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Field testing and analysis of stress within buried gas pipelines in subsidence areas in shanghai

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Abstract. The Ground subsidence resulting from high-rise buildings becomes more and more serious in recent years, especially accompanied with rapid urban constructions. In this paper, a field monitoring system for subsidence and stress of buried natural gas pipeline was established, located in the neighboring area of Shanghai Center Tower, the tallest building in China. A theoretical model in which buried gas pipe was treated as an elastic foundation beam was put forward, and the subsidence data was input into the numeric model to predict stresses. Field test showed that, the test section was seriously influenced by the construction of Shanghai Center,and the subsidence data and stress data were just at the beginning stage of gradual subsidence. Theoretical calculation showed that the calculated stresses were compared with measured data and the calculations were validated.

Key words. Buried gas pipeline, settlement and stress monitoring, stress calculation.

1. Introduction

Natural gas is playing a more and more important role in Chinese domestic energy consumption. The safety and reliability of gas pipeline network are directly related to the the operation of the city. Recent years, the gas leakage accidents occurred occasionally due to corrosion or cracking of buried gas pipelines, the deformation of pipelines and ground subsidence are one of the most important reasons [1−3].

By the end of 2012, high-rise buildings (taller than 24m) in Shanghai accounted up to more than25, 000, and in Lujiazui area of Pudong district, more than 40 buildings taller than 100m have been distributed within 1.7 km^2, and average ground subsidence amounted up to 15mm per year. The ground subsidence will impact on the surrounding buried gas pipeline, it is highly essential to monitor the real state of buried gas pipelines in subsidence area, therefore to ensure safe operation of gas

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networks.

During modern urban construction processes, ground subsidence, maximum surface slope and pipeline subsidence were commonly-used indexes to evaluate the safety of buried pipelines. Due to the differences of buried pipeline in terms of material, function, soil environment, construction quality etc, it is impossible to evaluate the state of gas pipeline only by means of ground subsidence monitoring [4,5]. Pipeline stress monitoring can reflect internal stress quite precisely but it is also impractical to implement due to limitations from cost, soil property and long-term reliability of stress gauge involved. In this paper a buried gas pipe in the neighborhood of Shanghai Center was selected as research target and an on-site system for subsidence and stress monitoring was established to continually record stress state.

2. Experimental Facilities

The tallest building in China, Shanghai Center, with 124 floors above ground and 632m height, had a huge foundation pit 34960m^2 with depth of 31.2m. During the construction of Shanghai Center serious ground subsidence had been observed and reported. In order to ensure safe operation of neighboring gas networks, it was decided that a DN300 gas pipe located to the west of its foundation pit should be renovated. With sponsorship of Shanghai Gas Pudong Sales Corp., a research project was initiated to measure stresses within buried gas pipelines. Figure.1 is the onsite arrangement of the system. There are 14 sinking mark observations and 11 stress monitoring points with intervals of about 12m, while 2 data acquisition stations have been set to collect the strain testing data and transmit it through GPRS.

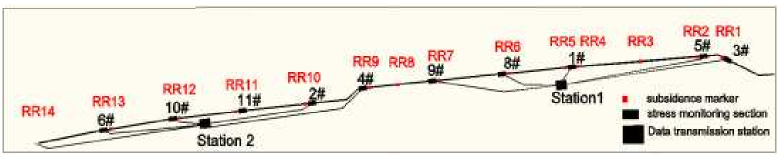


Fig. 1. Schematic diagram of monitoring equipment arrangement

Resistance strain gauge has been used as strain test sensor. For each test section 4 sets of strain-foils were uniformly arranged along circumference to record stress on left, right, top and bottom side of the pipe, while stainless steel sleeve was designed to protect against underground water. The length of stress test section is 1.5m with stain gage pasted in the middle, to avoid high temperature deformation and residual stress produced in welding. The state of pipeline settlement is obtained by regular monitoring of sinking mark observation, which is arranged on the top of the pipeline and installed with Gas Piping Construction.The subsidence marker consisted of annular collar, stainless steel pillar, protection sleeve and on-road cover. The settlement of pipeline is checked manually through level gauge and total station with the period of 3˜7 days according to the change of load and onsite testing results.

