

Article

Study on Construction and Reinforcement Technology of Dolomite Sanding Tunnel

Meiqian Wang ¹ , Wei Xu ¹, Hongyuan Mu ², Jian Mi ², Yonghong Wu ^{1,*} and Yangxing Wang ³

¹ Faculty of Civil and Architectural Engineering, Kunming University of Science and Technology, Kunming 650500, China; wangmeiqian@stu.kust.edu.cn (M.W.); 20080036@kust.edu.cn (W.X.)

² Yunnan Institute of Water & Hydropower Engineering Investigation, Design and Research, Kunming 650021, China; muhongyuan@ynwdi.com (H.M.); mijian@ynwdi.com (J.M.)

³ China Railway Tunnel Stock Co., Ltd., Zhengzhou 450000, China; wangyangxing@creg.com

* Correspondence: 20130112@kust.edu.cn

Abstract: The No. 2 conduit of the Xiaopu Tunnel in the Yuxi section of central Yunnan's water diversion project is taken as the research object, starting from the geological conditions along with the characteristics, formation mechanism and evolutionary model of dolomite sanding. This paper discusses the engineering problems of the project's tunnels with dolomite sanding in the water-rich section, and its corresponding engineering reinforcement plan. It was found that in the tunnel section with normal level of dolomite sanding, there was no water seepage, where measures such as advanced small conduit, mechanical excavation, short grubbing and strong support could all be adopted for safe passage. Even in the water seepage section of the weak dolomite sanding tunnel, the surrounding rock was found in close interlock with strong self-stability. The excavation and support were implemented according to the category of normal surrounding rock. In the water-rich sections with strong and intense dolomite sanding, gushing of water and sand were quite frequent, with developed fissures, broken rock masses and rich waters. During the engineering operation, phosphoric acid and sodium silicate slurry in addition to urea formaldehyde resin and oxalic acid slurry plus Malisan and liquid catalyst slurry were first prepared for water plugging. Then, pure water slurry was used for surrounding rock reinforcement, which exerted an excellent effect. This method can provide reference for reinforcing tunnels of sandy dolomite in other areas of projects.

Keywords: tunnels with dolomite sanding; grouting; water and sand inflow; surrounding rock reinforcement



Citation: Wang, M.; Xu, W.; Mu, H.; Mi, J.; Wu, Y.; Wang, Y. Study on Construction and Reinforcement Technology of Dolomite Sanding Tunnel. *Sustainability* **2022**, *14*, 9217. <https://doi.org/10.3390/su14159217>

Academic Editor: Kaihui Li

Received: 24 May 2022

Accepted: 22 July 2022

Published: 27 July 2022

Publisher's Note: MDPI stays neutral with regard to jurisdictional claims in published maps and institutional affiliations.



Copyright: © 2022 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<https://creativecommons.org/licenses/by/4.0/>).

1. Introduction

With the rapid growth of China's high-speed railways, high-speed roads, urban rails and water projects, tunnel engineering has also entered a period of fast development. With the increase in larger, longer and deeper tunnels, there are increasingly complex geological problems encountered in various construction projects. The commonly unfavorable geological conditions include fault fracture zone, karst development zone, water-rich area, coal seam, gas-logged zone, geothermal anomaly area and so forth. Although there have already been plenty of engineering solution practices and studies for tackling these unfavorable conditions, accidents caused by geological hazards are still quite frequent.

Dolomite sanding is a unique karst geological phenomenon occurring in dolomite distribution area [1]. The rock strength of dolomite reduces after dissolution, and its residue comprises sand mixed with dolomite block stones of uneven particle sizes, which can also be manually scattered into sand. This specific type of karst geological phenomenon is defined as "dolomite sanding [1]". Li et al. [2] reported that dolomite sanding is a special geological occurrence of dolomite with microcrystalline fine-crystal structure under a complex geological tectonic environment following multi-stage tectonic movements, whose rock mass was weathered into fine sand, gravel or fragments due to the joint action of

dissolution and weathering, resulting in a great reduction of the rock mass weight. Ma [3] briefly stated “dolomite sanding” as the reason for dolomite fragmentation. Lynton [4] altered the mixture of seawater and atmospheric water by evaporation, and promoted dolomitization by sulfate reduction. When the surface temperature was slightly higher, crystal enlargement and chemical reaction would occur, thus masking the primary properties of dolomite. Zhang et al. [5] believed that rock containing impure mineral compositions of calcite and dolomite lay in a dispersed form between minerals, and the loose dolomite powders were finally generated under the continuous dissolution effect of the solution. Pei et al. [6] conducted microscopic research on dolomite in the third segment of Sinian System’s Dengying Formation (Zd3) of the Da Guangbao landslide, before revealing that the compression shear crystals of the rock mass in the slide zone were twisted and fractured along the cleavage plane. In addition, the transgranular cracks were developed, which was manifested by the loose erection of some crystals and the loss of intergranular connection. Rong et al. [7] believed that the porosity of dolomite was higher than that of limestone, which could provide better channels for seepage of surface-water and groundwater, and render it easier to form dolomite crystal shedding and weathering products scattered from dolomite sand. Chen et al. [8] and Fang et al. [9] both proved that the presence of 1–2 mM aqueous $\text{Si}(\text{OH})_4$ in a high Mg: Ca-ratio solution at room temperature would promote dolomite precipitation and inhibit aragonite formation. Yan et al. [10] believed that the metal sulfide minerals in the mining area were oxidized into sulfuric acid water which then dissolved the dolomite into sand (powder). Hu [11] and Zhao, et al. [12,13] conducted an indoor dissolution test of dolomite and the study of a micro-dissolution mechanism to clarify that the micro-dissolution characteristics of dolomite were mainly manifested in the first dissolution of various joints and fissures in crystals under chemical action, thus the strengths of bonding forces between them were reduced. Then, mechanical disintegration and falling-off occurred under the physical action of water flow, and finally dolomite sands (powders) were generated. Luo et al. [14] analyzed the influencing factors of seismic fracture damage extent of landslide dolomite rock mass under strong earthquake. The analysis was conducted from the perspective of dynamics based on fatigue test through numerous field investigations at the scene of Da Guangbao landslide. To predict the strain softening and permeability evolution of bearing rocks, Zhang et al. [15] established the specific model of rock strain softening and permeability evolution model to consider the influence of confining pressure. Xiong et al. [16] solved the damage evolution equation of sanding rock mass based on continuum mechanics and irreversible thermodynamics, and proposed a three-dimensional finite method of element calculation for elastic-plastic damage of sanding rock mass, by applying this method to reflect the failure process of sanding rock mass under the interference of excavation and engineering. To study the influence of water content on the physical and mechanical properties of sanding dolomite, Zhang [17] demonstrated that the peak strength and elastic modulus of sanding dolomite were greatly affected by water content. With an increase in water content, the damage constitutive model’s parameters m and F gradually decreased. Research by Jamel Tourir and James et al. showed that dolomite sand and powdery material were often generated from dolomite dissolution [18,19]. Detlev [20] took eight surface outcrops in Jurassic “Franconian dolomite” in Bavaria of Southeastern Germany as examples to describe the evolution process of dolomite sanding. The theory proposed by Choquete et al. [21] about the disintegration of microcrystalline dolomite into coarse-grained structures was of great significance to the study of near-surface dolomite sediments. This theory was referred to both in the study of Triassic dolomites in Hungary by Poros et al. [22] and in the research of late Jurassic dolomites in Southern Germany by Koch et al. [23]. Karmen Fio et al. [24] studied the marine carbonate rocks of periods from late Permian to early Triassic, which identified the characteristics of Permian–Triassic dolomite sanding in Velebit mountain of Croatia as high carbonate content through analysis of stable isotopes ($\delta^{13}\text{C}$, $\delta^{18}\text{O}$) and major, trace, and rare earth elements (REE). Liu et al. [25] analyzed the vulnerability of sanding soil in Florida to toxic metal pollution and the effectiveness of humic-acid Active

Dolomite Phosphate Rock (ADPR) and Biological Carbon (BC) to fixate Cd^{2+} and Pb^{2+} in soil restoration. Esteban et al. [26] mentioned the influence of hydrothermal action, Machel et al. [27] hypothesized that dolomites were dissolved by sulfate during hydrocarbon impregnation, and Poros et al. [22] not only induced the above theories but also established a new model of dolomite sanding caused by freeze–thaw process when studying Triassic dolomites in Hungary. Orsolya et al. [28] investigated Triassic dolomites in Hungary, selected seven rock-cores for stable isotope analysis, and for identifying the relationship between dolomitization and hydrothermal dissolution. Giuseppe et al. [29] studied the dissolution of dolomite by macro methods (via pH-stat system and mixed flow reactor) and micro-characterization methods (via atomic force and transmission electron microscopy). At the release rates of Ca and Mg, the variations to micromorphology and chemical structure of the dissolving reaction were identified by chemical analysis.

