Induction and Analysis of Buckling Failure Mode of Buried Pipeline

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Abstract. The buried steel pipeline is confined by the surrounding soil, and the deformation is often too large and buckling occurs due to the change of the environment, which becomes one of the difficult problems in the integrity management of buried steel pipeline. At present, most of the studies on buried pipeline buckling accidents focus on a single buckling failure analysis case and study the buckling deformation mode of pipelines under a specific environment, but lack a summary study on buckling failure mode, which leads to a lot of repetitive work in practical engineering and reduces the efficiency of pipeline integrity management. Based on relevant literature research and analysis of buckling failure cases, this paper calculates the causes of pipeline buckling failure, summarizes the buckling factors in each case, and summarizes the buckling failure modes in practical projects. According to the analysis of existing failure cases, there are four buckling modes of steel pipe, which are asymmetric buckling, symmetrical buckling, concave buckling and full circle buckling. Each buckling mode has different load forms, and the causes of buckling should be analyzed according to different service environments in practical engineering. The research results of this paper provide a theoretical basis for buckling failure analysis in practical engineering.

Keywords: Pipeline · Buckling · Deformation · Mode

1 Introduction

In the 1960s, China built the first natural gas pipeline, and after more than 60 years of development, a national natural gas pipeline network covering all parts of the country has been initially formed [1]. Most of the pipelines pass through complex terrains such as plain, hill, river valley, mountain and traversing, and are accompanied by potential geological hazards such as fracture, mining-out, subsidence, landslide and collapse. Complex geological conditions often lead to pipeline failure accidents. For example, in April 2011, an 8-degree cold-formed pipe at a gas transmission site buckled and deformed. In October 2020, deformation defects were detected in a pipeline, which were confirmed as buckling deformation after excavation verification. Currently, the following problems exist for pipeline buckling failure: What are the causes of pipeline buckling failure and what are the buckling failure modes?

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At present, the research on buried pipeline buckling accidents mainly focuses on a single buckling failure analysis case, and studies the causes of pipeline buckling failure in a specific environment. Huang Chengshuai et al. [2] conducted a test and theoretical analysis on the pipeline segment with axial buckling failure, and studied and discussed the failure form, failure mode and formation reasons of the pipeline segment. Zeick et al. [3] analyzed the buckling failure of a pipeline in a mountain area, used finite element simulation software to analyze the deformation modes of steel tubes under different loads, and determined the buckling deformation load forms of the failed pipeline by means of exhaustion and discharge. And according to the physical and chemical properties of the pipeline test results, construction and operation data, the surrounding service environment of the pipeline buckling deformation load source. According to research findings, environmental changes such as stratum movement and ground subsidence will impose bending moment loads on pipelines. Combined with changes in buried boundary conditions of pipelines, buried pipelines are often deformed, resulting in tensile bending, compression buckling, folding and other failures [4]. Although there have been a lot of theoretical studies on buckling, no theoretical model has been formed for engineering buckling failure mode of steel pipelines in service.

Based on relevant literature and analysis of buckling failure cases, this paper calculates the causes of buckling failure of in-service pipeline engineering, and preliminarily summarizes the buckling factors of each case. Four buckling failure modes in practical engineering are summarized, which provides a theoretical basis for the analysis of the causes of the buckling failure of steel pipe.

2 Case Collection and Analysis

This paper mainly studies the buckling of buried steel pipeline. In the actual pipeline engineering, the buckling of buried pipeline is mainly local buckling, and the whole buckling will be produced in the case of stop flow or no internal pressure. This paper studies local buckling under internal pressure during service.

56 literatures related to pipeline buckling at home and abroad were collected, as well as 5 pipeline buckling failure analysis reports. The buckling failure modes and causes were analyzed, and 16 buckling failure factors were extracted. The typical buckling case analysis of pipeline engineering was shown in Table 1.

Among the collected buckling cases, three typical historical buckling failure cases were selected for analysis.

