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Slurry Discharge Pipeline Damage and Wear Due to Transporting Rock Particles during Slurry Shield Tunneling: A Case Study Based on In Situ Observed Results

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Abstract: Rock particles in excavated materials can damage and wear down slurry discharge pipelines when slurry shield tunneling occurs in a pebble layer and rock ground. This pipeline damage and wear, if not properly dealt with, can lead to a broken-down tunneling machine. Based on a slurry shield tunneling project in China, damage and wear were thoroughly examined. The observed pipeline wear and leaks, transported rock particles, mechanical properties, and flow rate of the carrier slurry were presented. The measured results showed that the wear rates of a straight pipe, a pipe along a curved tunnel, a 60° inclined pipe, and a 90° elbow pipe in pebble ground were approximately 0.71 mm/100 rings, 1 mm/100 rings, 2.14 mm/100 rings, and 4 mm/100 rings, respectively. When the machine drove into rock ground, the wear rates increased by one to two times, which could be attributed to the sharper particle shapes. Countermeasures to address these issues, such as adjusting the pipeline layout, welding reinforcement plates in advance, and preparing additional pipes, were highlighted. The wear rates of different types of pipes, the effectiveness of new pipeline fixing methods, and the probability of pipeline leaks in different strata were discussed in detail.

Keywords: slurry discharge pipeline; rock particle; damage and wear; slurry shield tunneling

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1. Introduction

Currently, slurry shield tunneling machines are widely utilized to excavate tunnels in complex ground, especially with high water pressures, because of their merits of high safety and efficiency [1]. In regard to slurry shield tunneling, two distinct technologies are involved: the first is hydraulic support using slurry suspension, usually with a controlled pressurized air cushion; the second involves the hydraulic conveyance of the excavated materials through a closed slurry circuit. Slurry transport plays an extremely important role in safe and highly efficient slurry shield tunneling. When slurry shield tunneling in pebble and cobble ground, rock–soil interface mixed ground, and rock ground occurs, rock particles and rock fragments are discharged due to rock chipping in the excavated soils, inevitably causing wear on the slurry discharge pipelines. Over time, the worn pipelines thin out, start leaking, and occasionally even burst. The damaged and worn slurry discharge pipelines, if not properly dealt with, will lead to tunneling machine breakdowns, tunneling delays, and cost overruns. Therefore, a thorough examination of slurry discharge pipeline damage and wear during slurry shield tunneling is of great engineering significance. As more slurry shield tunnels are built and more large rock particles are transported, this demand becomes urgent.

Hydraulic transport, slurry transport, or slurry pipelining, referred to as the transport of solids in the form of (fine grained) particles in a liquid or gaseous carrier fluid by pipelines over long distances, has been extensively used in dredging, drilling, mining, food and paper production, and other processes. As a result, particle-flow-induced damage and wear in pipelines have been noted and well studied. Theoretical derivation and laboratory testing methods have been widely used in early studies on pipeline wear. Summer [2] found that the hardness parameter values of slurry and pipe materials show a strong correlation with the erosion capability of a slurry, and they suggested future abrasion studies on pipeline slurry erosion. Concerning the powder technology mechanisms of abrasive and erosive wear by hard particles in pipelines, Hutchings [3] concluded that the dominant mechanism depends not only on the material subjected to wear and the nature of the particles but also, in many cases, on the conditions under which the particles move against the surface. Gupta et al. [4] established the effect of velocity, concentration, and particle size on erosion wear using a pot tester and proposed two correlations of the expected erosion wear for two pipe materials. Using a slurry pot tester, Gandhi et al. [5] studied erosion wear due to the cutting action of solid particles in solid–liquid mixture flows and found that the parametric dependence on velocity is comparatively much stronger than that on either solid concentration or particle size. Yabuk et al. [6] determined the critical impact velocity in the erosion of metallic materials by solid particle impact using experiments and theoretically derived the critical impact velocity by analyzing the behavior of the material surface impacted by a spherical solid particle. Oka et al. [7] proposed a predictive equation for estimating erosion damage caused by solid particle impact, discussed the impact angle dependence of erosion damage to several materials, and concluded that material hardness should be a dependent variable in terms of impact velocity dependence and impact angle dependence in the equations. Oka and Yoshida [8] concluded that a predictive equation containing both material hardness and the load relaxation ratio could be used to estimate experimental erosion damage data for many types of materials under a variety of impact conditions. Pereira et al. [9] investigated numerical models for predicting erosion due to particles in a 90° elbow pipe in the oil industry and tested four different correlations for the erosion rate, namely, the Ahlert, Neilson & Gilchrist, Oka, and Zhang models. Arabnejad et al. [10] proposed a semimechanistic model for the erosion of different target materials due to solid particles and found that the angle dependence in the new model changes with the particle shape and velocity. Rawat et al. [11] studied the erosion wear on pipelines caused by high-concentration fly ash slurries using a modified pot tester and found that erosion has a stronger dependence on concentration than on relative velocity. Coker and Peursem [12] presented a model predicting pipeline erosion from smooth river sands, and particles with diameters of 50 to 350 μm, velocities of 3.5–6 m/s, and sand slurry concentrations of 10–40% by volume were considered in the model. Javaheria et al. [13] presented a review of the literature covering research into the effects of the main parameters influencing the slurry erosion of different types of steels and discussed the types of bench-scale erosion test rigs, the mechanisms involved, and the behaviors of different microstructures under slurry erosion conditions. With the continuous development of computer technology, computational fluid dynamics combined with discrete particle models (CFD-DPM) have been introduced into the study of pipe wear. Singh et al. [14] investigated the erosion wear of a 90° elbow pipe using the computational fluid dynamics code FLUENT and found that the erosion wear increased exponentially with velocity, particle size, and concentration. Huard and Adane [15] developed a web-based erosion–corrosion model for dense, settling, horizontal, aqueous slurry pipe flow in oil sands and mining applications and explored the validation of the model. Singh [16] presented an overview of the particulate wear that occurs in various components of slurry pumps, pipeline systems, and hydraulic turbines due to the mechanical action caused by the flow of solid–liquid mixtures and discussed further investigations to develop more accurate and flexible models that can be used to predict the particulate wear in a wide range of applications.

Different from the abovementioned industrial applications, the slurry transport of rock particles during slurry shield driving has two evident characteristics. The first concerns the size of the particles that should be carried. Natural particles (sand, pebble, gravel, cobble, etc.) accrue in slurry discharge pipelines when tunneling in pebble and cobble ground, and rock fragments from rock cutting accrue when tunneling in rock ground or rock–soil interface mixed ground. The maximum particle sizes encountered possibly lie between several centimeters and more than tens of centimeters in large-diameter slurry shield tunneling. The sizes of the involved particles in other industrial applications are small and usually range from tens of microns to several millimeters. The second characteristic is the carrier used. When slurry shield tunneling in difficult ground, such as pebble and cobble layers, the liquid carrier fluid must form a filter cake at the cutting face to guarantee the initial safety of the cutting face. Usually, specially prepared suspensions composed of bentonite, carboxymethyl cellulose, water, and other additives are employed as the support medium, which also act as carriers to convey excavated rock particles. These suspensions have a higher density and viscosity, and their physical and mechanical properties are much different from the carriers of water or gas used in other industrial applications. These two characteristics together contribute to the different action mechanisms between rock particles and pipelines, severely damaging and wearing down the slurry discharge pipelines of a slurry shield machine. However, the literature on rock-particle-induced damage and wear of slurry discharge pipelines is limited. A typical example was centered on pipe wear caused by Bukit Timah granite rock fragments in Singapore. Based on measuring the changes in the thickness of the slurry discharge pipelines at a slurry shield tunneling project in Singapore, the effect of the abrasiveness of the Bukit Timah granite on the wear of slurry discharge pipelines was investigated, the average wear rates of slurry discharge pipes used for Bukit Timah granite were determined, and the correlation between the slurry discharge velocity and the wear rate of the slurry discharge pipes was derived [17–20]. These studies focused on the wear rate of the pipeline under different lithological conditions and carried out a large number of fits. The results showed that the wear rates of weathering grades G(I) to G(IV) of Bukit Timah granite were highly similar to each other, whereas the wear rates of the G(V) grade and mixed ground were 1.55 times higher than those of the G(I) to G(IV) grades. Another study examined slurry discharge pipeline wear during slurry shield tunneling in China. Dong [21] analyzed the reasons for wear and vibration in slurry pipelines and proposed vibration and wear reduction measures such as thickening eccentric designs, increasing wear rings, and adding vibration damping pipes at pipeline connections. Wang [22] conducted an analysis of the blockage of pebbles in a slurry discharge pipe. Huang et al. [23] investigated the effects of pipe material, flow rate, slurry density, and solid particle size on the wear rate. Huo et al. [24] proposed adopting flexible piping to solve the severe wear at the elbow position of a pipeline. In these reports, the issues of pipeline wear and damage were raised, the wear was measured, and measures to combat pipeline damage and wear were introduced. However, the types of slurry pipelines involved in these studies were relatively homogeneous; a comprehensive survey of slurry discharge pipeline damage and wear does not exist, and the failure of slurry discharge pipe joints, the damage to slurry pumps, and how to lay pipe in an existing tunnel have not been addressed in previous studies.

