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An analysis of soil composition and mechanical properties of riverbanks in a braided reach of the Lower Yellow River

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The channel adjustment in a braided reach is very prominent in the fluvial processes of the Lower Yellow River, in which the process of bank erosion plays an important role, especially during the period of clear water scouring. The process of bank erosion is closely related to soil composition and mechanical properties of the riverbanks. In this paper, the recent bank erosion process in a braided reach between Huayuankou and Gaocun was firstly investigated after the water impoundment and sediment detention of the Xiaolangdi Reservoir, and then a field observation and indoor soil tests were conducted at 10 typical riverbanks in the braided reach. Through analyzing the experimental results, changes of riverbank-soil composition and mechanical properties were found, and the two real reasons causing serious bank erosion in the braided reach were identified. The following conclusions were drawn from this study: (i) the majority of riverbanks are made up of cohesive soil, and can be characterized by obvious vertical stratification structures of soil composition; (ii) these riverbanks are very erodible due to the lower clay-content and weak erosion-resistant strength in the bank soil, with its critical shear stress value (0.1—0.3 Pa) being much less than that of the average near-bank flow shear stress (2.0—3.0 Pa), which is one important reason causing serious bank erosion; (iii) frequent occurrence of bank failure during flood seasons usually results from the fact that the values of shear strength parameters such as the cohesion and internal friction angle decrease with the increase of water content in riverbank soil, and the value of cohesion reduces drastically from 34 to 4 kPa with the increase of water content, which is another important reason causing serious bank erosion in the braided reach.

Lower Yellow River, braided reach, riverbank erosion, riverbank-soil composition, mechanical properties, erosion-resistant strength, shear strength

The Mengjin-Gaocun reach with a length of about 286 km is a famous braided reach in the Lower Yellow River (LYR), and for the convenience of analysis later in this paper, this braided reach is further divided into three stretches, i.e. the reach upstream of Huayuankou with a length of 108 km, the reach between Huayuankou and Jiahetan with a length of 101 km, and the reach between Jiahetan and Gaocun with a length of 77 km. The latter two reaches are used in this paper as the study reach. The plan view of the Lower Yellow River is shown in Figure 1. This braided reach is characterized by a distance of 5 to 20 km between the left and right levees, a channel width of 1.0 to 3.5 km, and a longitudinal channel slope of 1.72‰ to 2.65‰. The elevation differ-

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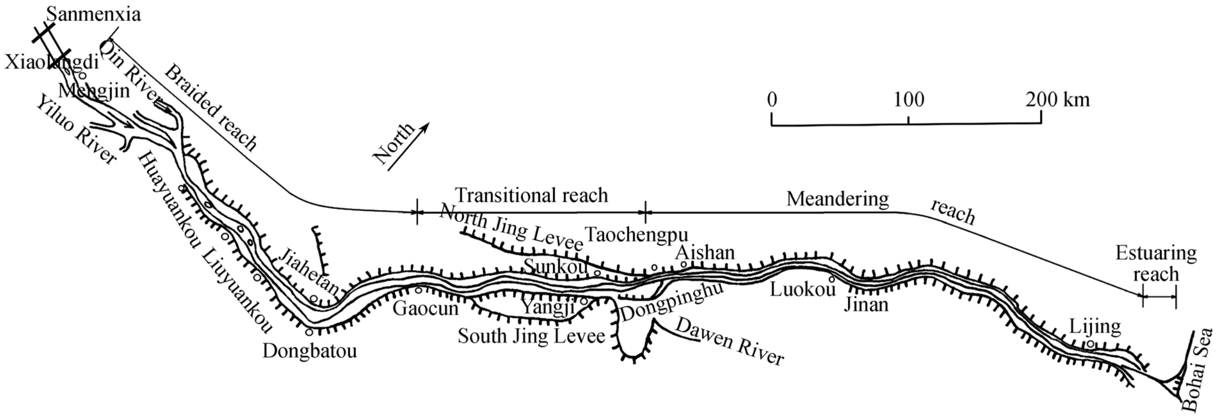

Figure 1 Plane view of the Lower Yellow River.

