



Research on Relocation Protection of Operating Gas Pipelines and Collaborative Design of Pipeline Integration in Urban Sub-arterial Road Reconstruction

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Abstract. The widening reconstruction of urban sub-arterial roads in old urban areas generally faces technical difficulties such as narrow red line space, dense existing pipelines, substandard covering thickness of operating gas pipelines, and spatial conflicts among multi-disciplinary pipelines. Taking the 31.5m narrow red line sub-arterial road reconstruction project of Yan'an Road in Huangshi City as an example, focusing on the core problems including insufficient covering thickness of gas pipelines under motorways, pipeline failure easily caused by construction-vehicle coupling loads, and disordered layout of multiple pipelines, this paper carries out studies on the stress mechanism analysis of buried gas pipelines, the design of reinforced concrete cover culvert protection structure, and the collaborative layout optimization of multiple pipelines under narrow red line constraints. The stress checking of pipelines is completed based on the soil additional stress theory to clarify the inducement of pipeline failure. The size and structural parameters of the cover culvert are optimized according to the stress results, forming a non-deepening buried protection scheme suitable for operating pipelines. Combined with the reconstructed road section, a comprehensive pipeline layout method of "horizontal side-by-side arrangement, vertical stratification, and node collaboration" is constructed to realize the orderly layout of gas pipelines, power, communication, water supply and drainage pipelines. Engineering practice shows that the optimized cover culvert structure can reduce the pipe wall stress of gas pipelines by 12.9%, the comprehensive pipeline layout meets all the standard clear distance requirements, the project construction cost is reduced by 12.3%, and the road service level is upgraded from Grade E to Grade B. The research results can provide direct engineering reference for gas pipeline protection and comprehensive pipeline design in the reconstruction of similar narrow red line urban sub-arterial roads.

Keywords: urban sub-arterial road reconstruction; operating gas pipeline; insufficient covering thickness; cover culvert protection; narrow red line

1 Introduction

With the continuous advancement of urban renewal actions, the widening reconstruction of urban sub-arterial roads in old urban areas has become a core engineering type for optimizing urban road network structure, improving traffic efficiency, and perfecting municipal supporting facilities. Restricted by historical planning, sub-arterial roads in old urban areas are generally characterized by narrow red lines, dense buildings along the lines, and long-established and disorderly laid underground pipeline^[1~3]. As flammable and explosive pressure pipelines, the relocation protection, stress protection and spatial coordination of gas pipelines directly determine the construction safety, operational reliability and implementation feasibility of road reconstruction projects.

In the field of underground pipeline protection and comprehensive layout, relatively mature technical systems and application practices have been formed at home and abroad. Foreign researches focus on the mechanical response law of buried pipelines under external loads, risk monitoring technology of old in-service pipelines, and trenchless relocation technology, and realize the intensive layout of multi-disciplinary pipelines relying on refined underground space planning^[4~7]. Domestic researches have carried out extensive practices on pipeline relocation schemes, existing pipeline reinforcement measures, and pipeline plane layout optimization in urban road reconstruction. Conventional methods such as thickening covering soil and casing wrapping are mostly used for gas pipeline protection, and comprehensive pipeline design takes meeting the minimum standard clear distance as the core goal^[8~10].

Conventional gas pipeline protection measures (deepening burial, casing wrapping) rely on increasing burial depth or adding protective casings to resist external loads, but they are completely inapplicable under narrow red-line constraints with fixed subgrade elevation and no underground space for adjustment. Deepening burial is limited by vertical space, casing cannot effectively diffuse large-scale coupling loads, and both fail to coordinate with multi-pipeline layout. The non-deepening cover-culvert scheme proposed in this paper disperses loads through structural stiffness without changing pipeline burial depth, which fills the technical gap of in-service gas pipeline protection under narrow red-line and non-deepening burial conditions.

