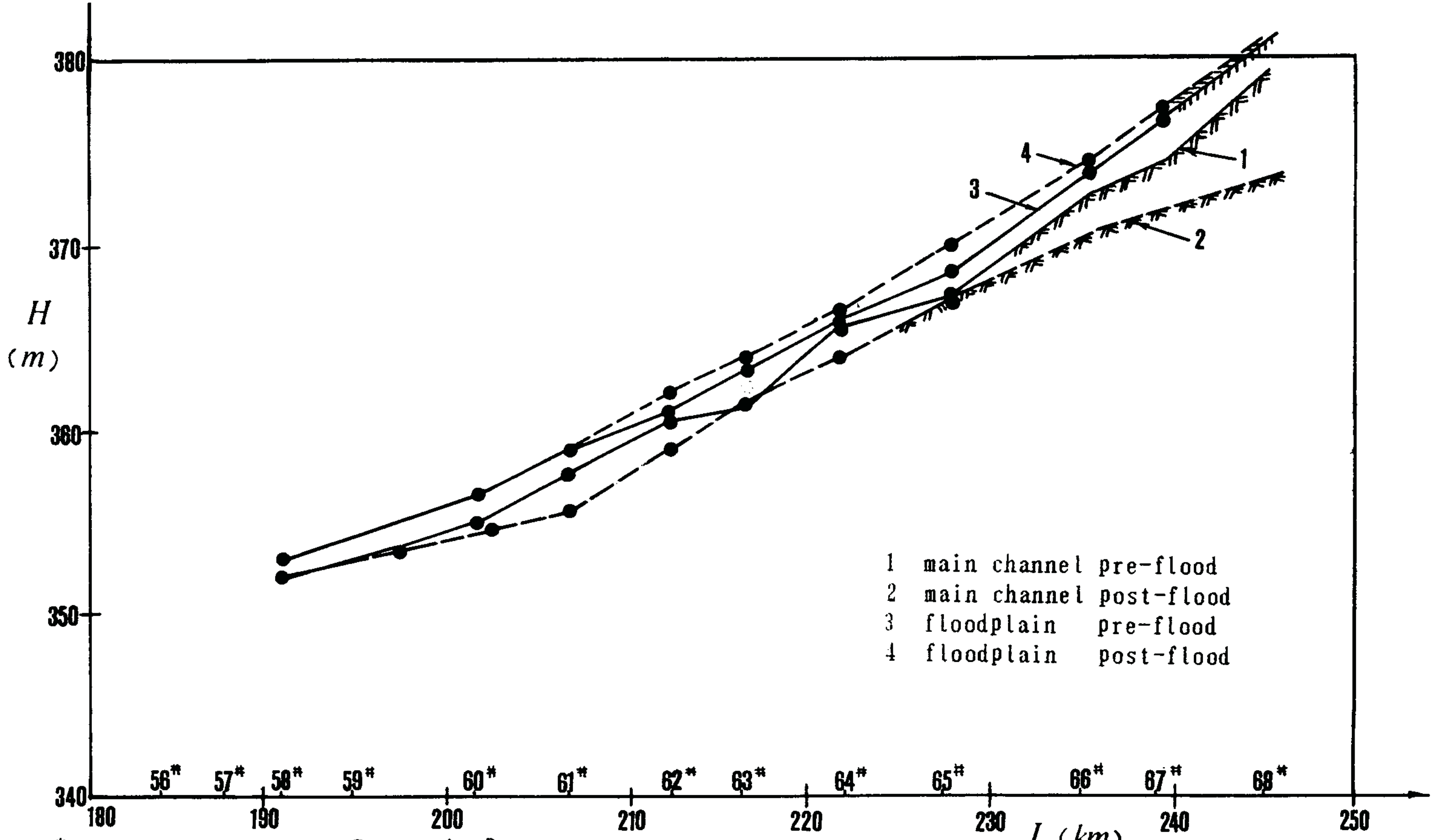


Figure 1.3. The variation with time of the end-point of backwater siltation along the Weihe River.



*L is the distance to Sanmenxia Dam

Figure 1.4. The longitudinal profile of the reach from Longmen to Tongguan.

The most striking fact was the unusual change of water stage and the rapid, vigorous river deformation associated with the hyperconcentrated flood in the Lower Yellow River in 1977. The variation of the water stage was contrary to that previously predicted by routine method. The water level dropped during the rising limb of the flood and the drop was followed by a rapid rise in the water level (2.84 m in 1.5 hours). Besides, the hyperconcentrated flood changed channel shape greatly. During the passage of hyperconcentrated flood, the wide, shallow, braided river could be transformed into a narrow, deep, meandering river with a single channel. Correspondingly, the velocity in the river channel was so high that many spur dikes and levees were undermined. It became the most critical situation in flood- control since the establishment of the PRC in 1949, and will later be discussed in greater detail.

1.2 HYPERCONCENTRATED FLOW IN RESERVOIRS

Hyperconcentrated flow can pass through a reservoir without severe siltation and can be released from a reservoir if bottom sluices are installed and opened. In this way serious reservoir sedimentation can be avoided or alleviated. Examples of hyperconcentrated flow passing through Sanmenxia reservoir are listed in Table 1.3.

