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RESEARCH

Sediment settlement rate and consolidation time of filling reclamation in coal mining subsidence land

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Abstract
With the continuous growth of the population and the continuous reduction of cultivated land, China's food security is greatly threatened. In addition, China's coal mining has been mainly underground mining, causing land subsidence and damaging existing cultivated land. This effect intensifies the contradiction between the growth of the risk population and the reduction of cultivated land. The reclamation of mining subsidence land with Yellow River sediment is often used as an effective way to improve the recovery rate of cultivated land. Shortening the reclamation time and realizing continuous filling are significant issues. The work presented in this paper studied the sediment settlement rate and consolidation time by combining theory, field filling and reclamation tests and numerical simulations. A field filling test study was carried out in the lowlands of Jibeiwang Village, Qihe County, Shandong Province, China. By calculating the drainage consolidation time, the consolidation factor of 0.015656 m^2/d, and the time factor for sediment consolidation of 0.575 were determined. The sediment consolidation time for this test was 9.18 days. The calculation of sediment deposition rate and consolidation time is of great practical significance to guide the Yellow River sediment filling, realize continuous filling, and save reclamation time and cost.

Keywords Yellow River sediment · Mining subsidence land · Filling reclamation · Consolidation time

1 Introduction

China has a large population and limited per capita cultivated land; in general, cultivated resources per capita account for only 36% of the world's average (Hu et al. 2018a, b, c). Cultivated land resources are the core elements to ensure food security (Lu et al. 2019). However, for various reasons, China's cultivated land is decreasing in different ways, which poses a great threat to China's food security. Land damage caused by coal mining is one of the reasons for the decrease in cultivated land. Coal has always been the main energy source in China, accounting for approximately 64% of the primary energy (Hu et al. 2013a, b). The national coal production reached 3.99 billion tons, accounting for 47.6% of the world coal production in 2019 (BP 2020). As China's coal production mostly uses underground mining, it inevitably causes land subsidence and damage (Wang et al. 2015; Lian et al. 2020; Bi et al. 2021). There are coal mining subsidence areas in 151 counties in 23 provinces in China, with a total area of 20,000 km^2 (Zhang 2017). Even some resource-based cities have coal mining subsidence areas exceeding 10% of their total urban area (Hu and Guo 2018).

The large-scale mining of coal has made many significant negative impacts on the environment (Chen and Hu 2018), such as land occupation by coal gangue hills, land subsidence, landscape changes, toxic gas emissions, and water and soil pollution caused by well water discharges (Hu et al. 2012). Among them, land subsidence is one of the most significant environmental problems, especially in the economically developed and densely populated areas with high phreatic water levels in Central and East China, where land resources are scarce, with many people and less land. Most of the coal mines are located in plain areas. The land above

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the coal mining face is normally cultivated. The combined area of coal mines and grain cultivation is relatively large. Approximately 85% of the subsidence land is cultivated land (Hu et al. 2013a; b).

In areas with high phreatic water levels, land subsidence will lead to a large areas of water accumulation (Yang et al. 2014), which will seriously damage the land and the ecological environment (Xiao et al. 2021a, b; He et al. 2020; Ren et al. 2020). After coal mining, the water accumulation areas of mining subsidence land in some mining areas can reach more than 50% of the subsidence area (Xiao et al. 2013). In the subsidence areas, permanent ponding and swamps easily form in cultivated farmland, and crop production is reduced or even stopped, which seriously affects crop yield (Lu 2010; Mai et al. 2011). A large amount of normally cultivated farmland has lost its normal farming function and has been abandoned after subsidence, which made the contradiction of more people and less land in the mining area more prominent, seriously affecting the agricultural production and life of the local people. At the same time, the social economy and ecological environment of mining areas have also been seriously affected, posing a threat to the sustainable and stable development of the mining areas (Xiao et al. 2021a, b; Ren et al. 2019). Therefore, the reclamation of coal mining subsidence land has become an urgent problem in our country.

Some scholars have studied the one-time filling reclamation technology using Yellow River sediments. Hu (1997) proposed the basic principle of one-time filling, which uses various filling materials (such as coal gangue, fly ash, river sediments, etc.) as filling materials to fill the mining subsidence land at one time, cover a certain thickness of soil after reaching the design elevation, and form a reconstructed soil profile. Related research showed that Yellow River sediment has a low risk of heavy metal contamination and is a new green and healthy filling reclamation material (Hu et al. 2013a, b; Duo et al. 2018). The one-time filling reclamation technology with Yellow River sediment has been tested in Jining City, Shandong Province, China, and the results showed that this filling method is feasible, but the quality of reclaimed soil needs to be improved (Hu et al. 2015).

To address the problems of one-time filling, Hu and Guo (2018) proposed a multiple filling reclamation technique based on the principles of soil science and soil reconstruction to construct an innovative multilayer soil profile structure of "soil layer + sediment layer + soil layer + sediment layer…". This method of interposing a soil layer on top of a Yellow River sediment layer to construct a multilayered soil profile configuration can overcome the negative impact of the poor water retention characteristic of the Yellow River sediment layer and improve soil productivity. Relevant studies have shown that the modified soil profile with an intercalated soil layers has the highest crop yield and can store more water and nutrients. As the thickness of an intercalated soil layer increases, it delays soil drainage (He et al. 2013). However, how can this multilayer structure be realized in practice? The existing one-time filling process first strips the topsoil and subsoil in the area to be filled, collecting as much covering soil as possible in situ, then fills the Yellow River sediment at one time, and finally covers the soil. Therefore, to realize the multilayer soil profile structure, multiple filling and multiple soil backfilling operations are needed. The Yellow River sediment filling is transported hydraulicly. After the water–sediment mixture reaches the subsided land, the sediment will be left in the subsided land and the transport water will be drained away. After the sediment is consolidated, the soil layer will be backfilled. The drainage and consolidation of the Yellow River sediment takes time, and multiple fillings require multiple waiting times for sediment drainage and consolidation, which increases the reclamation cycle.

Shortening the reclamation time and achieving continuous filling is an urgent problem, and Hu et al. (2017) proposed a solution of alternate filling in separate strips, namely, the multilayer filling reclamation method. The multilayer filling time of the Yellow River sediment alternation mainly involves the filling time, drainage consolidation time and backfilling core soil time. The backfilling core soil time is related to the power of the excavator and does not need special research. The filling time is related to the sediment settlement law and sediment deposition in the strip. The filling sediment settlement consolidation time is directly related to the filling reclamation time. Therefore, the study of sediment settlement and consolidation time is the key technical point for realizing continuous filling.

The current research on sediment settlement and consolidation has mainly been theoretical research. Hu and Guo (2018) proposed a continuous process to achieve multiple soil stripping and backfilling by alternating multiple fillings and explored the relationship between sediment consolidation time, settlement time and backfilling time to achieve the purpose of continuous filling. Wang (2016) discussed the calculation methods of the water surface line, sediment settlement rate and siltation thickness of reclamation strips and proposed the theoretical basis of the filling times and filling interval of reclamation strips.

In summary, there have been few studies on sediment settlement and consolidation time, and they have mainly been focused on theoretical studies, and few investigators have explored sediment settlement and consolidation time through field tests. In the work presented in this paper, field filling and reclamation tests were carried out using the subsidence land of the Qiuji coal mine as the study area. in addition, numerical simulations of Yellow River sediment filling were carried out with the help of the Eulerian model of fluid dynamics (using Fluent software) to study the sediment