ence between the floodplain and the main channel is relatively small, less than 2.0 m in the reach between Huayuankou and Gaocun, and this reach is generally quite straight with a sinuosity coefficient of 1.15. In addition, the braided reach is composed of many wide and narrow stretches. In a wide stretch with a long stream length, there are numerous sand bars and complicated branches appearing at low water stages. This kind of planform results in flow diverging and frequent shifting of the main streamline. In a narrow stretch with a short stream length, the natural clay spurs or artificial bank protection works constrain the channel shifting, which causes a narrow channel to be formed. During flood seasons, there is a high level of channel deformation and shifting of the main stream in the braided reach. The special channel adjustment in the braided reach is closely linked to the boundary condition of river-bank-soil composition, and the channel stability is very weak in this reach because of its relatively coarser composition, lower clay content and lower erosion-resistant strength in riverbank soil[1,2]. During the period of water impoundment and sediment detention of the Sanmenxia Reservoir, the sediment entering the LYR reduced greatly, and the mean annual sediment amount at Xiaolangdi section changed from 1.45×10^9 tons in the 1950s to 0.57×10^9 tons during the period from 1961 to 1964, which caused an extreme scour in the LYR. Over the period from 1961 to 1964, 2.14×10^9 tons sediment was scoured in the LYR. The accumulative scour volume reached 1.52×10^9 m^3 in the reach upstream of Gaocun, which accounted for 71% of the total scour volume occurred in the LYR[3]. According to the observed statistical data, about 200 km^2 of the floodplain in the Huayuankou-Gaocun reach experienced continuous bank erosion caused by the flows with low concentrations released from the reservoir during this period. As a result, the channel width below the elevation of low floodplain in the reach between Huayuankou and Dongbatou increased from 2563 to 3633 m, namely almost 1000 m wider after the four-year operation of the reservoir. During this period, the mean annual scoured sediment amount reached 0.558×10^9 tons, of which about 43.3% was fine-grained sediment with mean size being finer than 0.025 mm. Therefore, about 35% of the scoured sediment resulted from the process of bank erosion because the scoured sediment from the main channel only accounted for 5% to 10% of the total scoured sediment in the LYR[1,4].

At present, the operational mode of water impoundment and sediment detention is being used in the Xiaolangdi Reservoir since September 1999. During this period, the majority of medium-coarse- and coarser-grained sediments were silted in the reservoir, which led to a sedimentation volume of 1.782×10^9 m^3, and a flushing sediment ratio of 17%. Therefore, the mean sediment concentration released from the Xiaolangdi Reservoir was relatively low, and the mean annul sediment amount entering the LYR was about 60×10^6 tons, which caused a continuous degradation in the LYR. According to the calculated result from the observed cross sections, the accumulative scour volume reached 0.77×10^9 m^3 in the reach between Xiaolangdi and Lijin with a length of 760 km, of which 77% of the scoured sediment volume occurred in the braided reach upstream of Gaocun. Furthermore, the mean area of main channel below a bankfull stage increased from 1800 to 4270 m^2, and the scoured sediment volume from bank erosion accounted for about 45.6% of the total scour volume in the braided reach. Therefore, the evolution of main channel was closely related to the process of bank erosion in the braided reach[5].

From the above analysis, it can be deduced that the channel adjustment in the braided reach is very prominent in the fluvial processes of the LYR, and the process of bank erosion plays an important role in the channel adjustment of the braided reach, especially during the current period of clear water scouring. The process of bank erosion is closely related to riverbank-soil composition and corresponding mechanical properties. However, due to the lack of riverbank soil data, related researches about this field in the LYR have not been reported yet. Therefore, study on the analysis of riverbank-soil composition and mechanical properties in the braided reach will not only enhance our understanding of the characteristics of fluvial processes in the LYR but also provide related parameters for the simulation of bank erosion process in movable-bed river models and numerical models. In this study, the recent bank erosion phenomenon along the reach was firstly analyzed, and a field observation of riverbanks at 10 typical sections in the braided reach between Huayuankou and Gaocun and further indoor soil tests were made. A part of results for this study is presented here, which focuses on the variations of soil composition and mechanical properties of the riverbanks, and the reasons causing currently serious bank erosion in the braided reach are also proposed quantitively.

1 Recent bank erosion in the braided reach

Two aspects are usually included in the channel adjustment of LYR during the clear water scouring, namely the longitudinal degradation and lateral widening of the main channel. The process of longitudinal degradation can lead to undercutting of cross sections, while the process of lateral channel shifting or bank erosion can cause widening of cross sections. Before the construction of a reservoir, bank erosion usually occurs in one local reach, while bank accretion also happens often in another local reach, which can keep the dynamic balance of channel width. After the construction of a reservoir, the effects of smoothing of flood peaks and decreasing of incoming sediment supply destroy the relative balance relationship between bank erosion and bank accretion, which often causes serious bank erosion to take place in the braided reach[1]. At present, continuous degradation has occurred in the LYR due to the water impoundment and sediment detention of the Xiaolangdi Reservoir, which caused lateral main-channel widening with bed-level undercutting in some local reaches. However, no obvious overflow floods happened during the period since the start of water impoundment, so widening of the main channel in the braided reach was solely caused by the process of bank erosion. The widening phenomenon is prominent in the braided reach between Huayuankou and Gaocun, especially in the reach between Huayuankou and Jiahetan due to relatively imperfect control engineering and floodplain-protection engineering.

By analyzing the cross sections' data observed before a flood and after the flood from 1999 to 2005, the main-channel width and depth just below a bankfull stage at each section were obtained, and then a length-weighted mean method was used to calculate the average main-channel width and depth in different reaches. Statistical results show that the average main-channel width in the Huayuankou-Jiahetan reach increased from 1210 m after the flood season in 1999 to 1770 m after the flood season in 2005, with an increase rate up to 47%, and accordingly, the average main-channel depth increased from 1.5 to 2.6 m over this period, with an increase rate up to 68%. The average main-channel width in the Jiahetan-Gaocun reach increased from initially 650 to 890 m, with an increase rate up to 36%, and accordingly, the average main-channel depth increased from 2.3 to 3.6 m over this period, with an increase rate up to 57%. The ratios of the sediment from bank erosion to the total scour volume were 54% and 50% in these two reaches, respectively[5]. Therefore, it can be concluded that the sediment from bank erosion accounted for almost half of the total scour volume in the study reach during this period.