At present, there are few studies on the dolomite sanding mechanism and its engineering characteristics, engineering effects, deformation and destruction mechanisms, engineering solution measures and so forth. Currently, engineering geological problems related to dolomite sanding are mainly concentrated on underground projects of transportation and water sectors in Southwest China regions such as Yunnan, Guizhou, Sichuan and Chongqing [30–33]. For example, due to the influence of complex geological conditions such as sanding dolomites, the phenomenon of water and sand gushings in the tunnels had been frequent. Consequently, the Xiushan tunnel of Yumeng railway in Yunnan Province took nearly 8 years to finalize. Further, a few projects in Yunnan Province suffered problems regarding uneven settlement of dolomite sanding foundation and reservoir (Hongyan reservoir) leakage [34]. Wang et al. [31], based on the sanding phenomenon of dolomite developed from Triassic and Cambrian in five tunnels of Guizhou, analyzed both the sanding patterns and characteristics of dolomite, proposing the reinforcement methods and solutions under the specific condition of argillaceous dolomite sanding. Based on the double-track centralized tunnel project of the Chengdu–Kunming railway, Jiang et al. [35] revealed that the necessary conditions for dolomite to become sand gushings were being sandy in water environment; Zhou et al. [36] investigated the Emeishan–Miyi section tunnel of the Chengdu Kunming railway extension project crossing the sandy dolomite stratum from September 2017 to November 2020, with four water and sand gushing accidents at different levels occurring at different positions of the tunnel surface. Moreover, the reconstructed Jiermu (Jixin) tunnel [37] of the Chengdu–Kunming Railway in Sichuan Province also passed through the sanding dolomite stratum of Dengying Formation of Sinian System, with “water and sand gushing” also occurring frequently in the water-rich section. Based on the Jixin tunnel project of the Chengdu–Kunming double-track railway, Wang et al. [38] adopted the methods of advanced geological prediction, theoretical analysis and continuous–discrete coupling numerical analysis to thoroughly study the tunnel face destabilization mechanism in sanding dolomite stratum, before revealing the conditions of tunnel face destabilization along with the displacement and failure pattern of the rock surrounding the tunnel face after destabilization. Xu et al. [39] asserted that the Da Guangbao landslide was induced by Wenchuan earthquake, while the rock mass fragmentation and cracking in the slide zone were the result of the formation and evolution of dolomites’ strongly dissolving sanding layers. Focusing on the engineering example of the Ying Erling tunnel of Rong–Wu expressway, Bai et al. [40] verified the favorable results of this project in both safety and quality by adopting fast, stable and strong procedures of engineering. To study the curtain grouting treatment technology of the tunnel’s dolomite sanding sections, Luo et al. [41] applied calculation, numerical simulation and engineering practice to obtain the key influencing factors of this technology, namely the grouting pressure, grouting material, grouting thickness and grouting technique. Their results showed that the high-pressure splitting method should be adopted for curtain grouting in solid sanding-dolomite layer of silty fine sand, with the final grouting pressure being recommended to set between 3–5 MPa. Moreover, Ping et al. [36] analyzed the mineral composition of dolomite due to the great challenges and risks from tunnel engineering, discussed the sanding mechanism

of dolomite at the macro-, meso- and micro levels, and obtained the parameters of sanding dolomite under different sanding conditions. In addition, water and sand gushings had also occurred in the dolomite sanding section of Yingpanshan tunnel of the Dali-Ruili railway. Moreover, 36.5 m upstream of Xiaopu tunnel's No. 2 conduit in Yuxi section of WDPCY, the construction adit and the main exit of Che'naju tunnel, water gushing occurred at the very start of the engineering. This could prove that the surrounding rock of the tunnels in sanding dolomite areas were unstable. During tunnel construction, there had been continuous geological engineering problems such as high ground stress, large deformation of soft rocks, water and mud gushings, water and sand gushings of dolomite sandy stratum, TBM jamming and so on [42–45]. This has caused more construction difficulties to the tunnel excavation, increased the project costs and extended the construction period. At present, the grouting materials used in the tunnel are mainly single-liquid cement slurry, double-liquid cement slurry and ultra-fine cement slurry [46]. The diffusion range of grouting was studied by numerical simulations [47,48]. The grouting time determination was mainly based on cylindrical diffusion theory and spherical diffusion theory [49,50]. The grouting theory for fractured rock mass was mainly according to the Baker formula, and the curtain thickness was mainly calculated by Wagoner and Kolymbs theories [51].

The WDPCY-based in-depth theoretical and practical research on the dolomite sanding mechanism, engineering geological characteristics, engineering effects and engineering control measures for sanding dolomite stratum have already become an urgent geological need in tunnel engineering and an inevitable demand that must be met by specific tunnel reinforcements.

2. Overview of Tunnel Engineering

2.1. Current Situation of Tunnel Construction

The water transmission line of the Yuxi section is located at the intersection between the front arc of Yunnan ε -type structure and the middle part of the east branch of Qinghai-Tibet-Yunnan-Myanmar-Indonesia η -type structural system. This area is categorized as the first-class structural unit of the Yangtze para-platform and is further divided into second–third-class structural units: Belonging to the Kunming plateau fold bundle of the East Yunnan platform fold belt. The project area has frequent seismicity and complex geological structure, most of which are in uplift denudation state. There are no Paleozoic Silurian, Ordovician or Cretaceous strata along the water transmission line, no exposed intrusive rocks, except for a small amount of exposed volcanic rocks, and only the Kunyang group of metamorphic rocks that are largely exposed. The total length of the water transmission line in Yuxi section is 77.069 km, crossing various strata including the Quaternary incompact one at a total length of 3.493 km, accounting for 4.53% of the total length of the line in this section. The cumulative length of the clastic rock is 44.889 km, accounting for 58.25%. The total length of carbonate rock is 20.724 km, accounting for 26.9%. The cumulative length of metamorphic rock is 5.855 km, accounting for 7.6%. The total length of magmatic rocks (mainly basalt) is 2.108 km, accounting for 2.73%. In general, these rocks are of soft-medium hardness.

As of December 2021, the tunnels discovered fierce and intense phenomena of dolomite (see Figure 1) included the following seven: No. 2 conduit of Xiaopu tunnel (see Figure 1a) with the upstream and downstream surfaces, Xiaopu No. 3 conduit, Lanaju construction adit, Lanaju entry, Lao Jianshan tunnel exit (see Figure 1b), Da Tangzi tunnel's entry and exit and Luo Fengshan tunnel entry (see Figure 1c). Most of these tunnel sections were located above the groundwater level, dry, anhydrous, with class V surrounding rocks. Only the Xiaopu 2# main tunnel sections at upstream, downstream and the rear of Lanaju adit were all greatly affected by groundwater. In total, the dolomite sanding tunnel section was 2418.2 m in length. In case of extremely uneven distribution, the development of the tunnel sections with fierce and intense dolomite sanding would be of a large regional tectonic fault background, mostly distributed in strips, sacs or chicken nests. According to the categorization of surrounding rocks on site, those of category III₂ accounted for 11.2% and

those of category IV accounted for 22.3%, the rocks of category V accounted for 66.4%, respectively. Geological hazards occurred frequently when the sanding extended to the water and sand gushings' tunnel section with strong water abundance and high water head. The statistics of fierce and intense sanding tunnel sections are listed in Table 1, with no effective treatment measures found yet.

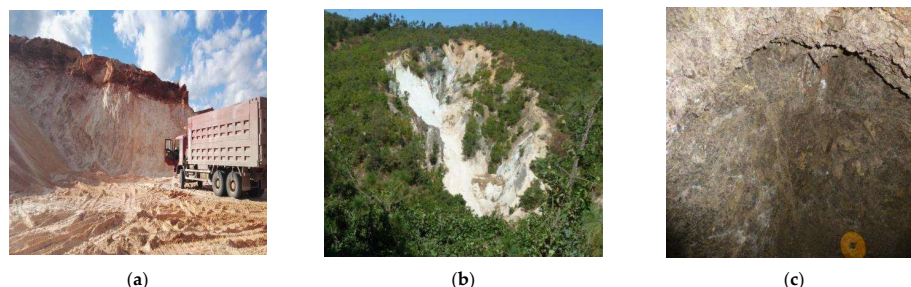


Figure 1. Typical intense and fierce sanding dolomite exposed on the surface and exploration adit. (a) Fierce sanding around the 7th village at the Xiaopu tunnel section. (b) Fierce sanding around the section of the Yu-Jiang expressway in Lao Jianshan Tunnel. (c) Intense sanding in exploration adit of Luo Fengshan tunnel.