In this study, data from a slurry shield tunneling machine used to dig a tunnel for the Beijing South-to-North Water Diversion Auxiliary Project were introduced. The tunnel, 6 m in outer diameter and 5.4 m in inner diameter, ran through a pebble layer and rock ground. During machine driving, natural rock particles from the pebble layer and rock fragments due to rock cutting when tunneling through the rock ground were transported in the slurry discharge pipelines of the slurry shield machine. Based on field-measured and observed data, the mechanisms and causes resulting in the observed large, uneven damages and wear were identified and assessed. Countermeasures to address issues such as adjusting pipeline layout, welding reinforcement plates in advance, and preparing additional pipelines were highlighted. The wear rates of different types of pipelines, the effectiveness of new pipeline fixing methods, and the probability of pipeline leaks in different strata were discussed in detail.

2. Project Overview

The Beijing South-to-North Water Diversion Auxiliary Project, which aims to partially solve city water supply problems, involves a ring of tunnels surrounding the city areas of Beijing, the capital of China. The target tunnel is the final part of the ring, and its completion means that this water supply project can be put into operation. The job site of the tunnel lies in the northwestern area of the city, and the ground surface is already well planned. As shown in Figure 1, there are many houses, scenic sites, and public facilities in the vicinity. The tunnel, 1711 m in length, was excavated by a slurry shield machine, and a launch shaft and a reception shaft were necessary to accommodate the machine. Usually, a separation plant is arranged near the launch shaft to optimally adapt to the requirements of the tunneling process. Due to the limitation of the ground surface, the separation plant was finally set up within close proximity of an auxiliary shaft, which was connected to the launch shaft by an existing tunnel approximately 842 m away from the launch shaft, as shown in Figure 1. The extended slurry feed pipelines and discharge lines were simply laid on the floor of the existing tunnel, which undoubtedly worsened the problem of pipeline damage and wear over the period of slurry shield driving.

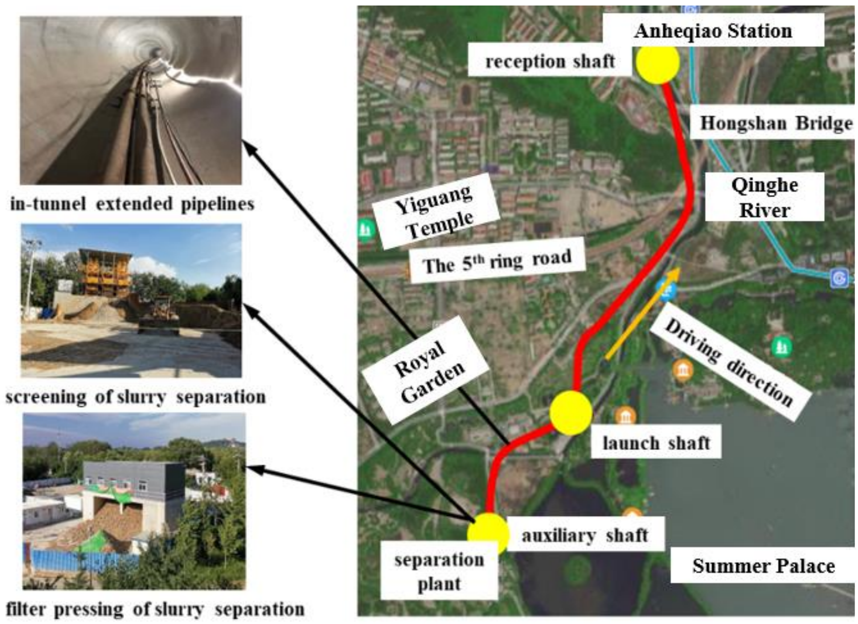

Figure 1. Plan view of the project.

As shown in Figure 2, after being launched, the slurry shield machine drove downslope at a slope of 2.1% until reaching a tunnel overburden depth of approximately 36 m and then drove almost horizontally to the end. Before tunnel excavation, a series of boreholes were drilled to examine the geological conditions. In this project, there were 10 boreholes in the cobble section, 17 boreholes in the bedrock section, and 1 borehole in the clay section. Soil and rock samples were tested to determine their geotechnical parameters. Finally, the excavated ground was divided into three sections, namely, the pebble layer, rock ground, and clay with gravel, which have horizontal lengths of 848 m, 830 m, and 33 m, respectively. Locally, sandy clay with gravel, siltstone, and mudstone were encountered. The pebble layer, with a pebble content of approximately 55–65% and grain size of 4–6 cm, is well graded in general and mainly backfilled by medium sand, and a small number of cobbles and boulders are found in the layer. The discovered pebble and cobble particles are rounded or subrounded but very hard, and the uniaxial compressive strength of some samples exceeds 200 MPa. The rock ground can be subdivided into two parts: a fault fracture zone and a zone of sandstone and quartz sandstone. The fault fracture zone mainly consists of weathered sandstone and quartz sandstone, and their strength, in the range of 5–101 MPa, is closely related to the degree of weathering. For the fresh sandstone and quartz sandstone encountered, a strength of over 100 MPa was measured in some test samples. Fragmented rock particles due to rock cutting by disc cutters of the slurry shield machine when tunneling in the rock ground exhibited sharp angularities.

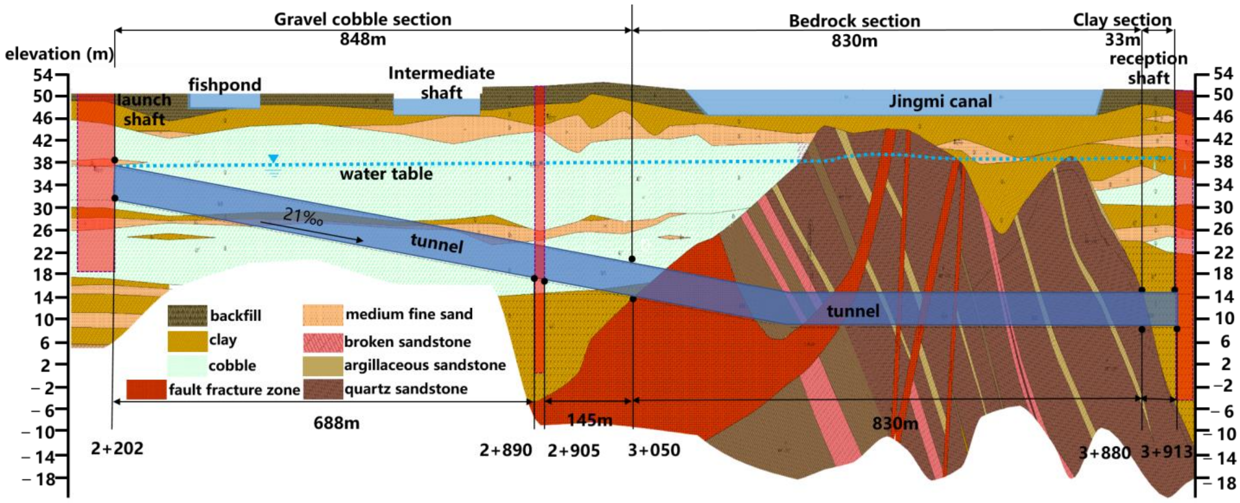

Figure 2. Longitudinal cross-section of the project.