The elevation of the bottom sluices is 280 m above the sea level, and the water depth in front of the dam was 33-37 m during the floods. The slope of the 40 km reach in front of the dam is only 0.0001, or even less. Under such conditions, nearly all the incoming sediment or even more in a few cases was released from the reservoir. In the latter case, some sediment was eroded from the bed in the reach just downstream from Tongguan Gauging Station (Qian et al., 1979).

Heisonglin Reservoir in Shaanxi Province is a small reservoir with a storage capacity of 8.6×10^6 m^3. It is located in a loess plateau region and the concentration of incoming floods is high. The average releasing rate, i.e. the ratio of the amount of sediment released from the reservoir in the form of density current to the total

Table 1.3. Examples of hyperconcentrated flood passing through Sanmenxia Reservoir in 1977.

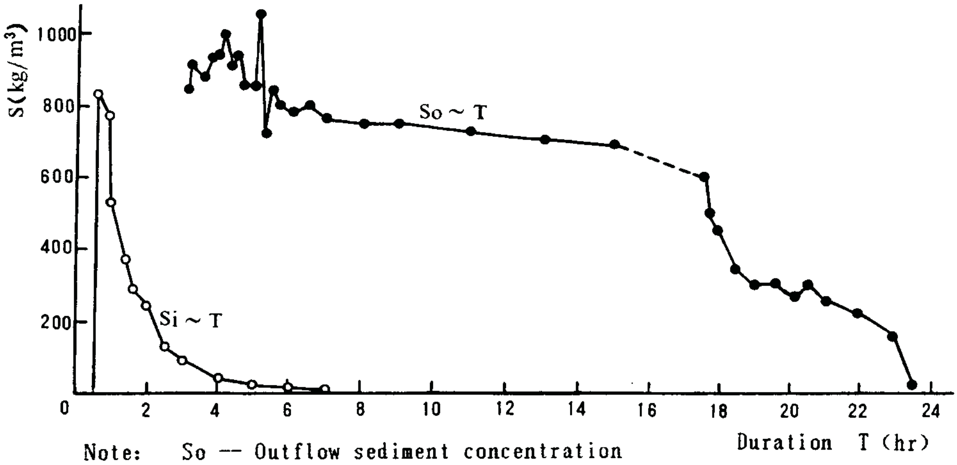
Time	Tongguan Gauging Station (inlet of the reservoir)			Maximum concentration at the outlet of reservoir (kg/m^3)	Maximum stage in front of the dam (m)	Corresponding storage capacity (10^6 m^3)	Releasing rate (%)*
	Peak discharge (m^3/s)	Maximum concentration (kg/m^3)	Average concentration (kg/m^3)				
July 6	13 600	616	367	589	317	400	91
August 3	12 000	238	178	320	313	190	115
August 6	15 400	911	276	911	315	290	113

*Releasing rate = released sediment/incoming sediment.

amount of incoming sediment, reaches 65% (Xia & Ren, 1980). Bajiazui Reservoir is a large reservoir with a total capacity of 525×10^6 m^3. The concentration of incoming flow there is even higher, reaching 573 kg/m^3. If the main channel is preserved and the stage in front of the dam is not very high, the releasing rate, which is the ratio between the released sediment and the incoming sediment, may reach 100%. Even under unfavorable conditons, the releasing rate of hyperconcentated density current is still higher than that of an ordinary density current (Jiao, 1989).

Hyperconcentrated density current has a high releasing rate because the density of a hyperconcentrated flow is much higher than that of clear water, so a hyperconcentrated flow can easily plunge to the bottom of a reservoir when it enters the backwater region. Due to its large density, the hyperconcentrated density current also has a much higher velocity than an ordinary density current. Due to its large viscosity, the turbulence in a hyperconcentrated density current is very weak. Therefore, the mixing of a hyperconcentrated density current and clear water at the interface is correspondingly weakened. Besides, particles settle much more slowly in hyperconcentrated flow than in an ordinary density current. As a result, the mixing and deterioration of hyperconcentrated density current along its course is much weaker and slower than that of an ordinary density current. Consequently, more sediment can be transported to the dam site.

Another important factor is the formation of subreservoir in front of the dam. That is, underneath the upper clear water turbid water with hyperconcentration exists. Due to the extremely low settling velocity, once the hyperconcentrated density current arrives at the dam and cannot be entirely released because of



Note: So — Outflow sediment concentration
Si — Inflow sediment concentration

Figure 1.5. Hydrograph of inflow and outflow sediment concentration during the release of muddy water from the underlying subreservoir, Hengshan reservoir.

Table 1.4. Hyperconcentrated flow released from an underlying muddy water subreservoir.