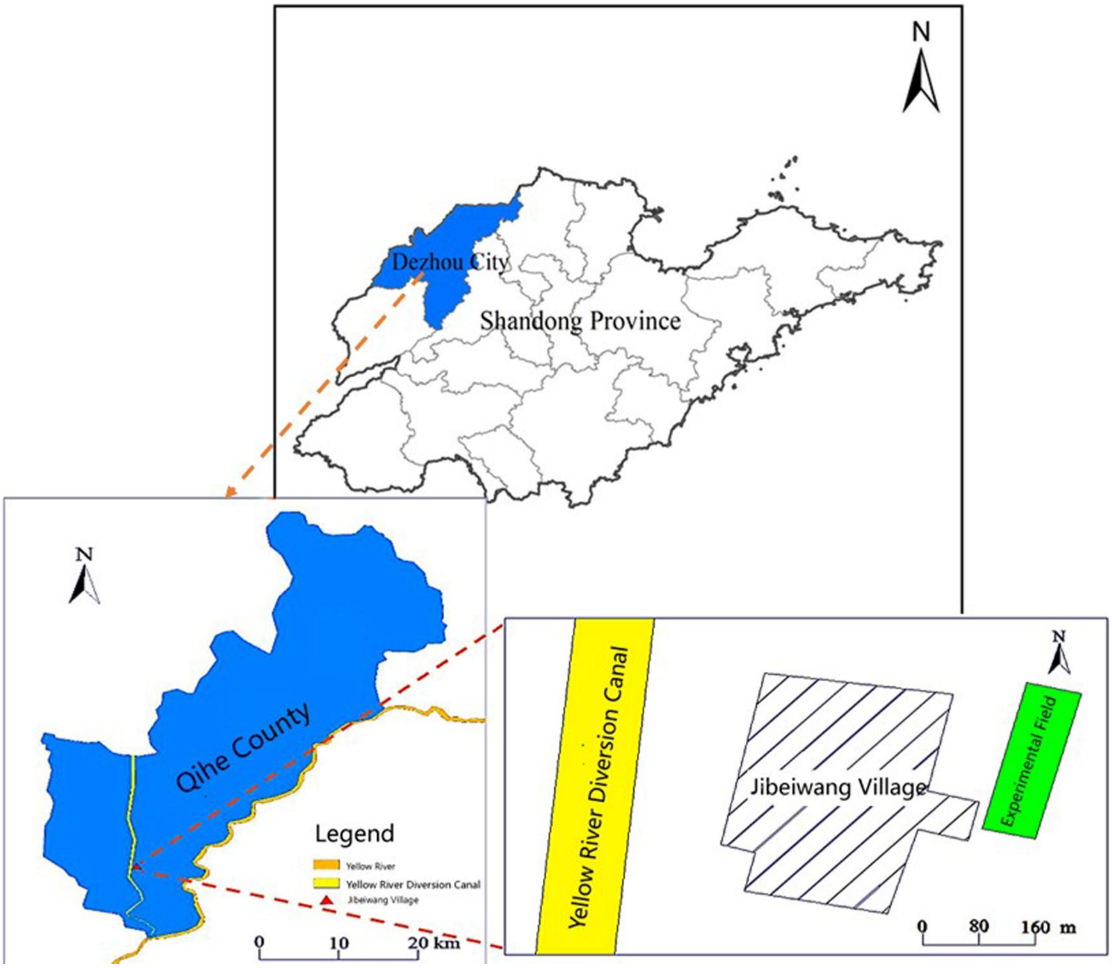

Fig. 1 Location map of the experimental site

settlement and consolidation time. The calculation of sediment settlement and consolidation time is of great practical significance in guiding filling with Yellow River sediment, achieving continuous filling, saving reclamation time and cost, and promoting the technology of filling reclamation.

2 Materials and methods

2.1 Study area

The experimental site is located east of Jibeiwang Village, Zhaoguan Town near the diversion of the Panzhuang main canal in Liangshan County, south of Dezhou City, Shandong Province (Fig. 1), which is a short distance away from the Panzhuang Diversion Yellow Trunk Canal. The distance from the canal is approximately 1 km and the experimental site covers an area of approximately 2.67 hm^2. The experimental site, which is a low-lying land with seasonal water accumulation, such as coal mining subsidence, is 1 m lower than the nearby normally cultivated farmland. The area belongs to the temperate monsoon climate zone, with four distinct seasons and a mild climate, and belongs to the alluvial plain of the lower Yellow River. The average annual temperature is 13.5 °C, the average annual rainfall is approximately 622 mm, and the sunshine duration is 2678.9 h. The frost-free period is 217 days.

Fig. 2 Maize production in lowland and normal farmland

2.2 The necessity of filling reclamation

Both coal mining subsidence and lowlands have led to reduced or even extinct crop yields. Figure 2, which compares maize production in lowland and normal farmland, shows the stark contrast of these land types. In particular, high amounts of submerged areas occur in Shandong, where summer rainfall is abundant and the water table is high. Rains inevitably cause water to accumulate in the lowlands and sinkholes. Coupled with high summer temperatures, the sun can cause stagnant water to become too hot and "burn" the corn. Therefore, it is necessary to carry out the filling and reclamation of low-lying land and subsidence land. Local farmers will also actively participate in and request filling and reclamation work to ensure food production.

2.3 Filling reclamation process

The filling was divided into strips of single fills, and the filling area was divided into several strips (Fig. 3). The first strip was used to fill the odd-numbered strips. The odd-numbered strips of topsoil and heart soil were placed near the even-numbered strips to be filled with odd-numbered strips and sand consolidation, backfilling and topsoil and began to peel off the even-numbered strips of topsoil and heart soil placed on the odd-numbered strips. The filling of the even-numbered strips so that alternate filling between strips can shorten the reclamation time.

On-site filling and reclamation in Jibei Wang Village, Qihe County, Shandong Province, the specific filling process was as follows:

(1) Due to the low terrain or coal mining subsidence, there was seasonal standing water, which should be drained away prior to the filling test.
(2) The area to be reclaimed was striped, with the length of the strip generally depending on the condition of the filling area and the width generally depending on the excavator's width. The operating radius was determined by a width that was twice as wide as the excavator's operating radius to facilitate the excavation and covering of the strips. Approximately 30 cm of topsoil and 70 cm of coresoil were stripped with the excavator and deposited in a nearby filling strip.
(3) Because the reclamation land to be filled is close to the diversion canal, and because the area to be filled is small, and because in July of each year there is no natural condition for the use of dredgers in the Panzhuang irrigation district, a combination mud pump high-pressure water gun relay construction system was available. In the reclamation by sediment filling from the Yellow River, the power of the slurry pump is 30 kW/h, the head is 25 m, the flow rate is 250 m^3/h, and the fresh water pump power is 22 kW/h for high-pressure water jets.
(4) The diameter of the rubber hose used for the sediment transportation pipeline is 200 mm, and the concentration of sediment in the pipeline was 200 kg/m^3. A 1 km pipeline was laid according to the distance of the test site from the main yellow channel, and a pressurized pump was placed between the main channel and the test site to ensure that the water–sediment mixture could be transported to the test site. Figure 4 shows the layout of the sand transportation pipelines and pressure pumps.
(5) After the Yellow River silt was transported by the pipeline to the strip in the area to be reclaimed, the sediment naturally settled in the strip, and the clear water was discharged to the nearby drainage ditch through the drainage port in the end dike, as shown in Fig. 4.
(6) After the filled clear water was discharged, large-scale machinery could be used to quickly carry out the slurry treatment through the strip to accelerate the discharge

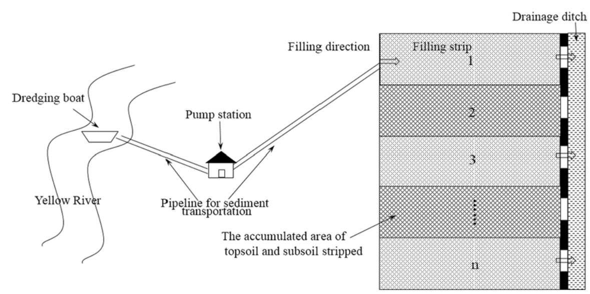

Fig. 3 Single filling diagram of a fill using Yellow River sediments with alternating strips

Fig. 4 Filling and drainage of the water–sediment mixture in the reclamation strip. **a** Filling; **b** Drainage

Fig. 5 Sampling site of Yellow River sediments

of the water accumulated in the sediment and sediment in the strip or the equipment could be moved back and forth in the strip during the filling process to manually extract the slurry to accelerate the sedimentation and consolidation of the filled sand.

(7) When the degree of consolidation could support the excavation machinery after the filling was completed, the topsoil and the core soil were backfilled separately by backfilling the core soil first and then backfilling the topsoil. The specific process was to cover the stripped core soil evenly with the sand and the topsoil evenly on the core soil. Finally, the land was levelled, and the soil was reconstructed to form cultivated land. Land levelling was performed to prepare for the planting of winter wheat at the end of September.

2.4 Yellow River sediment particle size test

In the process of sediment filling of the Yellow River, the diameter of the Yellow River sediment is an important factor that affects its hydraulic properties. By collecting Yellow River sediment to test its particle size we can also test its sedimentation rate to calculate a series of hydraulic parameters (such as roughness coefficient, recovery saturation rate coefficient, cross-sectional sand content, etc.) in the process of filling the Yellow River and accurately calculate the sedimentation rate, silt thickness and other important data that can accurately provide a reference and basis for reclamation.

