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YANGTZE DYKE AND ITS STRENGTHENING

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ABSTRACT: Levees play important role in flood prevention. More than 30,000 km length of levees protect the rich and populous plain regions of the middle and lower reaches of Yangtze River. However, the quality of the levee varies greatly in different regions. This paper summarizes the characteristic of Yangtze dyke, its main dangerous situations and hidden defects, together with the measures for handling these problems.

Key words: Levee, Yangtze River, dangerous situation, dyke, hidden defect

INTRODUCTION

Yangtze River (Changjiang River) is the biggest river in China, third biggest in the world. Being originated in Qingzang Plateau, the 6300 km long river runs across Qinghai, Xizang, Yunnan, Sichuan, Chongqing, Hubei, Hunan, Jiangxi, Anhui, Jiangsu, and Shanghai, etc., before it reaches the sea. Its catchment area is about 1.8×10^6 km^2, 18.75 percent of the land area of China. It covers altogether 19 provinces and municipalities. The regions in the middle and lower reaches of the Yangtze River are very rich and populous, with 415 million people, about 1/3 of the population of China, and covers agricultural acreage of 2400 km^2, one-forth of China.

The average rainfall is 1100mm per year in the pluvial catchment of Yangtze River. But it is not distributed through the year. Being fed by the storm rains, the Yangtze flood has a long period, from April to October, July and August being peak period for the main stream. The floods in the main stream and in the tributaries generally occur at different time. However, if they concur and join together, they will produce basin-wide severe floods such as those in the years of 1860, 1954 and 1998, respectively.

From Yichang (in Hubei province) to Hukou (in Jiangxi Province) is the middle course of Yangtze River, where the course from Zhicheng to Chenglingji is also called Jingjiang River (See Fig. 1). The river winds at Jingjiang with low flood discharging capacity, and consequently the flood situation is very severe. The 50 km long stretch downstream of Hukou is the lower reach of Yangtze River (see Fig. 1).

The recorded maximum peak discharge in the main stream is 1.1×10^5 m^3/s (at Zhicheng hydrologic station in 1860 and 1870), while it was 9.26×10^4 m^3/s at Datong hydrologic station in 1954. However, the safe discharge for Jingjiang river channel is $6.0\times10^4\sim7.0\times10^4$ m^3/s. The discharge in excess is diverted and impounded mainly by the reservoirs, lakes and low-lying lands, such as Dongting Lake, Poyang Lake, and Jingjiang Flood Diversion Basin, etc.. Dyke breaching is inevitable if the flood exceeds too much. In recent decades, due to enclosing of land for cultivation in the lakes and diversion areas, the flood diversion and storage capacity declined greatly. On the other hand, flood volume and peak discharge have increased resulting from the deforestation in the upstream reaches of Yangtze River, which has made the flood prevention situation more difficult.

In recent decades, many reservoirs have been built in Yangtze River and its tributaries. They play an important role in flood prevention during flood season. Altogether 763 reservoirs in the middle and upper reaches stored more than 3.4×10^{10} m^3 flood water in 1998. They reduced greatly the flood volume in the lower river channel, and made great contribution to the flood control regulation and rush repairs of the dykes. For example, the inflow of Danjiangkou Reservoir in Hanjiang River was 1.83×10^4 m^3/s, while the outflow was only 1280 m^3/s at the same time. It reduced the water level downstream by 0.9m, which guaranteed the safety of Wuhan City.

CHARACTERISTIC OF YANGTZE LEVEES

There are about 30,000 km length of levees with different standards in the middle and lower reaches of Yangtze River. They are generally built on the bank of the mainstream and tributaries while some on the lakeshores. The length of the main dykes is about 3600 km. The height

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Fig. 1 Sketch of Yangtze valley

is generally 8m~10m, some up to 15m. The characteristics of the dykes are as follows.

Centuries-old Construction

It was verified that the dykes along the main stream of Yangtze River were built several hundred years (even 2000 years) ago. For example, Jingjiang levee was first built in Dongjin dynasty (345 B. C.). The dykes were initially built along the stream to a small height and in subsequent years increased in height and strength, or repaired after dyke breaches. In recent years, local farmers constructed some dykes to enclose land for cultivation. These dykes were called polder dykes, often built outside the main dykes.