The pipes used for the slurry circuit, 300 mm in outer diameter and 250 mm in inner diameter, were made of Chinese standard Q235B mild steel. The key chemical composition of the steel is listed in Table 1. The slurry circulation system was composed of pipes (straight and curved), elbows/bends, pumps, pipe joints, and gate valves. As shown in Figure 3, a grooved joint was first employed due to its easy assembly and therefore lower labor cost, but was later changed to a flanged joint because of frequent leks at the grooved joints. Because the slurry discharged had a high content of large solids, a knife gate valve was used to completely shut off the fluid flow when necessary. The valve owes its ability to handle these fluids to a knife-edged disc.

Table 1. Chemical composition of Q235B steel.

Steel Grade	C	Mn	Si (≤)	S (≤)	P (≤)	Cu (≤)	Cr (≤)	Ni (≤)
Q235B	0.12~0.20%	0.30~0.70%	0.30%	0.045%	0.045%	0.30%	0.30%	0.30%

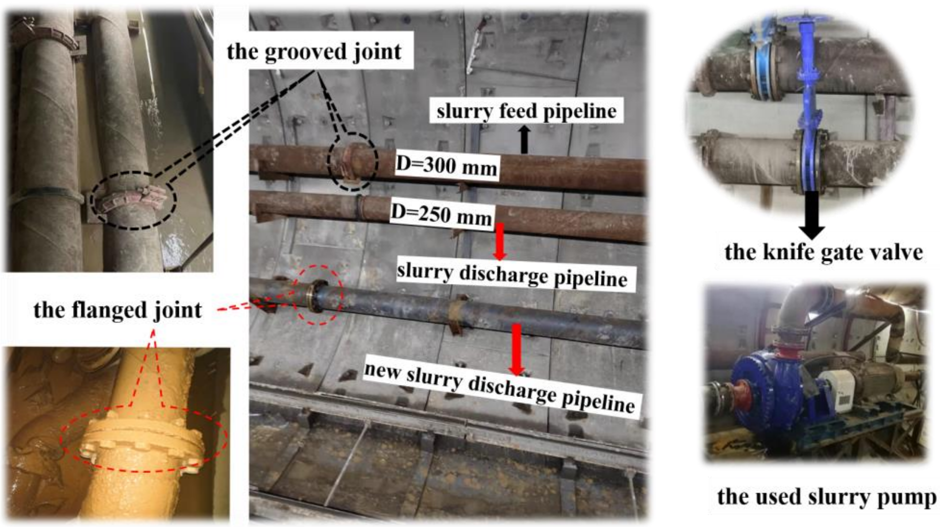

Figure 3. Main components of the slurry circulation system.

3. Large Rock Particles and Flow Rate of the Carrier Slurry

A segmental lining consisting of segment rings was employed in the construction. In terms of the ring number, the segment rings 1–740 were erected in the pebble layer, rings 741–1379 were located in the rock ground, and the remaining rings 1380–1416 were located in the sandy clay with gravel. Transporting the hard large particles caused severe damage and wear to the pipes and elbows/bends. The damage and wear were initially closely related to the physical and mechanical properties of the particles, such as their shape, size, and hardness, and were secondarily closely related to the in-pipeline movement of the particles. The first influencing factor was mainly determined by the excavated ground. Regarding the second factor, both the size and weight of the particles and the speed of the carrier fluid contributed to the movement of the particles in pipelines. Separated rock particles found at the separation plant at construction segment rings 9, 199, 499, 603, 649, and 729 are presented in Figure 4. The presented particles are generally rounded or subrounded, and the size of the large particles ranges from 3 to 7 cm. Separated rock particles found at rings 839, 1019, 1056, 1120, 1211, and 1216 are shown in Figure 5. As a result of rock cutting by disc rolling cutters, the large particles have sharp edges and a size of 2–5 cm.

Figure 4. Separated rock particles when shield tunneling in the pebble layer. (The Chinese characters on the card are the date, ring number, time and geological type of the rock particles being recorded).

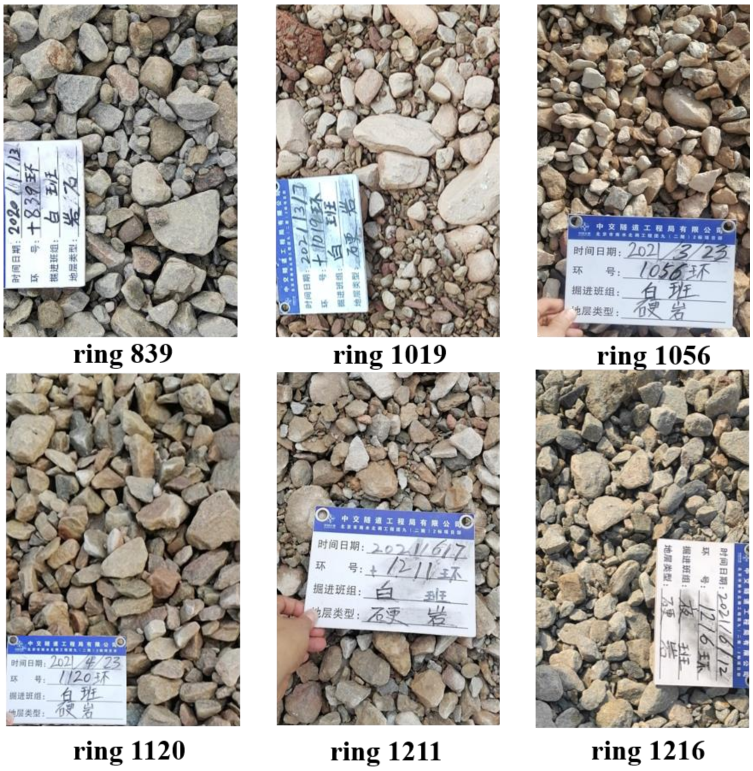

Figure 5. Separated particles when shield tunneling in the rock ground. (The Chinese characters on the card are the date, ring number, time and geological type of the rock particles being recorded).

The movement of the rock particles in pipelines is heavily dependent on the speed of the carrier fluid, whose average is the result of the flow rate divided by the internal cross-sectional area of the pipeline. The flow rate of the slurry discharge pipeline was adjusted to help maintain the stability of the cutting face in the varied ground during tunneling. As presented in Figure 6, a flow rate ranging from 7 to 10 m^3/min was employed in the pebble layer, and the flow rate was decreased to 4–7 m^3/min in the rock ground. Therefore, the speed of the rock fragments when tunneling in the rock ground was generally less than that of the rock particles in the pebble layer.