(1) Sediment sampling location

The sand mining site in the Panzhuang diversion canal used in the test was selected because it was close to the reclamation site to be filled. To ensure the accuracy of the sediment data, multiple sampling points were selected in the main channel, as shown in Fig. 5. The samples were air dried, ground and passed through

Table 1 Texture of Yellow River sediment

Particle size (μm)	Clay grain	Coarse clay grain	Fine powder grain	Medium powder grain	Coarse powder grain	Fine sand grain	Coarse sand grain
	< 1	1–2	2–5	5–10	10–50	50–250	250–1000
Percentage (%)	0	0	0	0	0	87.53	12.47
Texture type (according to Chinese soil texture)						Extremely heavy sand	

Table 2 Characteristic particle size data of the measured Yellow River sediment

Group		d_{10} (μm)	d_{15} (μm)	d_{50} (μm)	d_{60} (μm)	d_{85} (μm)	d_{90} (μm)	C_u
The first time	1	105.51	117.11	173.87	184.643	250.84	272.69	1.750
	2	106.57	118.06	173.94	186.284	250.67	272.58	1.748
	3	105.33	116.86	173.71	184.538	251.20	272.99	1.752
	4	101.48	112.68	168.03	180.026	245.98	269.19	1.774
	5	105.27	116.67	172.99	184.854	250.25	272.36	1.756
The second time	1	101.11	112.78	170.36	174.718	248.43	271.20	1.728
	2	96.30	107.32	161.93	166.310	240.48	264.11	1.727
	3	101.22	112.45	167.83	178.451	245.50	268.70	1.763
	4	96.83	107.67	160.98	168.387	238.62	262.23	1.739
	5	97.22	108.05	161.69	169.357	240.59	264.35	1.742
The third time	1	104.63	116.05	172.63	184.463	250.04	272.20	1.763
	2	106.63	118.22	174.36	184.257	250.45	272.32	1.728
	3	103.66	114.93	170.72	178.192	247.79	270.74	1.719
	4	105.02	116.37	172.39	185.360	249.17	271.57	1.765
	5	103.26	114.89	171.89	176.781	249.28	271.71	1.712

a 2 mm sieve in preparation for testing the sediment grain size.

(2) Experimental method

In this experiment, the BT-9300H laser particle size analyser produced by Dandong Baite Instrument Co., Ltd. was used to determine the particle size of the Yellow River sediment. Its technical parameters are as follows: test interval: 0.1–340 μm; accuracy error: < 1% (standard sample D50 value); sampling method: micro-sample cell type and circulating pump type; repeatability error: < 1% (standard sample D50 value); power supply: AC220 V, 50 Hz; power: 240 W; light source: semiconductor laser, wavelength: 635 ns, power: 3 mW; 76 photodetectors, full-range Mie scattering theory; appearance size: 660 mm × 280 mm × 290 mm; weight: 32 kg.

Before testing, the sediment samples were pretreated. To ensure the accuracy of the test data, the test procedure was carried out in strict accordance with the requirements of the "SL42-2010 Rules for the Analysis of Sediment Particles in Rivers". Each test was repeated three times, and five groups of sediment samples were selected for each operation.

(3) Results of sediment grain size analysis of the Yellow River. The results of the particle size measurements of the Yellow River sediment using the laser particle size analyser are shown in Tables 1 and 2.

From Table 2, we can see that 87.53% of the fine sand grains and 12.47% of the coarse sand grains in the sediment collected from the Panzhuang trunk canal were extremely heavy sandy soils. By studying the erosion and transport patterns of the sediment in the Yellow River, we could see that the sediment mainly came from the Loess Plateau. While fine-grained sediment enters the river in suspension and advances, and coarse-grained sediment is rapidly deposited in the river. In this study, sediment samples were taken from the Qi River section of the lower Panzhuang drainage channel of the Yellow River, and they were all large grain size sediments, which are sandy soils. The characteristic particle size values of sediment from 3 replicate tests of 5 groups of sediment samples are shown in Table 2: $d_{10} = 102.67$ μm, $d_{15} = 114.01$ μm, $d_{50} = 169.82$ μm, $d_{60} = 179.11$ μm, $d_{85} = 247.29$ μm, and $d_{90} = 269.93$ μm. The sediment sedimentation rate formula was chosen based on the size of the median particle size d50 of the sediment, which was determined by the analysis knowing that the sedimentation rate formula is appropriate to use the transition zone formula. Accordingly the formula calculated a sedimentation rate of 0.568 cm/s.

2.5 Parameters in the process of filling reclamation

Based on the Yellow River diversion and desilting technology in the Yellow River beach area, and considering the terrain of the area to be reclaimed and the layout of the original nearby drainage ditches, the length of the reclamation strip was set as 240 m, and considering the mechanical operation radius, the width of the strip was set as 8 m. The initial flow rate was 0.074 m^3/s as measured by the intelligent electromagnetic flowmeter Magne W3000 plus produced by Kaifeng Weili Flow Instrument Co., Ltd.; the flow rate was measured by the portable velocity metre sr-ls100 produced by Nanjing Shengrong Instrument Equipment Co., Ltd.; the initial flow rate of water and sediment is 1.162 m/s, and the sediment concentration and sediment density values at the inlet end were measured throughout the test. The sediment concentration at the inlet end was 200 kg/m^3, the sediment density was 1.4 g/cm^3, the clear water density was 1.0 g/cm^3, the strip depth was 1.0 m, the average sediment settling velocity was is 0.00568 m/s according to the sediment particle size, and the roughness coefficient was 0.024 (Zhu 2010).

3 Results and discussion

3.1 Hydraulic parameters, sedimentation rate and siltation thickness of the reclamation belt in the Yellow River

Considering the actual situation of the field filling and reclamation site construction, each reclamation strip had a length of 240 m and a width of 8 m. During the actual filling and reclamation process, the filling pipeline continuously moved forward. Advantages can be concluded as: (1) After filling and reclamation, the sediment was relatively flat, there was no need for it to be levelled, and the reclamation time could be shortened; (2) The sediment particle sizes were relatively uniform, thus we could avoid the uneven distribution of the sediment particle sizes due to the levelling thus affecting the reclamation land quality; (3) The filling pipeline was

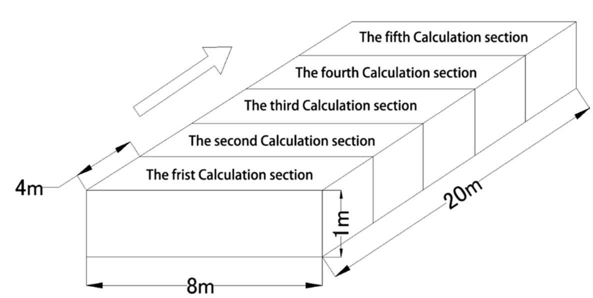

Fig. 6 Test design of field filling strips

Table 3 Hydraulic parameters, sediment settling rates and average siltation thickness values of the first calculation segment

Period (h)	$\bar{c}_1$	$\bar{J}_1$	U_{*1}	a_1	η_1	V_1	$\bar{D}_1$
0.0–0.2	30.4755	0.2010	0.5492	0.0030	3.6275	0.5798	0.0036
0.2–0.4	35.5569	0.0683	0.5085	0.0055	6.5785	2.1030	0.0131
0.4–0.6	38.4685	0.0394	0.4888	0.0076	8.8748	4.2556	0.0266
0.6–0.8	40.5723	0.0271	0.4760	0.0093	10.8410	6.9313	0.0433
0.8–1.0	42.2403	0.0205	0.4665	0.0110	12.5934	10.0646	0.0629
1.0–1.2	43.6322	0.0163	0.4590	0.0125	14.1903	13.6091	0.0851
1.2–1.4	44.8322	0.0135	0.4528	0.0139	15.6669	17.5294	0.1096
1.4–1.6	45.8902	0.0115	0.4476	0.0152	17.0461	21.7972	0.1362
1.6–1.8	46.8388	0.0099	0.4430	0.0165	18.3441	26.3891	0.1649
1.8–2.0	47.7000	0.0087	0.4390	0.0177	19.5728	31.2852	0.1955

Table 4 Hydraulic parameters, sediment settling rates and average siltation thickness values of the second calculation segment