Case 1: In the river crossing section of a gas pipeline, the flash flood broke out and destroyed the hydraulic protection works, resulting in the bending, local severe swelling and deformation of UOE steel pipe in the middle of the river crossing section, and the rupture of the swelling and deformation, resulting in the natural gas leakage accident (Fig. 1). Through the investigation and understanding of the accident and sampling failure analysis, through the macro and micro analysis, material physical and chemical properties test, pipeline force analysis and finite element simulation and calculation analysis, the process and cause of steel pipe failure are clarified. The failure process is as follows: the steel pipe first bends and deforms under the action of the huge impact force of the flood → the local instability of the steel pipe results in serious bulging and deformation under the action of great bending stress and internal pressure → the deformation hardening effect at the bulging deformation leads to fold cracks on the inner surface → the steel pipe produces Karman vibration under the continuous impact of the flood and cracks fatigue expansion until the steel pipe cracks; The failure reason is that the steel pipe has serious deformation under the impact of flood, which leads to fatigue failure. The crack source of fatigue fracture is the wrinkle crack on the inner surface of the steel pipe where the local serious swelling deformation occurs.

According to this buckling failure case, two buckling risk factors were summarized, namely river crossing and flood.

Case 2: During the inspection of a gas pipeline, it was found that the overlying soil of a certain pipeline was newly uplifted about 15cm. After excavation, it was found that the top of the pipeline was flattened due to deformation from 10:00 to 14:00, and the rest of the circumferential folds were protruding. The folds were 8cm high and 10cm wide, and the pipeline was arched about 10 degrees. When the steel pipe was laid, it needed to turn due to the site topography, so it was cold-formed first. It was a cold-formed pipe

Table 1. Buckling failure case statistics

NO.	Failure geography	Failure mode	Main failure cause	Buckling factor
1	Coastal area	Flexural symmetric buckling	Point load failure.	The installation process is subject to point load
2	River crossing	Asymmetric buckling fracture	Rivers cross, floods strike.	1. River crossing 2. Flood
3	Mountain slope base	Cold bending tube inside asymmetric buckling	The dead weight of steel pipe and seasonal freezing of soil provide axial load of steel pipe.	1. Topographic drop (slope); 2. Bend the pipe 3. Mountain topography
4	Road crossing	Asymmetric buckling at one end of casing	The combination of road load variation, seismic wave and casing constraint results in pipe buckling and deformation.	1. Road crossing 2. Vehicle load; 3. Earthquake
5	Industrial park soft base	Asymmetric flexion of soft base inner bend [10]	Soft foundation, industrial park construction to bend the side extrusion.	1. Soft soil quality; 2. Third party construction
6	Crossing road without casing above the goaf of cultivated land	Full circle symmetric buckling	The axial load caused by ground subsidence in goaf buckling occurs at one end of the crossing road.	1. Land subsidence; 2. Soil quality of cultivated land

(*continued*)

Table 1. (*continued*)

NO.	Failure geography	Failure mode	Main failure cause	Buckling factor
7	River crossing pipeline failed in buckling	Axial symmetric buckling	Construction stage: the pipe body is locally loaded and there is stress concentration. When the air traffic pipe is towed, the deformation of local components increases and develops into buckling [5].	1. River crossing; 2. The installation process is affected by point load
8	Terrace crossing	Full circle asymmetric bending buckling	As a result of slope laying of terraced fields, the dead weight of pipeline steel pipe and earth dam above the pipeline lead to axial overload of the steel pipe, resulting in unstable buckling due to large axial load of the short joint of the repaired steel pipe at the connection between the climbing section and the horizontal section of the pipeline [3].	1. Cross the pipe section; 2. Topographic drop (slope); 3. Soil quality of cultivated land