Figure 2 shows the changes of cross-sectional profiles at two typical sections of Heishi1 and Caogang in the Huayuankou to Jiahetan reach. Heishi1 section is located about 46 km downstream of the Huayuankou hydrometric station, and the left bank of this section is close to downstream of a water intake on the Yuanyang floodplain and a lot of floodplain-protection engineering works have been built around this location, which keeps the left bank relatively stable. However, around the right of Heishi1 section, no engineering work exists on the floodplain, which led to a 936 m bank retreat over the

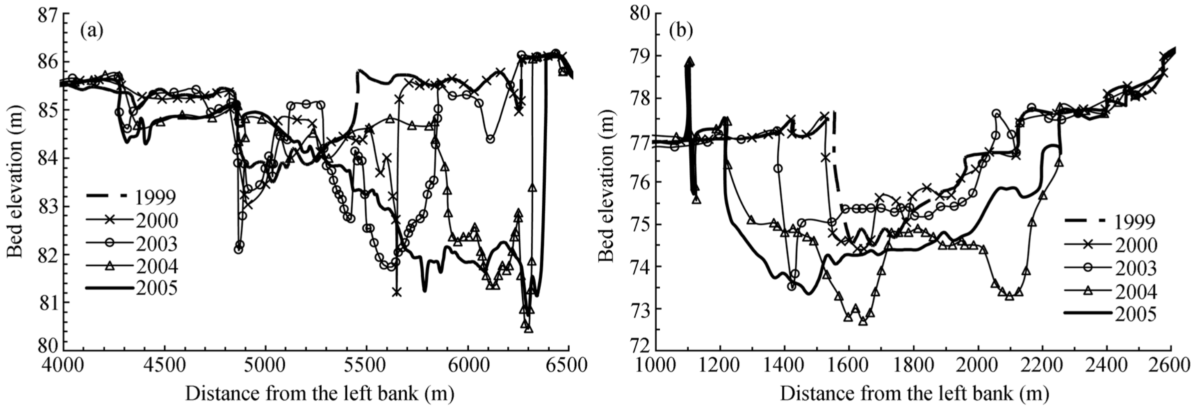

Figure 2 Changes of cross-sectional profiles at typical sections of Heishi1 (a) and Caogang (b).

past six years. During the flood season in 2004, the retreat distance of the right bank at this section reached 465 m due to the large volume of incoming water. Caogang section is located 3 km upstream of the Jiahetan hydrometric station, and its right bank is protected by the Fujunshi control engineering project. Therefore, the erosion intensity of the right floodplain's bank is relatively lower, with a 130 m retreat distance observed in the past six years. On the left bank at this section, the retreat distance reached 340 m over the same period due to the lack of bank-protection engineering. In the reach between Jiahetan and Gaocun, many control engineering and floodplain-protection engineering works have been built along the reach, so the level of bank erosion is relatively weak, and the phenomenon of main channel widening is also not so obvious. Therefore, it is crucial that the process of bank erosion is taken into consideration for the study of fluvial processes in the LYR during the current clear water scouring. Because the process of bank erosion is closely related to local soil composition and mechanical properties of the riverbanks, a field observation and indoor soil tests of the riverbanks in the braided reach were carried out.

2 Field sampling and indoor soil tests of the riverbanks

2.1 Field sampling of riverbank soil

Field sampling points of riverbank soil were usually located around the existing observation sections, according to the specific circumstance of bank erosion and the result of field observation in the braided reach. In addition, the locations of sampling points were often close to the side floodplain where the main stream approached, and were positioned precisely using a hand-held GPS. In this field observation exercise, the total number of sampling points was set to 10, in which 6 points were located in the reach between Huayuankou and Jiahetan, and 4 points were located in the reach between Jiahetan and Gaocun. Figure 3 shows the detailed locations of these sampling points. Table 1 indicates the latitude and longitude coordinates of sampling points and names of neighboring sections near the sampling points. All sampling points for this study were located on the right bank of the channel. The current side floodplain was formed from several high floods before the operation of the Xiaolangdi Reservoir, and soil composition and mechanical properties on the left or right riverbank should be more or less the same because lateral channel shifting usually occurred in this reach. Therefore, the study results from the sampling points on the right riverbanks can approximately represent the section-averaged values.

Due to the limitation of the sampling equipment, the maximum thickness of sampled riverbank-soil layers at each section was less than 1.5 m, and the method of stratified sampling was used in all riverbank-soil layers according to the difference of soil composition, and physical properties. For this study, 13 groups of undisturbed soil samples and 6 groups of bulk soil samples were collected. Undisturbed soil samples were packed with metal sampling tubes, while bulk sampling samples were packed with plastic bags. According to the results of field observation, the thickness of each soil layer was surveyed at a section, and each soil layer was also named on the spot by an experienced surveyor, and corresponding sketched maps of vertical stratification structure of each riverbank were also drawn in this study.