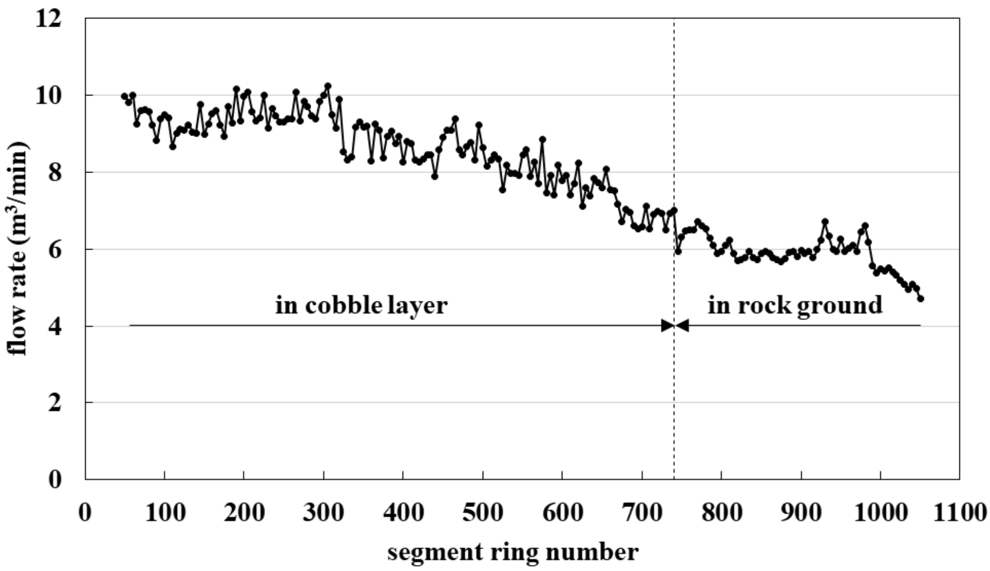

Figure 6. Flow rates of the slurry discharge pipeline at different segment rings.

To better form a filter cake and maintain the stability of the cutting face, a bentonite suspension was fed as the support media and accordingly played the role of a carrier to transport the excavated rock particles. The physical and mechanical properties of the carrier fluid were adjusted to adapt to the varied ground during tunneling. The carriers did influence the movement of the carried particles and the wear on pipelines associated with the particle movement. The slurry viscosity in terms of secondary and slurry specific gravity used in each segment ring is presented in Figure 7. Figure 7 shows that the specific gravity becomes significantly larger near rings 200 and 800. This is caused by the shield crossing a clay interlayer near ring 200 and reaching the fault fracture zone near ring 800, where the content of microscopic clay particles in the stratum increases. The slurry viscosity is measured by a Soviet funnel, and its magnitude depends on the amount of bentonite added and the microscopic particle content in the stratum and is therefore in dynamic fluctuation.

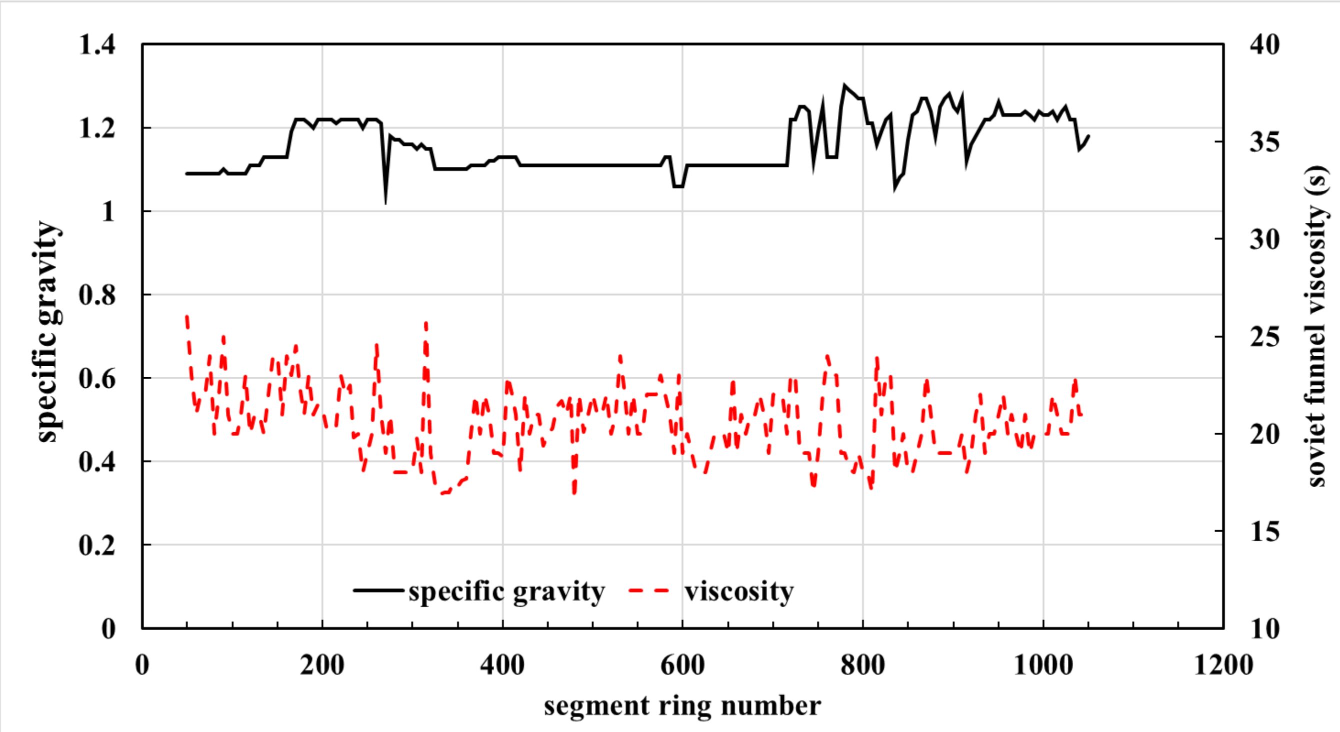

Figure 7. Varied properties of the fed bentonite suspension.

4. Damage and Wear of Components of the Slurry Transportation System

Contact between rock particles and the pipe wall surface is inevitable in slurry pipelining on account of the weight of the rock particles. The contact can be an impact or collision if the rock particles are large and the speed of the slurry is high. Frequent impacts can cause severe wear and even leaks in the pipes. This is true of other components of the slurry transportation system, such as the joints, valves, slurry pumps, and elbows/bends. Slurry gushing can occur in the middle of a pipe or at the joint, as shown in Figure 8a,b. For the pipelines laid in the existing tunnel, slurry even flooded the floor due to pipeline leaks, as presented in Figure 8c.

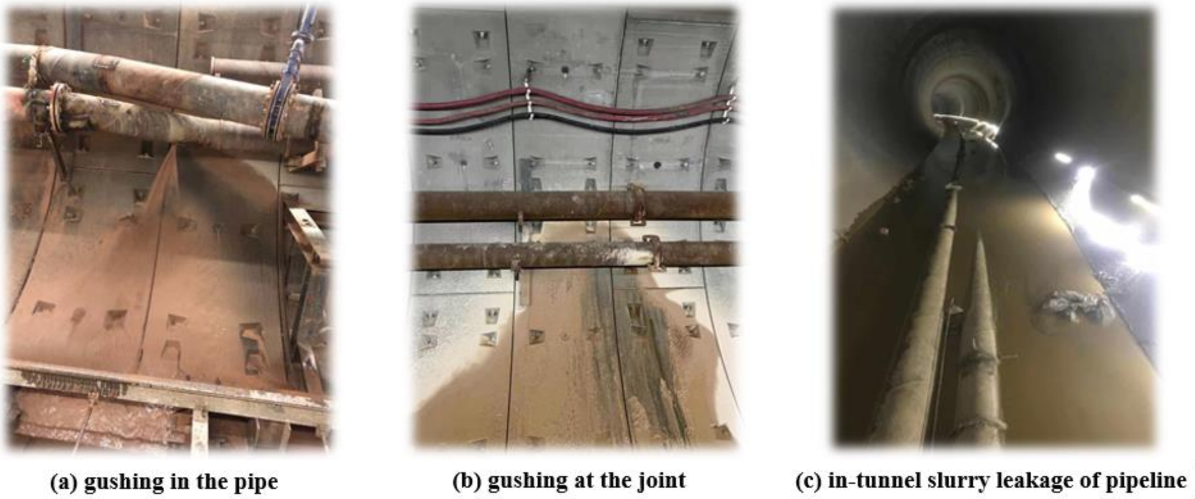

Figure 8. Leakages of pipelines.