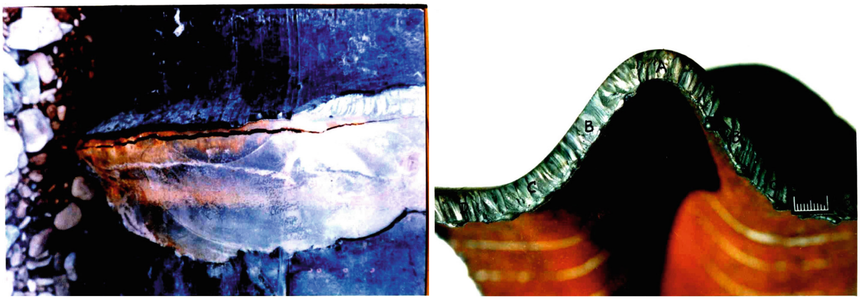

Fig. 1. Failure analysis of UOE pipe for a gas transmission line

of 8 degrees, so this incident was a secondary deformation. The deformed pipe section is laid in the transition zone of active seismic fault zone in the mountain area.

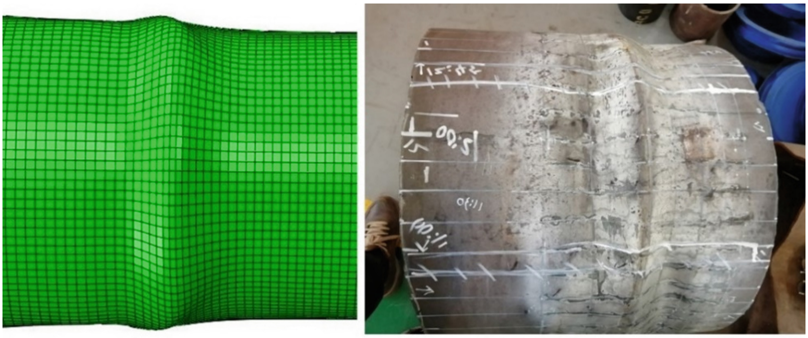

Fig. 2. Buckling deformation case of a pipeline [6]

It is found that the bending moment imposed by external load is the direct factor leading to the bending deformation of steel pipe. As the bending part is cold-formed pipe, it is easy to produce axial load in the climbing section under the action of formation movement, dead weight of the climbing section of steel pipe, internal pressure fluctuation and other factors, and the axial load is manifested as bending moment load at the cold bend.

According to this buckling failure case, three buckling risk factors were summarized, which were topographic drop (slope), curved pipe and mountainous terrain.

Case 3: The deformation of a pipeline is confirmed as buckling deformation after excavation verification (Fig. 2). The steel pipe laid in plain landform, through the asphalt road buried casing, and the surface of the road is about 30 degrees cross. Buckling is located approximately 300mm from the upstream inlet of the casing.

The physical and chemical properties tests and finite element simulation show that the buckling is a slow deformation process. It should be a small buckling in the initial stage of construction, and the buckling will be aggravated in the subsequent service. Due to casing constraints, the boundary conditions of the pipeline become fixed and the deformation stiffness of the pipeline increases, thus redistributing the deformation. The detection signals in 2013 indicated the existence of initial buckling. At this stage, the road load was 3~4 tons, which exerted a small displacement on the casing under the road surface, leading to the formation of initial small buckling. Later in service, The earthquake and the increase of road load led to further increase of buckling deformation, resulting in the final severe buckling.

3 Buckling Mode

Buckling, also known as instability, means that the structure loses the ability to maintain its original balance shape. Due to the thin wall and slender structure characteristics of the pipeline, it is easy to produce buckling failure when its stress and deformation conditions deteriorate slightly. The causes of pipe buckling usually include elastic instability under external pressure, local buckling caused by mechanical action or pipe defects, bending buckling and longitudinal buckling like “pressure rod”.

Pipeline buckling failure cases occur from time to time. Onshore pipelines are more prone to buckling due to the complex and varied environment they pass through and the limitations of pipeline material design. Compared with onshore pipelines, subsea pipelines may be more prone to buckling failure, especially during pipeline laying, but subsea pipelines are designed to take into account the failure of pipelines due to large deformation, so they are more resistant to large deformation.