Date (m.d.y.)	Inflow Smax (kg/m^3)	TWi (hr)	Outflow Smax (kg/m^3)	TSo (hr)	TSo/TWi	So/Si (%)
6.25.73	469	12.5	1220	206	16.5	48
7.7.75	649	20.5	1240	59	2.9	85
7.2.72	325	12.3	758	42	3.3	53
7.15.76	672	14.8	1015	31	2.1	50
8.13.79	344	12.1	1200	174.5	14.4	76
8.15.80	462	112.6	1010	164.5	1.46	52
7.24.81	833	3.4	1015	21.9	6.4	101
8.13.84	394	2.6	586	12.6	4.8	37.6
8.22.84	356	3.6	1120	38.7	10.5	16.1
7.23.76	407	12.0	851	20.0	1.67	75.2

Note: TWi = duration of incoming flood; TSo = duration of sediment sluicing; So/Si = ratio of sediment load outflow to inflow.

limited discharge capacity, a subreservoir of hyperconcentrated fluid is formed underneath the clear water. Sediment particles in the subreservoir settle at extremely low velocity, perhaps, several centimeters per hour, and the turbid water remains fluid for a rather long time. Within this period the turbid water can be consistently released if the bottom sluices remain open. Figure 1.5 shows an example taken from Hengshan Reservoir in which S_i and S_0 are the concentrations of the inflow and the outflow of the reservoir, respectively (Guo et al., 1985). The hyperconcentrated outflow lasted for about twenty hours with two-hours of incoming hyperconcentrated flood. More examples from the same reservoir are listed in Table 1.4.

Notice that in all these cases, the maximum outflow concentration is higher than the maximum inflow concentration. An explanation is that sediment particles in the underlying subreservoir settled, and the muddy water was condensed but remained fluid.

Hyperconcentrated flow can also be formed by emptying a deposited reservoir, when sediment is obtained from retrogressive scour and the lateral slippage of flood plain deposits during reservoir drawdown. The outflow concentration can be rather high. The maximum recorded concentration in Hengshan reservoir is 1320 kg/m^3.

If floods occur during the reservoir-emptying period and the dam has sufficient discharge capacity, intensive erosion may be caused by floods. Figure 1.6 depicts a flood recorded in the Hengshan Reservoir. The reservoir has been emptied when a flood with a peak discharge of 20 m^3/s arrived. Due to the combined action of retrogressive and longitudinal erosion, hyperconcentrated flow with an average concentration of 666 kg/m^3, that was much higher than the average inflow concentration of 212 kg/m^3, was formed. Two hundred-seven thousand tons of sediment were sluiced out of reservoir by the flood. In Figure 1.6, S_i and S_0 are the

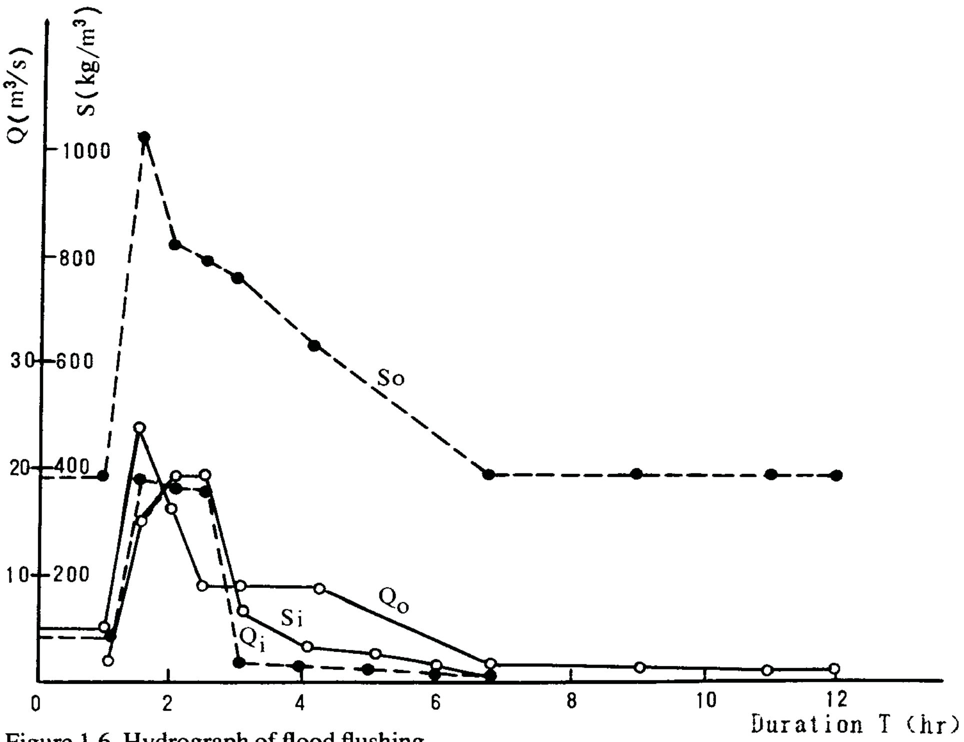


Figure 1.6. Hydrograph of flood flushing.

concentration of the inflow and the outflow of the reservoir, respectively, and Q_i and Q_o are the corresponding discharges.

1.3 HYPERCONCENTRATED DENSITY CURRENT IN RIVERS

Due to its large density and the corresponding large difference in density between it and clear water, a hyperconcentrated flow is liable to form a density current in reservoirs, as well as in rivers. Density current in rivers has been observed at some confluences.