Period (h)	$\bar{c}_2$	$\bar{J}_2$	U_{*2}	a_2	S_2	η_2	V_2	$\bar{D}_2$
0.0–0.2	31.6776	0.1004	0.4358	0.0040	404.7644	4.7728	0.7352	0.0046
0.2–0.4	36.1458	0.0399	0.4080	0.0067	392.3702	7.9158	2.3641	0.0148
0.4–0.6	38.8719	0.0240	0.3934	0.0090	382.7260	10.4152	4.5511	0.0284
0.6–0.8	40.8836	0.0168	0.3836	0.0109	374.4676	12.5680	7.1644	0.0448
0.8–1.0	42.4958	0.0128	0.3763	0.0127	367.1079	14.4902	10.1222	0.0633
1.0–1.2	43.8501	0.0103	0.3704	0.0144	360.4006	16.2426	13.3669	0.0835
1.2–1.4	45.0228	0.0086	0.3656	0.0160	354.1990	17.8623	16.8546	0.1053
1.4–1.6	46.0601	0.0073	0.3614	0.0175	348.4064	19.3738	20.5507	0.1284
1.6–1.8	46.9922	0.0063	0.3578	0.0190	342.9548	20.7949	24.4271	0.1527
1.8–2.0	47.8402	0.0056	0.3547	0.0204	337.7942	22.1384	28.4600	0.1779

Table 5 Hydraulic parameters, sediment settling rates and average siltation thickness values of the third calculation segment

Period (h)	$\bar{c}_3$	$\bar{J}_3$	U_{*3}	a_3	S_3	η_3	V_3	$\bar{D}_3$
0.0–0.2	32.6873	0.0572	0.3615	0.0050	385.4457	5.9520	0.8731	0.0055
0.2–0.4	36.6903	0.0255	0.3413	0.0079	361.3108	9.2409	2.5413	0.0159
0.4–0.6	39.2554	0.0159	0.3299	0.0103	342.8644	11.9013	4.6588	0.0291
0.6–0.8	41.1834	0.0114	0.3221	0.0125	327.4044	14.2048	7.0797	0.0442
0.8–1.0	42.7439	0.0088	0.3162	0.0145	313.9131	16.2653	9.7158	0.0607
1.0–1.2	44.0627	0.0071	0.3114	0.0163	301.8621	18.1446	12.5067	0.0782
1.2–1.4	45.2094	0.0059	0.3074	0.0180	290.9311	19.8811	15.4086	0.0963
1.4–1.6	46.2268	0.0051	0.3040	0.0197	280.9068	21.5006	18.3882	0.1149
1.6–1.8	47.1433	0.0044	0.3011	0.0213	271.6378	23.0219	21.4195	0.1339
1.8–2.0	47.9784	0.0039	0.2984	0.0228	263.0118	24.4587	24.4819	0.1530

constantly moving forward. In the process of forward filling by the pipeline, the silt that had been filled in the back was also in the process of drainage consolidation, which also accelerated the speed of sediment consolidation and shortened the reclamation time.

According to the on-site filling experience, the total length of the filling strip was 240 m. The sand pipeline was moved forward once for each 20 m length of fill, with consistent sand transfer operations and parameters for each section. This test only simulated the 20 m length of the reclamation process. The shorter the calculation period is, the more accurate the result. This test divided the 20 m fill length into five calculation sections of 4 m each, as shown in Fig. 6. The test measured an initial flow velocity of 1.162 m/s, with a flow velocity of 0.714 m/s at a distance of 4 m from the inlet pipe. The flow velocity was 0.514 m/s at a distance of 8 m from the inlet pipe and 0.358 m/s at a distance of 12 m from the inlet pipe, and a flow velocity of 0.215 m/s at a distance of 16 m from the inlet pipe. According to the flow velocity data, the calculation period can be set to 0.2 h. There were 10 calculation periods. The hydraulic parameter, sedimentation rate and silt thickness data in the reclamation zone of Ji Beibei Wang Village, Qihe County, Shandong Province, are shown in Tables 3, 4, 5, 6 and 7.

Table 6 Hydraulic parameters, sediment settling rates and average siltation thickness values of the fourth calculation segment

Period (h)	$\overline{c}_4$	$\overline{J}_4$	U_{*4}	a_4	S_4	η_4	V_4	$\overline{D}_4$
0.0–0.2	33.5616	0.0313	0.2892	0.0063	362.5040	7.4362	1.0259	0.0064
0.2–0.4	37.1971	0.0152	0.2747	0.0095	327.9225	10.9630	2.7363	0.0171
0.4–0.6	39.6210	0.0098	0.2662	0.0121	302.0591	13.8515	4.7769	0.0299
0.6–0.8	41.4728	0.0071	0.2602	0.0145	280.8974	16.3610	6.9960	0.0437
0.8–1.0	42.9850	0.0055	0.2556	0.0168	262.8542	18.6071	9.3068	0.0582
1.0–1.2	44.2703	0.0045	0.2518	0.0188	247.0904	20.6547	11.6536	0.0728
1.2–1.4	45.3923	0.0038	0.2487	0.0208	233.0909	22.5445	13.9991	0.0875
1.4–1.6	46.3906	0.0032	0.2460	0.0227	220.5101	24.3045	16.3170	0.1020
1.6–1.8	47.2919	0.0028	0.2437	0.0245	209.1017	25.9550	18.5891	0.1162
1.8–2.0	48.1147	0.0025	0.2416	0.0262	198.6825	27.5113	20.8021	0.1300

Table 7 Hydraulic parameters, sediment settling rates and average siltation thickness values of the fifth calculation segment

Period (h)	$\overline{c}_5$	$\overline{J}_5$	U_{*5}	a_5	S_5	η_5	V_5	$\overline{D}_5$
0.0–0.2	34.3349	0.0100	0.1752	0.0092	335.5475	10.7277	1.3699	0.0086
0.2–0.4	37.6716	0.0052	0.1672	0.0133	291.9722	15.1121	3.3584	0.0210
0.4–0.6	39.9705	0.0035	0.1623	0.0169	260.2194	18.7104	5.5588	0.0347
0.6–0.8	41.7523	0.0025	0.1588	0.0200	234.9398	21.8238	7.8052	0.0488
0.8–1.0	43.2195	0.0020	0.1561	0.0230	213.9446	24.5943	10.0125	0.0626
1.0–1.2	44.4731	0.0016	0.1539	0.0257	196.0547	27.1035	12.1336	0.0758
1.2–1.4	45.5715	0.0014	0.1520	0.0284	180.5417	29.4041	14.1423	0.0884
1.4–1.6	46.5516	0.0012	0.1504	0.0308	166.9161	31.5324	16.0244	0.1002
1.6–1.8	47.4382	0.0010	0.1490	0.0332	154.8293	33.5152	17.7735	0.1111
1.8–2.0	48.2490	0.0009	0.1478	0.0355	144.0224	35.3725	19.3880	0.1212

$\overline{c}_k$ refers to mean Xie Cai coefficient for a time period in Section k of the filling strip; $\overline{J}_k$ refers to average hydraulic gradient for a time period in Section k of the filling strip; U_{*k} is frictional flow velocity (m/s) for a time period in Section k of the filling strip; a_k is recovery saturation factor for a time period in Section k of the filling strip; S_k, S_{k+1} are sand content of upper and lower section groups (kg/m^3) for a time period in Section k of the filling strip; η_k is sedimentation rate (%) for a time period in Section k of the filling strip; V_k is silt volume (m^3) at the end of a period in Section k of the fill strip; $\overline{D}_k$ is Average silt thickness (m) at the end of the period for Section k of the filling strip.

The test was divided into 5 calculation section lengths and 10 calculation periods, as shown in Tables 3, 4, 5, 6 and 7. The cumulative silt heights for each calculation section were 0.84 m, 0.80 m, 0.73 m, 0.66 m, and 0.67 m. The data calculated by mathematical simulation and the data tested during the field filling test are basically the same, and the method of mathematical simulation can be used to calculate the sediment deposition and siltation of Yellow River sediment filling and reclamation, which will provide a reference and basis for future filling and reclamation projects.

3.2 Calculation of reclamation and drainage consolidation time

Filling the Yellow River sediment with the method of clear water settlement must be divided into multiple fillings. One filling cannot meet the needs. It takes a long time to fill and reclaim when using this method, which increases the cost of filling and reclamation. It was calculated that if the current water filling method was used for this filling, 19 rounds of filling and reclamation would be required to reach the design

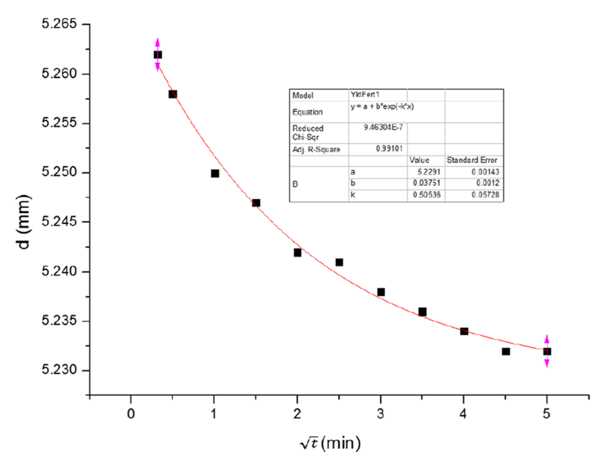

Fig. 7 Curve fitting equation of d–$\sqrt{t}$

elevation, which greatly increases the reclamation time. The interval of the net settlement method needed to consider the time during which the strip is filled with water and sand (T1), the hydrostatic settlement time of the sediment within the strip (T2), clear water drainage time (T3), supersaturated sediment drainage consolidation time (T4) and soil backfilling, grading, compaction time (T5). Therefore, the net water settlement method was not suitable for this test.