Table 1. Typical surrounding rocks and hazards in dolomite sanding sections of tunnels in construction.

Name	Length (m)	Sanding Level	Surrounding Rock Category (Proportion)	Groundwater Activity	Surrounding Rock Hazards in Tunnel
Xiaopu No. 2	622.2	Dominated by Zbdn weak sanding and mixed with intense sanding belts III ₂ (43.7%) IV (43.3%) V (13%)	Groundwater emerged at about 320 m, and water gushings occurred after 380 m at the normal rate of 10–12 L/s	Water gushing and small-scale blocks falling.	
Xiaopu No. 2 downstream	140.0	Dominated by Zbd sandstone mixed with shales and by weak sanding dolomites, with Zbdn fierce–intense sanding dolomite at about 25 m of the front section	IV (38.7%) V (61.3%)	Water gushing, at a normal rate of 10–12 L/s and a maximum rate of 20 L/s	The left wall of the front section experienced a large water gushing, sand gushing and collapse, with quicksand plastic flow gushing out of the tunnel. After scouring, irregularly banded cavities appeared in the right wall and side wall, making it difficult to shape the tunnel. In the fierce sanding section, the vault collapsed, the side wall fell seriously, making it difficult to shape the tunnel. Blocks fell severely from the vault in the rear section, but with no major geological hazard.
Xiaopu No. 3	178	Zbd strongly weathered sandstones mixed with shales and the intense–weak sanding dolomite belts. Zbdn fierce sanding dolomites mixed with diatom rocks at about 38 m of the entry section	V (100%)	After 53.8 m, the bottom plate went below the groundwater level, with medium activities in general and linear water flows at the normal rate of 5 L/s	
Lanaju entry	150	Zbd intense sanding dolomites	V (100%)	Located above the groundwater level and dry without water.	Small scale collapse but with no major geological hazard.
Lanaju construction adit	395.5	Zbdn intense sanding dolomites mixed with weak sanding at about 320 m from the entry, followed by Zbd sandstones mixed with shales and the intense sanding dolomite belts	IV (29.0%) V (71%)	After 290 m, the tunnel bottom plate went below the groundwater level, mainly with water seepage and dripping. Concentrated water gushing occurred at 386 m with the maximum rate of 15 L/s and the normal rate of 10 L/s	Mainly small-scale of collapses, with two large-scale landslides occurred successively. Affected by the fracture at 386 m, there came water gushings and mudslides in the tunnel, steel supports deformed, tunnel vault and right wall both collapsed with serious blocks falling.
Da Tangzi entry	470	Zbdn intense sanding dolomites mixed with blocks of weak sanding dolomites	IV (13.8%) V (86.2%)	Most of the tunnel sections were dominated by seepage and drippings, with linear water flows in some parts	Small scale collapses of tunnel vault, but with no major geological hazard.
Luo Fengshan tunnel exit	406	Dominated by Zbdn intense sanding dolomites, partially mixed with blocks of weak sanding dolomites	IV (9%) V (91%)	Located above the groundwater level and dry without water.	Small scale collapse of tunnel vault, but with no major geological hazard.

2.2. Overview of Dolomite Sanding Geology in Tunnel Construction

Dolomite sanding refers to the reduction of dolomite rock mass strength after dolomite dissolution, leaving sand mixed with dolomite block residue of uneven particle sizes, which will become sanding when pressed by an external force. The karst geological phenomenon of this specific process is called “dolomite sanding” [1]. The dolomite’s intense and fierce sanding is mainly presented as silty sands of loose structure mixed with dolomite blocks from strong dissolution. The dolomite blocks are of different sizes, and their spatial characteristics are presented as belt features. The solubility of dolomite is mainly determined by rock mineral composition and dolomite structure.

According to mineral analysis of on-site rock samples, the dolomite rock in the middle of Sinian System’s Dengying Formation (Zbd²) was shown to be pure, and its main mineral composition was dolostone. The secondary minerals were a small amount of irregularly fine-grained quartz as disordered dispersion interspersed between dolomite particles, while a small part of them was wrapped in sand debris or filled within the holes and caves. Cryptocrystalline colophonites in black were occasionally found in the interstitial distribution. Magnetite with fine grains was wrapped in dolomites.

The parts with intense dolomite sanding were mainly in strata of Zbd²⁻³ and Zbd²⁻² fine-grained dolomites, while the sanding levels of Zbd²⁻¹ fine-grained dolomite and silty argillaceous dolomite were relatively weaker. The coarser the dolomite grains were, the better their water permeability was and the more obvious the sanding development would be.

2.3. Characteristics of Sanding Dolomite

Dolomite sanding is mainly based on the mechanism of dolomite karstification. Its basic condition is that the section shows the characteristics of soluble rocks, groundwater and rock permeability. By analyzing the samples extracted from the WDPCY construction site, this study found that the level of WDPCY’s dolomite sanding was mainly affected by the lithology, groundwater developments, rock structures and joint fissures’ developmental characteristics.

(1) Rocky and mineral composition

The rocky and mineral identification results of sanding dolomites (Table 2) revealed that they were generally dominated by micro-fine crystal structure, at the grain sizes of 0.03~0.2 mm; The intense sanding dolomite was dominated by silty fine sand, accounting for 75~92%, without clay or colloidal group. The intensely sanding dolomite was dominated by breccia group, accounting for 68~87%, followed by sand and silt, with a small amount of clay and colloidal particle group.

(2) Rock mass integrity

RQD tests of sandy dolomite cores were carried out by geological boreholes in sections of the Xiaopu tunnel, Lanaju tunnel, Lao Jianshan tunnel and Da tangzi tunnel. The statistical results of these sanding dolomite boreholes (Table 3) showed that the RQD of intense sanding dolomite was generally 6.15~16.64%, and the RQD of medium sanding dolomite was mainly 31.44~44.70%.

(3) Acoustic characteristics of rock mass

Acoustic wave measurements over holes were conducted on the surfaces of the Xiaopu tunnel’s Qicun-Luna Section and the Lao Jianshan tunnel’s exit. The acoustic wave measurement results of boreholes and adits (Table 4) showed that the longitudinal wave velocity of fierce sanding dolomite was generally less than 1000 m/s. The longitudinal wave velocity of intense sanding dolomite was generally 1244~2890 m/s and its integrity coefficient was 0.05~0.15. The longitudinal wave velocity of medium sanding dolomite was generally 2556~4150 m/s and its integrity coefficient was 0.15~0.35.

Table 2. Summary of rocky and mineral identification results.

Sample Number	Identification Result
1	With a sanding globular powder-crystal and fine-grained structure, the rock was composed of dolomite and a little quartz. Dolomite recrystallization was weak, mostly in forms of powdery and fine crystals. Their grain sizes were 0.06~0.2 mm, with the powdery crystals constituting the intraclasts and spherulites, the fine crystals constituting the cements, and the quartz being scattered within the fine-grained dolomite as fine-grained debris. The dolomite content was 70%, the intraclasts and spherulites accounted for 20%, and the content of quartz was 10%, respectively.
2	With a micro-powder crystal structure, the rock was composed of dolomite and a small amount of quartz. The dolomite had a weak crystallization and mostly presented as micro-powder crystals, at the grain size of 0.03~0.05 mm, and there were a small amount of quartz silts and flake hydromica scattered between the grains. The dolomite content was 95%, the quartz content was no more than 5%, and the hydromica content was 2%, respectively.
3	The rock was composed mostly of microcrystalline dolomite and a few precipitated crystal dolomite. The microcrystalline dolomite mainly adhered to algal filaments, which condensed with each other into the shapes of blocks and lumps, while little-precipitated crystals of dolomite filled in the gaps between the lumps. Moreover, several secondary fissure penetrations within the rock were filled by fine-medium crystal dolomite and quartz. The content of algal lumps was 80%, the composition of precipitated crystal dolomite was 10%, and the constituent of bright crystal dolomite was 5~10%, with only a small amount of quartz.
4	Crushed crypto-fine crystalline structure. The rock was composed of silica and dolomite. The silica was cryptocrystalline, colloidal, feathery (as aggregate of opal and chalcedony) and microgranular aggregate (of microcrystalline quartz). The dolomite presented weak recrystallization and was mostly in fine-crystal shape at the grain sizes of 0.05~0.15 mm, scattered within the silica and partially concentrated in belt distribution. Under the action of strong stress, the rock was crushed, broken and cracked open, with pores filled by recrystallization (opal, chalcedony) of quartz veins. The content of silica was 80%, the composition of dolomite was 24%, with a small amount of secondary quartz.