Varied Quality without Comprehensive Design

Because constructed in different periods, it was impossible have well planned or designed the levees. The levees have been built with different soils without proper compaction, and the foundation was seldom carefully chosen or treated. Inevitably, there are hidden defects in the levees. Further more, the farmers used the soil nearby the dykes to built levees, which frequently destroyed the weakly pervious layers at surface. Also many pools were left near the dykes. These factors may create problems during flood.

Human and Biological Influence

Actually, Yangtze dykes are the remains of Chinese ancestorage. Traces of antiquity could often be found in the dykes, such as old dyke breaches, remnants of old structures passing through the dykes, coffins and tombs, etc.. The dykes were not always well protected during low flood year or drought period. On the other hand, sometimes the farmers dug up sand and constructed buildings near the dykes despite the regulation. These activities may lead to dangerous situations at high water level.

There are also many burrow holes of rats, snakes and ants, which are potential hidden defects in flood period. Termite is the most harmful creature. A huge anthill of 4m×3m×1.5m was once dug out in one of the dykes.

Two-Layer Foundation

Yangtze levees are mainly situated in the plain region called Jianghan Plain, in the middle reach of Yangtze River. Most of the foundations (more than 70 percent) are two-layer foundations consisting of the weakly pervious surface layer and the pervious underlying layer (see Fig. 2). Generally, the soil in the surface layer is clay, silty clay or silt, while the soil in the underlying layer is mainly pervious soil such as sandy gravel, sandy cobble and decomposed bedrock, etc. This two-layer structure is generally suitable for seepage control. But if the stream trenching destroys the surface layer at the river side of the dyke, or the excavation and reclamation destroy the surface layer at the land side, seepage failures such as soil flow and piping may be induced at high water level, which are the main causes of dangerous situations in flood period.

In some courses, there are some single-layer foundations made of clay or sand, and some multi-layer foundations made of alternate pervious and impervious soils.

DANGEROUS SITUATIONS AND HIDEN DEFECTS

According to the results of surveying and the experience of flood fighting, the principal hidden defects and dangerous situations are thought to be as follows (Yang 1999):

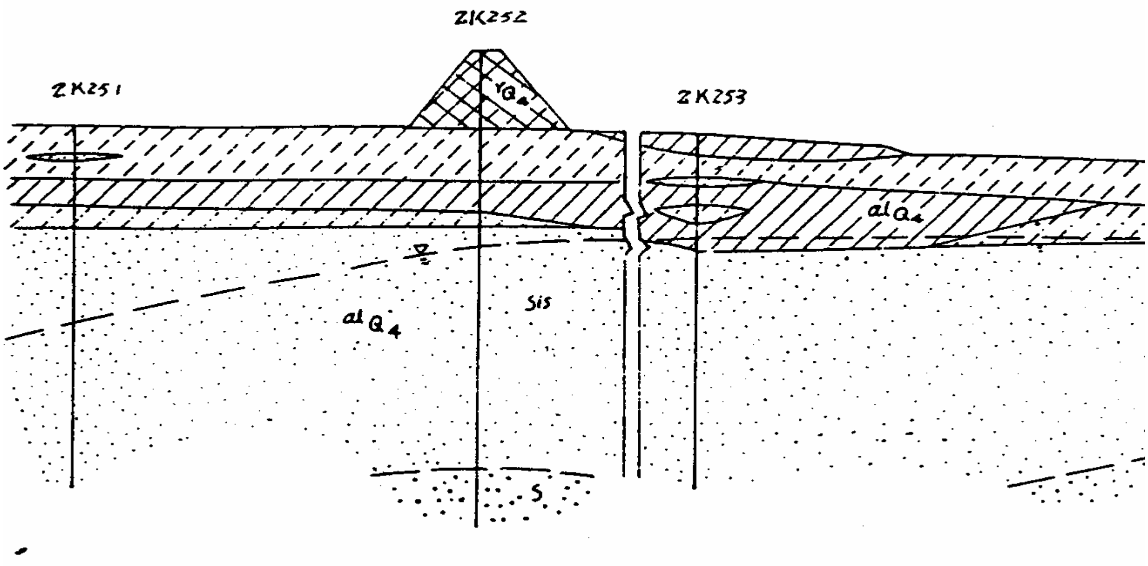


Fig. 2 Levee with two-layer foundation

Piping and Soil Flow in Levee Foundation

For the two-layer foundation of the dyke, the weakly pervious surface layer at land side of the dyke will be burdened with a high water pressure when the flood water reaches a high level. Seepage failure will occur if the exit hydraulic gradient is high. It has been shown by the investigation that the seepage failure involves direct scouring, piping, soil flow, and local soil flow, etc.. The most dangerous of all is the seepage failure occurring at the toe of levee back. With the soil particles being gradually carried away by the flow and the seepage failure developing toward the dyke, differential settlement, cracking, collapse, or even dyke breaching will be induced. It has been recorded that more than 60 percent of the dyke failures were caused by seepages.