4.1. Failure of Horizontal Straight Pipe

When slurry and rock particles travel quickly in a pipeline, they can add extra wear and tear to the inside. Pipeline leaks occur from the inside out, meaning that erosion works its way from the inside of the pipeline until it reaches the exterior surface. As a result of the accumulated abrasive erosion caused by the moving rock particles, wear and holes, either in the middle of a pipe or near a joint, can occur, as shown in Figure 9.

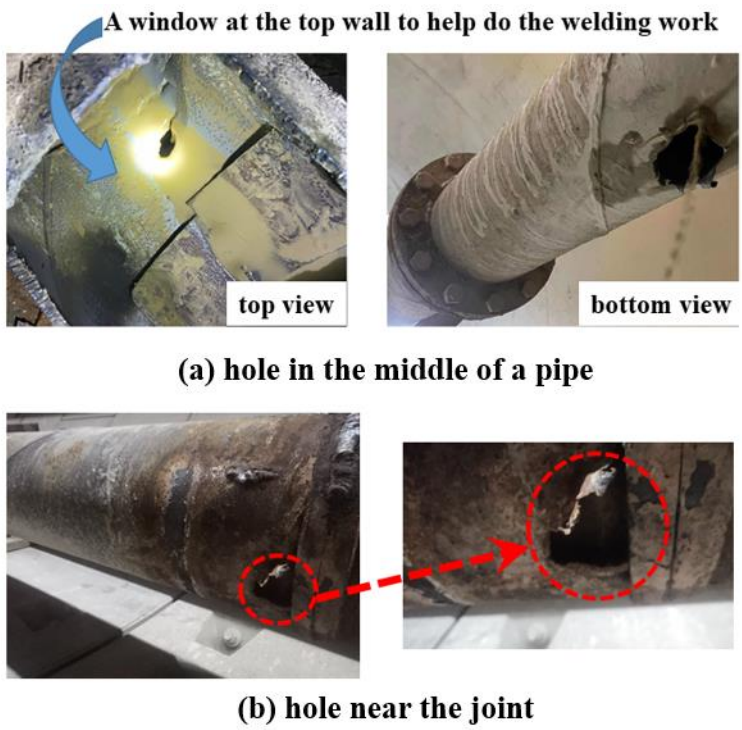

Figure 9. Worn-out pipes.

At the onset, two pipes of the slurry pipelining system were joined together by grooved pipe couplings with the aid of a rubber gasket, which, when impacted by many speedy rock particles, was liable to wear out. As shown in Figure 10, rubber gaskets were cracked or worn out over a period of use, which undoubtedly led to leaks in the pipelining system.

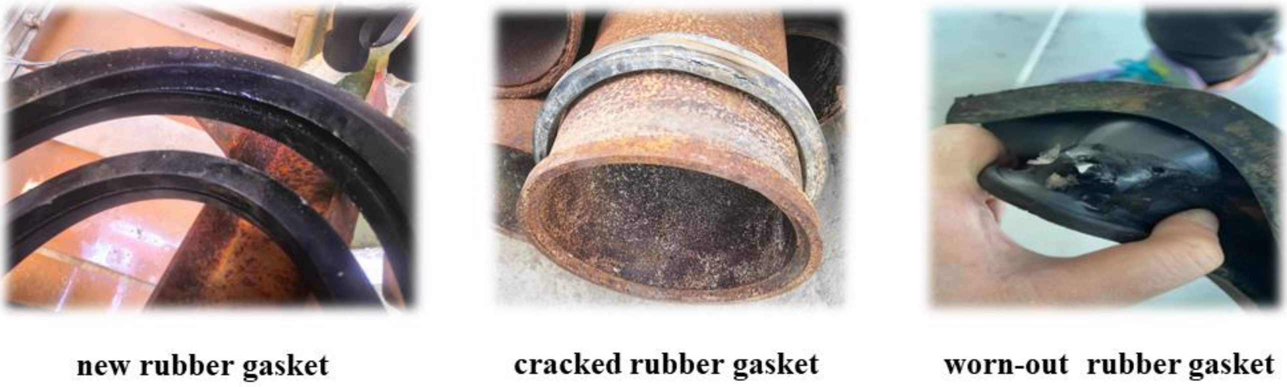

Figure 10. Damaged rubber gaskets.

4.2. Failure of Knife Gate Valves

Knife gate valves, suitable for handling slurries of viscous and abrasive media, were employed in the slurry circulation system. As a result of sustained impacts on the gate (the knife-edged disc) of the rock particles, a crescent-shaped gap was created between the disc and the valve body, as shown in Figure 11. The gap resulted in failure to shut off the particle-laden slurry when necessary.

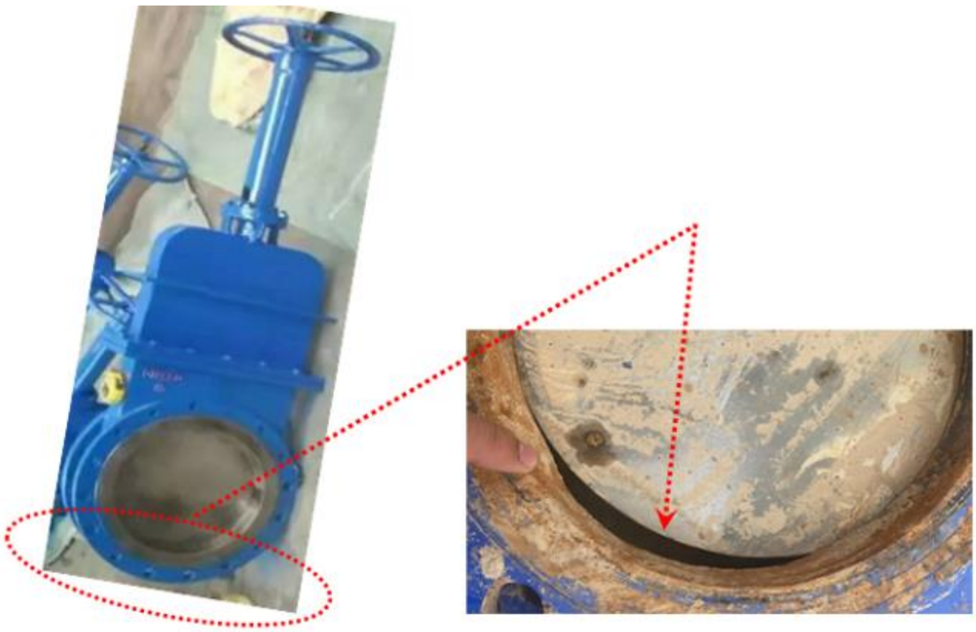

Figure 11. Gap between the disc and valve body.

4.3. Failure of the Slurry Pump

A slurry pump is designed to pump liquid containing solid particles, and hydroabrasive impact is the main cause of flow path wear in a slurry pump. Its intensity depends on many characteristics of the slurry and particles in the handled materials. In view of the large qualities of rock particles transported, the Warman slurry pump in use suffered substantial wear at the casing; as shown in Figure 12, a tiny hole was formed in the casing.

Figure 12. Worn-out pump casing.

4.4. Failure of the Elbows/Bends

Elbows/bends suffered more wear as a result of changes in the movement direction of the rock particles. To save cost, repaired elbows/bends and pipes were still put into operation, as shown in Figure 13. Severely damaged components, such as the two worn-out elbows presented in Figure 14, were abandoned.