3. Field Test and analysis of the Monitoring System

The tested gas pipe was of 8mm-thick Q235 steel with length of 130m, consisting of several 12m-long standard pipes and 11 test sections inserted. The 11 test sections (labelled as 1#˜6#, and 8#˜12#) were equipped with strain-foils, with interval of about 12m from one another. Meanwhile 14 subsidence markers were arranged, labelled as RR1˜RR14 in Fig.1. The depth of the pipe was 1m. 50cm thick layer of sand were backfilled under and above the gas pipes, respectively. The system was put into use in November17th, 2011, and preliminary data had been obtained.

3.1. Gas pipe subsidence data

In this paper all subsidence data were taken with respect to the original position exactly after finish of construction, and the negative means subsidence downwards and positive means float upwards. Shown in Fig.2 are subsidence data of 14 markers until Aug.2013, and apparent subsidence could be found. Basically the subsidence of gas pipe can be classified into three stages: foundation pit construction, soil rebound, and stable subsidence. Before Feb. 2012, the foundation pit of Shanghai Center was closed to finish, the gas pipe was proved to subside rapidly as a result of pit operation and water drainage. From Feb. 2012 to April 2012, the construction within pit finished and level of underground water increased. The gas pipe was found to float to some extent, and subsidence decreased. Some monitored points even gave positive values, suggesting that the gas pipe rose to a taller position than finished. From April 2012 on, the subsidence were found to decrease gradually since only impact of building load remained. In addition, the gas pipe was found to float a little bit during Jul-Sep, 2012, the rainy days. By Aug. 2013, the deepest subsidence was 17mm.

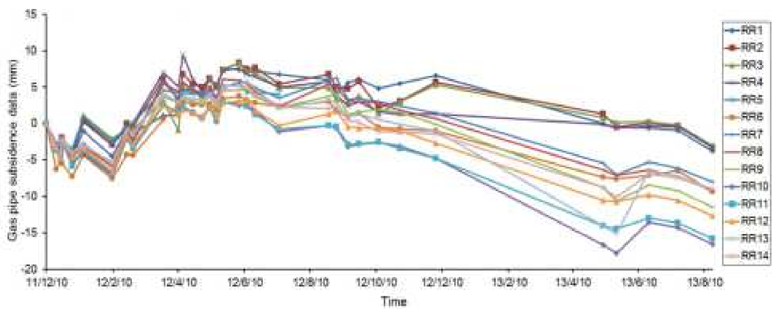
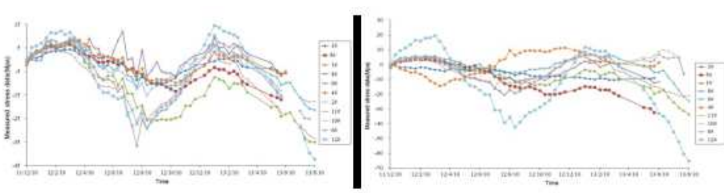


Fig. 2. Subsidence data by 10-Aug-2013

3.2. Stress data

As mentioned above, at each monitoring section 4 sets of strain-foils were uniformly arranged along circumference to record stress on left, right, top and bottom side of the pipe. Suffix -a, -b, -c, -d was designated to describe the following location:

"-a" denotes top, "-b" denotes close to Shanghai Center, "-c" denotes bottom, and "–d" denotes away from Shanghai Center. The measured stress data at "-a" and "-b" directions were illustrated in Fig.3.



(a) Position "-a" (b) Position "-b"

Fig. 3. Measured time-dependent stress data at different positions

From Fig.3(a) it can be found that measured stresses along gas pipe changes in a regular pattern. From Dec. 2011 the measured stresses were found to increase gradually and reached the maximum values (12MPa) in March, 2012. Afterwards the stresses decreased to negative values and reached -35MPa. Compared with allowable maximum 235MPa, the gas pipe can be considered as safe and sound up to now. The Fig.3(b) suggested that horizontal movement appeared to be more radical than vertical subsidence, leading to quite appreciable stresses.