Since the filling strip of this test was long (240 m), which is sufficient to meet the length of sediment settlement, it was sufficient to set the drainage outlet of the overflow weir at the end of the strip at the beginning of filling. In this process, filling and draining water at the end were carried out at the same time, and the interval time did not need to consider the static water settling time (T2) and drain water time (T3) of the sediment in the strip, which greatly shortened the interval time. When filling the end of the strip, we could consider using a geotextile to intercept the sediment so that the water could drain away the sediment and stay in the strip.

The key to this test was to determine the time to fill the Yellow River sediment (T1), the time to consolidate supersaturated sediment drainage (T4), and the time to backfill, level, and compact the soil (T5). It is crucial to determine the consolidation time (T4) of supersaturated sediment drainage. The sediment filling time in the Yellow River depended mainly on the initial filling flow and sediment concentration at the inlet end, and the rate of water drainage from the saturated soil depended mainly on the permeability and thickness of the sediment. Sediment consolidation required the disappearance of water content, increase in density, dissipation of pore water pressure, and increase in strength. The consolidation coefficient is the key parameter to determine the consolidation time. Using the square root of time to obtain the consolidation coefficient, the key is to determine the d–$\sqrt{t}$ curve of the plot, and the results are shown in Fig. 7.

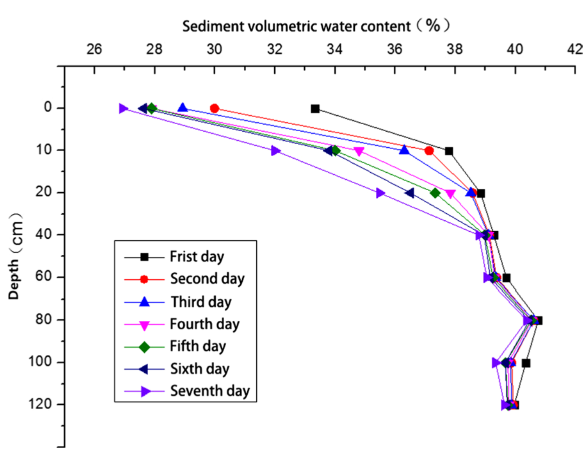

Fig. 8 Water changes in the filled sediment measured by a neutron metre

The equation "$y = 5.2291 + 0.03751x$" was fitted from the d–$\sqrt{t}$ curve to find the linear equation $y = 5.267 - 0.01932 \times$ required by the time square root method based on the fitted equation. From these two equations, we calculated $\sqrt{t_{90}} = 0.733$ and $\overline{h} = 0.262$, and the consolidation coefficient was calculated to be 1.812×10^{-3} cm^2/s $= 0.015656$ m^2/d.

According to previous studies (Wang 2016), the mechanical soil backfilling operations could be carried out when sediment consolidation reached approximately 75%, and a sediment consolidation level of 75% was defined as sediment consolidation point in this test. The time factor Tv for the sediment to reach consolidation is 0.575, and the sediment consolidation time for this test was 9.18 days.

To verify the accuracy of the drainage consolidation time, it was necessary to continuously monitor the water changes during the filling and reclamation process (Fig. 8). The water monitoring instrument was a neutron instrument. The neutron apparatus is rapid, does not need to take soil samples, has no hysteresis phenomenon, and was suitable for continuous fixed-point field observations.

Because the filling period was summer, which is the rainy season, seven days (July 25, 2016) with no rainfall and clear skies were selected for this test. The changes in filling sediment moisture were continuously monitored (Fig. 8) from the beginning of the monitoring period to 31 July. At the beginning of the monitoring, there was a small amount of standing water on the surface of the filled sediment, and the surface moisture of the filled sediment changed from 33.32% to 26.92%. The consolidation drainage time calculation results and test data were basically consistent.

3.3 Numerical simulation of sediment filling in the Yellow River

The elements of the Yellow River sediment reclamation process include sand, water and air, involving a total of three phases of solid, liquid and gas flow. We could consider using the mathematical model of fluid mechanics to simulate the reclamation process.

Computational fluid dynamics (CFD) quantitatively describes the numerical solution of a flow field in time and space by means of computer-driven numerical calculations and image display methods. Fluent, the most widely used international CFD numerical simulation software, is widely used for solid–liquid–gas three-phase flow simulations. Wang et al. (2015) reported the use of Fluent software to study the flow rate of slurry in a deep well coal mine auto-flow conveyor filling system. Pipelining of filling slurries is a typical solid–liquid two-phase flow simulation (Seay.

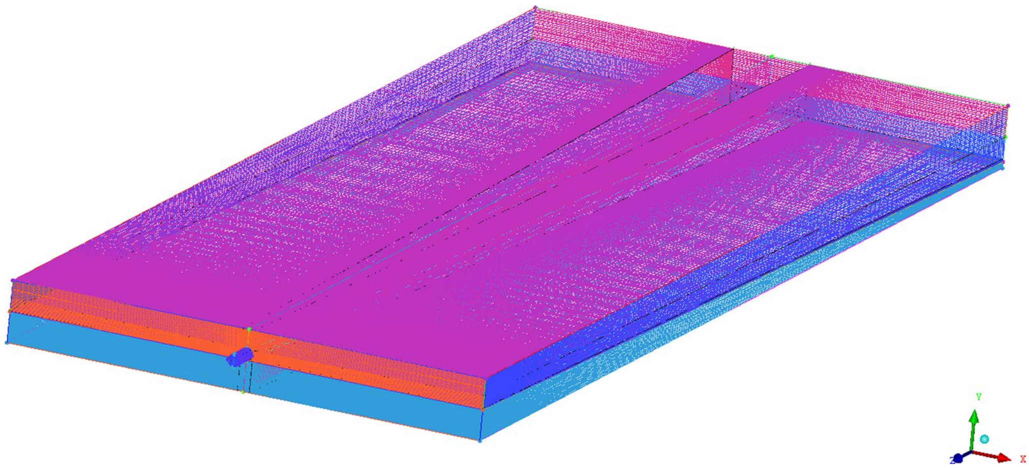

Fig. 9 Grid diagram of the numerical simulation of filling reclamation with Yellow River sediments

