



Design and Safety Guarantee of Gas Pipeline Renovation in Mountainous Counties

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Abstract. Restricted by special conditions such as sloping terrain, broken geology, high-intensity earthquakes and concentrated rainfall in mountainous counties of southwest China, the "bottle-to-pipe" renovation of gas pipeline networks generally faces technical problems including poor laying adaptability, uneven hydraulic distribution, high coupled risk of geological disasters and weak safety control. To solve the above pain points, taking a gas pipeline network renovation project in Yunnan Province as the engineering carrier, this study focuses on the core technologies of hydraulic optimization design and dual-dimensional guarantee of geology and safety for gas pipelines on sloping terrain in mountainous areas. A medium-low pressure graded transmission and distribution system is constructed, a hydraulic calculation model for mountainous pipeline networks is established by introducing topographic height difference correction coefficients, and researches are carried out on the selection of mountain composite pipes, composite laying of sloping pipelines, precise remediation of hidden dangers and intelligent safety control based on IoT perception. The academic contribution of this study lies in constructing a terrain-adapted integrated technical system for mountainous gas pipeline renovation, which fills the gap in specialized theoretical and technical research on "bottle-to-pipe" conversion in southwest mountainous sloping counties, and upgrades the standard-guided conventional design to a terrain-coupled academic design method. The study forms an integrated technical system of "hydraulic design-laying process-remediation of hidden dangers-safety control" suitable for mountainous counties, which can effectively offset the impact of topographic height difference on gas supply stability and resist compound disasters such as earthquakes, landslides and rain erosion. Engineering practice shows that the scheme realizes the pipeline renovation of 14,250 bottled gas users, reduces the pressure loss of the pipeline network by 12.3%, achieves 100% coverage of geological disaster prevention and control, eliminates all gas safety hidden dangers, and increases the gas penetration rate from 33% to over 92%. The research results can provide academic basis and engineering reference for the upgrading of gas infrastructure in similar counties in mountainous areas of southwest China.

Keywords: mountainous county; sloping terrain; gas pipeline network; bottle-to-pipe renovation; hydraulic optimization; intelligent IoT monitoring

1 Introduction

With the global urbanization extending deeply into mountainous counties, the renewal and safety operation of urban gas pipeline networks have become core research topics in the fields of municipal and energy engineering. Foreign researches on gas pipeline networks in mountainous towns have formed a standardized technical system for terrain-adaptive laying, pipeline geological disaster protection and intelligent leakage monitoring[1~3]. Key breakthroughs have been made in flexible design of pipelines in high-intensity earthquake areas and anti-deformation technology of pipeline networks in landslide areas. The whole-life-cycle online monitoring of pipeline networks is realized based on the Internet of Things and big data. Regions such as Europe, America and Japan have incorporated the coupling factors of terrain, geology and climate into the core indicators of mountain gas engineering design, and established a complete specification system[4~7].

Domestic researches on gas pipeline network renovation focus on the renewal of old pipeline networks in plain cities, implementation of bottled gas replacement policies and digital operation and maintenance control[8~9]. A large number of practical achievements have been accumulated in pipe selection, construction technology and safety early warning. At the national level, the renovation of aging urban gas pipelines and the pipeline renovation of bottled gas users have been continuously promoted[10].

Existing researches have obvious limitations: special researches on gas pipeline "bottle-to-pipe" renovation in sloping counties of southwest mountainous areas are relatively scarce, and the superposition impact of mountain slope on hydraulic distribution of pipeline networks, stability of pipeline laying and coupled risk of geological disasters is not fully considered; the pipeline network design standards and safety control modes in plain areas cannot be directly adapted to the topographic and geological characteristics of mountainous counties, and there is a lack of targeted academic innovation for mountainous terrain coupling effects; the pipeline network design standards and safety control modes in plain areas cannot be directly adapted to the topographic and geological characteristics of mountainous counties; the lack of an integrated technical system of "hydraulic optimization-geological protection-safety guarantee" for pipeline network renovation in mountainous counties leads to problems such as uneven gas supply, pipeline deformation and cracking, and repeated safety hazards in renovation projects.