Table 3. RQD statistics of sanding dolomite boreholes.

Major Lithology	Project	RQD/%			Notes
		Intense	Weak	Fresh	
Dolomite and dolomitic limestones	Group number	14	37	—	13 boreholes
	Maximum	43.00	85	—	
	Minimum	4.00	5	—	
	Average	16.64	54.75	—	
	Standard deviation	12.15	22.09	—	
	Coefficient of variation	0.73	0.4	—	
	Coefficient of statistical correction	0.65	0.89	—	
	Standard value	10.82	48.49	—	
Dolomite	Group number	9	89	—	11 boreholes
	Maximum	48	76	—	
	Minimum	3	2	—	
	Average	15.56	36.33	—	
	Standard deviation	15.03	26.99	—	
	Coefficient of variation	0.97	0.74	—	
	Coefficient of statistical correction	0.43	0.87	—	
	Standard value	6.15	38.86	—	
Quartz sandstone and shales mixed with dolomites	Group number	43	89	1	18 boreholes
	Maximum	60	76	—	
	Minimum	3	2	—	
	Average	29.87	36.33	35	
	Standard deviation	16.64	26.99	—	
	Coefficient of variation	0.56	0.74	—	
	Coefficient of statistical correction	0.85	0.87	—	
	Standard value	25.51	31.44	—	

Table 4. Statistics of acoustic wave measurement results of sanding dolomite.

Project	Medium Sanding	Intense Sanding	Fierce Sanding
Group number	57	65	69
Maximum	4150	2890	1099
Minimum	1420	761	372
Average	2719	1354	692
Large value's mean	3333	1954	849
Small value's mean	2126	1047	522
Standard deviation	717	517	196
Coefficient of variation	0.264	0.382	0.282
Coefficient of statistical correction	0.94	0.919	0.942

(4) Permeability of rock mass

The results of borehole water-pressure tests in the sanding dolomite section revealed that the rock mass here was mainly of weak-medium permeability which was generally 2~10 Lu, partially 10~30 Lu, and maximally 35 Lu. According to the prediction results, the water gushing in the sanding dolomite tunnel section would generally be at the normal rate of 15.7~49 m³/(d·m) and the maximum rate of 40~142 m³/(d·m).

According to the statistical results, the fierce sanding dolomite mainly consisted of silty fine sand, and the intense sanding dolomite was mainly composed of breccia formation. The RQD was generally 6.15~16.64%, and the rock quality index was inferior. The average longitudinal wave velocity of intense sanding dolomite was 1354 m/s, and that of fierce sanding dolomite was 692 m/s. To summarize, the rock mass of this sanding dolomite section was dominated by weak-medium permeability.

2.4. Formation Mechanism and Evolution Model of Dolomite Sanding in WDPCY Tunnels

2.4.1. Mechanism of Dolomite Sanding Dissolution

The morphological characteristics and corresponding dissolution mechanism of dolomite karst sanding in WDPCY tunnels were very different from those in limestone strata. The latter mainly generated various peculiar forms of the karst due to differential dissolution, while the dolomite in the study area, whether medium or fully intense sanding, were mainly characterized by overall uniform dissolution and determined by both the macro lithology and micro dissolution characteristics.

Firstly, the dolomite in the study area belonged to the pure type, and the mineral composition was essentially dolostone, with little content of other soluble substances, which provided the material basis and fundamental reason for its homogenized dissolution. Moreover, the level of its karst sanding was closely related to the particle size and structure of its component minerals, which was mainly reflected in the higher dissolution intensity of dolomite with coarser particles and a looser structure. The relationship between karst sanding intensities of dolomite with different rock structures in the study area was: medium~fine crystalline dolomite > fine~silty crystalline dolomite > silty~micritic dolomite.

Secondly, the microscopic dissolution characteristics of dolomite presented further supporting evidence of homogenized dissolution. The above studies have already covered the microscopic dissolution characteristics of dolomite, besides the development of various pores, joints and micro-fissures within the dolomites in the study area. The dissolution often occurred primarily through the intergranular and intracrystalline pores, so that they could gradually expand and extend, or penetrate and dissolve along the crystal interface. During the dissolution process, there was frequent crystal disintegration and falling off, resulting in the progressive weakening of the bonding forces among dolomite crystals and the incremental loosening of the structures. Finally, it turned into dolomite sands or powdery materials.

In addition, the overall homogenized dissolution of dolomite in the study area shared a certain relationship with the infiltration and migration characteristics of groundwater, which was mainly reflected by the phenomenon that the groundwater in the bank slope of the underground powerhouse area had already formed smooth seepage. As a result, the groundwater basically presented a stably centralized drainage condition. Therefore, the karst development in this area was generally weak, with conspicuously uneven phenomenon occurring only in some parts. Due to the existence of tectonic movement and adverse geological phenomena, the rock mass in the bank slope had broken, the groundwater conditions became relatively complex, forming a network system with slow permeation and migration, which was conducive to the homogenized dissolution of the rock mass as a whole. Therefore, under the action of flowing groundwater, the initial stage of this dissolution was mainly chemical, but at the later stage, the pores in the rock expanded and the permeability intensified, causing the dissolution to be dominated by physical-mechanical damages. After long-term chemical dissolution and physical damage, dolomite sands or powders were generated eventually.

2.4.2. Evolution Model of Dolomite Sanding

All karst phenomena are the final product of continuous dissolution over a long period of geological history. The dissolution effect occurs not only under the influence of the micro-dissolution characteristics dominated by the specific features of rock lithology, but also under the regulation of macro groundwater, geological structure, shallow superficial reconstruction, climate and other factors. In this chapter, the formation process of karst sanding of dolomite in the deep area of this study was simplified into one model, as shown in Figure 2.

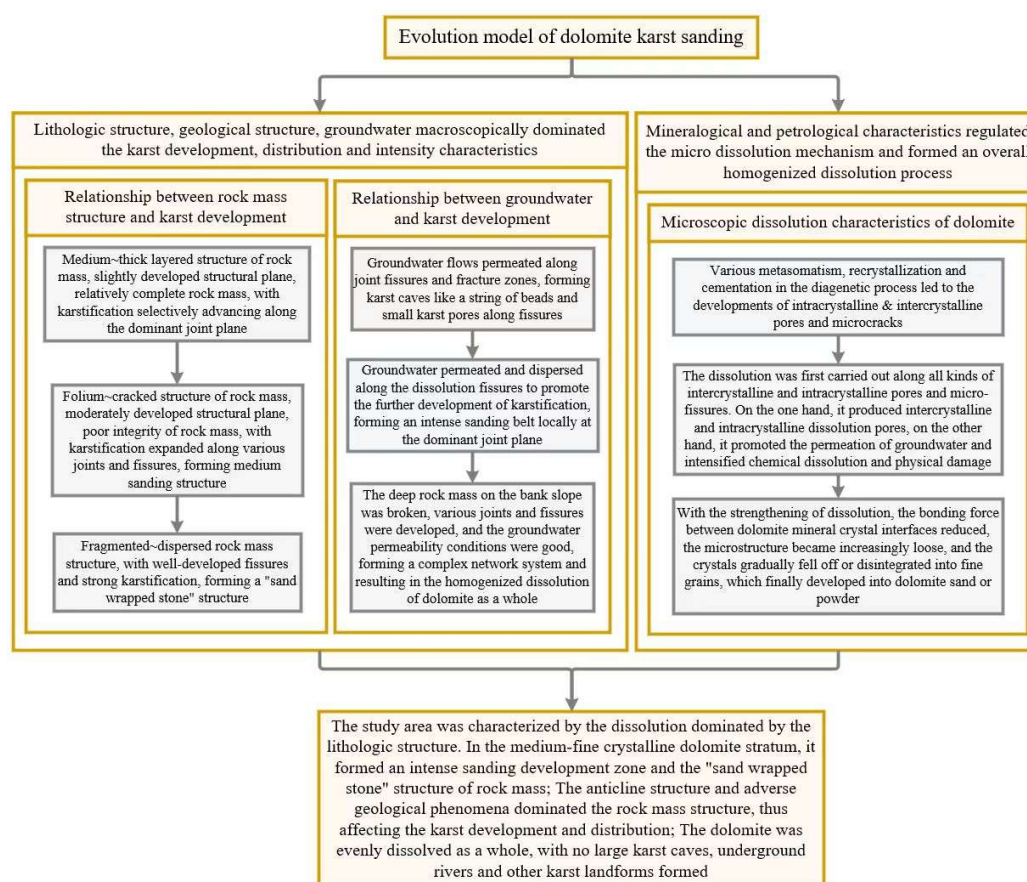


Figure 2. Simplified diagram of dolomitic karst sanding evolution model of WDPCY tunnels.