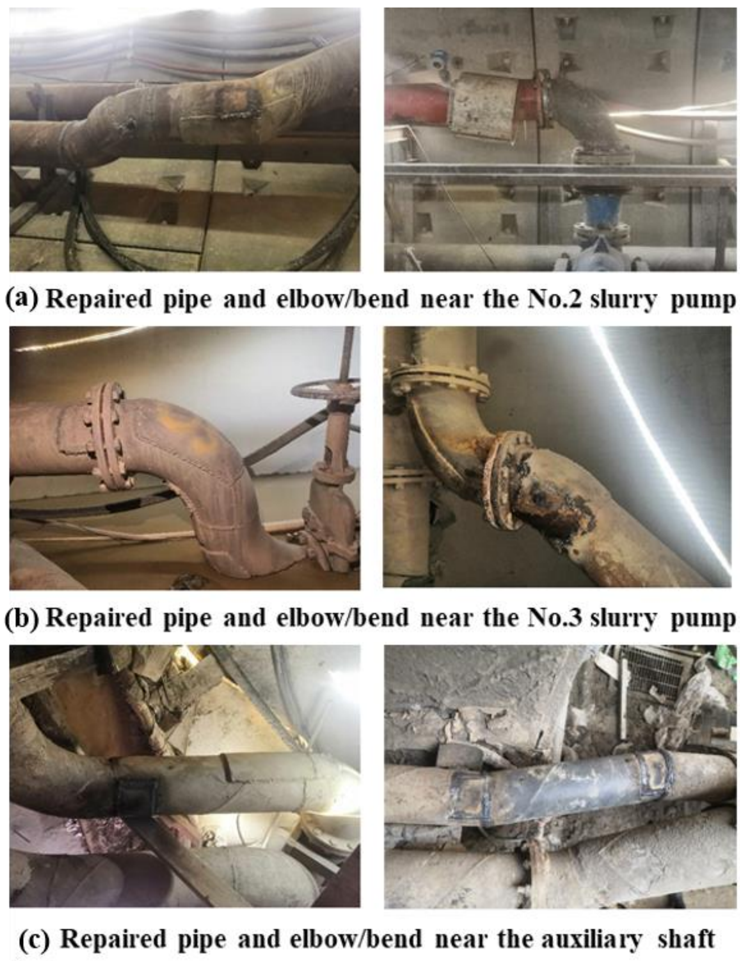

Figure 13. Repaired elbows/bends and pipes at work.

Figure 14. Worn-out elbows.

5. Countermeasures Taken against Pipeline Damage and Wear

Because of the pipeline leak and considerable slurry loss, the shield machine had to stop, and repairs to the damaged pipeline were carried out, delaying the tunneling work. For example, in March 2021, the machine was stopped due to pipeline leaks for 132.5 h, accounting for 32.7% of the total machine stoppage time and 17.8% of the total construction time; in April 2021, the duration of machine stoppage due to pipeline leaks was 219 h, accounting for 54.1% of the total machine stoppage time and 29.4% of the total construction time; in May 2021, the duration of machine stoppage time due to pipeline leaks was 101 h, accounting for 24.9% of the total machine stoppage time and 13.5% of the total construction time. The transported hard particles caused damage and wear to the pipeline, which accordingly led to pipeline leaks and considerable lost time to cope with the pipeline leaks. Tunnel construction was severely delayed, and countermeasures were necessary to reduce the frequency of leaks and the wearing out of the pipeline, consequently reducing the maintenance time for the slurry circulation system.

5.1. Monitoring the Wear of Pipelines

A construction schedule is heavily influenced by the issue of pipeline wear, and monitoring wear at representative positions of the pipeline system is of great engineering significance for taking measures against slurry leaks beforehand. Some representative results are introduced below. Eight monitoring points were arranged at four positions on the pipeline system, with two monitoring points at each position. The four positions were chosen at a 90° elbow pipe, at a straight pipe inclined at 60° with the horizontal line, at a pipe installed along the tunnel at curves with a small radius, and at a pipe installed along a straight tunnel section. From the construction of segment ring 1 to that of ring 1000, wear monitoring of the selected positions was performed. Wear mainly occurred at the pipe bottom wall, and ultrasonic thickness gauges were used to measure the varied thickness of the pipe bottom wall; the wear amount was defined as the decrease in pipe thickness. The monitored results are presented in Figure 15.

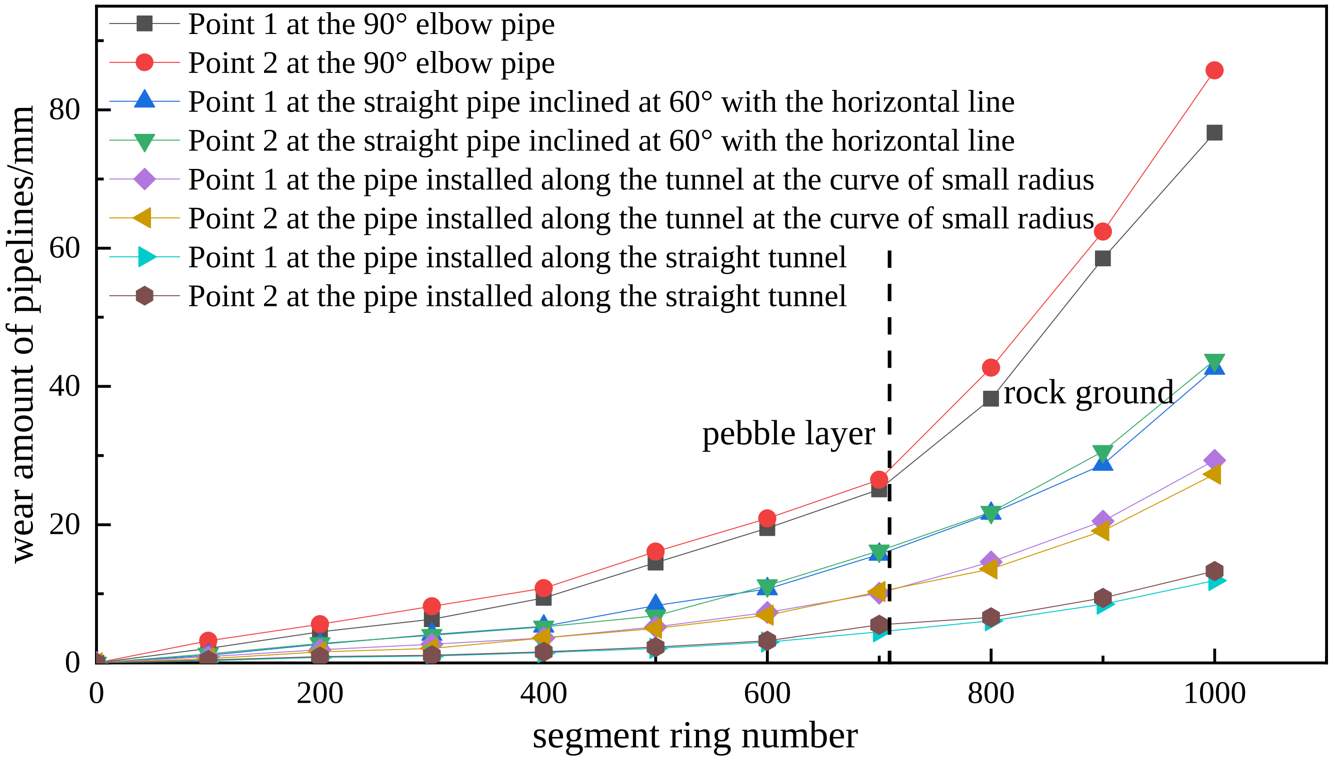

Figure 15. In situ measured wear in the pipeline.

5.2. Countermeasures Taken for the Pipeline

5.2.1. Mounting Method of the Pipeline in the Existing Tunnel

The secondary lining of the existing tunnel, generated from cast-in-place concrete, had already been completed. To protect the finished structure, fixed installations of the slurry pipeline were not allowed. Initially, channel bars, 10 mm wide and 1.5 m long, were laid on the floor. The slurry feed lines and the slurry discharge lines were simply placed on the channel bars with upright columns at the two sides to prevent roll, as shown in Figure 16. However, excessive vibration occurred, and slurry leaks, particularly at the joints, were frequently encountered. Worn-out pipeline sections were difficult to repair due to the wear-outs/holes at the bottom of the pipes, often causing an uncontemplated halt to construction. To address these issues, updating the mounting of the pipeline was performed.