1.3.1 *Density current at the confluence of the Weihe River and the Yellow River (Wan & Niu, 1989)*

The Weihe River converges with the Yellow River at Tongguan. Tongguan Gauging Station is located just downstream from the confluence, as shown in Figure 1.2. Whenever hyperconcentrated flood from the Weihe River pours itself into the Yellow River and the latter is not flooding and relatively clear, the turbid flow of Weihe River immediately plunges underneath the relatively clear water of the Yellow River. A mass of debris, driftwood and leaves accumulating on the water surface along the front of plunging clearly shows the plunging of turbid flow of Weihe River. This phenomenon is quite similar to that associated with the plunging of a density current in a reservoir. In the meantime, at Tongguan Gauging Station a distinct interface marked by abrupt change in both concentration and velocity can be detected by field survey. The plunging of the turbid flow of Weihe River can be proved by comparing the oncoming discharge of Weihe River and the part discharge of the lower turbid layer at Tongguan Gauging Station. Quite often vigorous erosion at Tongguan is associated with the hyperconcentrated density current. All these will be discussed in detail in Chapter 10.

1.3.2 *Density current at the confluence of North Luohe River and Weihe River*

Not far from the confluence of the Weihe River and the Yellow River is the North Luohe River and Weihe River (Figure 1.2). Density current also occurs in this reach (Zeng et al., 1986).

Provided the discharge of the Yellow River is large and that of the Weihe River is small, the lower reach of the Weihe River is influenced by a backwater effect, and the slope of the water surface is very gentle or even reversed. In such situation, a hyperconcentrtated flood coming from the North Luohe River will plunge to the bottom of the Weihe River near the confluence. The turbid water moves both downstream and upstream along the Weihe River, and rapid siltation simultaneously takes place. As an example, velocity profiles taken at Huayin

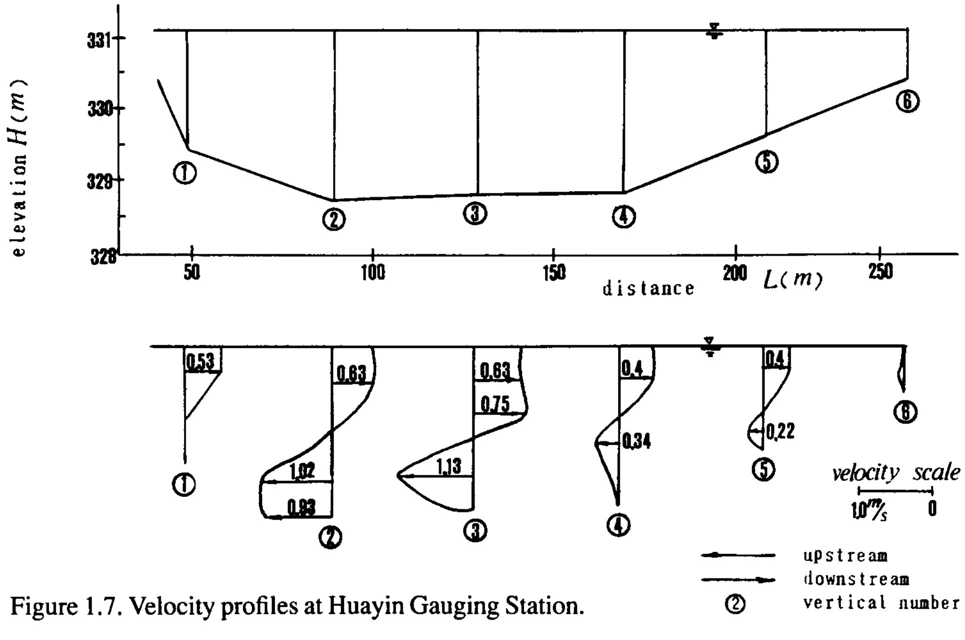


Figure 1.7. Velocity profiles at Huayin Gauging Station.