It could be seen from several modules in the figure that the geological backgrounds such as lithology, rock mass structure and groundwater jointly dominated the macroscopic development characteristics of dolomite karst in the study area. They also determined the main evolution process from the initial to the final morphology of karst development, including different rock mass structures forming different karst sanding morphological characteristics, besides the mutually promoting relationship between groundwater permeation and karst development. The mineralogical and petrological characteristics of dolomite dominated their microscopical dissolution mechanism. The homogenized dissolution process with the joint effect of not only corrosion through intercrystalline/intercrystalline pores and microcracks but also chemical and physical damage within the rock finally forming the dolomite sand and powder in the deep area of this study.

2.4.3. Problems and Risks Caused by Sanding Collapse Cavity in Tunnel Construction

The strength of dolomite depends on the degree of sanding. The compressive strengths of intense and full sanding rocks are mostly lower than 5 MPa. Tunnels are prone to destabilization and collapses after starting excavation. Sanding cavity collapse during tunnel construction often occurs in the section where dolomite is developed.

The settlement failure to the initial supports of tunnels at Yuxi section occurred in the XQZK7~XQZK212 part and the failure surfaces were concentrated on the right side, which was dominated by the fragmentation failure of the initial support concrete and by the tensile cracking along the steel supports. The lithology of the damaged section was intense and fierce sanding dolomite, which imposed great damage on the rock mass by reducing the rock strength, softening the structural plane and lowering the plane's mechanical properties, as mainly reflected in the lack of bonding force and poor self-stability of the surrounding rocks. The advanced shed-pipe grouting method was adopted in the construction, but produced poor grouting effect.

The stratum crossed by tunnels at the Yuxi section was a dolomite sanding one with abundant groundwater. It exhibited poor stability at the section where groundwater was particularly developed. The rock mass softened severely due to the soaking from fissure waters, and the self-stability of the tunnel face was also poor, resulting in destabilization. Sanding dolomite was prone to generating waterways under the dragging force of groundwater, resulting in water and mud gushing. Consequently, the risk of tunnel excavation turned extremely high. Therefore, the dolomite in the sanding section must be treated before engineering.

3. Methods

The influence of engineering geological conditions of dolomite sanding on the underground project was manifested in the structure/stability of surrounding rocks and the steadiness of tunnel walls supporting the lining structure. For the structure of surrounding rocks around the main underground water-diversion tunnel crossing the bank slope of this section, the major types were class IV~V but predominantly class V. The primary reason for the low classification of surrounding rocks and poor structure of rock mass in the deeply-buried tunnel was the dolomite sanding effect, of which the extent gradually intensified with the tensile deformation and failure process of rock mass inside the tunnel. The impacts of underground engineering on the geology of crossed sanding dolomite mainly included the variation of hydro-geological conditions, seepage, collapse, drying up of surface water, loss of groundwater, loss of surface vegetation and rocky desertification.

To mitigate the excavation and construction risks of WDPCY tunnels in the sanding dolomite strata, focus should be not only on the destabilization of the tunnel face but also on the water-sand gushing in the water/rich strata and intense-fierce sanding sections. The applicable excavation methods mainly include the milling method, freezing method and conventional method.

For the moderate sanding dolomite in the WDPCY areas and the good self-stability of the tunnel face, the construction method of blasting and milling excavation was adopted. During the drilling, the relevant parameters were adjusted to retain about 50 cm of rock stratum on the excavation face after blasting. After mucking, the under-excavated rock stratum should be handled with the milling bit. This method could reduce the disturbance to surrounding rock strata during excavation, restrict excessive excavation, and lower the time of erection and shotcrete processes.

Full-face milling method: through the construction field test, the maximum milling speed in this rock stratum type could reach 50 m³/h. During the milling, each footage was controlled at 0.5~0.8 m. The use of milling could avoid the disturbance of explosion waves to the surrounding rock stratum during blasting, maintain the integrity of the surrounding rocks, reduce their collapse occurrence during the erection process after starting excavation, and mitigate the subsequent force of the surrounding rocks on the arch frame.

Freezing method: Artificial refrigeration was applied to freeze the water and soil together around the contour line of the tunnel to be excavated, so that a frozen soil wall or sealed frozen soil body could effectively resist soil pressure and isolate groundwater, after which the tunnel could be excavated more smoothly. This method would be inapplicable when the water content in rock mass was minimal or the groundwater velocity was relatively high.

Advanced support: Medium shed-pipe was adopted with advanced small conduits for grouting reinforcement to prevent destabilization of the tunnel face. In the section with rich groundwater, the excavation face was limited and dug by parts. Each cycle of excavation adopted shotcrete to seal the tunnel face, for avoiding water seepage and destabilization from excessive exposure of rocks surrounding the tunnel face. At the beginning of excavation, the reserved deformation should be adequate to prevent intrusion caused by excessive settlement. The excavation footage was properly adjusted according to the surrounding rock conditions on site and controlled within the range of 0.5~1.0 m.

Initial support: U-shaped composite lining was used. When the surrounding rocks were poor, the spacing of arch frames was reduced. The arch frame should be installed close to the tunnel face to reduce the gap between them and prevent the collapse of the exposed parts in the gap. The principles of quick excavation should be followed, quick support and quick closure, the project team could be excavating and supporting the upper, middle, lower steps, respectively, implementing the excavation and support simultaneously and the cycle rapidly. Drainage and discharge measures were also taken inside the tunnel, while ditches were excavated at the arch feet of the initial supports to avoid softening of the arch frame or the base caused by arch feet soaking.

4. Discussion

Due to the poor diffusion of slurries in dolomite sanding stratum, single grouting was not sufficiently effective to form a whole reinforcement. Therefore, it was particularly important to select appropriate advanced supporting methods and grouting materials. Through the field construction test and summary, compared with other supporting methods, the following support methods and grouting materials were selected for the specific rock mass of sanding dolomite:

1. In the tunnel section of moderate sanding dolomite without external water, the surrounding rock was intense-fierce sanding dolomite without water seepage. It could be passed safely by taking measures such as advanced small conduits, mechanical excavations, short grubbing and strong supports.
2. In the tunnel section of weak sanding dolomites, even if water seepage occurred, the surrounding rocks would remain closely interlocked and present strong self-stability, therefore, the excavations and supports were implemented according to the circumstance of handling the normal category of surrounding rocks. For weak sanding dolomite, the geology could be identified as class III₂ surrounding rocks based on relevant criteria, therefore, the excavations and supports were carried out according to the circumstance

of handling the conventional category of surrounding rocks. For example, the seepage of Xiaopu No. 2 was up to $6000 \text{ m}^3/\text{day}$, but the degree of sanding ranged from weak to intense, therefore, excavations and supports were carried out according to the circumstance of handling the conventional category of surrounding rocks, with some parts being properly strengthened, as shown in Figures 3 and 4.



Figure 3. Sanding dolomite layer of Xiaopu 2# construction adit.



Figure 4. Intense sanding dolomite seepage of Xiaopu 2# construction adit.

3. The surrounding rock structure of the tunnel face was Zbd thick-layer dolomite, which was intense and fierce sanding with developed fissures. The rock mass was broken and rich in water, making it vulnerable to water and sand gushing, causing potential safety hazards for tunnel construction. The sand and water gushing present an extremely challenging issue to tackle.

During shotcrete supporting for YX6 + 747~YX6 + 745.8 sections, the arch line from the left side of the tunnel face to the main vault was scoured by water gushing, accompanied with gushing of fine sanding rocks. They gradually expanded, resulting in not only the 4.5 m circular length and 9 m height of the arch line from the lower part of the left side to the vault, but also the collapse of 8~10 m along the axis of the tunnel. The buried depth of the tunnel here was 150 m, and the groundwater level was speculated to be 100 m higher than the top of the tunnel. There were multiple jets of water gushing at the arch and side walls. The water volume was visualized on site as about $15 \text{ L/s}\cdot\text{m}$. After the initial water body turned turbid, it gradually became clear, as shown in Figure 5.