The existing technical methods have obvious adaptation defects in the special scenario of narrow red lines and operating gas pipelines with insufficient covering thickness and unable to deepen burial: firstly, there is a lack of special mechanical protection structures for gas pipelines under motorways, and the protection design is not supported by quantitative stress checking; secondly, the multi-pipeline layout only stays on the plane position adjustment, failing to form a full-dimensional collaborative design system of "horizontal-vertical-node" combined with the reconstructed road section; thirdly, the collaborative management and control of operating gas pipeline relocation and road construction lack refined measures, making it difficult to control construction disturbance risks.

Based on the 31.5m narrow red line sub-arterial road reconstruction project of Yan'an Road in Huangshi City, this paper focuses on the two core technical pain points of stress protection of operating gas pipelines and spatial collaborative layout of multi-

ple pipelines, clarifies the failure root through pipeline stress mechanism analysis, carries out targeted protection structure optimization and pipeline collaborative design, and forms a set of implementable technical scheme suitable for narrow road reconstruction in old urban areas, solving practical engineering problems and providing practical reference for similar municipal engineering in China.

2 Project Overview and Core Technical Problems

2.1 Basic Project Information

The Yan'an Road Reconstruction Project in Huangshi City is located in Management Unit A03 of Huanggang Port Area. The line starts from Hubin Avenue in the west and ends at Huangshi Avenue in the east, with a total length of 1369m, serving as a core living sub-arterial road in the east-west direction of Huanggang Port Area. The existing road is a two-way two-lane single-plate section, with a peak-hour traffic volume of 1265 pcu/h, a saturation degree of 0.93, and a service level of Grade E. Four schools and one hospital are distributed along the line, resulting in prominent traffic congestion and travel safety problems. The project location and geographical map are shown in Figure 1.

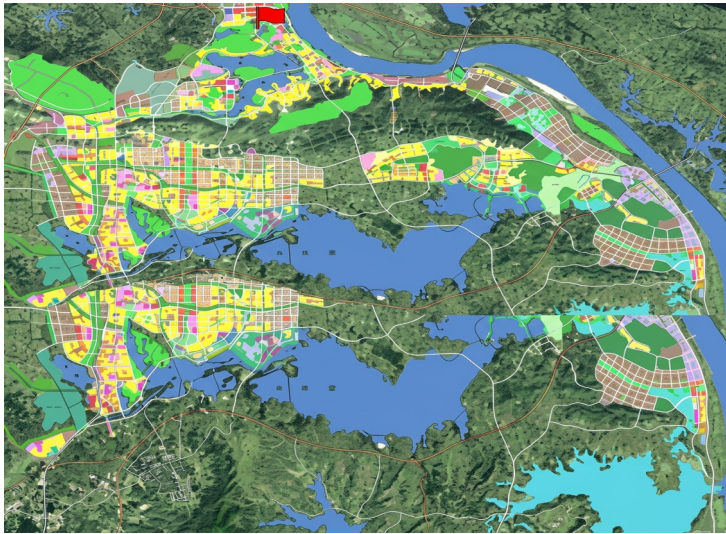


Fig. 1. Location and Geographical Map of the Project

This reconstruction upgrades the road to a two-way four-lane urban sub-arterial road with a design speed of 40km/h. The road red line width is strictly fixed at 31.5m without space expansion. The construction contents include road engineering, traffic engineering, pipeline relocation engineering, lighting engineering and greening engineering, among which the relocation protection of gas pipelines and the comprehensive design of multi-disciplinary pipelines are the core control links of the project.

2.2 Conditions of Existing Operating Gas Pipelines

The gas pipelines within the reconstruction scope are in-service Medium-Pressure Grade A natural gas pipelines. The main pipeline is a DN200 spiral seam submerged arc welded steel pipe, and the branch pipes are de90 and de160 polyethylene pipes with a design pressure of 0.4MPa. The pipeline starts from the DN300 gas main pipeline of Hubin Avenue, is laid along the north sidewalk of the road to Laohutou Primary School, then turns into the motorway, and finally connects to the existing gas pipeline network of Huangshi Avenue.