3.3. Calculations

3.3.1. Force analysis of gas pipe The shape change of gas pipe subjected to ground subsidence is a combination of axial stretching (or compressing) and bending effect. If axial force and flexural moment can be deduced the stress at any longitudinal location can be calculated. Most of force and stress analysis for buried pipes available are based upon elastic foundation beam [6,7], taking into consideration the interactive effect between pipe and soil. With reference to Winkler's model, the flexural moment and forces can be calculated from change of pipe shape.

The buried gas pipe can be considered as a beam within elastic foundations. Therefore following equation which describes relationship between displacement and load can be deduced under elastic foundation beam theory [8]:

$$EI\frac{d^4y}{dx^4} + ky = q_{(x)} \tag{1}$$

Where: EI-bending rigidity of beam cross-section; k-foundation coefficient; y-displacement of the pipe; q - load applied to the pipe.

If the shape of beam can be achieved, following equation can be used to determine flexural moment and shearing force at any location:

$$\left.\begin{array}{l} M = -EI\frac{d\theta}{dx} = -EI\frac{d^2y}{dx^2} \\ Q = \frac{dM}{dx} = -EI\frac{d^3y}{dx^3} \end{array}\right\} \tag{2}$$

From Eqn (2) it can been that if displacement (e.g. subsidence) at different locations can be input to determine the shape of buried pipe, flexural moment and shearing can also be derived from derivatives. Therefore stress can be determined as well.

3.3.2. Comparison between calculated/measured stresses The discreteness of pipe subsidence data from on-site measurement cannot represent the actual shape of buried pipe. In addition Eqn (2) requires that input shape curve should be mathematically smooth and continuous. In this paper 6-order polynomial was fitted from discrete subsidence data, and stresses were calculated.

To input fitted curve into Eqn(2) can give stress along longitudinal axis. Shown in Fig.4 are comparison between calculated stresses and measured stress (from monitoring system) at different locations, for some specific dates. Quite good agreement can be found from the comparisons, suggesting the technical approach that determines stress from subsidence measurement seem feasible enough. However the calculated stresses were a bit smaller than measured values. This can be attributed to traffic load, soil frictions, etc, all of which had been neglected in above model. The bending section between 9# and 10# has some impact upon the prediction accuracy in the neighboring area.

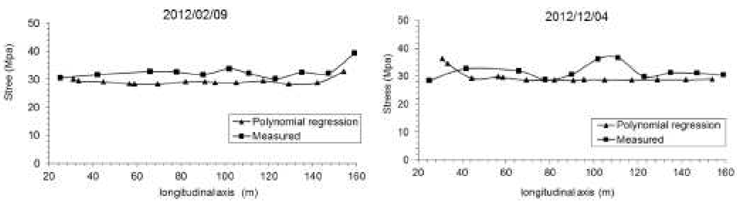


Fig. 4. Comparison of calculated stresses with measured stresses

The technical approach which determines stress within buried gas pipe from least square regressive curve can give quite reasonable agreement with measured values. Because measured subsidence data contain errors inevitably the regressed curve cannot represent the shape of buried pipe completely. In particular more discrepancy was found to exist at both ends.

4. Results and conclusions

Combined the construction of the gas pipeline, an on-site monitoring system for settlement and stress-strain is established, located in the neighboring area of Shanghai Center Tower. The on-site measurement data showed that test section was seriously influenced by the construction of Shanghai Center. Three stages, namely construction of foundation pit, soil rebound, and stable subsidence, can be observed. During the last stage the gas pipe are found to subside gradually, but some float are observed due to underground water movement.

The measured stress values are found to be increase gradually. The stresses fluctuated from positive to negative. Analysis of four strain-foil at the same crosssections suggested that gas pipe is subjected to both axis force and bending effect. Meanwhile horizontal displacement happens together with vertical subsidence.

A method based upon elastic foundation beam was incorporated to calculate stress at different locations. Good agreement between calculated stresses and measured stresses suggest the feasibility of proposed approach. But the number of subsidence should be increased to minimize error resulting from polynomial fitting processes.

Ground subsidence resulting from high-rise buildings has been proved to be a long, slow effect. Up to now subsidence data and stress data show that it is just at the beginning stage of gradual subsidence. The absolute values for stress were much lower than maximum allowable. The calculation method proposed remains to be checked and validated in the long run.

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