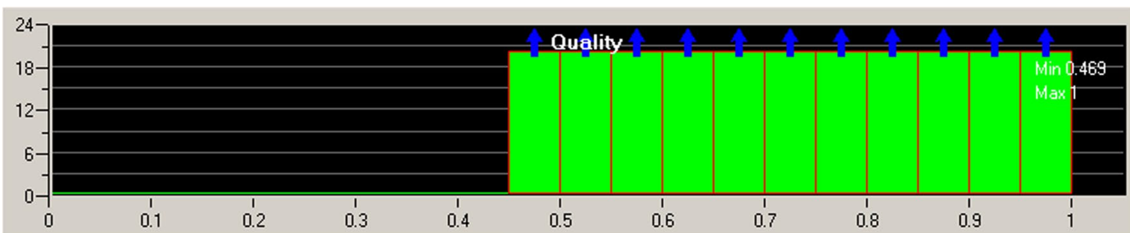

Fig. 10 Check chart of grid quality

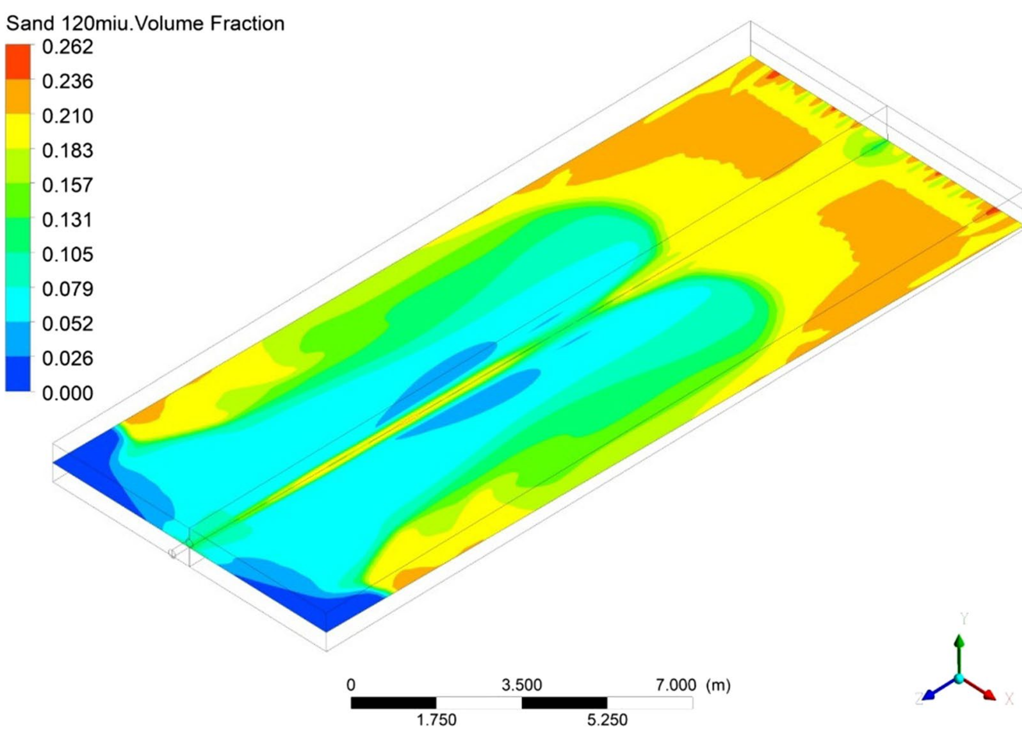

Fig. 11 Volume percentage of 120 μm sediment at 81.515 s

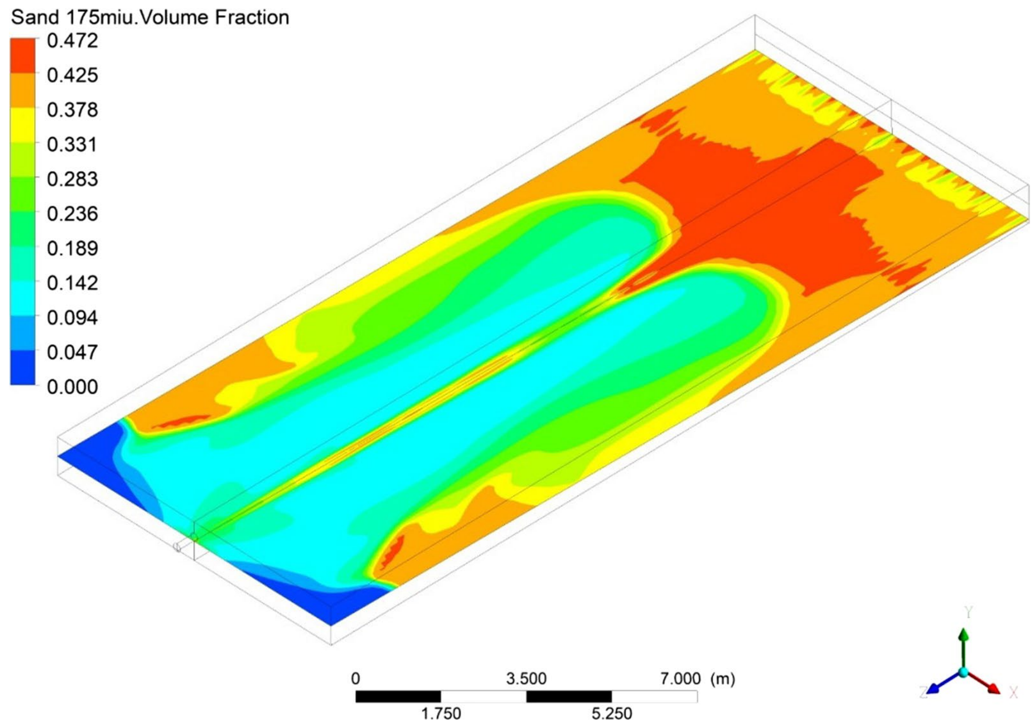

Fig. 12 Volume percentage of 175 µm sediment at 81.515 s

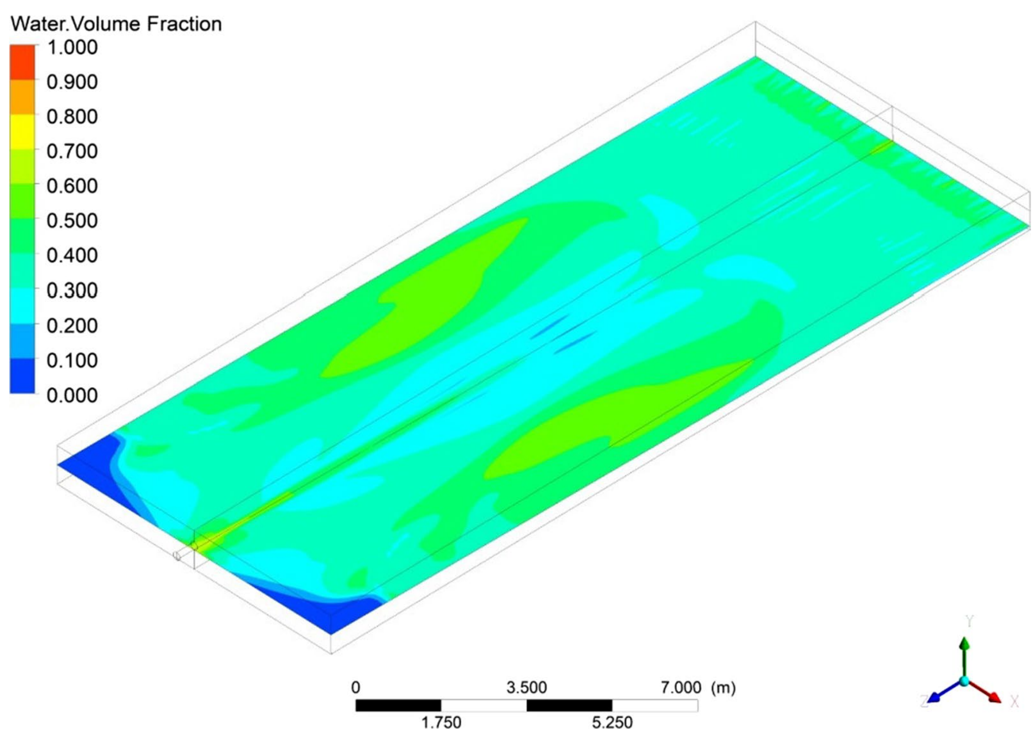

Fig. 13 Volume percentage of water at 81.515 s

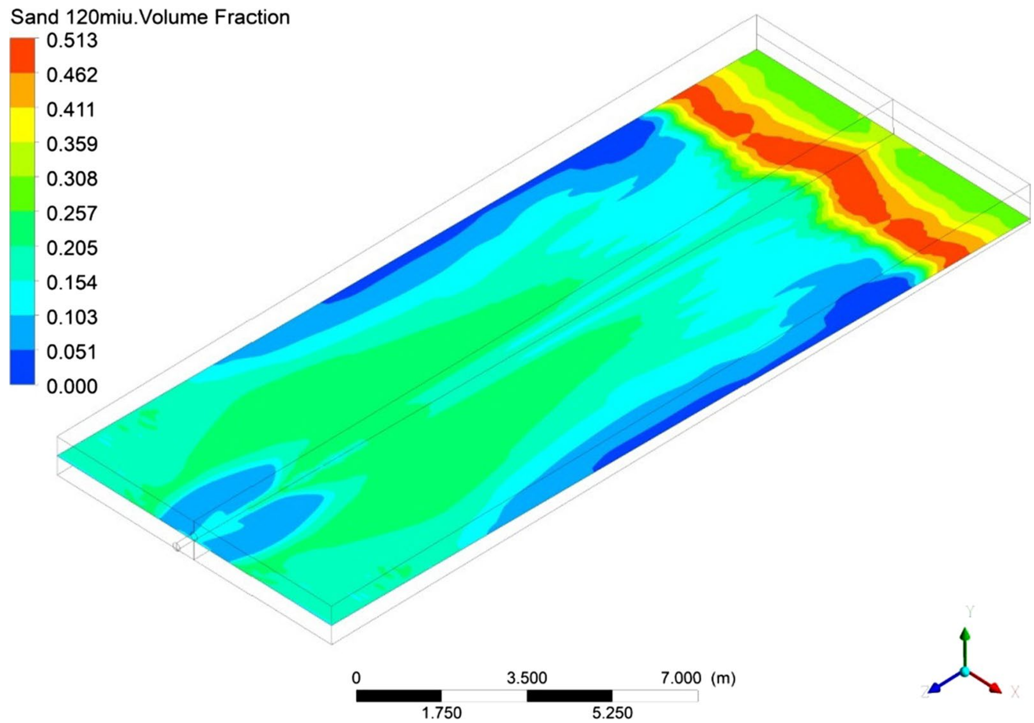

Fig. 14 Volume percentage of 120 μm sediment at 386.415 s

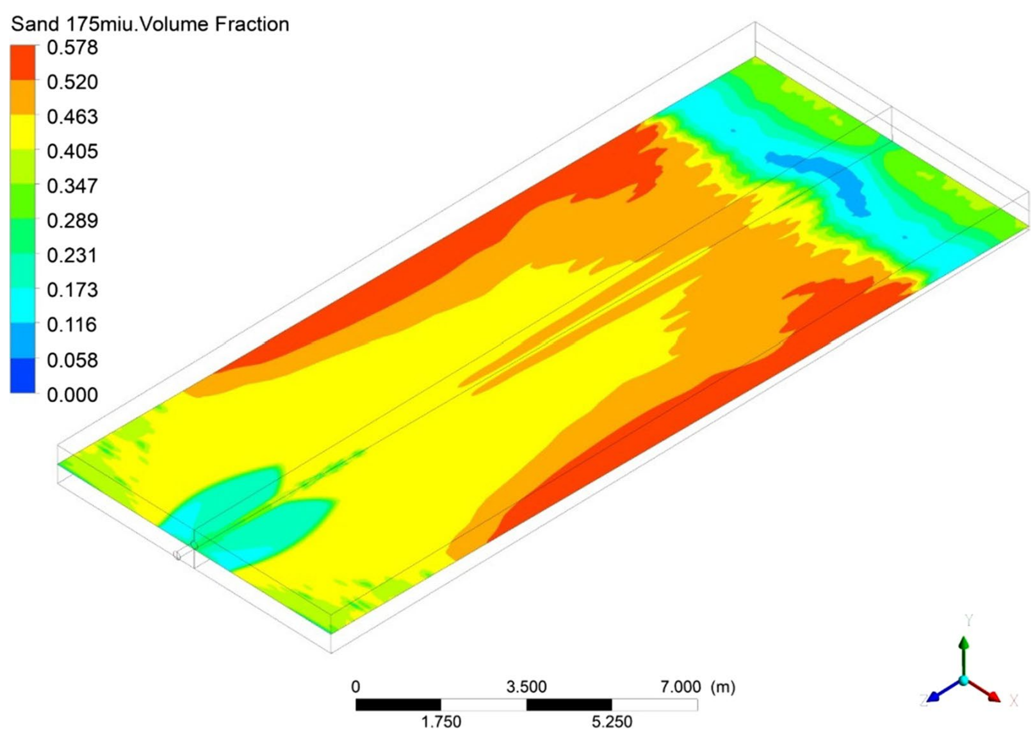

Fig. 15 Volume percentage of 175 μm sediment at 386.415 s

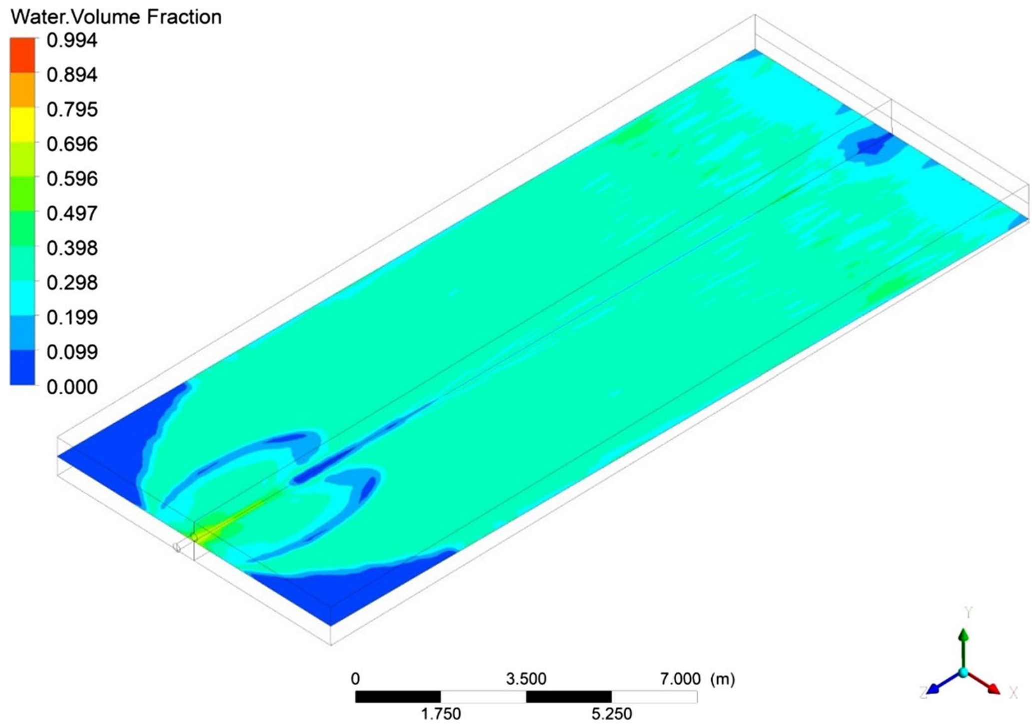

Fig. 16 Volume percentage of water at 386.415 s

2009; Mcneil and Stuart 2003). For mud flow and hydraulic transportation, a mixture model or Euler model could be used. In this study, the Euler model was selected according to the needs of the problem.

The computational grid is the core of any hydrodynamic computation. It usually divides the computational domain into thousands or even millions of cells on which the computational solution variables are calculated and stored. To truly simulate the flow and settlement consolidation of the Yellow River sediment in the strip, a grid diagram is first was built in Fluent, as shown in Fig. 9.

The mesh quality, as shown in Fig. 10, was above 0.45, which met the needs of high-precision calculations for multiphase flow.

To simulate the movement of sediment of different particle sizes, two different particle sizes, 120 µm and 175 µm, were selected in this experiment to simulate their movements at different moments. Due to the large number of simulation results, the motion states at 81.515 s and 386.415 s were selected for presentation. The results are shown in Figs. 11, 12, 14, 15 and 16. Figures 11, 12 and 13 show the 81.515 s moment for 120 µm sediment, and 175 µm volume ratio of sediment to water, respectively. Figures 14, 15 and 16 show the volume ratios of 120 µm sediment, 175 µm sediment and water, respectively, at 386.415 s.