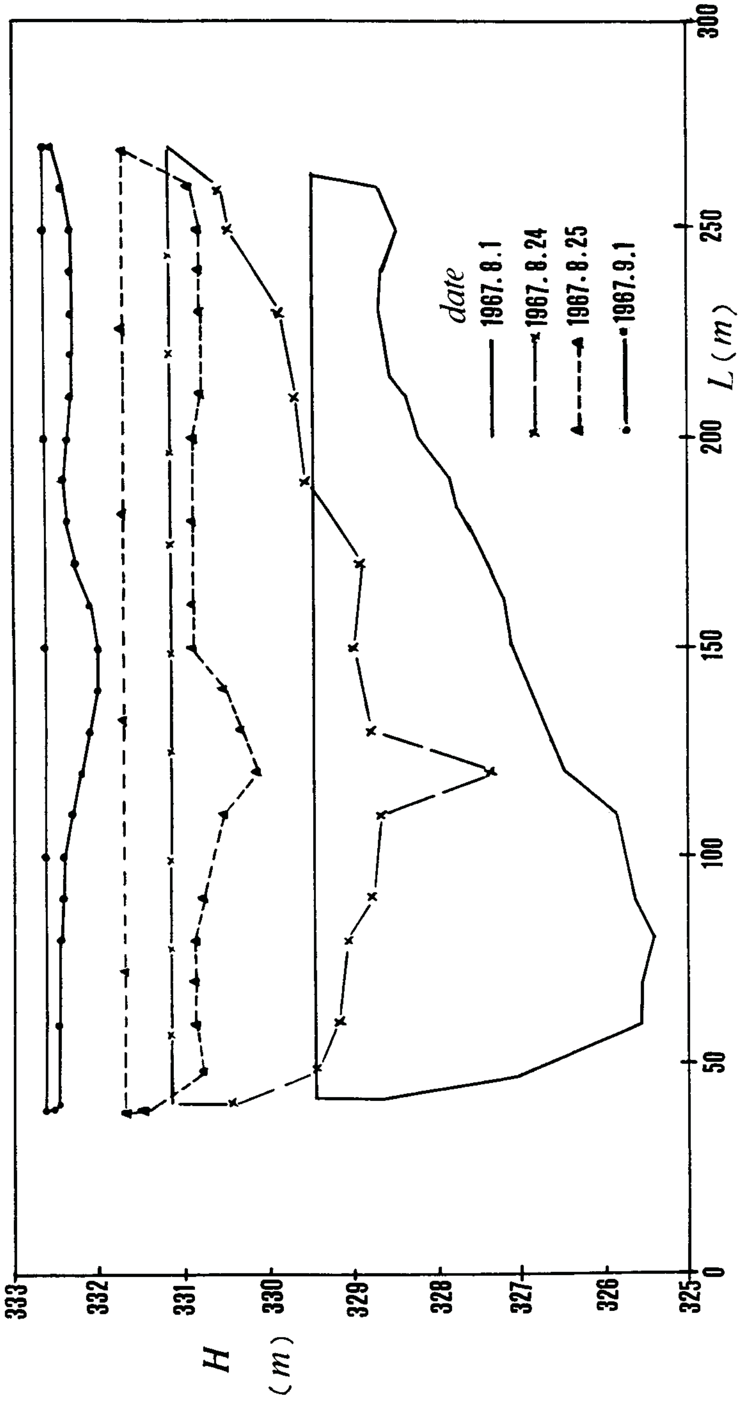


Figure 1.8. Cross-sectional changes at Huayin Guaging Station.

Gauging Station, which is located just upstream of the confluence (Figure 1.2), are shown in Figure 1.7. The upper layer with sediment concentration 28.7 kg/m^3 moved downstream and the lower layer with sediment concentration 774 kg/m^3 moved upstream at a velocity of more than 1 m/s. This reach was seriously silted during that period. The changes in the cross section at Huayin Gauging Station are shown in Figure 1.8.

1.4 HYPERCONCENTRATED TURBIDITY CURRENT

Density current occurs along a sloping ocean bottom provided liquid adjacent to the bottom contains suspended sediment that causes the average density of the mixture to be greater than the density of the surrounding clear water. Such flow is called turbidity current by geologists. Turbidity current may be initiated by a turbid river entering the sea, by wave action, or by earthquake-induced mud slump. Earthquake-induced mud slump may be of large-scale and develops into a huge turbidity current at extremely high concentrations. It is also a kind of hyperconcentrated flow.

A huge turbidity current was initiated by an earthquake which occurred in the Grand Banks region off Newfoundland in 1929. The progress of the current was measured by the orderly breaking of submarine cables. This phenomenon has been well explained by a series of papers (Heezen & Ewing, 1952; Plapp & Mitchell, 1966; Bagnold, 1962).

Six cables on the continental slope in the epicentral area broke first. Another five cables broke in order indicating the progress of the current down the slope and out onto the ocean bottom. The last cable, located 480 km from the epicenter,

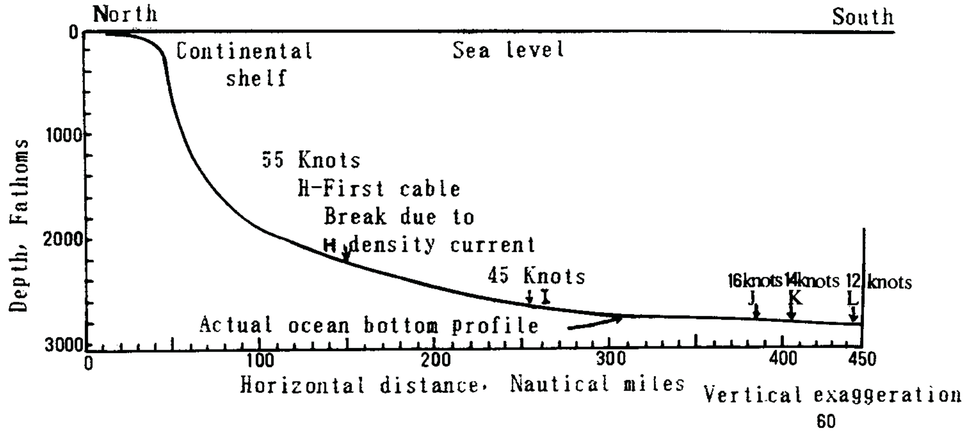


Figure 1.9. Ocean bottom profile, cable break locations, and observed current velocities for the 1929 Grand Banks turbidity current, after Heezen & Ewing (1952).

broke 13 hours and 17 minutes later. The local velocity of the turbidity current could then be estimated by correlating distance and time of breakage. Local velocities and the ocean bottom profile are shown in Figure 1.9 (after Heezen & Ewing, 1952). According to Plapp & Mitchell's (1960) analysis, the thickness of the turbidity current was 300-400 m and the average velocity was over 20 m/s on continental slopes of 6×10^{-3} and 9.8 m/s on the ocean floor where the slope was 10^{-3}.