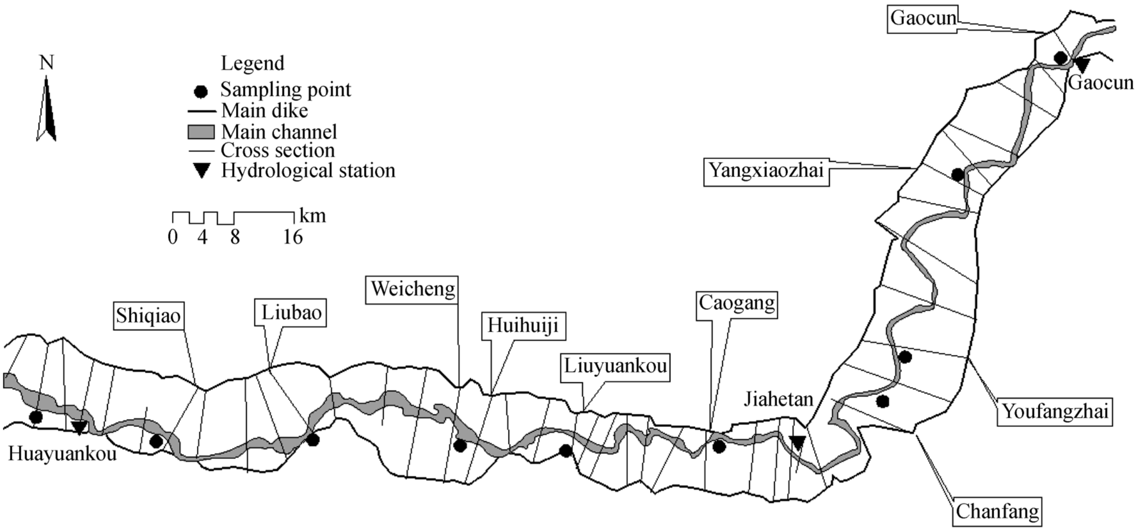

Figure 3 Locations of riverbank-soil sampling points in the reach between Huayuankou and Gaocun.

Table 1 Coordinates and names of neighboring sections near sampling points

No.	Section name	Description of detailed location	Latitude and longitude coordinates	
1	Huayuankou	upstream of Huayuankou section, and about 1 km downstream of Nanguotou	–	–
2	Shenzhuang	near Shenzhuang section, and 1248 m upstream of Shiqiao section	113°46′1.5″	34°54′30.1″
3	Xinzhai	near Xinzhai section, and 416 m upstream of Liubao section	113°59′20.1″	34°55′9.3″
4	Weicheng	near Weicheng1 section, and 1949 m upstream of Huihuizhai section	114°12′5.6″	34°54′52.3″
5	Liuyuankou	near Liuyuankou1 section, and 768 m upstream of this section	114°21′15.3″	34°54′25.7″
6	Jiahetan	100 m downstream of Kaifeng Yellow River Bridge	114°34′29.8″	34°55′23.1″
7	Wangxiaozhuang	near the Dongbatou control engineering, 2348 m downstream of Chanfang section	114°49′1.4″	34°58′37.2″
8	Wangjiadi	near the Wangjiadi control engineering, 1737 m upstream of Youfangzhai section	114°49′53.8″	35°1′29.0″
9	Yangxiaozhai	near Yangxiaozhai section, 903 m downstream of this section	114°55′37.0″	35°14′55.0″
10	Gaocun	near the Gaocun Hydrometric Station	115°4′39.5″	35°22′57.8″

Note: The date of field sampling was from September 16—17, 2006.

2.2 Indoor soil tests of riverbank soil

The criteria for the classification of soil grains and soil types were based on the Standard of Soil Test Method (GB/T 50123-1999) and Specification of Soil Test (SL237-1999). In order to study the bank soil composition and mechanical properties in the braided reach, indoor soil tests included the determination of particle-size analysis, specific gravity, limit water content, soil density, shear strength, and so on. Experimental results were obtained for a series of indicators such as the soil type, gradation, shear strength and compactness of bank soil. Table 2 shows the experimental results of riverbank-soil physical and mechanical properties in the braided reach. Some physical indicators and shear strength parameters were not presented because these soil layers were very thin or uncovered.