Through case analysis, four modes of pipe buckling are summarized: asymmetric buckling, symmetrical buckling, concave and convex buckling and full circle buckling. The summary of buckling modes is shown in Table 2 and Fig. 3. Asymmetric buckling shows asymmetric distribution of buckling morphology in axial direction. Symmetric buckling shows that the axial distribution of buckling morphology is symmetrical. The concave-convex buckling shows that there are bumps and depressions in the buckling morphology. Full circle buckling shows that the buckling is distributed throughout the circumference of the pipe.

Table 2. Summary of buckling mode of steel pipe

Buckling mode	Description	Legend
Asymmetric buckling	The buckling morphology is asymmetrically distributed in axial direction	Fig. 3 (a)
Symmetric buckling	The buckling morphology is symmetrically distributed in axial direction	Fig. 3 (b)
Concave-convex buckling	Bulge and depression exist in the buckling morphology	Fig. 3 (c)
Full circle buckling	The buckling is distributed throughout the circumference of the pipe	Fig. 3 (d)

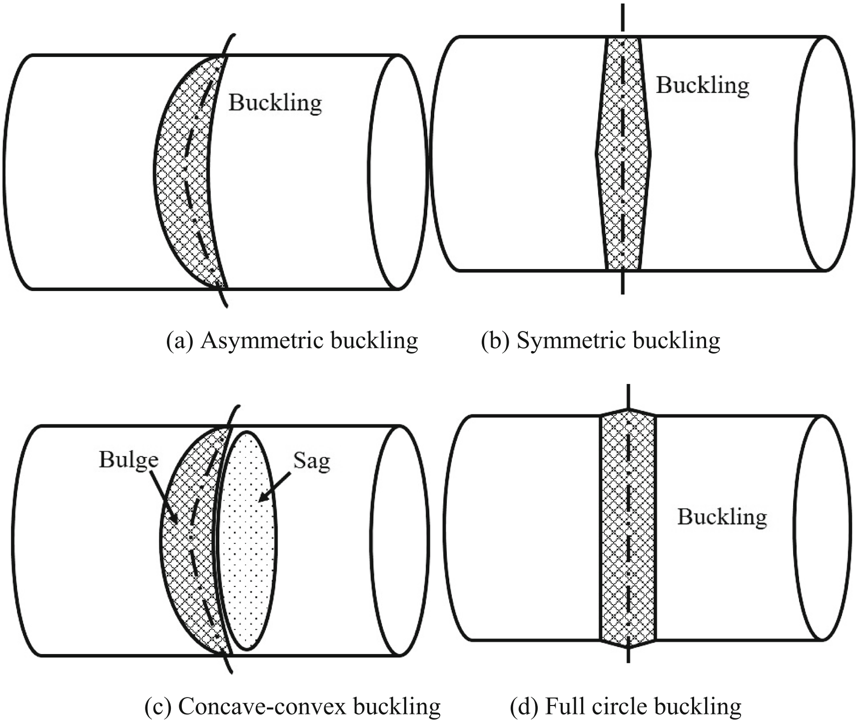

Fig. 3. Schematic diagram of four buckling modes and actual cases **a** Asymmetric buckling, **b** Symmetric buckling **c** Concave-convex buckling **d** Full circle buckling

4 Conclusion

In this paper, the buckling failure analysis of steel pipe and related literature were investigated and analyzed, the causes of pipe buckling failure were calculated, and the buckling factors in each case were summarized. There are four models of steel pipe buckling, which are asymmetric buckling, symmetric buckling, concave buckling and full circle buckling. Each buckling mode has different load forms.

Based on the research results of this paper, pipeline operators can find high risk scenarios of buckling failure according to the service environment along the pipeline, and then take measures to release the stress of the pipeline, so as to avoid excessive stress concentration caused by external load and prevent buckling failure accidents.

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