Infiltration

If the high flood stage is maintained for a long time, the saturation line in the soaked dyke will rise to a high level. The seepage force and the erosion effect of the seepage flow exiting at the downstream slope decrease the safety of the levee slope, and even cause levee slide. This kind of infiltration happens in the poorly compacted new embankment with anisotropic seepage coefficients.

Some dykes, especially the second-order and the third-order dykes, were simply embanked without either seepage prevention treatment or good compaction. Also the soil used to build the dykes was not carefully selected. Infiltration will be more dangerous in these dykes.

Levee Slide

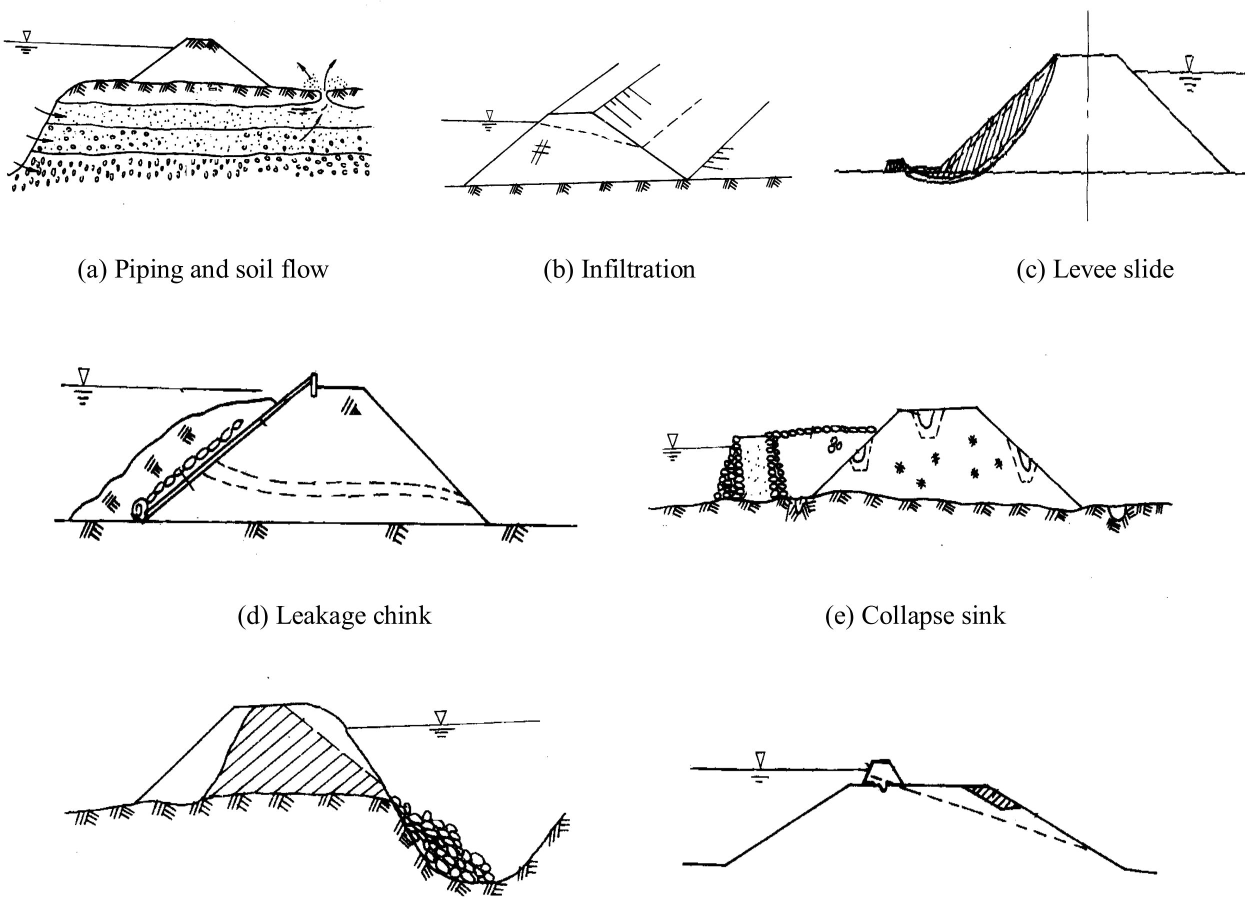
Levee slide can be induced by infiltration, since the infiltration softens the levee body and the seepage force increases the downward action. Levee slide may also happen in the case if there is a pool at the levee toe and the levee is seated on muck or mucky soil.