3 Changes of riverbank-soil composition

3.1 Vertical stratification structure of riverbank-soil composition

It can be found from soil test results that the majority of riverbanks are composed of cohesive soil, and only several riverbanks are composed of noncohesive soil in the study reach. The classification standard of cohesive and non-cohesive soils is based on this publication[6]. In addition, there exists an obvious structure of vertical stratification in the composition of riverbank soil. The upper soil layers in most riverbanks belong to a kind of low-liquid-limit clay with very fine-grained soil, with their average clay-grain content of 13.1%. The lower soil layers in a majority of riverbanks belong to a kind of silty sand or sand with fine-grained soil, and their aver-

Table 2 Experimental results of riverbank-soil physical and mechanical properties in the braided reach

Section name	Thickness of soil layer (cm)	Sample name	Clay content (%)	Plasticity index (I_p)	Physical indicators in natural conditions					Shear strength parameters	
					Water content ω (%)	Wet density ρ (g/cm^3)	Dry density ρ_d (g/cm^3)	Void ratio e	Saturation degree S_r (%)	Cohesion c (kPa)	Internal friction angle ϕ (°)
Huayuankou	surface layer (30)	CL	4.5	13.2	20.7	2.031	1.68	0.599	93	31.0	36.8
	underlayer (20)	SM	3.2		15.3	1.720	1.49	0.797	51.5	27.4	34.5
Shenzhuang	surface layer (6)	CL	26.1	16.7							
	underlayer (20)	SM	2.2		20.2	2.018	1.68	0.596	90.8	32.8	33.7
Xinzhai	surface layer (34)	CL	34.9	21.9	25.6	1.735	1.38	0.976	71.6	25.6	26.1
	middle layer (36)	CL	8.5	17.6	33.6	1.875	1.40	0.924	98.2	18.3	26.7
	underlayer (3)	CH	57.3	35.3							
Weicheng	surface layer (43)	CL	6.8	15.7	27.1	1.862	1.46	0.843	86.8	22.7	32.7
	middle layer (24)	CL	5.5	11.5	17.3	1.850	1.58	0.706	66.0	26.4	35.6
	underlayer (*)	SF	1.1								
Liuyuankou	monolayer (130)	CL	5.7	12.3	26.2	1.795	1.42	0.898	78.8	18.8	26.3
Jiahetan	monolayer (*)	SM	3.3		22.8	2.047	1.67	0.614	99.9	4.10	35.8
Wangxiao-zhuang	monolayer (*)	CL	5.1	16	26.6	1.904	1.50	0.782	91.2	16.6	29.3
Wangjiadi	surface layer (3)	CL	17	11.7	21.5	2.011	1.66	0.625	92.5		
	middle layer (10)	CL	10.5	13.1	25.4	1.968	1.57	0.720	95.2	16.3	28.4
	underlayer (*)	SM	3.7		32.2	1.790	1.35	0.979	88.1		
Yangxiazhai	monolayer (30)	CL	5.5	16.6	23.5	1.982	1.60	0.689	92.5	34.0	29.8
Gaocun	surface layer (5)	CL	22.5	10.4							
	underlayer (*)	CL	23.4	15.2	38.5	1.861	1.34	1.017	102.6	4.10	26.7

CH, high liquid limit clay; CL, low liquid limit clay; SM, silty sand; SF, fine-grained sand; (*), unexposed soil layer.

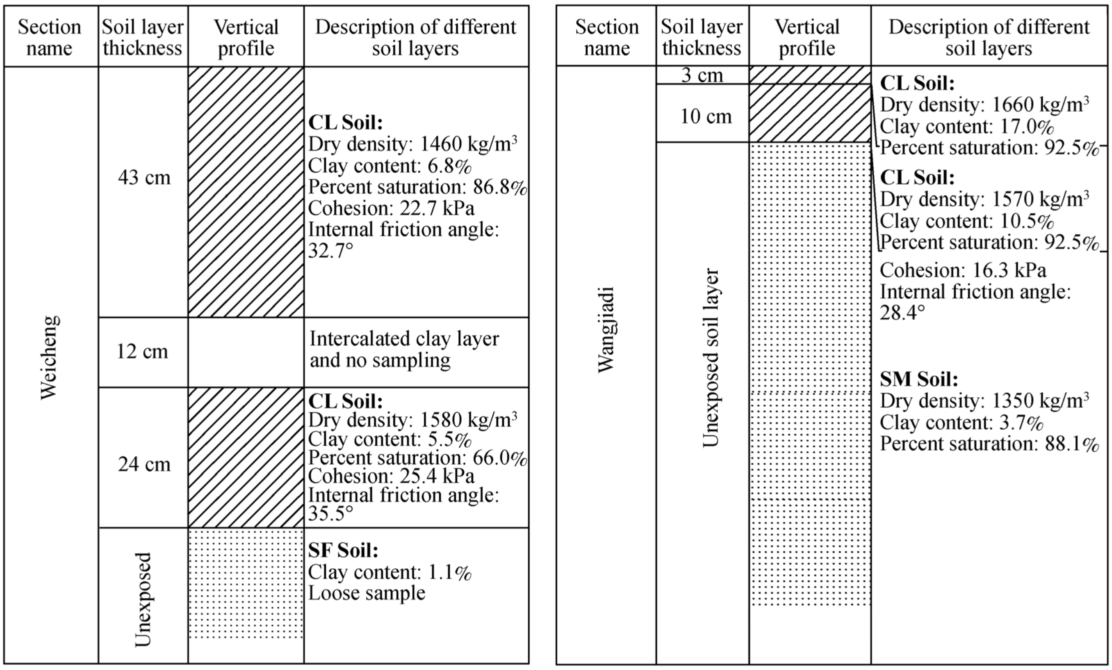

Figure 4 Vertical stratification structures of typical riverbank soils.

age clay-grain content is about 6.2%. A very thin clay seam can be found between the upper layer of low-liquid-limit clay and the lower layer of silty sand at some sampling points.