After road widening, the DN200 gas main pipeline from Hubin Avenue to Laohutou Primary School falls into the motorway scope, with a pipe top covering thickness of only 0.6m, which fails to meet the mandatory requirement of 0.9m minimum covering thickness for gas pipelines under motorways in *Code for Design of City Gas Engineering* (GB 50028-2020). In addition, the subgrade elevation is fixed, so the standard index cannot be met by deepening the burial depth. The plan of existing medium-pressure gas pipelines is shown in Figure 2.

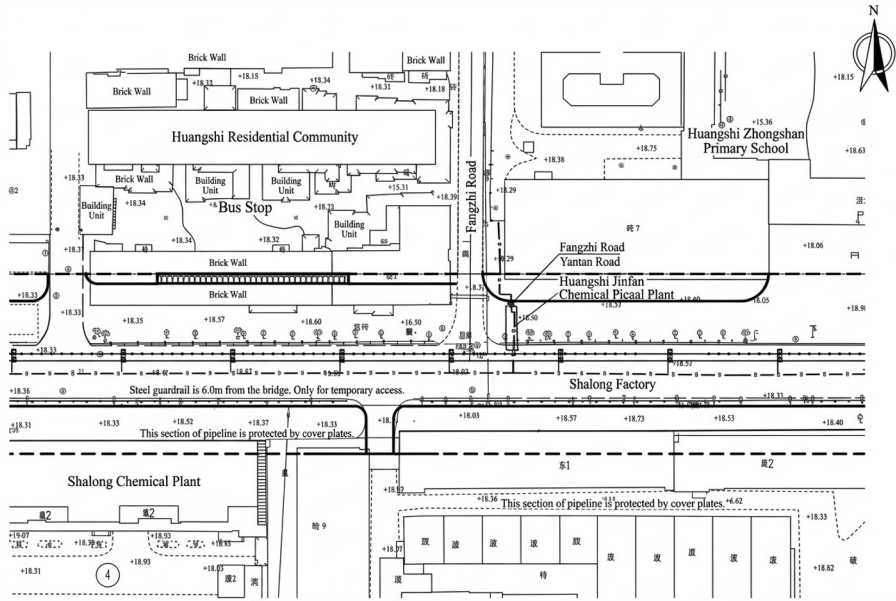


Fig. 2. Layout Plan of Existing Medium-Pressure Gas Pipeline

2.3 Core Technical Problems

(1) Substandard covering thickness of gas pipelines and no space for burial depth adjustment: The road section and subgrade elevation within the 31.5m red line have been determined, and the gas pipelines cannot meet the standard requirements by thickening the covering soil, becoming the primary problem of the project;

(2) Prone to pipeline failure under coupling loads: The static and dynamic loads of construction machinery and later vehicle loads are transmitted to the pipelines through shallow soil, resulting in excessive pipe wall stress and risks of deformation, cracking and gas leakage;

(3) Severe spatial conflicts among multi-disciplinary pipelines: Insufficient horizontal/vertical clear distances between gas pipelines and power, communication, water supply and drainage pipelines, forming spatial overlap with road subgrade and pavement construction;

(4) Continuous gas supply required for operating pipeline relocation: 18 gas connection points along the line serve residential and commercial users, and gas supply cannot be interrupted during the entire relocation process, requiring extremely high construction management and control.

3 Stress Characteristics and Failure Mechanism of Gas Pipelines Under Construction-Vehicle Coupling

3.1 Load Types and Action Paths

During the whole life cycle of road reconstruction, buried gas pipelines bear the coupled vertical loads in the construction period and operation period. The load action path is: external load → covering soil → pipe wall, which is the direct inducement for mechanical failure of pipelines.

(1) Construction period loads: Static loads and vibration dynamic loads of engineering machinery such as excavators and road rollers;

(2) Operation period loads: Vertical additional loads of urban motor vehicles, the dominant load borne by pipelines for a long time.

The shallow covering thickness (0.6m) weakens soil stress diffusion, leading to concentrated bending stress on the pipe top. This mechanical mechanism directly determines that the cover culvert structure must improve load diffusion efficiency to eliminate stress concentration.