Levee slide usually occurred at the downstream slope. Sometimes it occurred at the upstream slope of the levee. Slide of the upstream slope may be induced by the drawn down after the high flood. In addition, bank caving, as well as the scouring of the upstream slope of the levee, can also induce levee slide.

Leakage Chink and Collapse Sink

Holes and chinks in the dykes mostly come from the holes of rats and ants, rotten bodies of animals and plants, old remains, and remnants of old buildings. Sometimes, there may be crack in the dyke resulting from the constructional defects. Under the action of seepage force and the softening effect on the soaked dykes in flood period, these holes and chinks may lead to collapse in local areas (Collapse sink), or water may flow directly from the chinks (Leakage chinks) through the dyke body.

The collapse sink reduces the area of the cross-section of the dyke, and shortens the seepage path of water, which can lead to seepage failure and levee slide. The leakage chink lets the water go directly through the dyke body and exits at the levee back or levee foundation. It may finally cause the levee breach. Generally, collapse sinks and leakage chinks are often very dangerous for the dyke, to which much attention should be paid.



(a) Piping and soil flow (b) Infiltration (c) Levee slide

(d) Leakage chink (e) Collapse sink

(f) Bank caving (g) Overtopping

Fig. 3 Main dangerous situations

Bank Caving

In a sense, bank caving does not happen directly to the dyke itself, but it does great harm to the dyke.

Bank caving usually happens to the concave shore of the river when the high flood stage declines to a relatively low level in flood period. Sometimes it happens in low water period. Though its comprehensive mechanism is not available at present, the seepage of underground water to the river channel, the erosion effect of water flow, and the repeated scouring action of waves, are thought to be the main causes. For the river channel of Yangtze with two-layer foundation, the cohesionless sand particles in the sub-layer can be easily carried away by the water flow. Bank caving is very serious in such courses. For example, on Jun. 11, 1994, bank caving at the north gate of Xianning Dyke (in Hubei province) made the bank recede for 100m in 24 hours, while on Oct. 14, 1998, it was 100m in 3 hours. The dyke was then in danger, and people had to build a new dyke nearby. In Mahu of Sichuan province, two bank caving cases, occurring on Jan. 3 and Jan. 8 of 1990, respectively, killed 24 lives, and a bank of 1200m in length and 200m in width with the earth volume of 5.0×10^6 m^3 fell into the river. Bank caving is another important dangerous aspect for the dyke.

Overtopping

Overtopping occurs if the flood level exceeds the elevation of the levee crest, or wind and wave make the water flow over the levee. The overtopping may induce dyke breaching quickly. Rush repairs such as building sub-dykes to ward off the water are necessary. Geotextile bags were often used to build such interim sub-dykes.

Figure 3 shows the main dangerous situation in the safety of the dykes.

DYKES IN 1998 FLOOD

The flood of 1998 is the biggest in Yangtze River in the past 50 years, second biggest in the twentieth century.