Figure 4 shows a clear indication of vertical stratification structures of riverbank-soil composition near Weicheng section and Wangjiadi section. The upper soil layer near Weicheng section is made up of low-liquid-limit clay with an average clay-grain content of 6.3%, and the lower soil layer is composed of sand with fine-grained soil, with an average clay-grain content of 1.1%. For the bank soil near Wangjiadi section, the upper soil layer is also composed of low-liquid-limit clay with an average clay-grain content of 12%, and the lower soil layer is composed of silty sand with an average clay-grain content of 3.7%. Therefore, it can be concluded that the formation of bank soil experienced two kinds of processes with different flow intensity, and the lower soil layer in a riverbank is usually the result of sediment deposition from the main stream with relatively high flow velocity, while the upper soil layer is often made up of sediment deposition from the overland flow with relatively low flow velocity. Obviously, the vertical stratification structure of riverbank-soil composition is closely related to the lateral shifting of the main stream in the braided reach[7].

3.2 Changes of riverbank-soil composition along the reach

Although the majority of riverbank soils are composed of cohesive soil, the variation of riverbank-soil composition along the reach is very significant in the study reach. Clay-grain contents of the upper soil layers range from 3.3% to 34.9%, and the median diameters of soil grain vary from 0.009 to 0.082 mm. Clay-grain contents of the lower soil layers range from 1.1% to 23.4%, and the median diameters of soil grain vary from 0.013 to 0.143 mm. The value of soil uniformity coefficient in most of the lower soil layers is less than 3.0, and however, this value near Gaocun is greater than 3.0.

From Figure 5, it can be seen that the median diameters of riverbank soils have a slight tendency of decreasing along the reach, however, this trend is not so obvious, which may be caused by the special location of riverbanks and local channel adjustment near the riverbank[7,8]. The median diameters of lower soil layers near sections of Huayuankou, Jiahetan, and Gaocun after the flood in 2006 are 0.086, 0.082, and 0.013 mm, respectively. It can be found only at these three sections, an obvious tendency of decreasing in median diameter can be observed for the riverbank-soil composition along the reach. However, under a normal circumstance, there exists a very clear trend of decreasing in the median diameter for the bed-material composition in the main channel. The median diameters of bed material in the main channel in 2006 were 0.206, 0.142, and 0.133 mm near the hydrological stations of Huayuankou, Jiahetan and Gaocun, respectively, which shows the clear tendency of decreasing in diameter along the reach.

4 Changes of mechanical properties of riverbank soil

From the above results of soil tests, it is clear that the majority of riverbanks in the braided reach are composed of cohesive soil. The erosion process of cohesive riverbank usually includes two phases: lateral erosion by the flow and mass failure under gravity or other factors[9–12]. The mechanical properties of cohesive riverbank can often be presented by its erosion-resistant strength and shear strength, and these two parameters have an important effect on the stability of riverbank

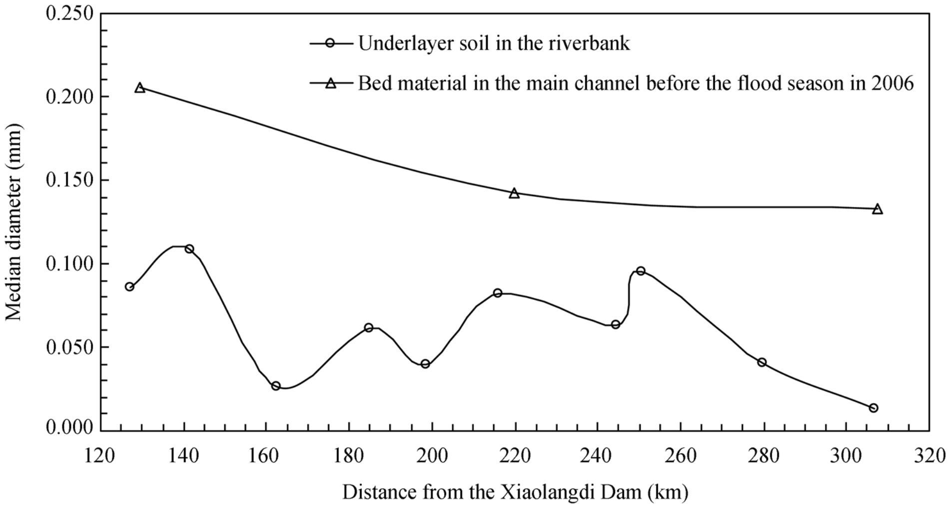

Figure 5 Changes of median diameters in the main-channel bed material and riverbank soil.

slope.