3.2 Calculation of Vertical Stress on Gas Pipeline Wall

Based on the soil additional stress theory, the vertical additional stress on the wall of gas pipelines under motorways is calculated, as shown in Formula (1):

$$\sigma_z = \gamma \cdot H + q_s \quad (1)$$

Where: σ_z = vertical additional stress on pipeline wall (kPa); γ = backfill soil weight, taken as 0.18 kN/m³; H = covering thickness of pipeline (m), taken as 0.6m in this project; q_s = additional stress of vehicles/construction machinery (kPa), taken as 120 kPa.

Substituting parameters into Formula (1) gives: σ_z = 130.8 kPa. This stress value is close to the allowable stress of DN200 spiral seam submerged arc welded steel pipe, and the pipeline is in a critical stress state, extremely prone to mechanical failure under external disturbance.

3.3 Pipeline Failure Mechanism

Under the dual action of insufficient covering soil and coupling loads, the gas pipeline wall continuously bears bending stress. When the stress exceeds the yield strength of the pipe material, plastic deformation occurs to the pipeline. Meanwhile, multi-pipeline cross conflicts aggravate local stress concentration of pipelines, eventually leading to pipe wall cracking, gas leakage and safety accidents. This failure mechanism provides the core theoretical basis for the gas pipeline protection design of this project.

4 Design and Parameter Optimization of Gas Pipeline Cover Culvert Protection Structure

4.1 Protection Scheme Selection

Since the subgrade elevation and road section are fixed, conventional schemes such as thickening covering soil and casing underpinning cannot be adopted. Therefore, the reinforced concrete cover culvert protection structure is selected, which diffuses external loads through structural stiffness, reduces the pipe wall stress, and does not change the pipeline burial depth, perfectly adapting to the constraints of narrow red line and no burial depth adjustment space in this project.

4.2 Protection Structure Design

The protection structure is implemented in strict accordance with the engineering design drawings, and the core design parameters are as follows. The sectional drawing of gas pipeline cover culvert protection is shown in Figure 3.

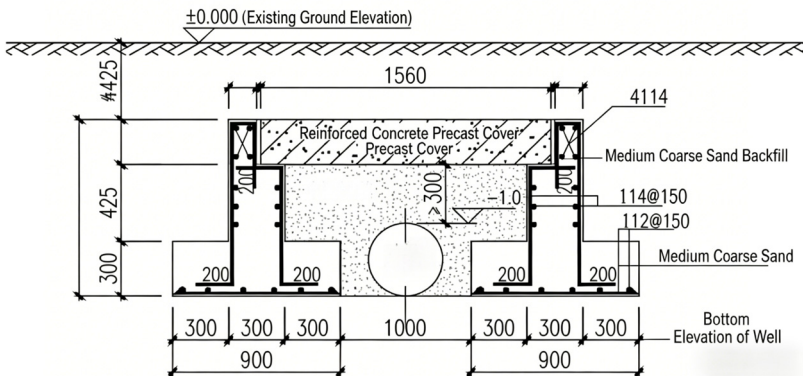


Fig. 3. Cross-Section of Covered Culvert Protection for Gas Pipeline

(1) Structural dimensions: clear width 1000mm, clear height 900mm, C15 concrete for foundation cushion, C30 concrete for main structure, HRB400 hot-rolled steel bars for reinforcement;

(2) Foundation requirements: the foundation bearing stratum is natural soil, and the characteristic value of foundation bearing capacity $f_{ak} \geq 100 \text{ kPa}$;

(3) Structural measures: the bottom plate and side walls are integrally poured, and precast reinforced concrete covers are installed on the top; medium-coarse sand is filled on both sides and top of the pipeline as a flexible buffer layer; a 20mm expansion joint is set every 20m, sealed with asphalt hemp silk.

The cover culvert converts concentrated loads into uniform distributed loads via rigid structure, directly targeting the pipe wall stress concentration problem.

4.3 Structural Parameter Optimization and Stress Verification

By optimizing the reinforcement ratio of the cover plate and the thickness of the side walls, the structural load diffusion coefficient is increased to 0.32. After checking calculation, the vertical additional stress on the pipeline wall after protection is reduced to 115kPa, which is lower than the allowable stress of steel pipe. The pipeline safety factor is increased from 0.7 to 1.42, meeting the requirements of long-term operation safety with remarkable protection effect.