Mountainous counties in southwest China generally have typical characteristics such as large topographic relief, broken geological structure, high seismic fortification intensity, concentrated rainfall prone to landslides and collapses, dense old communities and high proportion of bottled liquefied petroleum gas users. Gas pipeline network renovation is a core livelihood project to guarantee people's gas use and prevent urban public safety risks.

Against this background, taking the gas pipeline "bottle-to-pipe" renovation project in a county of Yunnan Province as an example, this paper closely focuses on the core constraints of sloping terrain in mountainous areas, conducts theoretical analysis, engineering design and practical verification research on the key technologies of hydraulic optimization design and dual-dimensional guarantee of geology and safety

for pipeline networks, and forms an academic innovation system integrating terrain correction theory, composite disaster resistance technology and intelligent closed-loop control, constructs a gas pipeline renovation technical system suitable for mountainous counties, improves the safety design theory of gas in mountainous towns, and provides replicable technical solutions and practical references for the upgrading of gas infrastructure in similar counties in mountainous areas of southwest China.

2 Engineering Characteristics of Gas Pipeline Renovation in Mountainous Counties

2.1 Project Overview

This research relies on a gas pipeline network renovation project in Yunnan Province, which is a key livelihood project at the county level in Yunnan Province with a total investment of 86.3238 million yuan, implemented under the EPC general contracting mode. The core task of the project is the "bottle-to-pipe" renovation of 14,250 bottled liquefied petroleum gas users in the main urban area and the remediation of potential safety hazards in the existing courtyard pipeline network. It is a typical gas pipeline renovation project in mountainous counties that implements the national special renovation of urban gas safety and the "Gasification Yunnan" strategy of Yunnan Province.

2.2 Core Constraints of Gas Pipeline Networks in Mountainous Counties

The project is located on the south bank of Jinsha River in the northwest of Wumeng Mountains, a typical sloping county in the southwest mountainous area. The pipeline network renovation faces four core constraints:

(1) Topographic constraint: The main urban area is a single sloping terrain high in the west and low in the east, with a slope of $10^{\circ}\sim 25^{\circ}$ and an altitude difference of 500~1050m. The pipeline network laying must strictly adapt to the sloping trend;

(2) Geological constraint: Located in the eastern Yunnan-southwestern Sichuan seismic belt with a seismic fortification intensity of VIII degree, the geological structure is broken, landslides and collapses occur frequently, and the pipeline has extremely high requirements for deformation resistance and earthquake resistance;

(3) Current constraint: The county's gas penetration rate is only 33%, 14,250 households in the main urban area rely on bottled liquefied petroleum gas. The existing pipeline network has 17 major hidden dangers and 53 general hidden dangers, mainly including pipeline occupation, crossing of closed spaces and insufficient safety spacing of pressure regulating facilities;

(4) Climatic constraint: Rainfall is concentrated from June to September (accounting for more than 70% of the whole year), and the temperature difference between day and night is large. The pipeline must resist the double effects of rain erosion and temperature stress.

3 Hydraulic Optimization Design of Gas Pipeline Network on Sloping Terrain in Mountainous Areas

3.1 Adaptive Design of Medium-Low Pressure Transmission and Distribution System

In contrast to the single-stage pressure system widely used in plain areas (which fails to offset terrain height difference-induced pressure fluctuations), this study abandons the plain-oriented single-stage pressure system and adopts a three-stage graded transmission and distribution system of medium pressure A-medium pressure B-low pressure to realize stable low-pressure household access through building pressure regulation. The flow of the transmission and distribution system is shown in Figure 1.