Figure 16. Pipelines on channel bars.

As shown in Figure 17, newly designed brackets to support pipelines were generally ladder-shaped with two channel bars, 1000 cm in length, at the two sides. A semicircular steel arc with a diameter of 300 mm and width of 100 mm at the top was used to fix the slurry discharge pipeline; a semicircular steel arc with a diameter of 250 mm and width of 100 mm at the bottom was used to fasten the slurry feed pipeline. The steel arches were made from abandoned slurry pipeline components.

Figure 17. New brackets for pipeline.

As shown in Figure 18, fixed welding between the steel arch and the pipe wall was performed to reduce pipeline leaks associated with pipeline vibration. Most importantly, a working space for repairing leak points of the elevated slurry discharge pipeline was created.

Figure 18. The elevated pipeline on the brackets.

5.2.2. Application of Wear-Resistant Elbows/Bends

Wear-resistant elbows with eccentric thickening were designed and adopted, as shown in Figure 19. The outside wall is 20 mm in thickness, and the inside wall is 10 mm in thickness. The usage of 90° elbows was minimized as much as possible, and the 90° elbows were replaced with 45° elbows to reduce the impact on the pipeline due to rock particle veering, consequently reducing pipeline wear.

Figure 19. A wear-resistant 45° elbow.

5.2.3. Welding Reinforcement Plates to Bends in Advance

Performing a jobsite statistical analysis of leak locations in advance allowed us to weld reinforcement steel plates to bends outside pipeline walls liable to be worn out, as shown in Figure 20. The outside wall of the bend pipe was changed to 40 mm in thickness after reinforcement. The reinforced bends could work well for shield driving of approximately 300 segmental ring width according to the experiences gained in the construction.

Figure 20. Welding reinforcement plates in advance to protect bends in walls.

5.2.4. Rotating Straight Pipes 180 Degrees for Reuse

It was discovered at the jobsite that substantial wear occurred at the bottom half of the straight pipes, and no visible wear was found at the upper half. As a result, it was feasible to reuse the worn pipelines by rotating them 180 degrees, which was completed during construction to save cost.

5.2.5. Preparing Additional Pipes Beforehand

Particularly at the later stage of construction, leaks were increasingly frequently encountered in the pipeline. Repair work was required for such a long duration that it was no longer economical, and the use of newly installed pipes was a reasonable solution. Referring to the in situ measured wear rate of pipes to reasonably evaluate the life of the pipeline, additional pipes were installed in time before the worst scenarios occurred, as presented in Figure 21. The prepared pipes could be quickly installed when necessary to reduce machine stoppage time.

Figure 21. Preparing additional pipes beforehand.

6. Discussion

6.1. Pipeline Damage and Wear

Damage and wear caused by transported rock particles were found in each component of the pipeline system. To address pipeline wear, wear-monitoring work was performed, and the results are presented in Figure 15. The largest wear amounts measured were more than 80 mm at the two points of the 90° elbow pipe, indicating that the 90° elbow was the most severely worn part. The straight pipe inclined at 60° with the horizontal was second, with an attained wear amount of approximately 40 mm. The total wear amounts were approximately 27 mm at the monitoring points of the pipeline installed at the tunnel along a small radius curve. For monitoring points along straight pipe sections, the wear amounts were the lowest, at approximately 12 mm. It was found that before segment ring 705, the measured wear rates were slow, at approximately 4 mm per 100 rings of the 90° elbow pipe, approximately 2.14 mm per 100 rings of the 60° inclined pipe, approximately 1 mm per 100 rings of the pipe along the curved tunnel with a small radius, and approximately 0.71 mm per 100 rings of the straight tunnel segment. After segment ring 705, the machine drove into rock ground, and the wear rates increased by one to two times.

The results are analyzed as follows: The damage and wear of slurry discharge pipelines are influenced by many factors, such as the mechanical properties of the carrier slurry, the flow rate of the slurry, the pipeline type (pipe or elbow/bend), and, most importantly, the physical and mechanical properties of the transported rock particles. Referring to Figure 6, the flow rate of the slurry in the pebble layer is generally higher than that in the rock ground, but the observed pipeline wear results exhibit a higher wear rate when tunneling into rock ground. Thus, there must exist another dominating factor that governs pipeline damage and wear. From the rock particles shown in Figures 5 and 6, the reasons could be attributed to the angularities of the rock fragments from rock cutting with disc cutters. Angular rock particles with sharp edges produce more wear and tear on pipelines compared with rounded and subrounded rock particles from the pebble layer.

6.2. Effect of Pipeline Arrangement and Fixation

The important lesson gained in the slurry shield tunneling project concerns the pipeline arrangement and fixation of the slurry circulation system. The slurry feed pipeline and discharge line, approximately 842 m in length, were put in an existing tunnel next to the new tunnel. The secondary lining of cast-in-situ concrete of the finished tunnel was completed, and no damage to the lining was allowed. Therefore, the in-tunnel pipelines were simply laid on brackets on the tunnel floor, as shown in Figure 16. Not enough space was left under the pipeline to perform repair work, and a window had to be cut at the pipeline top, as shown in Figure 9a. In the window, welding steel pads onto the broken pipeline was carried out from within the pipeline. Performing repairs in this fashion undoubtedly created excess work and delayed project construction.

To address the issues of in-tunnel slurry discharge pipeline leaks, a new mounting method was adopted to arrange the pipelines on the redesigned brackets, as shown in Figures 17 and 18. This new arrangement allowed more efficient welding work to occur on the broken pipelines. Additionally, the pipelines could be more tightly fixed with the new brackets, thus reducing the transported rock particle-induced vibrations and wear on the pipelines.

6.3. Pipeline Leaks When Tunneling in Different Ground

Rock particles that were transported in the pipeline were different in the changed ground. As a result, the pipeline damage and wear varied, and this was true of the pipeline leaks. Taking tunneling from July 2020 to May 2021 as an example, 941 segment rings in total were finished, with many occurrences of pipeline leaks as a result of pipeline damage and wear. The number of occurrences was 143 in 11 months, as shown in Table 2. The first 448 segment rings were in the pebble layer, and the remaining 500 rings were in rock ground.

Table 2. Occurrences of pipeline leakages from July 2020 to May 2021.

Time	Number of Leaks	Finished Segment Rings per Month	Damage Ratio	Ground Type
July 2020	15	156	9.62%	Cobble layer
August 2020	13	176	7.39%	Cobble layer
September 2020	5	30	16.67%	Cobble layer
October 2020	0	15	0.00%	Cobble layer
December 2020	2	64	3.12%	Cobble layer
December 2020	5	95	5.26%	Rock ground/fault fracture zone
November 2020	17	89	19.10%	Rock ground/fault fracture zone
January 2021	14	77	18.18%	Rock ground/fault fracture zone
February 2021	6	74	8.11%	Rock ground/fault fracture zone
March 2021	20	89	22.47%	Rock ground/fault fracture zone
April 2021	36	61	59.02%	Rock ground/sandstone and quartz sandstone
May 2021	10	15	66.67%	Rock ground/sandstone and quartz sandstone
In total	143	941	15.20%	-

There is a strong correlation between the pipeline leaks and the finished segment rings per month. As an indicator of the pipeline leak frequency, the damage ratio in Table 2 is defined as the ratio of the number of pipeline leaks to the finished segment rings per month. The calculated pipeline damage ratios have experienced sharp increases since December 2020, and very high ratios of 59.02% and 66.67% were reached in April 2021 and May 2021, respectively. The high increases were closely related to the ground encountered. In December 2020, the tunneling ground changed from a pebble layer to rock ground. Fragmented rock particles due to rock cutting by the disc cutters of the slurry shield machine when tunneling in the rock ground exhibited sharp angularities, which undoubtedly caused severe damage and wear to the slurry discharge pipeline and consequently more pipeline leaks. In April 2021 and May 2021, fresh sandstone and quartz sandstone were encountered, and hard rock particles intensified the damage and wear of the slurry discharge pipeline and increased pipeline leaks. Meanwhile, the long service life of some pipeline segments also contributed to the high increase in pipeline leaks.