Table 1 Maximum flood stage and maximum discharge at main hydrologic station

Name of the station	1998 Yangtze flood				1954 Yangtze flood				Highest historical water level (m)
	Water level (m)	Date	Discharge (m^3/s)	Date	Water level (m)	Date	Discharge (m^3/s)	Date	
Yichang	54.50	Aug. 17	63300	Aug. 16	55.73	Aug. 7	66800	Aug. 7	/
Zhicheng	50.62	Aug. 17	68800	Aug. 17	50.61	Aug. 7	71900	Aug. 7	50.74 (in 1981)
Shashi	45.22	Aug. 17	53700	Aug. 17	44.67	Aug. 7	50000	Aug. 7	44.67 (in 1954)
Jianli	38.31	Aug. 17	46300	Aug. 17	36.57	Aug. 8	36500	Aug. 8	37.06 (in 1996)
Chenglingji	35.94	Aug. 20	35900	Jul. 31	34.55	Aug. 3	43400	Aug. 21	35.31 (in 1996)
Lianhuatang	35.80	Aug. 20	/	/	33.95	Aug. 7	/	/	35.01 (in 1996)
Luoshan	34.95	Aug. 20	67800	Jul. 26	33.17	Aug. 8	78800	Aug. 7	34.17 (in 1996)
Hankou	29.43	Aug. 20	71100	Aug. 19	29.73	Aug. 18	76100	Aug. 14	29.73 (in 1954)
Jiujiang	23.03	Aug. 2	73100	Aug. 22	22.08	Jul. 16	/	/	22.20 in 1995)
Hukou	22.59	Jul. 31	31900	Jun. 26	21.68	Jul. 16	22400	Jun. 20	21.80 (in 1995)
Datong	16.32	Aug. 2	82300	Aug. 1	16.64	Aug. 1	92600	Aug. 1	16.64 (in 1954)

Although the maximum discharge in many courses was less than that of 1954 Flood, the maximum flood level in most of the middle and lower reaches was about 0.5~1.0m, even up to 2.0m, higher than 1954 (see Table 1). This was mainly attributed to the encroachment for cultivation in lakes and in other flood storage areas. Such encroachments have reduced the total area of lakes in the middle-lower reaches for 10,000 km^2, and reduced the storage capacity to 1.8×10^{10} m^3. Further more, in comparison with the flood of 1954, dyke breach happened much less, both in the mainstream and in tributaries, which made the volume of flood diversion and detention by dyke breaches reduce from 1.023×10^{11} m^3 (in 1954) to 1.0×10^{10} m^3 (in 1998). Additionally, the floods in the mainstream and tributaries concurred and joined up along the middle-lower reaches of Yangtze River. These factors kept the flood level high for quite a long time. The water level in many stretches exceeded the highest historical level. Table 1 presents the maximum water level and corresponding peak discharge at main hydrologic stations (Li 1999).

The unusual climate in 1998 caused the continuous heavy rain in the catchment of Yangtze River. From June to August, the heavy rain, with long duration and extensive, induced successive flood peaks in the middle and lower courses of Yangtze River (altogether 8 flood peaks at Yichang hydrologic station), and resulted in a basin-wide large flood. The time of the flood level exceeding the highest historic level was about 10~40days at main stations. The maximum peak floods were 63,300 m^3/s at Yichang Hydrologic Station, 71,100 m^3/s at Hankou Hydrologic Station, and 82,300 m^3/s at Datong Hydrologic Station, respectively (Ji 1999, Tan and Wu 1999). The flood disaster covered 3.53×10^5 km^2, in which 1526 lives were lost, 2.316 million people suffered losses with the collapse of 2.1285 million houses, inundation of 2.39×10^5 km^2 farmland, and 1975 breaches of polder dykes.

The 98' Flood endangered the Yangtze dykes in the middle and lower reaches. 73,825 dangerous situations were located on the dykes, including 26,005 piping cases, 16,421 leakage chinks, 8,333 infiltration cases, 13,494 dyke slides, 493 bank caving events, 2,554 dangerous events on culverts, and 3,000 other emergencies. The emergency situation mostly happened on the third-order levees. Only 12.7 percent happened on the main levees (including the first-order and the second-order levees). Among 1975 dyke breach cases, only one breach occurred on the main dyke (at Jiujiang city, in Jiangxi province).

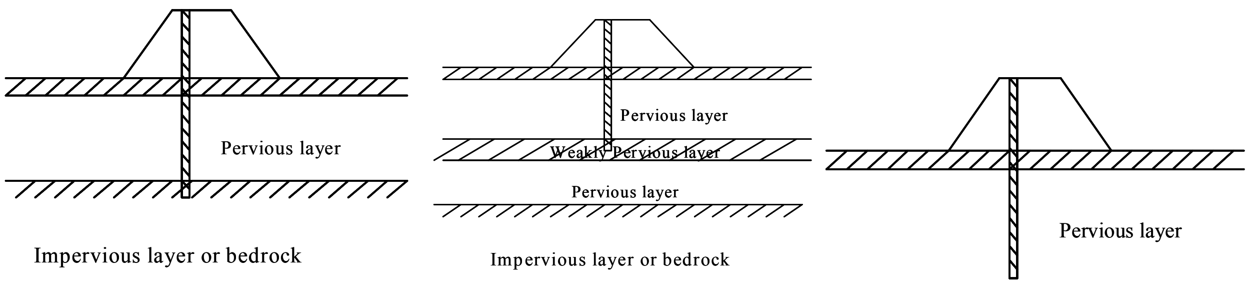
The principal dyke breaches in 98' Flood happened at (Wang et al. 1999):

1) Jiujiang city, in Jiangxi province

At 13:30 on Aug. 7, piping occurred at the land side of the dyke. The piping developed quickly and finally caused breaching of the dyke. The flow rate at the breach exceeded 400 m^3/s. People finally closed the breach at 18:00 on Aug. 9.