Figure 11 shows that the sedimentation amount of 120 µm sediment was relatively small at 81.515 s, and the basic settlement was at the end of the strip. As shown in Fig. 12, the sedimentation amount of 175 µm sediment was relatively large at 81.515 s, and the sediment basically settled at the front end of the strip. Figure 14 shows that the 120 µm sediment deposition at 386.415 s was low and largely settled in the end zone. Figure 15 shows that the sedimentation of 175 µm sediment at 386.415 s was relatively high, and the sediment basically settled in the middle of the strip on both sides. Through comparative analysis, it is known that the filling sediment was transported to a certain moment in which the coarse particles settle faster than the fine particles. The coarse particles more than the fine particles settle first. That is, coarse particles settle closer to the inlet location.

3.4 Analysis of the effect of filling reclamation with Yellow River sediments

Related research has shown that filling reclamation with Yellow River sediments can achieve relatively good results. Shao (2017) conducted a field planting experiment in the same subsidence area as described in this paper, that is, the subsidence area of the Qiuji coal mine. The results showed that the interlayer soil profile pattern of “sediment-soil-sediment” filled many times has a good effect, which is conducive to corn seed germination, plant growth and root growth and to maintaining surface soil water, available nutrients (available nitrogen, available phosphorus and available potassium) and organic matter content and even higher thousand grain weight and yield of maize in some interlayer profile patterns than in the control plots. Duo (2019) also obtained the same result. Hu and Guo (2018) conducted a field planting experiment at the Qiuji coal mine in Shandong Province, and the results showed that wheat yield in the interlayer soil profile pattern could reach or even exceed that of the control farmland in the same year.