Despite the great difference in their sizes, turbidity flow and density current in reservoirs share some general characteristics and mechanism.

1.5 HYPERCONCENTRATED FLOW IN CANALS (WAN & XU, 1984)

Most tributaries in the middle reach of the Yellow River carry heavy sediment loads, and hyperconcentrated floods occur quite often. In the past, flows with concentrations higher than 167 kg/m^3 were not allowed to be diverted into irrigation districts because of concern over canal siltation. Irrigation districts suffered from drought even though hyperconcentrated floods passed by their diversion works. In the 1960's in the Luohui Irrigation District people succeeded in raising the concentration limitation for irrigation. Since 1974, field measurement and corresponding laboratory studies have been carried out. The results of these studies indicated that the transport of sediment by hyperconcentrated flow does not require high flow velocity or high flow intensity. In most canals, flow with a velocity of about 1 m/s is enough to carry heavy sediment loads without serious siltation. Experience has been accumulated and a series of rules of thumb for canal design and operation have been worked out. Concentration limitations for irrigation have been abolished and hyperconcentrated flow has been conveyed to most parts of the Luohui Irrigation District. Irrigation by using turbid water at high concentration is called hyperconcentrated irrigation. In 1977, flow at a concentration of 964 kg/m^3 was conveyed through 50 km of canals. The experience and knowledge of hyperconcentrated irrigation obtained in the Luohui Irrigation District is now referred to by other irrigation districts. By the way of hyperconcentrated irrigation/warping not only water, but also nutrient-rich sediments have been utilized as resources. Based on statistics from 1969 to 1985, 2.06×10^8 m^3 of muddy water (concentration higher than 167 kg/m^3), which amounts to 20% of the total water diverted in summer, and 1.06×10^8t of sediment, which amounts to 9.8% of the sediment load of the North Luohe River, were diverted and utilized. On average, 5000 hectares of land were irrigated by muddy water every year, and 3720 hectares of alkaline-saline land have been improved by warping. The gross output value of the land increased by about $10 million due to the use of hyperconcentrated irrigation/warping.

1.6 DEBRIS FLOW

Debris flow is widespread throughout the world, occurring in Japan, Rusland, the United States, China, etc. In the southeastern part of Tibet, the western and northeastern parts of Yunnan Province and the mountainous area of west Sichun Province debris flow occurs quite often. In the Xiaojiang River Basin (Yunan Province), with a total area of 3120 km^2, 500-1000 episodes of debris flow take place every year (Li, 1980). A well equipped experimental station has been established there for the systematic observation and measurement of debris flow (Kang, 1990).

Debris flow is a kind of hyperconcentrated flow. It carries large amounts of granular particles with wide size composition, from large stones to clay particles, and its density may reach 1.9-2.2 g/cm^3. The velocity of debris flow can be rather high. The maximun recorded velocity in China is 13.4 m/s (Zhang & Yuan, 1980). Hence it is a powerful destructive force and threatens railways, highways, lives and the property of local citizens. Volcanic debris flows and other hyperconcentrated flows resulting from them have been observed and studied by Scott & Dinehart (1985). Volcanic debris flows are named as lahars. And the hyperconcentrated streamflow following lahar is named as lahar-runout flow. Lahars are formed in the following ways:

1. By the bulking of lake-breakout flood surges with eroded alluvium;
2. From flood surges produced from snowmelt by hot lithic pyroclastic;
3. From material catastrophically ejected and mixed with water of hydrothermal and glacial or snowmelt origin.

Recorded velocities of lahar-runout flows range from 4 to 7 m/s, which are substantially higher than the common streamflow velocities. The concentration of lahar-runout flows reaches 530-1590 kg/m^3 (20-60% in volume).

It will later be pointed out that there are some similarities in composition size, transport mechanism, and fluvial processes between lahar-runout flow and hyperconcentrated flow in river. Debris flow will be discussed in detail in Chapter 11.

1.7 HYDROTRANSPORT AND DENSECOAL HYDROTRANSPORT

Pipe hydrotransport is a widely adopted form of hydraulic transport. The maximum diameter of existing pipe systems in the world (up to 1990) is 510 mm, and the maximum length is 400 km. The maximum transport capacity amounts to 1.2×10^7 t/y. One of the tendencies of development is to utilize hydrotransport at hyperconcentration. In many hydrotransport systems, the concentration by weight is over 50%. In this way, energy and water can sometimes be saved.