2) Anzao polder, in Hunan province

Dyke breaching occurred at the night of July 24, resulting from the seepage failure in the levee foundation. A part of the levee collapsed with 20m in length and water overtopped the dyke.



(a) Total blocking (b) Partially blocking (c) Suspending

Fig. 4 Seepage control in vertical direction

3) Mengxi polder, in Hubei province

In the afternoon of July 25, four leakage chinks in a pool at the land side of the dyke were found and quickly treated. But leakage chinks turned up again at the night of Aug. 7, which developed quickly and caused collapse of a 20m long section of the levee. Then the water overtopped the dyke and breaching occurred.

4) Hezhen polder of Paizhou, in Hubei province

On July 31, sand boiling occurred in the ground about 40m from the toe of the levee. The boiling continued despite the treatment being made. Two breaches turned up and developed quickly, which finally resulted in the dyke breaking for 100m in length.

5) Linan polder, in Hunan province

On July 14, the flood stage exceeded the elevation of levee crest. The sub-dyke was immediately built. But the flood stage continued to rise, till it was 1.0m higher than the levee crest and made 3 big breaches in the dykes. One of the breaches was 228 m in length and 19.2 m in depth, one was 298 m in length and 14.8 m in depth, and one was 188 m in length and 18.9 m in depth, respectively. The flood also made 5 small breaches in the dyke. The dyke broke at last.

6) Xiguan polder, in Hunan province

In the morning of July 24, overtopping occurred at three places along the 2.8 km long dyke. A sub-dyke of 0.5m~0.8m in height was built hurriedly. But it was broken through very soon. The flood made a 492 m long, 15.5 m deep breach in the dyke. The whole Xiguan polder was then destroyed.

7) Jiangzhou polder, in Jiangxi province

On Aug. 4, bubbling springs turned up at night. They developed quickly and led to subsiding of the levee body. Cracking developed and the levee broke at last.

STRENGTHENING OF YANGTZE DYKE

Though the 98' Flood made 73,825 dangerous situations, losses caused by it was much less than those by 1931 or 1954 floods. Prompt emergency repairs and strengthening played an important role in the flood fighting.

In view of the severe flood control situation revealed in the 98' flood, much investment was made in Yangtze valley. The key flood protection plan involved "closing hillsides for forestation, returning exploited land to forestry, removing polder dykes for flood running, returning cropland to the lake, strengthening main dykes, dredging rivers and lakes" (Wei and Zhong 1999). Since it was densely populated in the stretches, it is not easy for the plan to be implemented.

As for dyke strengthening, the main measures are thought to be as follows:

Heightening and Thickening

According to the specifications, the ratio of levee slope should be smaller than 1:3, and the width of the levee crest should be from 8m to 10m, with the top level being 0.5m higher than the flood control level. Since it need too much of soil, this project could only be implemented stage by stage. The first-stage work involved 5×10^7 m^3 of earth and is now being done.

The heightening and thickening of dykes were generally made at the downstream slope. Sometimes they had to be done at the river side. Since there is always thick layer of clay in the river reaches with low shear strength, the important thing was how to employ this kind of soil to build dykes. In a few places, dykes were built heterogeneously with different soils, while in cities, reinforced concrete and cement-rubble masonry were usually used to build the dyke due to the expensive cost of land and soil.

Seepage Control of the Dyke and the Foundation

It was recorded in 98' Flood that most of the dangerous situations were caused by seepage and related slides. So seepage control aroused much attention in the following years. Counter-seepage treatment was made in the most dangerous places. It involved several hundred miles of dykes. The principal counter-seepage measures were deep mixing, grouting, building diaphragm wall with plastic concrete (while the trench was made by sawing), and high pressure jet grouting. The seepage control in vertical direction essentially had the following three methods (see Fig. 4).