Other studies have also shown that reclamation using lake and river bottom sediments has achieved relatively good results. Darmody et al. (2004) conducted an indoor planting experiment using sediments from the Illinois River in central Illinois and showed that Illinois River sediments can be used to grow crops with proper management and that experimentally grown lettuce, barley, radishes, tomatoes and snap beans were more desirable in terms of germination rate and yield. Woodard (1999) conducted an indoor planting experiment by mixing sediment from a freshwater lake in South Dakota with agricultural production soil or sand. The results showed that with the increasing proportion of sediments, the concentrations of stem dry matter, total nitrogen, total phosphorus and total potassium and the absorption of available nitrogen, available phosphorus and available potassium increased significantly, which was conducive to improving soil productivity. To alleviate the contradictory conflicts between humans and land and ensure food security, reclamation technology is a proven method to reclaim subsidence land with the goal of increasing the rate of cultivated reclaimed land.

4 Conclusions

The research presented in this paper is of great significance to the scientific guidance of filling reclamation. The purpose of filling and reclamation is to ensure that fine-grained sediments with high nutrient contents can also be deposited in the strip, thus improving the quality of reclaimed land. This paper makes use of the law of sediment settlement and siltation, based on the combination of theoretical research and the practice of filling and reclamation, to provide a reference for scientific reclamation.

A field filling test study was carried out in the lowlands of Jibeiwang Village, Qihe County, Shandong Province, to calculate the hydraulic parameters and sedimentation volume of the filling process by theoretical formulas. In this test, the cumulative silt heights of the calculated sections, drainage consolidation time and test data are generally consistent.

The Euler module of the Fluent model was used to simulate the Yellow River sediment filling process. Numerical simulation results show that coarse-particle sediment settles before fine-particle sediment, i.e., when the filling sediment is moved to a certain point, the coarse-particle sediment settles closer to the inlet than the fine-particle sediment, and the simulation results are in accordance with the law of sediment movement.

In conclusion, the research on the settling and consolidation time of Yellow River sediment in this paper provides a theoretical scientific basis and practical engineering guidance for the promotion and application of Yellow River sediment filling technology in coal mining subsidence land.

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Author contributions Linghua Duo and Zhenqi Hu conceptualized, wrote, and revised this paper. Zhenqi Hu funded and reviewed this paper. Kun Yang and Yanan Li analyzed data and reviewed the paper.

Declarations

Competing interests The authors declare that they have no competing interests.

References

Bi Y, Xie L, Wang Z et al (2021) Arbuscular mycorrhizal symbiosis facilitates apricot seedling (*Prunus sibirica* L.) growth and photosynthesis in northwest China. Int J Coal Sci Technol 8(4):473–482

BP (2020) BP statistical review of world energy 2020. BP

Chen C, Hu ZQ (2018) Research advances in formation mechanism of ground crack due to coal mining subsidence in China. J China Coal Soc 43(3):810–823

Darmody RG, Marlin JC, Talbott J, Green RA, Stohr C (2004) Dredged Illinois River sediments: plant growth and metal uptake. J Environ Qual 33(33):458–464
Duo LH (2019) Key technologies of subsidence land reclamation filled with Yellow River sediments by alternating mutli-times and multilayers. China University of Mining and Technology, Beijing
Duo LH, Hu ZQ (2018) Soil quality change after reclaiming subsidence land with Yellow River sediments. Sustainability 10(11):4310
He Y, Hu KL, Wang H, Huang YF, Chen DL, Li BG, Li Y (2013) Modeling of water and nitrogen utilization of layered soil profiles under a wheat-maize cropping system. Math Comput Model 58(3–4):596–605
He TT, Xiao W, Zhao YL, Deng XY, Hu ZQ (2020) Identification of waterlogging in Eastern China induced by mining subsidence: A case study of Google Earth Engine time-series analysis applied to the Huainan coal field. Remote Sens Environ 242:1–13
Hu ZQ (1997) Principle and method of soil profile reconstruction for coal mine land reclamation. J China Coal Soc 06:59–64
Hu BN, Guo WY (2018) Mining subsidence area status, syntheses governance model and governance recommendation. Coal Min Technol 23(2):1–4
Hu ZQ, Wang PJ, Li J (2012) Ecological restoration of abandoned mine land in China. J Resour Ecol 3(4):289–296
Hu ZQ, Xiao W, Wang PJ, Zhao YL (2013a) Concurrent mining and reclamation for underground coal mining. J China Coal Soc 38(2):301–307
Hu ZQ, Li L, Zhao YL, Feng XW (2013b) Morphology development evaluation of reclaimed soil in coal-mining subsidence areas with high groundwater levels. Trans Chin Soc Agric Eng 29(5):95–101
Hu ZQ, Wang PJ, Shao F (2015) Technique for filling reclamation of mining subsidence land with Yellow River sediment. Trans Chin Soc Agric Eng 31(3):288–295
Hu ZQ, Shao F, Duo LH, Wu SY, Li XY, Kevin MS (2017) Technique of reclaiming subsided land with Yellow River sediments in the form of spaced strips. J China Coal Soc 42(3):557–566
Hu Q, Wu WB, Xiang MT, Chen D, Long YQ, Song Q, Liu YZ, Lu M, Yu QY (2018a) Spatio-Temporal changes in global cultivated land over 2000–2010. Scientia A Gricultura Sinica 51:1091–1105
Hu ZQ, Duo LH, Shao F (2018b) Optimal thickness of soil cover for reclaiming subsided land with Yellow River sediments. Sustainability 10(11):3853
Hu ZQ, Duo LH, Wang XT (2018c) Principles and methods of interlayer filling reclamation in coal mining subsidence. J China Coal Soc 43(01):198–206
Lian X, Hu H, Li T et al (2020) Main geological and mining factors affecting ground cracks induced by underground coal mining in Shanxi Province, China. Int J Coal Sci Technol 7(2):362–370
Lu YJ (2010) Effect of compaction treatment on soil moisture of waste rock filling and Reclamation. Coal Sci Technol 38(11):125–128
Lu D, Wang YH, Yang QY, He HY, Sun KC (2019) Exploring a moderate fallow scale of cultivated land in China from the perspective of food security. Int J Environ Res Public Health 16(22):4329–4332
Mai XM, Zhao YL, Gong BK (2011) Study on the change law of soil moisture content in coal mining subsidence land at high phreatic level in Dongtan coal mine. J China Coal Soc 37(3):48–51
Mcneil DA, Stuart AD (2003) The effects of a highly viscous liquid phase on vertically upward two-phase flow in a pipe. Int J Multiph Flow 29(9):1523–1549
Ren H, Zhao YL, Xiao Wu, Hu ZQ (2019) A review of UAV monitoring in mining areas: current status and future perspectives. Int J Coal Sci Technol 6(3):320–333
Ren H, Xiao W, Zhao YL, Hu ZQ (2020) Land damage assessment using maize aboveground biomass estimated from unmanned aerial vehicle in high groundwater level regions affected by underground coal mining. Environ Sci Pollut Res 27:21666–21679
Seay A (2009) Pipe lining abrasion testing for paste backfill operations. Miner Eng 22(12):1088–1090
Shao F (2017) Soil profile reconstruction in reclaiming subsided land with Yellow River Sediment. China University of Mining and Technology, Beijing
Wang PJ (2016) Technique of filling and drainage of water-sediment mixture used to reclaim mining subsidence land in Eastern China. China University of Mining and Technology, Beijing
Wang PJ, Shao F, Liu JT, Li JY, Hu ZQ, Russell SY (2015) Simulated experiment on drainage and fine sediment retention effects of geotextiles in land reclamation with Yellow River sediments. Trans Chin Soc Agric Eng 31(17):72–80
Woodard H (1999) Plant growth on soils mixed with dredged lake sediment. Environ Lett 34(6):24
Xiao W, Hu ZQ, Li TQ, Wang FJ, Li H, Liu KK (2013) Dynamic subsidence simulation and land reclamation efficiency analysis of surface ground above mining block. Coal Sci Technol 41(8):126–128
Xiao W, Zheng WX, Zhao YL, Chen JL, Hu ZQ (2021a) Examining the relationship between coal mining subsidence and crop failure in plains with a high underground water table. J Soils Sediments 21:2908–2921
Xiao W, Chen WQ, Deng XY (2021b) Coupling and coordination of coal mining intensity and socioecological resilience. Ecol Indic 131:108167
Yang GH, Hu ZQ, Zhao YL (2014) Proposals on countermeasures of reclamation control in coal mining subsidence land with high underground water level. Coal Eng 06:91–95
Zhang WZ (2017) Preliminary study on relocation and reconstruction policy and comprehensive treatment planning of coal mining subsidence areas in China. Institute of Geographical Sciences and Resources, Chinese Academy of Sciences, Beijing
Zhu JY (2010) Sediment design of water conservancy and hydropower projects. China Water Resources and Hydropower Press, Beijing