Densecoal is a suspension consisting of coal, water and additives which behaves practically in the same way as oil (Klose & Kunst, 1985). The suspension can be directly burnt as fuel, i.e. without the need for dewatering. Densecoal can be transported by train, ship or pipeline. Densecoal hydrotransport is also a kind of hyperconcentrated flow. Results of studies on rheological properties and mechanics of hyperconcentrated flow in rivers can be referred for densecoal hydrotransport. There are some astonishing similarities between the size composition of hydrotransported material and that of sediment in hyperconcentrated flow in rivers, and many experiments on hyperconcentrated flow have been carried out in pipes or in closed conduits.

1.8 SUMMARY CONCLUSION

Lots of hyperconcentrated flow phenomena occur in nature, agriculture and industry. Some of them are closely related to the development of construction. These phenomena attract the attention of research workers and engineers, and promote the study on hyperconcentrated flow. Some studies have brought people benefits. It can be expected that deep understanding of the mechanism of hyperconcentrated flow will substantially favor the development of agriculture and industry. There are a variety of types of hyperconcentrated flow. Each type of hyperconcentrated flow has its own peculiarities, and together they also have some commonalities. The exploration of the common laws governing various kinds of hyperconcentrated flow will promote the development of sediment transport theory and bring people great advantages.

REFERENCES

Bagnold, R.A. 1962. Auto-suspension of transported sediment: turbidity currents. *Proc. Royal. Soc. London, Ser. A*, Vol. 265(1322): 314-319.

Guo, Z., B. Zhou, L. Ling & D. Li 1985. The hyperconcentrated flow and its related problems in operation at Hengshan Reservoir. *Proc. International Workshop on Flow at Hyperconcentrations of Sediment*: 3-1.

Heezen, B.C. & M. Ewing 1952. Turbidity currents and submarine slumps, and the 1929 Grand Banks earthquarkes. *Amer. J. Sci.*, Vol. 250: 849-873.

Jiao, E. 1989. Study on hyperconcentrated flow in Bajiazui Reservoir, *Report of Institute of Hydraulic Research, Yellow River Conservancy Commission* (in Chinese).

Kang, Z. 1990. Motion characteristics of debris flow at Jiangjia Gully, Yunnan Province, China, Circular No.3. *Publication of Internatinal Research and Training Centre on Erosion and Sedimentation*, pp. 38.

Klose, R & W.D. Kunst, 1985. Densecoal – Densephase flow behaviour of Datong, Fugu and Shenmu coal and densecoal combustion. *Proc. of International Workshop on Flow at Hyperconcentrations of Sediment, Publication of International Research and Training Centre on Erosion and Sedimentation*: 4-2.

Li, J. 1980. Debris flow in Xiaojiang River basin, Yunnan Province (in Chinese). *Proc. Debris Flow by Chengdu Geography Institute*: 34-42.

Plapp, J.E. & J.P. Mitchell 1960. A Hydrodynamic theory of turbidity currents. *J. Geophys. Res.*, Vol. 65(3): 983-992.

Qi, P. 1987. Conveying hyperconcentrated floods through narrow-deep channel into sea is the main measure of solving problems relating to sediment of the Yellow River (in Chinese). *Report of Institute of Hydraulic Research, Yellow River Conservancy Commision.*

Qian, N. (Ning Chien), Z. Wan & Y. Qian 1979. The flow with heavy sediment concentration in the Yellow River Basin (in Chinese). *J. Qinghua University*, Vol.19(2): 1-17.

Qian, N. (Ning Chien), K. Wang, L. Yan & R. Fu 1980. The source of coarse sediment in the middle reaches of the Yellow River and its effect on the siltation of the Lower Yellow River (in Chinese). *Proc. of The International Symposium on River Sedimentation*: 53-62.

Scott, K.M. & R.L. Dinehart 1985. Sediment transport and deposit characteristics of hyperconcentrated streamflow evolved from lahars at mount St. Helens, Washington. *Proc. International Workshop on Flow at Hyperconcentrations of Sediment, Publication of International Research and Training Centre on Erosion and Sedimentation*: 3-2.

Wan, Z. & Z. Niu 1989. Hyperconcentrated density current in rivers. *Proc. of 23th Congress of International Association for Hydraulic Research.*

Wan, Z. & S. Sheng 1978. Hyperconcentrated flow on the Yellow River and its tributaries (in Chinese). *Selected Papers of the Symposium on Sediment Problems on the Yellow River*, Vol. 1(2): 141-158.

Wan, Z. & Y. Xu 1984. The utilization of hyperconcentrated flow and its mechanism. *Proc. 4th Congress APD, IAHR*: 1791-1808.

Wan, Z., Y. Qian, W. Yang & W. Zhao 1979. Laboratory study on hyperconcentrated flow (in Chinese). *People's Yellow River*, No.1, 1979: 53-65.

Xia, M. & Z. Ren 1980. Methods of sluicing sediment from Heisonglin Reservoir and its utilization downstream (in Chinese). *Proc. of The International Symposium on River Sedimentation*, Vol.2: 717-726.

Zeng, Q., W. Zhou & X. Yang 1986. Development of sedimentation for the Weihe River and its relations to Tongguan Constraint and intrusion of flood of the Yellow River (in Chinese). *J. of Sediment Research*, No.3: 13-28.