According to *Code for Gas Engineering Projects* (GB 55009-2021) and combined with the gas supply demand in mountainous areas, the design parameters of pipeline network pressure are determined as follows: Medium pressure A pipeline: design pressure 0.4MPa, operating pressure 0.1~0.36MPa; Medium pressure B pipeline: design pressure 0.2MPa, operating pressure 0.099MPa; Low pressure pipeline: design pressure 5kPa, operating pressure 2~3kPa; Rated pressure of user gas appliances: 2kPa.

This graded system can effectively offset the pressure fluctuation caused by the height difference of sloping terrain and ensure the stability of gas supply pressure at end users.

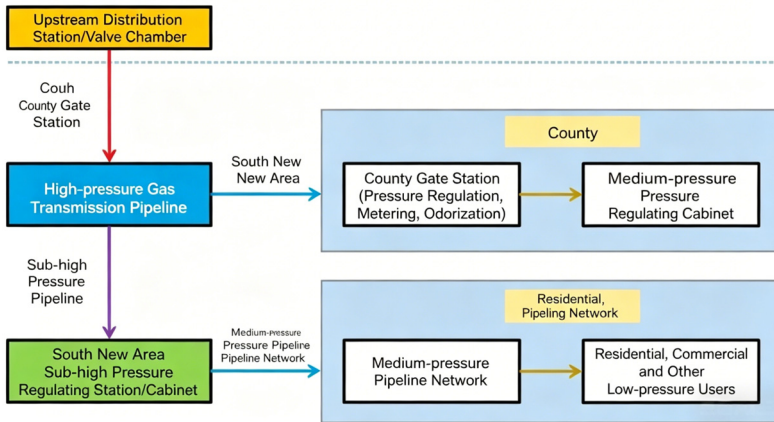


Fig. 1. Urban Gas Pipeline Transmission and Distribution System

3.2 Hydraulic Calculation Model of Gas Pipeline Network on Sloping Terrain in Mountainous Areas

Aiming at the distortion of pressure loss of pipeline network on sloping terrain, which does not exist in flat plain pipeline networks, a hydraulic calculation model of gas pipeline network in mountainous areas is established by introducing the topographic height difference correction coefficient Kh .

The formula for friction loss per unit length of medium pressure gas pipeline is Formula (1):

$$\frac{P_1^2-P_2^2}{L}=1.27\times10^{10}\lambda\frac{Q^2}{d^5}\rho\frac{T}{T_0}Z \tag{1}$$

Where: P_1 and P_2 are the absolute pressures at the starting and ending points of the pipeline (kPa); L is the calculated length of the pipeline (km); Q is the calculated flow rate (m^3/h); d is the inner diameter of the pipeline (mm); λ is the friction resistance coefficient; Z is the compression factor (taken as 1 under normal pressure in mountainous areas).

The modified formula for pressure loss of low pressure gas pipeline on sloping terrain is Formula (2):

$$\frac{\Delta P}{l}=6.26\times10^7\lambda\frac{Q^2}{d^5}\rho\frac{T}{T_0}\cdot K_h \tag{2}$$

Where: K_h is the sloping terrain height difference correction coefficient (1.05~1.12 for $10^\circ\sim25^\circ$ slopes), a terrain-specific parameter not required in plain hydraulic calculations, which is used to offset the influence of sloping terrain on the pressure loss of low-pressure pipeline network.

Calculation shows that the maximum gas supply flow of the newly built dn63 PE pipe is $300\text{ Nm}^3/\text{h}$, which can meet the simultaneous gas demand of 900 households; the pressure drop of the low-pressure pipeline in the courtyard is controlled at 600~1100Pa, which is 12.3% lower than that of the traditional plain design scheme.

3.3 Refined Safety Spacing Design in Mountainous Areas

Mountainous counties have dense buildings and complex pipeline crossings. Based on *Code for Design of City Gas Engineering* (GB 50028-2020), a refined safety spacing standard for mountainous areas is formulated. The horizontal clear distance between underground gas pipelines and structures is shown in Table 1.