To prevent the mud gushing following the water and sand gushing, tunnel slag with good water permeability was added with rubble and stacked sandbags to push back and plug immediately, while a back pressure wall was stacked close to the tunnel face to keep the sand and soil of the collapsing bodies from being lost and tumbling. Advanced pre-consolidation grouting was adopted for the tunnel face to strengthen the surrounding rocks in front and control the water plugging. C30 concrete grouting wall with a thickness of 2.0 m was poured at the mileage of YX6 + 745.8. A total of 36 advanced pre-consolidation grouting holes in the form of five rings were drilled on the tunnel face according to the design requirements, as shown in Figures 6–8. The advanced pre-consolidation grouting

implemented the backward sectional grouting process. In the sections difficult for hole-drilling, forward sectional drilling with the pipe was adopted for grouting construction.



Figure 5. Water and sand gushing from fierce sanding dolomite in Xiaopu 2# construction adit. (a) Xiaopu 2# adit's fierce sanding dolomite with water gushing. (b) Xiaopu 2# adit's fierce sanding dolomite with sand gushing.

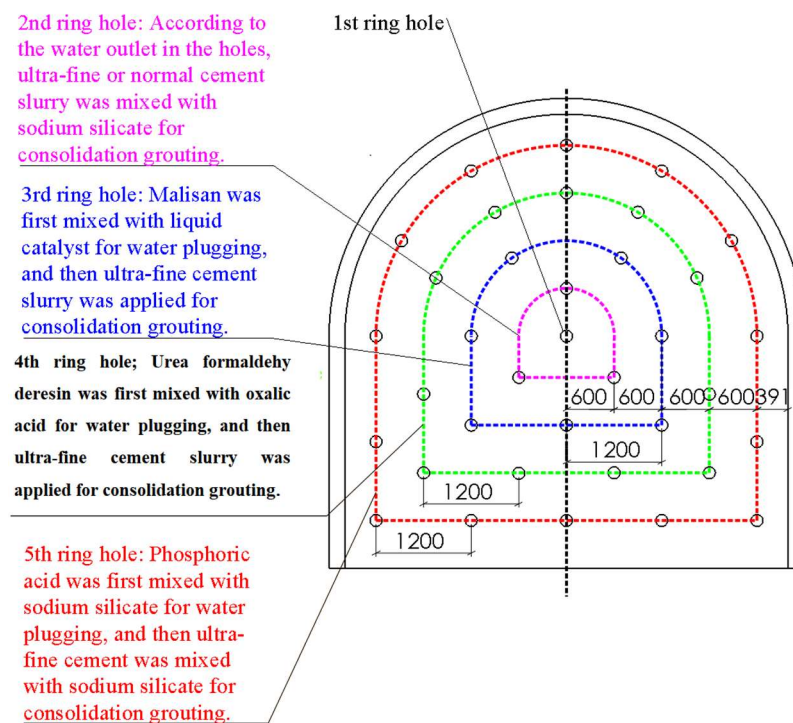


Figure 6. Layout of advanced consolidation grouting holes in the tunnel face.

Double liquid slurries of phosphoric acid and sodium silicate: The water plugging effect was effective but the strength was low. It was mainly applied for water plugging in the outer ring. After double liquid grouting, a pure water slurry was needed for further grouting. Sodium silicate was 40 Be ($\rho = 1.38 \text{ g/cm}^3$), phosphoric acid (weak acid, $\rho = 1.7 \text{ g/cm}^3$) was 85%. Before grouting, sodium silicate and water was diluted at 1:1 into sodium silicate solution, while these two were also diluted at 1:10 into phosphoric acid solution, then the two prepared solutions were mixed for rock mass water plugging and grouting at the ratio of 1:1. Afterwards, a 1:1 ultra-fine cement slurry was obtained to consolidate the surrounding rocks.

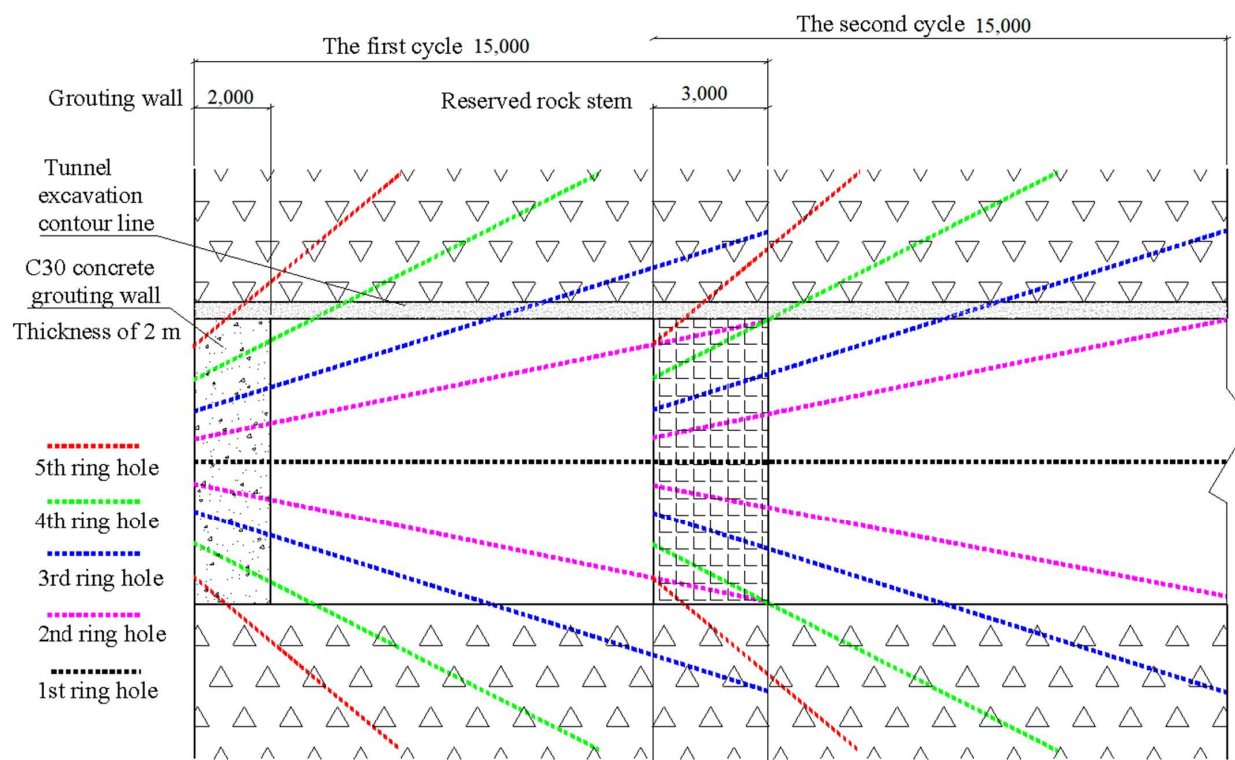


Figure 7. Layout plan of advanced consolidation grouting holes.



Figure 8. Actual layout of advanced grouting holes in the tunnel face.

Double liquid slurries of urea formaldehyde resins and oxalic acid: The water plugging effect was moderate, but the tight body presented high strength. It was used for grouting in the intermediate rings. The aggregate of the grouting bodies was modified by urea formaldehyde resin, the curing agent was oxalic acid, and the concentration was 5%. Firstly, the additive with 2% mass of the modified urea formaldehyde resins was added and stirred into Solution A for the grouting. Next, oxalic acid was added by 1/60 of the modified urea formaldehyde resins and stirred with water into Solution B for the grouting. Then, Solution A and B were added into the grouting pipe simultaneously at the ratio of 1:1 for rock mass water plugging and grouting. Finally, 1:1 ultra-fine cement slurry was obtained to consolidate the surrounding rocks.

Double liquid slurries of Malisan and liquid catalyst: The water plugging effect was moderate, the groutability was good, which was applicable for microcrack grouting. The volume mix ratio of Malisan material and catalyst was 1:1, while the mass mix ratio was 1:1.17, for rock mass water-plugging and grouting. Then, 1:1 ultra-fine cement slurry was also adopted to consolidate the surrounding rocks.