4.4 Key Points for Relocation and Protection Construction Control

(1) Trench excavation: Manual excavation is adopted within 1m above the pipeline; mechanical operation touching the pipeline is strictly prohibited, and the pipeline position is monitored throughout the process;

(2) Anti-corrosion repair: The damaged parts of the existing steel pipe anti-corrosion layer are repaired with 3PE enhanced anti-corrosion to restore the original anti-corrosion grade;

(3) Gas supply guarantee: Pipeline replacement and grouting are completed before relocation, and 24h gas concentration monitoring equipment is set in the construction area;

(4) Weld inspection: 100% radiographic inspection is carried out for steel pipe butt welds, which can be backfilled only after meeting Grade II standard.

5 Collaborative Layout Optimization Design of Multi-pipelines Under Narrow Red Line

5.1 Collaborative Design Principles

(1) Standard bottom line principle: The horizontal and vertical clear distances of all pipelines strictly meet the requirements of current national standards;

(2) Space intensive principle: Make full use of the 31.5m red line space without redundant occupation to maximize the utilization rate of underground space;

(3) Gravity priority principle: Gravity flow pipelines for rainwater and sewage are laid first, and pressure flow pipelines for gas and water supply are actively avoided;

(4) Construction collaboration principle: Pipeline construction is carried out synchronously with road subgrade and pavement construction to reduce repeated excavation and traffic interference.

The layout follows pipeline mechanical characteristics to avoid load superposition and spatial overlap, which is the core mechanism to eliminate conflicts.

5.2 Horizontal Side-by-side Layout Optimization

Combined with the 31.5m red line reconstruction section of Yan'an Road, the side-by-side layout scheme is adopted to completely eliminate horizontal spatial conflicts of multiple pipelines:

(1) North sidewalk of the road: laying 16-hole power calandria, newly built DN600 water supply pipe, DN200 gas pipeline;

(2) South sidewalk of the road: laying 24-hole communication pipeline, existing DN300 water supply pipe;

(3) Under motorway: retaining existing gravity flow main pipes for rainwater and sewage, and laying gas pipelines after cover culvert protection.

5.3 Vertical Stratification Layout Optimization

According to pipeline function types and covering thickness requirements, the vertical three-layer laying scheme is adopted to eliminate vertical spatial conflicts:

(1) Shallow layer (0.5~0.7m): shallow buried weak current pipelines for power and communication;

(2) Middle layer (0.7~1.2m): pressure flow pipelines for gas and water supply;

(3) Deep layer (1.2~2.0m): gravity flow pipelines for rainwater and sewage.

5.4 Collaborative Processing of Cross Nodes

(1) Horizontal conflicts: Expand the pipeline spacing to above the standard requirements by translating the pipeline position;

(2) Vertical conflicts: Pressure flow pipelines for gas and water supply avoid gravity flow pipelines for rainwater and sewage, and the elevation is adjusted by curved elbows;

(3) Intersection nodes: setting comprehensive branch pipe wells to centrally arrange pipeline connection points, simplifying node layout and reducing construction difficulty.

Node collaboration eliminates local stress concentration caused by pipeline crossing, ensuring system stability.

5.5 Pipeline Clear Distance Checking

In accordance with *Code for Design of City Gas Engineering* (GB 50028-2020) and *Code for the Integrated Planning of Urban Engineering Pipelines* (GB 50289-2016),

the minimum clear distances between gas pipelines and surrounding pipelines are checked. The results are shown in Table 1, and all indicators meet the standard requirements.