The content of silt and clay in a riverbank-soil composition is usually used to express indirectly its property of erosion-resistance, which is a qualitative expression used in the river geomorphology[13−15]. In order to analyze quantitively the erosion-resistant property of riverbank soil, the method of critical shear stress or incipient velocity from river dynamics should be used to determine the value of erosion-resistance. For cohesive riverbanks, aggregates or crumbs of soil, rather than individual particles, are usually eroded under the action of not only the submerged weight, the lift and drag forces but also the cohesive force between grains. The cohesive force depends heavily on the mineralogy, moisture content, and other soil properties[9,16]. In general, the near-bank flow shear force is the dominant driving force, which acts on the bank surface, and the submerged weight and cohesive force are the leading resistance, which can keep the aggregates undetached. If the driving force is much greater than the resistance from the bank, the soil on the bank surface can be entrained, which finally leads to bank failure under gravity. Bank failure is a process in which the upper soil layer of a bank slides or falls toward the bank-toe under the influence of gravity or other factors. It is usually caused by over-deepening due to bed scouring or by lowering of related shear strength parameters in riverbank soil. As the degree of bank stability decreases to a critical value, a block of riverbank soil collapses. In addition to the action of gravitational force, bank failure can also be caused by various mechanisms[10,17], such as wetting-drying, freezing-thawing, rapid fall of the in-channel stage after a high-flow event, and seepage-piping. For cohesive riverbanks, if the internal shear stress is greater than the shear-resistant strength on the critical potential failure surface, a part of upper bank soil will slip and fail. Whether the cohesive bank fails or not mainly depends on the balance of driving and resisting forces on a failure surface. The driving forces are related to the mechanical properties of riverbank soil and riverbank geometry. The resisting forces are correlated with the cohesion, the internal friction angle, and other factors. In the braided reach of the LYR, the majority of riverbanks include lower contents of clay-grain in the lower soil layers, so the property of erosion-resistance is very weak in riverbank soil. However, the near-bank velocity in the braided reach is relatively high due to its large longitudinal channel slope and lower bed roughness. Therefore, the toe of riverbank can be scoured even if the channel is under the state of deposition. According to the results from soil tests, void ratios in most of riverbank soils are relatively large, ranging from 0.6 to 1.0, and riverbank soils can be taken as a kind of freshly deposited clayer soil. Thus many formulas proposed by researchers can be used to calculate the incipient velocity or critical shear stress of riverbank soil[18,19]. The formula of critical shear stress proposed by Tang[20], accounted simultaneously for the action of the submerged weight force, the lift force, the drag and cohesive forces for the freshly deposited clayer soil. This formula can be expressed as

$$\tau_{\mathrm{c}} = 6.68\times 10^{2}\times d + \frac{3.67\times 10^{-6}}{d}, \qquad (1)$$

where τ_{c} is the critical shear stress (N/m^2) and d is the median diameter of soil (m). This formula is valid as the median diameter ranges from 0.001 to 200 mm. It should be pointed out that the above formula cannot account for the effect of bank vegetation on the critical shear stress, but it may be considered later as indicated by Huang et al.[21]. From eq. (1) it can be seen that the soils can be scoured more easily as its diameter is in the range from 0.08 to 0.10 mm. According to the results from soil tests, the diameters of lower soil layers in the study reach ranged from 0.013 to 0.109 mm, so the critical shear stress calculated by Tang's formula[20] is in the range from 0.10 to 0.30 N/m^2. If the longitudinal channel slope equals approximately to the value of water surface slope, and the water depth near the bank equals to half of the mean depth below a bankfull stage, the hydraulic shear stress acted on the bank can be predicted by 2 to 3 N/m^2 using these data. Therefore, due to the lower clay-content and weak erosion-resistance, the value of critical shear stress for riverbank soil is one order lower than that of the near-bank flow shear stress in the braided reach, which is one important reason for serious bank erosion in the braided reach.

The cohesion and internal friction angle can be taken as the shear strength of riverbank soil, which is an indicator associated with the stability degree of bank slope. From the experimental results, it can be seen that there exists a close relationship between water content and shear strength indicators. Figures 6(a) and 6(b) show the relationships between the water content of low-limit-liquid clay and their cohesion and internal friction angle

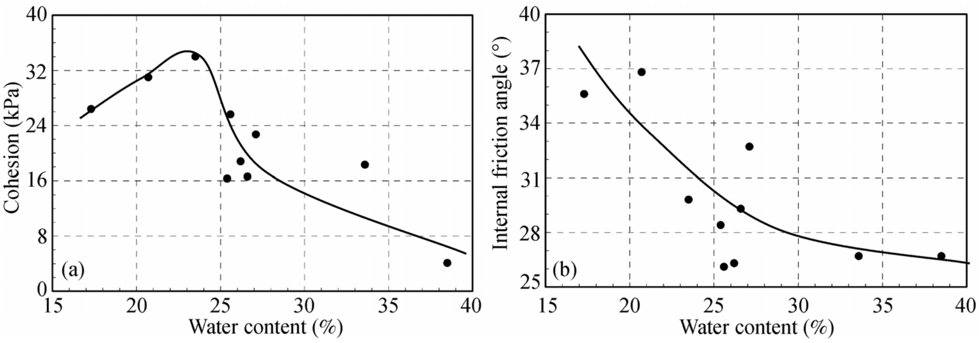

Figure 6 Relationships between water content and shear strength parameters in riverbank soil. (a) Relationship between water content and cohesion; (b) relationship between water content and internal friction angle.