The pre-consolidation grouting of intense and fierce sanding dolomite was tested according to the water yield from the on-site boreholes and the positions of the grouting holes. The grouting slurry was added with the mixtures of phosphoric acid and sodium silicate slurries with urea formaldehyde resins and oxalic acid slurries besides Malisan and liquid catalyst slurries. The grouting slurry was first applied for water plugging then mixed with pure water slurry for reinforcing the surrounding rocks, at a grouting pressure of 1.5~4 MPa. After the grouting was solidified for 48 h, a 20 m deep advanced exploratory hole was drilled in the middle of the tunnel face, while there was no water in the hole. Then, the tunnel face was opened wide without water seepage and the sanding dolomite consolidated, which basically achieved the expected grouting effect. See details in Figures 9–12.



Figure 9. Grouting effect of upper-step excavation face.



Figure 10. Solidifying effect of phosphoric acid and sodium silicate slurries.



Figure 11. Effect after Malisan grouting.



Figure 12. Effect after urea formaldehyde resin grouting.

5. Conclusions

In tunnel engineering, the effects of grouting reinforcement mainly include forming a stable supporting structure, enhancing the strength and stiffness of surrounding rocks, and improving the geological environment. Grouting reinforcement could reunite and reinforce the initially broken rock mass into a whole body, which greatly improved the overall strain and supporting capacity of the entire tunnel structure. Simultaneously, it might also connect the surrounding rocks and the tunnel linings to form an overall strain and increase the structural stability. Therefore, this paper draws the following conclusions:

For the tunnel section of moderate sanding dolomite without water seepage, measures such as advanced small conduits, mechanical excavations, short grubbing and strong supports could all be adopted for safe passage. In the tunnel section of weak sanding dolomite, even when there was water seepage, the surrounding rocks remained closely interlocked and presented strong self-stability. The excavations and supports could be carried out according to the circumstance of handling the normal category of surrounding rocks. For tunnel construction with intense/fierce sanding dolomite, phosphoric acid and sodium silicate slurries with urea formaldehyde resins and oxalic acid slurries besides Malisan and liquid catalyst slurries were first used for water plugging, then pure water slurries were applied for surrounding rock reinforcement, which has already exerted an excellent effect. Grouting reinforcement might not only increase the internal friction angle and cohesion of surrounding rocks but also improve their overall stability. Grouting could also block the flow and permeation of groundwater, thus effectively optimizing the engineering geological environment.

The geological conditions of dolomite sanding determine whether collapse, mud, sand and water gushing will occur during tunnel construction. This research is of great significance in choosing the corresponding reinforcement measures according to the sanding degree in tunnel construction. Based on field tests, the reinforcement effect of single grout was not ideal, but the joint application of multiple grouts could achieve the ideal results and minimized the hazard of sanding dolomite to tunnel construction. This research work is of practical significance for both academic and tunnel engineering including the design, construction and maintenance of sandy dolomite tunnel.

Author Contributions: Conceptualization, M.W. and Y.W. (Yonghong Wu); methodology, M.W.; software, M.W.; validation, W.X., J.M. and Y.W. (Yangxing Wang); formal analysis, M.W.; investigation, M.W.; resources, H.M.; data curation, Y.W. (Yonghong Wu); writing—original draft preparation, M.W.; writing—review and editing, Y.W. (Yonghong Wu); visualization, W.X.; supervision, Y.W. (Yonghong Wu); project administration, W.X. and Y.W. (Yonghong Wu); funding acquisition, Y.W. (Yonghong Wu). All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by [The Major Science and Technology Special Plan of Yunnan Province Science and Technology Department] grant number [202002AF080003], [The sponsorship from National Natural Science Foundation of China] grant number [51669009] and [The Yunnan Institute of Water and Hydropower Engineering Investigation, Design and Research] grant number [KKKF0202006249].

Institutional Review Board Statement: Ethical review and approval were not obtained for this study because no intervention was applied to the participants.

Informed Consent Statement: Written informed consent has not been obtained from the respondents of the interviews of this study due to the cultural and socio-political conditions of the countries in which data were collected.

Data Availability Statement: The data have been collected using public funds, but at the time of the publication of this paper, they have not been shared in a repository.

Acknowledgments: The information provided by the project management department for Yuxi sections of Water Diversion Project in Central Yunnan of China Railway Tunnel Group Co., Ltd.

Conflicts of Interest: The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, or in the decision to publish the results.

Abbreviations

WDPCY	Water Diversion Project in Central Yunnan
REE	Rare earth elements
ADPR	Active Dolomite Phosphate Rock
BC	Biological Carbon
RQD	Rock Quality Designation

References

1. Zhang, L.X. *Study on Formation Mechanism and Engineering Characteristics of Dolomite Karst Sanding*; Chengdu University of Technology: Chengdu, China, 2012.
2. Li, J.G.; Mu, H.Y.; Mi, J. Preliminary study on engineering geological characteristics of sanding dolomite. In Proceedings of the 2nd National Rock Tunnel Boring Machine Engineering Technology Seminar, Urumqi, China, 2018; pp. 40–46.
3. Ma, W.K. Dolomite sanding and its influence on the development and utilization of “Baoshan Mihuang” Marble. *Resour. Dev.* **2018**, *2*, 46–61.
4. Lynton, S.L. The origin of massive dolomite. *J. Geol. Educ.* **1985**, *33*, 112–115.
5. Zhang, Z.Y.; Wang, S.T.; Wang, L.S. *Principles of Engineering Geological Analysis*; Geological Publishing House: Beijing, China, 2016.
6. Pei, X.G.; Huang, R.Q.; Cui, S.G.; Du, Y.; Zhang, W.F. Rock mass fragmentation characteristics of Da Guangbao landslide and its engineering geological significance. *J. Rock Mech. Eng.* **2015**, *34* (Suppl. 1), 3106–3115.
7. Rong, K.F.; Rong, Q.; Liu, Z.Y. *A New Viewpoint on Karst Research: Taking Zhijin Cave in the South of Dushan, Guizhou as an Example*; Geological Publishing House: Beijing, China, 2009.
8. Chen, J.H.; Ao, X.Q.; Xie, Y.; Yin, Y.L. Effects of iron ion dissolution and migration from phosphorite on the surface properties of dolomite. *Colloids Surf. A Physicochem. Eng. Aspects* **2022**, *641*, 128618. [\[CrossRef\]](#)
9. Fang, Y.H.; Xu, H.F. Dissolved silica-catalyzed disordered dolomite precipitation. *Am. Mineral.* **2022**, *107*, 443–452. [\[CrossRef\]](#)
10. Yan, Z.W.; Zhang, J.F.; Huang, S.J.; Wang, H.J. Characteristics and genesis of interlayer dissolution residual deposits in Dongxiang Copper Mine, Jiangxi Province. *China Karst.* **2007**, *26*, 126–131.
11. Hu, X.B. *Study on Characteristics and Mechanism of Dolomite Karst Sanding in the Deep Bank Slope of Meigu River Pingtuo Hydropower Station*; Chengdu University of Technology: Chengdu, China, 2009.
12. Zhao, Q.H. *Report on Dolomite Sanding in Areas around Meigu River Pingtuo Hydropower Station*; College of Environment and Civil Engineering, Chengdu University of Technology: Chengdu, China, 2008.
13. Zhao, Q.H.; Zhang, L.X.; Hu, X.B.; Han, G.; Zhao, X. Laboratory dissolution test and microscopic dissolution mechanism of dolomite in an area. *J. Eng. Geol.* **2012**, *20*, 576–584.
14. Luo, J.; Pei, X.J.; Huang, R.Q.; Du, Y. Study on influencing factors of seismic crack damage extent of landslide rock mass under strong earthquake. *J. Geotech. Eng.* **2015**, *37*, 1105–1114.
15. Zhang, C.H.; Zheng, X.M. Rock strain softening and permeability evolution model and experimental verification. *J. Geotech. Eng.* **2016**, *38*, 1125–1132.