7. Conclusions

The damage and wear of a slurry discharge pipeline during slurry shield tunneling in a pebble layer and rock ground were investigated over a period of slurry shield tunneling for a water supply project in Beijing, China. The following conclusions can be drawn:

(1) Controlled by the movement of the transported rock particles, damage and wear mainly occurred at the bottom wall of the pipeline. Compared with straight pipes, elbows/bends were more easily worn out. Inclined straight pipes had a higher wear rate than horizontal straight pipes. Pipes installed along curved tunnels suffered more wear than those in straight tunnels. The reduction in slurry velocity reduced pipe wear, while sharp particle shapes increased wear, and the shape of the particles had a greater impact.

(2) The measured results showed that the wear rates of the straight pipe, pipe along the curved tunnel, 60° inclined pipe, and 90° elbow pipe in pebble ground were approximately 0.71 mm/100 rings, 1 mm/100 rings, 2.14 mm/100 rings, and 4 mm/100 rings, respectively. After segment ring 705, the machine drove into rock ground, and the wear rates increased by one to two times, which could be attributed to the rock particles of the pebble layer being polished and the rock fragmentations in the rock ground having sharp edges.

(3) The arrangement of the pipeline should favor pipeline inspection and maintenance. Because of the insufficient space to repair the worn-out bottom walls of the pipeline, the slurry discharge pipeline should not be mounted on the tunnel floor. Additionally, pipelines should be tightly fixed to reduce their movement.

(4) To fight pipeline wear and leaks and maintain sustained shield tunneling, countermeasures should be planned and prepared beforehand. First, the layout of pipelines in an existing tunnel should favor pipeline maintenance and repair. Second, for long tunnel projects, preparing a slurry discharge pipeline system ready for use is suggested, especially at the rear half of the tunnel. Third, wear-resistant elbows/bends should be used, and reinforcement plates should be welded to them in advance to prevent the occurrence of leaks. Other measures, such as rotating a worn pipe 180 degrees for reuse and exchanging slurry feed lines and slurry discharge lines, are also proposed.

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References

1. Min, F.; Zhu, W.; Han, X. Filter cake formation for slurry shield tunneling in highly permeable sand. *Tunn. Undergr. Space Technol.* **2013**, *38*, 423–430. [CrossRef]
2. Summer, R.M. *A Review of Pipeline Slurry Erosion Measurements and Research Recommendations*; ASTM International: West Conshohocken, PA, USA, 1987; pp. 91–100.
3. Hutchings, I.M. Mechanisms of wear in powder technology: A review. *Powder Technol.* **1993**, *76*, 3–13. [CrossRef]
4. Gupta, R.; Singh, S.N.; Sehadri, V. Prediction of uneven wear in a slurry pipeline on the basis of measurements in a pot tester. *Wear* **1995**, *184*, 169–178. [CrossRef]
5. Gandhi, B.K.; Singh, S.N.; Seshadri, V. Study of the parametric dependence of erosion wear for the parallel flow of solid–liquid mixtures. *Tribol. Int.* **1999**, *32*, 275–282. [CrossRef]
6. Yabuki, A.; Matsumura, M. Theoretical equation of the critical impact velocity in solid particles impact erosion. *Wear* **1999**, *233*, 476–483. [CrossRef]
7. Oka, Y.I.; Okamura, K.; Yoshida, T. Practical estimation of erosion damage caused by solid particle impact: Part 1: Effects of impact parameters on a predictive equation. *Wear* **2005**, *259*, 95–101. [CrossRef]
8. Oka, Y.I.; Yoshida, T. Practical estimation of erosion damage caused by solid particle impact: Part 2: Mechanical properties of materials directly associated with erosion damage. *Wear* **2005**, *259*, 102–109. [CrossRef]
9. Pereira, G.C.; de Souza, F.J.; de Moro Martins, D.A. Numerical prediction of the erosion due to particles in elbows. *Powder Technol.* **2014**, *261*, 105–117. [CrossRef]
10. Arabnejad, H.; Mansouri, A.; Shirazi, S.A.; McLaury, B.S. Development of mechanistic erosion equation for solid particles. *Wear* **2015**, *332*, 1044–1050. [CrossRef]
11. Rawat, A.; Singh, S.N.; Seshadri, V. Erosion wear studies on high concentration fly ash slurries. *Wear* **2017**, *378*, 114–125. [CrossRef]
12. Coker, E.H.; Van Peursem, D. The erosion of horizontal sand slurry pipelines resulting from inter-particle collision. *Wear* **2018**, *400*, 74–81. [CrossRef]
13. Javaheri, V.; Porter, D.; Kuokkala, V.T. Slurry erosion of steel—Review of tests, mechanisms and materials. *Wear* **2018**, *408*, 248–273. [CrossRef]
14. Singh, V.; Kumar, S.; Mohapatra, S.K. Modeling of erosion wear of sand water slurry flow through pipe bend using CFD. *J. Appl. Fluid Mech.* **2019**, *12*, 679–687. [CrossRef]
15. Huard, M.; Adane, K.F. Validation of a Dense Slurry Pipeline Erosion-Corrosion Model. In Proceedings of the CORROSION 2020, Houston, TX, USA, 14–18 June 2020.
16. Singh, J. A Review on Mechanisms and Testing of Wear in Slurry Pumps, Pipeline Circuits, and Hydraulic Turbines. *J. Tribol.* **2021**, *143*, 090801. [CrossRef]
17. Pak, Y.T.; Kim, T.K.; Ko, T.Y. A study on the discharge pipes wear of slurry shield TBM in rock strata. *J. Korean Tunn. Undergr. Space Assoc.* **2017**, *19*, 57–70. [CrossRef]
18. Ko, T.Y.; Pak, Y.T.; Yoon, D.H.; Kim, S.; Kim, T.K. Slurry pipe wear in shield TBM. In Proceedings of the YSRM 2017—The 4th ISRM Young Scholars' Symposium on Rock Mechanics and NDRM 2017—The 5th International Symposium on New Development in Rock Engineering—An ISRM Specialised Conference, Jeju, Republic of Korea, 11–13 May 2017; pp. 458–460.
19. Ko, T.Y.; Pak, Y.T.; Kim, T.K.; Son, S.M. Effect of rock abrasiveness on slurry shield tunneling. In Proceedings of the International Conference on Tunnel Boring Machines in Difficult Grounds (TBM DiGs), Wuhan, China, 20–22 November 2017; pp. 1–8.
20. Ko, T.Y.; Lee, S.S. Effect of rock abrasiveness on wear of shield tunnelling in bukit timah granite. *Appl. Sci.* **2020**, *10*, 3231. [CrossRef]
21. Dong, B. Countermeasures for reducing wear and vibration of slurry pipe of slurry shield. *Tunn. Constr.* **2016**, *36*, 1385–1388. (In Chinese)

22. Wang, F. The difficulties and countermeasures in shield construction of Yellow River tunnel of Lanzhou Metro Line 1. *Railw. Stand. Design* **2017**, *61*, 93–99. (In Chinese)
23. Huang, B.; Li, X.; Chen, C. Study of abrasion of slurry pipe of large-diameter slurry shield boring in complex strata. *Tunn. Constr.* **2016**, *36*, 490–496. (In Chinese)
24. Hou, B.; Xu, Z.; Hu, X.; Guo, G. Analysis of technical difficulties and control measures for slurry shield boring in sandy cobble strata: A case study of Yellow River crossing tunnel of Lanzhou Metro. *Tunn. Constr.* **2018**, *38*, 846–850. (In Chinese)