1) Total blocking

By this method, the seepage of the underground water is completely held up by the counter-seepage underground cut-off wall penetrating into the impervious layer or the bedrock. Theoretically, this kind of treatment can completely prevent the seepage and seepage failures. However, in order to reach the impervious layer or the bedrock, the wall will often be quite deep and expensive. Additionally, inland inundation and salinization will be induced if the underground water cannot be exuded to the river in low water period. So one ought to be very careful in applying this method.

2) Partially Blocking

According to this method, the vertical cut-off wall is penetrated into a relatively weakly pervious layer. Although the seepage is partially blocked, it was indicated by experiments and numerical analysis that the hydraulic gradient is greatly reduced at the outcrop. As a result, the resistance against the seepage failure is greatly increased.

3) Suspending

If the pervious upper layer is too thick for the wall to reach the weakly pervious or the impervious lower layers, the wall is just built for a certain depth in the pervious upper layer. In a sense, it is being "suspended" in the pervious upper layer. The seepage path is extended by this method, whereas the hydraulic gradient at the exit is not decreased remarkably, only about 10 percent. However, it is shown by experiments that although it has little effect on the hydraulic gradient, this method can restrain the development of the seepage failure. On the other hand, this method is also useful in treating such hidden defects as cracking and holes in the dyke.

Apart from the abovementioned methods, inclined impervious wall made of cohesive soil or geomembrane was also used in some dykes.

Relief well is another means of seepage control. Several types of relief wells are now applied in Yangtze valley. However, they get choked up easily and are not quite easy to be repaired. These shortcomings prevent its application and development in practice.

Bank Protection

Bank protection (bank caving treatment) covered 40 percent of the total investment on the strengthening project of Yangtze dykes. Dumping riprap is the main method to protect the bank slope. However, this primitive method cost 100 m^3 of block stones for a meter length of the bank. Altogether 7×10^7 m^3 of stones has been dumped into the Yangtze River since 1992. The exploitation of stones is disadvantageous for the environment. In recent years, mattress and concrete monolith enclosed with wire basket were used to stabilize the bank. And the fabric form was also used in some places.

SCIENTIFIC RESEARCH ON YANGTZE DYKE

Till 98' Flood, little scientific research was made on Yangtze dyke. The calamitous flood revealed many problems existed in the flood control works, and promoted the study on the dykes in Yangtze valley. The study involved:

a) Failure mechanism of Yangtze dyke

b) Detection of hidden defects in the dyke

c) Dyke management on the basis of GIS

d) Safety evaluation and related indexes

e) Risk analysis

f) Relationship between the dyke strengthening and watershed planning: the joint operation of dykes, reservoirs, lakes, and other flood diversion areas

Failure Mechanism of the Dyke

1) Stability against dyke sliding

Limit equilibrium method, FEM, and stochastic FEM were to be used to study the stability against the sliding of the dyke, in which the influence of seepage under saturated/unsaturated condition was to be considered.

2) Seepage failure

Seepage failure was the main cause of dyke failure in Yangtze valley. The mechanism of seepage failure and seepage control measures were to be studied through making model experiments and numerical analyses, as well as summarizing the pervious experience in seepage treatment.

3) Bank caving

The research on the failure mechanism, affecting elements, and the treatment measure were to be involved in this study. The scouring effect of the flow and the outward seepage of the underground water were thought to be the main causes for bank caving. It is also very important to evaluate the advantage and disadvantage of dumping ripraps in bank protection.

Detection of Hidden Defects in the Dyke

By now, several non-destructive detection techniques such as exploratory radar, frequency domain electro-magnetic sounding, high density electric current, and flow field method have been applied to detect the leakage chinks and other hidden defects in Yangtze dykes.

Safety Evaluation of the Dyke

Safety evaluation and related evaluation indexes of the dyke are important in making modern dyke management and watershed planning. GIS will be a great aid in the study. The theories on statistics and reliability analysis are very important, too.

CONCLUSIONS

a) The levee plays an important role in the protection of the rich and populous plain regions of the middle lower reaches of Yangtze River.

b) It is shown by statistics that most of the dangerous situations and dyke failures was induced by seepage failures and bank caving. Therefore much attention need to be paid to seepage control and bank caving treatment.

c) GIS can be a great aid in dyke management and flood control.

d) The environmental impact assessment need to be made in the comprehensive reclamation of river basin. It is important to keep mankind and the nature in harmony.

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