16. Xiong, Q.R.; Xiao, M.; Hu, T.Q. Numerical simulation of elastic-plastic damage of sanding rock mass under excavation interference. *J. Sichuan Univ. Nat. Sci. Ed.* **2013**, *50*, 90–96.
17. Zhang, Z.Q. Study on mechanical properties of sanding dolomite with different water contents. *Technol. Innov.* **2022**, *4*, 79–82.
18. Bischoff, J.; Julia, R.; Wayne, C.; Rosenbauer, R. Karstification without carbonic acid: Bedrock dissolution by gypsum-driven dedolomitization. *Geology* **1994**, *22*, 995–998. [[CrossRef](#)]
19. Touir, J.; Soussi, M.; Troudi, H. Polyphased dolomitization of a shoal-rimmed carbonate platform: Example from the middle Turonian Bireno dolomites of central Tunisia. *Cretac. Res.* **2009**, *30*, 785–804. [[CrossRef](#)]
20. Detlev, K.R.; Axel, G.; Rolf, D.N. The alteration and disintegration of dolostones with stoichiometric dolomite crystals to dolomite sand: New insights from the Franconian Alb (Upper Jurassic, SE Germany). *Ger. J. Geol.* **2018**, *169*, 27–46. [[CrossRef](#)]
21. Choquette, P.W.; Hiatt, E.E. Shallow—Burial dolomite cement: A major component of many ancient sucrosic dolomites. *Sedimentology* **2008**, *55*, 423–460. [[CrossRef](#)]
22. Poros, Z.; Machel, H.G.; Mindszenty, A.; Molnar, F. Cryogenic powderization of Triassic dolostones in the Buda Hills, Hungary. *Int. J. Earth Sci.* **2013**, *102*, 1513–1539. [[CrossRef](#)]
23. Koch, R. Dolomite and Dolomitizerfall im Malm Süddeutschlands—Verbreitung, Bildungsmodelle, Dolomit-Karst. *Laichinger Höhlenfreund* **2011**, *46*, 75–92.
24. Fio, K.; Spangenberg, J.E.; Vlahović, I.; Sremac, J.; Velić, I.; Mrinjek, E. Stable isotope and trace element stratigraphy across the Permian–Triassic transition: A redefinition of the boundary in the Velebit Mountain, Croatia. *Chem. Geol.* **2010**, *278*, 38–57. [[CrossRef](#)]
25. Liu, B.B.; He, Z.; Liu, R.; Montenegro, A.C.; Ellis, M.; Li, Q.; Baligar, V.C. Comparative effectiveness of activated dolomite phosphate rock and biochar for immobilizing cadmium and lead in soils. *Chemosphere* **2021**, *266*, 129202. [[CrossRef](#)]
26. Esteban, M.; Budai, T.; Juhász, E.; Lapointe, P. Alteration of Triassic carbonates in the Budai Mountains—a hydrothermal model. *Cent. Eur. Geol.* **2009**, *52*, 1–29. [[CrossRef](#)]
27. Machel, H.G.; Borrero, M.L.; Dembicki, E.; Huebscher, H.; Ping, L.; Zhao, Y. The Grosmont: The world’s largest unconventional oil reservoir hosted in carbonate rocks. *Geol. Soc. London Spec. Publ.* **2012**, *370*, 49–81. [[CrossRef](#)]
28. Györi, O.; Haas, J.; Hips, K.; Lukoczki, G.; Budai, T.; Demény, A.; Szöcs, E. Dolomitization of shallow-water, mixed siliciclastic-carbonate sequences: The lower Triassic ramp succession of the Transdanubian Range, Hungary. *Sediment. Geol.* **2020**, *395*, 105549. [[CrossRef](#)]
29. Saldi, G.D.; Causserand, C.; Schott, J.; Jordan, G. Dolomite dissolution mechanisms at acidic pH: New insights from high resolution pH-stat and mixed-flow reactor experiments associated to AFM and TEM observations. *Chem. Geol.* **2021**, *584*, 120521. [[CrossRef](#)]
30. Ding, R.C. Study on tunnel construction technology under the condition of dolomite sanding stratum. *China Build. Mater. Sci. Technol.* **2020**, 118–119.
31. Wang, P.P.; Yao, J.; Jiang, L. Characteristics of dolomite sanding in Guizhou and its influence on tunnel support structure. *J. Guizhou Univ. Nat. Sci. Ed.* **2019**, *36*, 44–48.
32. Luo, H. *Study on Influencing Factors of Curtain Grouting in Sanding Dolomite Section*; Chongqing Jiaotong University: Chongqing, China, 2018.
33. Zhao, Y.C.; Zhang, Z.P. Influence of neotectonic movement on surrounding rock stability of Qilu Lake’s water diversion tunnel. *Resour. Environ. Eng.* **2015**, *29*, 636–639.
34. Li, B.; Liu, M.; Li, Z.X.; Li, Y.C. Drilling in completely strongly weathered dolomite broken stratum. Foundation Engineering and Anchor Grouting Technology. In Proceedings of the Symposium on Foundation Engineering and Anchor Grouting Technologies, 2009; pp. 401–403.
35. Jiang, Y.F.; Zhou, P.; Zhou, F.C.; Lin, J.Y.; Li, J.Y.; Lin, M.; Qi, Y.L.; Wang, Z.J. Failure analysis and control measures for tunnel faces in water-rich sandy dolomite formations. *Eng. Fail. Anal.* **2022**, *138*, 106350. [[CrossRef](#)]
36. Zhou, P.; Jiang, Y.F.; Zhou, F.C.; Wu, F.; Qi, Y.L. Disaster mechanism of tunnel face with large section in sandy dolomite stratum. *Eng. Fail. Anal.* **2022**, *131*, 105905. [[CrossRef](#)]
37. Wang, H.C. Feasibility study on shield constructions of tunnels crossing broken zones with high pressure and rich water. *Sichuan Archit.* **2019**, *39*, 293–294.
38. Wang, Z.J.; Du, Y.W.; Jiang, Y.F.; Wu, F.; Qi, Y.L.; Zhou, P. Study on destabilization mechanism of tunnel face in sanding dolomite stratum. *J. Rock Mech. Eng.* **2021**, *40* (Suppl. 2), 3118–3126.
39. Xu, X.G.; Li, S.G.; Wang, X.Q.; Wang, L.S.; Zhang, J.; Zhu, L. Discussion on formation mechanism and kinematic characteristics of Da Guangbao landslide in an County. *J. Eng. Geol.* **2013**, *21*, 269–281.
40. Bai, Y.; Li, M.H. Treatment measures for small karst cavity in Yingerling tunnel crossing sanding dolomite section. *Constr. Technol.* **2020**, *49*, 802–804.
41. Luo, H.; Deng, F.; He, G.; Chen, Y.B. Curtain grouting treatment technology for dolomite sanding sections of tunnel. *Sci. Technol. Eng.* **2020**, *20*, 7441–7450.
42. Niu, X.Q.; Zhang, C.J. Some Key Technical Issues on Construction of Ultra—long Deep—buried Water Conveyance Tunnel under Complex Geological Conditions. *Tunn. Constr.* **2019**, *39*, 523–536.
43. Wang, Z.Q.; Li, G.C. An overview of geological problems on long-distance water diversion projects in China. *J. Eng. Geol.* **2020**, *28*, 412–420. [[CrossRef](#)]

-
44. Wang, W.S.; Chen, C.S.; Wang, J.X.; Shi, C.P.; Li, Y.Q. Major Engineering Geological Problems of Xianglushan Deep-buried Long Tunnel in Central Yunnan Water Diversion Project. *J. Yangtze River Sci. Res. Inst.* **2020**, *37*, 154–159. [[CrossRef](#)]
 45. Zhang, X.H.; Fu, P.; Yin, J.M.; Liu, Y.K. In-situ stress characteristics and active tectonic response of Xianglushan tunnel of Middle Yunnan Water Diversion Project. *Chin. J. Geotech. Eng.* **2021**, *143*, 130–139. [[CrossRef](#)]
 46. Zhang, X.D. Study of Material for Curtain Grouting in Karst Tunnel. *Chin. J. Undergr. Space Eng.* **2005**, *1*, 432–434.
 47. Bai, H.Y.; Wang, D.L. Numerical simulation on effect of multiple holes chemical grouting under confined aquifer. *Eng. Village* **2014**, *2*, 442–444.

-
48. Gurpersaud, N.; Chuaqui, M.; Lees, D.; Lam, W.; Hu, F. Intake Shaft Grout Curtain for the Niagara Tunnel Project. In Proceedings of the Fourth International Conference on Grouting and Deep Mixing, New Orleans, LA, USA, 15–18 February 2012; pp. 903–913.
 49. Lin, C.T. Extension to the Discontinuous Deformation Analysis for Jointed Rock Masses and other Blocky Systems. Ph.D. Thesis, University of Colorado Boulder, Boulder, CO, USA, 1995.
 50. Karol, R.H. *Chemical Grouting and Soil Stabilization*; Marcel Dekker, Inc.: New York, NY, USA, 2003.
 51. Wagner, P.; Kolymbas, D. Groundwater ingress to tunnels—The exact analytical solution. *Tunn. Undergr. Space Technol.* **2007**, *22*, 23–27. [[CrossRef](#)]