Table 1. Horizontal Clear Distance between Underground Gas Pipelines and Buildings/Structures

Item	Medium Pressure B ($\leq 0.2\text{MPa}$)/m	Medium Pressure A ($\leq 0.4\text{MPa}$)/m
Building foundation	1.0	1.5
Water supply pipe	0.5	0.5
Directly buried power cable	0.5	0.5
Directly buried heat pipe	1.0	1.0

This standard takes into account both safety requirements and the tight land use status in mountainous areas, eliminating the safety risk of pipeline crossings in dense areas.

4 Design of Pipeline Laying and Pipe Selection Adaptable to Mountainous Areas

4.1 Selection of Mountain Composite Pipes

In view of the characteristics of soil corrosion, geological vibration and large temperature difference in mountainous areas, different from the single pipe material scheme commonly used in plain areas, a layered composite pipe scheme is determined through technical comparison.

(1) Buried medium and low pressure pipelines: PE100 grade SDR11 polyethylene pipes, with good corrosion resistance and seismic flexibility, suitable for mountainous soil and geological deformation;

(2) Overhead pipelines: 20# seamless steel pipes (epoxy resin coated externally), with excellent weather resistance and seismic resistance, suitable for mountain overhead laying;

(3) Indoor pipelines: thin-walled stainless steel pipes, corrosion-resistant and long service life, meeting indoor safety use requirements.

Compared with the pure steel pipe scheme, this pipe scheme reduces the cost by 18.7% and extends the service life of the pipeline network to 50 years.

4.2 Composite Laying Process of Pipeline Network on Sloping Terrain

Different from the full direct-buried laying process dominant in plain areas, a direct burial + overhead composite laying process is adopted to adapt to mountain slopes, rainfall and geological disasters, with the core design requirements as follows:

(1) Buried pipeline: the covering thickness of pipe top $\geq 1.2\text{m}$, trench excavation with slope (slope rate 0.5), layered backfilling of fine sand and graded crushed stone (compaction degree $\geq 90\%$), the trench detail is shown in Figure 2;

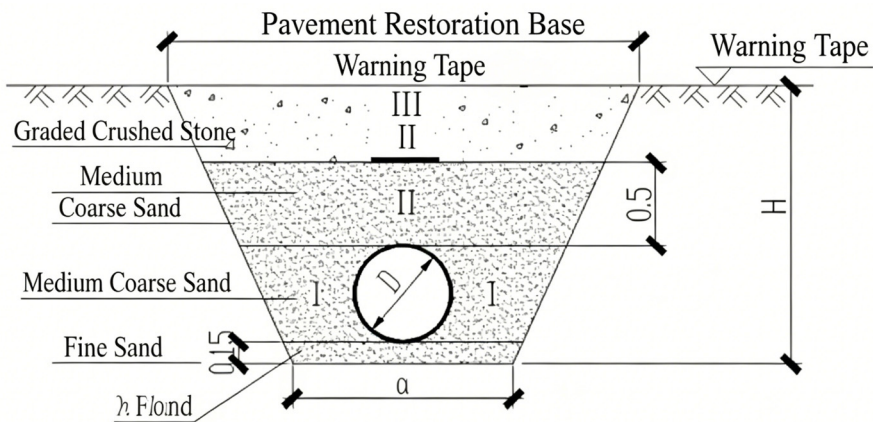


Fig. 2. Trench Detail Drawing

(2) Overhead pipeline: laid along the external wall of the building, the clear distance from door and window openings $\geq 0.3\text{m}$, the wall thickness of risers in high-rise buildings $\geq 4\text{mm}$, connected with lightning protection network every 25m (grounding resistance $\leq 10\Omega$);

(3) Crossing protection: directional drilling/pipe jacking for highway crossing, buried pipe in dry season for ditch crossing, vertical clear distance from other pipelines $\geq 0.3\text{m}$, and insulation isolation protection set.

This laying process can resist compound risks such as slope landslide, rain erosion and earthquake vibration, and reduce the pipeline damage rate by more than 90%.