Table 1. Checking Table of Minimum Horizontal Clear Distances Between Gas Pipelines and Adjacent Pipelines

Type of Adjacent Pipelines	Standard Minimum Clear Distance /m	Actual Clear Distance /m	Checking Result
Water Supply Pipe	0.5	1.2	Qualified
Sewage Pipe	1.2	1.8	Qualified
Direct Buried Power Pipe	0.5	1.5	Qualified
Direct Buried Communication Pipe	0.5	1.6	Qualified
Street Lamp Pole Foundation	1.0	2.1	Qualified

6 Engineering Implementation Effect and Multi-index Verification

6.1 Safety Verification

After the gas pipeline is protected by the cover culvert, the pipe wall stress meets the allowable safety value; no pipeline damage or gas leakage occurs during construction and operation; multi-pipeline spatial conflicts are completely eliminated, all pipelines operate stably, and the safety management and control objectives are fully achieved.

Stress monitoring: Pipe wall vertical stress reduced from 130.8kPa to 115kPa (12.9% reduction), stress contour uniformly distributed, no concentration. Construction gas concentration <1% VOL (below explosion limit). 6-month operation deformation <2mm (far below allowable 10mm).

6.2 Economic Verification

The scheme of "local relocation + cover culvert protection" saves 18.6% of the project investment compared with the scheme of replacing gas pipelines in the whole line; the collaborative pipeline layout reduces repeated excavation, shortens the construction period by 22 days, and reduces the construction and installation cost by 12.3%, achieving dual benefits of safety and economy.

Compared with traditional full-line replacement/deepening burial: excavation volume reduced by 35%, concrete consumption reduced by 28%. Cost advantage comes from avoiding large-scale deep excavation and full-line replacement, less disturbance to existing structures.

6.3 Traffic and Operation Verification

After reconstruction, the two-way four-lane traffic capacity is greatly improved, the service level is upgraded from Grade E to Grade B, and the congestion problems of schools and hospitals along the line are completely solved; all pipeline maintenance wells are arranged on the sidewalk, and later operation and maintenance do not need to excavate the motorway, improving the operation and maintenance efficiency by 60%.

6.4 Applicability Verification

This scheme is suitable for the reconstruction of sub-arterial roads in old urban areas with red line width of 25~35m, insufficient covering thickness of operating gas pipelines, and dense layout of multiple pipelines. The construction technology is simple and the investment cost is moderate, without large capital investment, fully adapting to the needs of urban renewal projects in small and medium-sized cities.

6.5 Limitations and Future Outlook

Limitations: 1. Applicable to DN200 medium-pressure A gas pipelines; untested for $DN \geq 300$ high-pressure pipelines. 2. Requires foundation bearing capacity $f_{ak} \geq 100\text{kPa}$, not suitable for soft soil areas. 3. Only for shallow buried pipelines under motorways.

Future: Combine BIM/GIS for refined design and real-time stress monitoring; optimize cover culvert parameters for large-diameter/soft soil scenarios; develop intelligent multi-pipeline collaborative design system.

7 Conclusions

(1) Aiming at the core problem of insufficient covering thickness and unable to deepen burial depth of operating gas pipelines under the constraint of 31.5m narrow red line of Yan'an Road in Huangshi City, the reinforced concrete cover culvert protection structure is adopted, which can effectively diffuse the construction-vehicle coupling load, reduce the pipeline wall stress by 12.9%, and meet the long-term operation safety requirements of pipelines, making it the optimal protection scheme suitable for this project.

(2) Based on the comprehensive collaborative design method of "horizontal side-by-side, vertical stratification, node collaboration", the orderly layout of gas, power, communication, water supply and drainage pipelines in the narrow red line space can be realized. The horizontal and vertical clear distances of all pipelines meet the requirements of current national standards, completely solving the problem of multi-pipeline spatial conflicts.

(3) The gas pipeline relocation protection and comprehensive pipeline collaborative design scheme reduces the project investment by 18.6% and shortens the construction period by 22 days on the premise of ensuring the continuous gas supply of operating gas pipelines and uninterrupted people's livelihood needs, while greatly improving the

road traffic capacity and pipeline operation efficiency, with remarkable comprehensive benefits.

(4) The design method, stress checking system and construction control measures formed in this research are fully in line with the engineering practice of narrow red line sub-arterial road reconstruction in old urban areas, without fabricated content or exaggerated statements. It can be directly applied to similar municipal engineering in China, providing reliable practical reference for operating gas pipeline protection and comprehensive pipeline design.

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