Zhang, S. & J. Yuan 1980. Impulsive force of debris flow and its measurement (in Chinese). *Proc. Debris Flow by Chengdu Geography Institute*: 137-142.

CHAPTER 2

Basic patterns of motion of hyperconcentrated flow

2.1 DIFFERENT FORMS OF GRAIN MOVEMENT

Although phenomenological and empirical approaches are widely used in the investigation of hyperconcentrated flow, and the results of these approaches are rather encouraging, a complete understanding of hyperconcentrated flow also requires further study on the mechanism involved. Particularly, it is necessary to consider the force by which solid grains are supported in a flowing mixture.

In general, solid particles have larger specific weight than the liquid phase, and tend to settle downward. To maintain the movement of solid grains in flow, a force is needed to balance the submerged weight of solid particles and prevent them from depositing. According to origins of the forces, solid particles carried by a flow can be classified as bed load, suspended load and neutrally buoyant load.

2.1.1 *Bed load*

Bed load refers to the solid grains whose submerged weight (= weight of grains minus buoyancy force) is supported by dispersive force or contact force. When the average shear stress on the bed of an alluvial channel exceeds a critical tractive stress for the bed material, solid particles on the bed statistically may begin to move in the direction of flow. They move in different ways depending on flow conditions, ratio of the density of the fluid and that of particles, and size of particles. One mode of movement of particles is by rolling and sliding on the bed. Sediment transported in this way, whose submerged weight is supported by contact force, is known as contact load. A second mode of bed load movement is by hopping or bouncing along the bed. Thus for some time the particle loses contact with the bed. Material transported in this way is supported by dispersive force and is known as saltation load. Saltation load is an important mode of transport in case of noncohesive material of relatively high fall velocity, such as sand in air and gravels in water. In a few cases, such as in debris flow with less clay material and hydrotransport of cohesionless material in pipelines, such mode of sediment transport may extend into the whole flow depth. These will be discussed in Chapter 7.

The concept of dispersive force was advanced by Bagnold (1954, 1956). He studied collision between solid particles in a hyperconcentrated flow and proposed that the collision between particles results in a repulsive force, namely the dispersive force. The dispersive force keeps bed load particles an average distance apart from each other during their course of motion. Nevertheless, collision of particles results also in a great resistance to the flow. The mechanism of the dispersive force is illustrated, in general, by the following example (Wang & Qian, 1985a). As shown in Figure 2.1, particle P located at the point 1 at instant t_1 moves at a velocity, $\vec{V}$, elative to particle P_1, and it reaches point 2 at instant t_2 after collision with P_1 and its velocity changes to $\vec{V}'$. Such abrupt change in velocity, both in magnitude and direction, because of collision, causes an acceleration. The average acceleration during the time interval $t_2 - t_1$ is

$$\vec{a} = \frac{(\vec{V} - \vec{V})}{(t_2 - t_1)} = \frac{\Delta\vec{V}}{\Delta t} \tag{2.1}$$

According to Newton's second law, particle P must be subjected to action of a force. An average value of the force can be given by

$$\vec{f} = M\vec{a} = \frac{M((\Delta\vec{V}\cdot\vec{i})\vec{i} + (\Delta\vec{V}\cdot\vec{j})\vec{j})}{\Delta t} \tag{2.2}$$

where M is the mass of the particle P, $\vec{i}$ and $\vec{j}$ are the basic vectors in the longitudinal and vertical directions, respectively. $\Delta\vec{V}$ and its two components are shown in Figure 2.1. They represent the force $\vec{f}$ and two force components in the longitudinal and the vertical directions. The dispersive stress is the sum of such forces acting on the particles in unit area. The component in the flow direction, T, and the vertical direction, P, of the dispersive stress are respectively referred to dispersive shear stress and dispersive pressure.

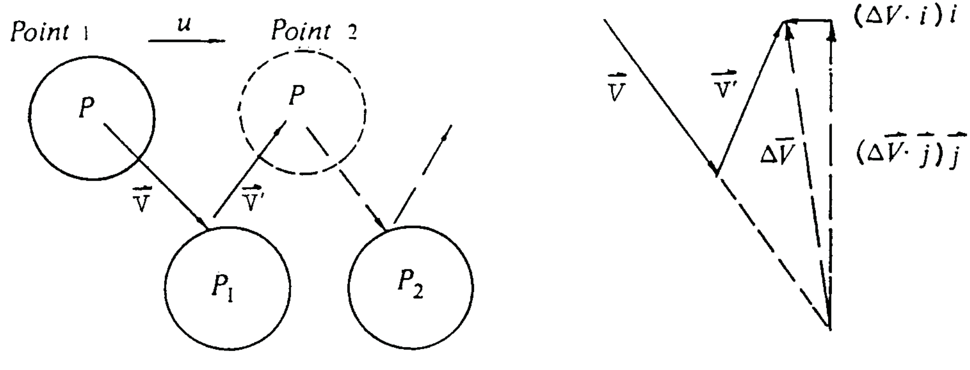


Figure 2.1. The dispersive force as a result of collisions between moving particles.