5 Precise Remediation Technology for Potential Hazards of Gas Pipeline Networks in Mountainous Counties

5.1 Classification and Distribution Characteristics of Pipeline Network Hidden Dangers

On-site investigation shows that the hidden dangers of the county's gas pipeline network have significant mountainous characteristics and concentrated types:

(1) Major hidden dangers: 17 pipelines crossing closed spaces and 3 medium-pressure pipelines occupied;

(2) General hidden dangers: 4 low-pressure pipelines occupied, 53 defects of pressure regulating facilities (no anti-collision bars, insufficient spacing, deformed boxes);

(3) Indoor hidden dangers: 14,250 bottled gas users have no safety protection facilities, with a complete blank of safety protection.

5.2 Targeted Remediation Scheme for Hidden Dangers

A precise remediation mode of "one hidden danger, one strategy" is adopted with core measures as follows:

(1) Remediation of pipeline hidden dangers: relocate and reform 340m of hidden danger pipelines, demolish 9 temporary structures, and completely solve the problems of pipeline occupation and crossing of closed spaces;

(2) Remediation of pressure regulating facilities: add 13 anti-collision bars, relocate and reform 2 pressure regulating facilities, replace 1 box, and install 32 leakage alarm devices;

(3) Completion of indoor safety protection: equip 14,250 households with leakage alarm + emergency cut-off valve + self-closing valve + stainless steel corrugated hose to realize full coverage of indoor safety protection.

5.3 Coupled Protection Design for Geological Disasters

In view of the high seismic intensity and landslide risk in mountainous areas, triple protection of earthquake resistance-flood control-corrosion prevention is added:

- (1) Seismic design: flexible connection of pipelines to adapt to VIII-degree seismic fortification, and flexible joints added in fault zones;
- (2) Flood control design: pipelines avoid gully areas in rainy seasons, and reinforced sleeves are adopted for crossing drainage sections;
- (3) Anti-corrosion design: 3PE enhanced anti-corrosion + sacrificial anode cathodic protection for buried steel pipes, with a spark leak detection voltage of 15kV.

6 Closed-Loop Safety Guarantee System for Mountain Pipeline Network Based on IoT Perception

6.1 Architecture of Intelligent Pipeline Network Digital Platform

In view of the difficulties in pipeline network supervision and hidden danger investigation in mountainous areas, an intelligent information platform for underground pipeline network is built, which is divided into data integration layer, data analysis layer, business application layer and user interaction layer to realize the whole-life-cycle intelligent control of pipeline network. The distribution of existing sensing devices is shown in Figure 3.



Fig. 3. Current Distribution of IoT Sensing Devices for Gas Pipelines in a County

6.2 Layout of Mountain-Adaptive IoT Sensing Devices

Combined with the distribution characteristics of mountainous pipeline networks, full-coverage and high-reliability sensing devices are deployed:

- (1) Pressure regulating tanks: install 180 sets of pressure monitoring and remote transmission equipment to monitor pressure fluctuations in real time;
- (2) Indoor: install 14,250 intelligent household gas alarm detectors linked with emergency cut-off valves;
- (3) High-risk pipe sections: install combustible gas sensors every 500m along the pipeline to realize real-time leakage monitoring.

6.3 Closed-Loop Mechanism for Safety Operation and Emergency Response

A closed-loop system of "daily operation-monitoring and early warning-emergency disposal-performance control" is constructed:

- (1) Daily operation: entrust professional gas companies with 24h emergency repair, indoor safety inspection every six months, and monthly detection of gas odorization concentration;
- (2) Emergency response: formulate graded emergency plans for gas leakage, fire and explosion, distinguish social plans from enterprise plans, and conduct regular practical drills;
- (3) Performance control: set the goal of "zero accidents, zero deaths, zero pollution", assess operation and maintenance quality quarterly to form a closed-loop control.