in the study reach, respectively. From these figures, it can be seen that the cohesion can reach its maximum value of 34 kPa with a critical water content of about 24%. As the water content is reduced to less than this value, the cohesion will increase with the increase of the water content. The value of cohesion will decrease as the water content is greater than this value. The cohesion reduces quickly from 34 to 16 kPa as the water content increases from 24% to 27%, and then changes slightly as the value of water content is greater than 27%. Furthermore, there also exists an obvious relationship between the water content and internal friction angel for the low-limit-liquid clay. The value of internal friction angle will decrease from 37° to 26° as the water content increases from 17% to 39%. Zhao et al.[22] made a field observation and indoor soil tests of the riverbank soil in the reach upstream of Huayuankou, and found the similar relationships between the water content and shear strength indicators. Therefore, the value of water content can reflect indirectly the magnitude of shear strength, and generally speaking, both the cohesion and internal friction angle decrease as the value of water content increases.

Therefore, the variation of riverbank stability degree in the braided reach can be caused by not only the action of hydrodynamic factors from the river but also the change of mechanical properties of the riverbank soil. During dry floods, the soil pressure produced by the bank soil itself is very small due to dry soil and its low specific weight, and however, the cohesion and internal friction angle are relatively higher, compared with the values under the state of saturation, which leads to more stable bank slope. On the contrary, during flood seasons, the cohesion and internal friction angle decrease greatly after the riverbank soil is saturated by water, so the shear strength will reduce correspondingly. After the withdrawal of the in-channel flow, the wet specific weight of riverbank soil is much greater than its dry specific weight, and the soil pressure from the riverbank itself increases, which causes easily the failure of a riverbank. Generally speaking, the critical vertical height of cohesive riverbank can be predicted by related formulas from soil mechanics[9], and it can be written as

$$H_{\mathrm{c}} = (2c/\gamma_{bk})\tan(45+\phi/2), \qquad (2)$$

in which c and ϕ are the cohesion (kN/m^2) and internal friction angle (radian), respectively; H_{c} is the critical vertical height (m); and γ_{bk} is the specific weight of riverbank soil (kN/m^3). Strictly speaking, eq. (2) is valid only for uniform cohesive banks, and it may cause error as it is used to calculate the critical vertical height for natural riverbanks. According to the experimental results from soil tests carried out in this study, the values of specific weight, cohesion, and internal friction angle can be determined for dry and wet riverbank soil, so eq. (2) can be used to predict roughly the critical vertical height under different conditions, with all estimated results being shown in Table 3.

It can be seen from Table 3 that the critical vertical height for wet riverbank soil is much lower than that for dry riverbank soil. If the critical height is 6.6 m during a dry season, it will reduce to 0.80 m when saturated after a flood season. Namely, a stable riverbank with a 6.6 m height during a dry season, will collapse after a high flood, even without the action of external hydrodynamic forces. Thus Table 3 indicates that the cohesion reduces greatly with the increase of water content, and it can cause the riverbank to fail easily, which is another important reason for explaining why the phenomenon of bank erosion in the braided reach is so severe during the clear water scouring.

Table 3 Critical vertical heights of riverbank soil under different conditions

Condition	Water content ω (%)	Specific density γ_{bk} (kN/m^3)	Cohesion c (kN/m^2)	Internal friction angle ϕ (°)	$\tan(45+\phi/2)$	Critical height H_c (m)
Dry soil	24.0	17.0	34.0	31.0	1.8	6.6
Wet soil	39.0	20.0	4.0	26.0	1.6	0.8

5 Conclusions

In this paper, the situation of bank erosion during the recent clear water scouring in the braided reach between Huayuankou and Gaocun was firstly analyzed, and then a field observation and indoor soil tests of riverbank soil samples were carried out at 10 typical sections. Based on the results from this study, the authors presented the variations of soil composition and mechanical properties of the riverbanks in the braided reach, and proposed quantitively the two reasons causing serious bank erosion in this reach. Main conclusions drawn from this study are as follows.

(i) The majority of riverbanks in the braided reach belong to cohesive banks, with clear vertical stratification structures. The upper soil layers are usually made up of low-limit-liquid clay and the lower soil layers are usually made up of silty sand or sand with fine-grained soil. Furthermore, the material composition of riverbank soil changes greatly along the reach.

(ii) One of mechanical properties of riverbank soil is the erosion-resistant strength which can be represented by the critical shear stress. The near-bank flow shear stress is usually much greater than the critical shear stress in riverbank soil due to its lower clay content and weak erosion-resistance, which is one of the important reasons causing serious bank erosion in the braided reach.

(iii) Another mechanical property of riverbank soil is the shear strength which can be represented by the cohesion and internal friction angle, and their values reduce greatly with the increase of water content. After the riverbank soil is saturated during a flood season, the cohesion will decrease sharply, and the riverbank will collapse easily, which is another important reason causing serious bank erosion in the braided reach.

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