7 Project Implementation Control and Benefit Analysis

7.1 Core Project Quantities

The core quantities of the project focus on bottle-to-pipe renovation and hidden danger remediation, as shown in Table 2.

Table 2. Main Quantities of Courtyard and Indoor Projects

No.	Item Name	Specification	Unit	Quantity
1	Medium and low pressure pressure regulating tank	$Q=50\text{m}^3/\text{h}$	set	180
2	Buried PE pipe	de63	m	22020
3	IoT gas meter	G2.5	piece	14250
4	Indoor safety facilities	Alarm + cut-off valve	set	14250

7.2 Comprehensive Project Benefits

- (1) Safety benefits: eliminate 17 major hidden dangers and 53 general hidden dangers, achieve full coverage of indoor safety protection, and reduce the risk of gas accidents to zero;

(2) Livelihood benefits: 14,250 households complete bottle-to-pipe renovation, gas penetration rate increases from 33% to over 92%, and residents' gas cost decreases by 30%;

(3) Environmental benefits: replace bottled liquefied petroleum gas, reduce carbon emissions by about 12,000 tons per year, and significantly reduce air pollutant emissions;

(4) Social benefits: improve municipal infrastructure in mountainous areas, enhance the safety resilience of counties, and support rural revitalization and new urbanization.

8 Conclusions

8.1 Core Academic Innovations and Engineering Contributions

(1) Focusing on the core innovation of hydraulic optimization and dual-dimensional guarantee of geology and safety for gas pipeline renovation on sloping terrain in mountainous areas, this paper constructs an integrated technical system of "hydraulic design-laying process-remediation of hidden dangers-safety control" suitable for mountainous counties in southwest China, which upgrades standard-guided conventional design to terrain-coupled academic design, and fills the research gap of specialized "bottle-to-pipe" renovation technology for southwest mountainous sloping counties, solving the technical problems of difficult pipeline laying, uneven gas supply and weak risk prevention and control in mountainous areas.

(2) The hydraulic calculation model with the correction coefficient of height difference on sloping terrain can accurately optimize the pressure distribution of mountainous pipeline networks, reducing the pressure loss by 12.3% compared with traditional plain schemes; the composite laying and pipe selection scheme can effectively resist compound geological disasters such as earthquakes, landslides and rain erosion in mountainous areas, and greatly improve the stability of pipelines.

(3) The safety guarantee system of "geological protection + precise remediation of hidden dangers + intelligent IoT monitoring + emergency closed-loop" realizes the whole-life-cycle safety control of gas pipeline networks in mountainous counties, with 100% hidden danger elimination rate and 100% safety prevention and control coverage, providing systematic technical support for gas safety in mountainous areas.

(4) After the implementation of the project, 14,250 households have completed the bottle-to-pipe renovation, with remarkable safety, livelihood, environmental and social benefits. The research results can be directly applied to the gas pipeline renovation projects of similar sloping counties in southwest mountainous areas, with important academic value and engineering application prospects.

8.2 Research Limitations

(1) The hydraulic correction coefficient K_h is verified only for slopes of $10^\circ\sim 25^\circ$; its applicability to steeper slopes ($>25^\circ$) needs further verification.

(2) The intelligent monitoring system is oriented to conventional working conditions, and its adaptive algorithm under extreme geological disasters (e.g., large-scale landslides) needs to be optimized.

(3) The economic benefit evaluation only covers short-term operation and maintenance, and long-term life-cycle cost analysis needs to be supplemented.

8.3 Future Work

(1) Expand the scope of slope gradient research to establish a universal hydraulic correction model for full-gradient mountainous terrain.

(2) Develop an intelligent early warning algorithm coupled with real-time geological disaster monitoring data to improve the system's disaster response capability.

(3) Carry out long-term tracking of pipeline network operation to form a full-life-cycle performance evaluation system for mountainous gas pipelines.

(4) Promote the technical system to plateau mountainous and karst landform areas to expand its application scope.

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