

Original Research Article

The mechanical properties of the rubber gasketed joints on ductile iron pipes

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Abstract: The mechanical properties of the rubber gasketed joints on ductile iron pipes are analyzed, which are commonly used in the water supply system. The theoretical calculation formulas of the maximum pull force and moment in the the rubber gasketed joints are deduced, and the maximum safe rotation is given. Based on the early test results, the stiffness matrix of the rubber gasketed joints on ductile iron pipes is established. Outcome of the research project can offer theoretical and technical support for the numerical simulations on the rubber gasketed joints.

Keywords: Ductile iron pipeline; gasketed joints; mechanical properties; stiffness matrix

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1. Introduction

In modern industrial development, underground pipelines have long occupied an important position and have been widely used in oil, natural gas, heat, water supply and drainage, communications, electricity, transportation and other fields. Some of these pipelines are known as "lifeline" projects for transporting water and natural gas that support urban life. The action of earthquake easily causes a great deal of damage and various serious secondary disasters^[1]. Summing up the previous earthquake damage experience^[2,3], it can be seen that if the corrosion factor of the pipe is not considered, the joint damage is the main failure mode of the pipe in earthquake compared with the strength of the pipe itself. Therefore, domestic and foreign scholars have conducted a large number of theoretical and experimental researches on the failure mode and mechanical properties of the pipe joint.

Singhai, AC.^[4] conducted a series of experimental

studies on the mechanical properties of flexible connection pipes, including axial, bending and torsion tests. Wham, B. P. *et al.*^[5,6] carried out a comparative study of axial pull-out test and bending test under large deformation on commonly used joints and improved joints. Combined with finite element numerical analysis, it is proposed that the joints leakage is only related to the stress distribution of rubber gaskets, not to the loading path. Zhou Jinghai *et al.*^[7,8] conducted pull-out tests on flexible joints of ductile iron pipes and UPVC pipes, and analyzed the relationship between axial tension and displacement under different pipe diameters and with and without water pressure. None of the above studies considered that the rubber gasket is super-elastic, nor did they consider the coupling effect of various stress and strain fields under non-linear conditions. In terms of performance test of pipeline joints, Institute of Beijing Municipal Engineering Research, Institute of Building

Standard and Design Research, General Institute of Construction and Research of Ministry of Metallurgy, *et al.*^[9] have carried out a series of experimental studies on tensile properties of pipeline joints, and proposed the axial allowable displacement value of pipeline joints, which provides reference basis for seismic damage analysis of pipelines and revision of relevant standards. Han Yang *et al.*^[10,11] preliminarily analyzed the non-linear coupling characteristics of rubber gasketed joints based on the axial pull-out, lateral bending and pull-bending coupling tests under different pipe diameters, with and without water pressure and different loading modes. Zhong Zilan *et al.*^[12] conducted axial drawing and transverse bending tests on ductile iron pipelines with gasketed joints, and analyzed mechanical properties and failure modes of the axial resistance and transverse bending resistance of repaired pipe joints, and established a failure criteria of repaired pipeline joints. The above scholars have made outstanding contributions to the research on earthquake resistance of buried pipelines, but due to various factors, the stress of buried pipelines under earthquake is extremely complicated^[13]. Finite element analysis technology has been widely used in various complicated engineering structure analysis, which avoids the complexity and limitation of test conditions and greatly improves the research efficiency. It has become the development trend of modern

scientific research^[14,15]. However, the development of finite element analysis technology for sectional socket buried pipelines is relatively slow, mainly due to the lack of necessary joint stiffness matrix.

On the basis of summarizing the previous research results and combining with the previous test results^[16-18], this paper puts forward the theoretical calculation formulas of the maximum pull force and moment in the the rubber gasketed joints, and establishes the stiffness matrix of the rubber gasketed joints on ductile iron pipes. It ensures the safety of lifeline engineering and provides data reference basis to the nonlinear response analysis and seismic design of buried pipelines under site disaster environment.

2. Analysis of mechanical properties of gasketed joints

The ideal design of lifeline engineering pipeline is that the pipe body and joints are ductile so that the pipeline can move along with the ground. In this paper, the mechanical characteristics of joints are analyzed, taking the rubber gasketed joints on ductile iron sectional pipes which are commonly used in municipal water supply system in China as an example. This kind of pipeline joint is a slide-in socket connection, and the joint is sealed by super-elastic rubber gasket. The T-joint of slide-in ductile iron pipe is shown in **Figure 1**.

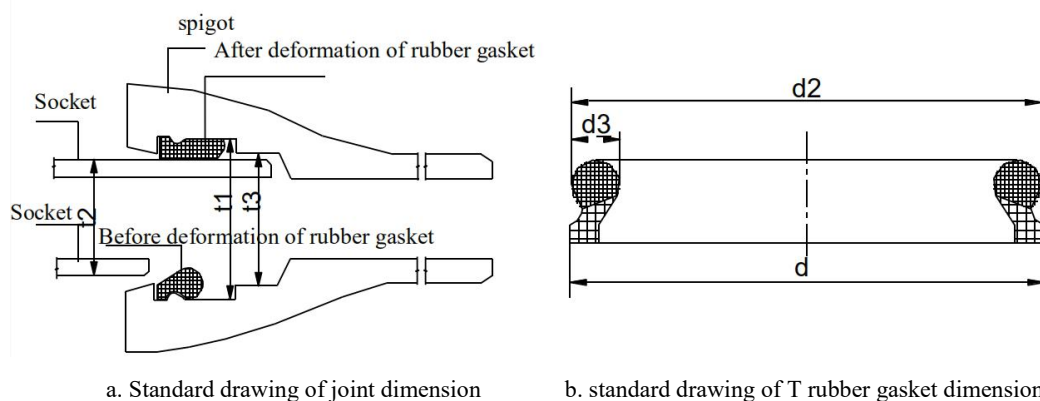


Figure 1. Standard drawing of T-joint of slide-in ductile iron pipe

2.1 Analysis of axial mechanical properties

For socket-type gasketed joint pipe section, the joint mainly relies on the friction force between the rubber gasket after compression and the socket to resist axial load. When the axial load is less than the maximum static friction force between them, the joint is considered safe. On the other hand, the socket can also bear a small

amount of displacement at the joint when inserted at a certain distance. As the load continues to increase, when the axial load is greater than the sliding friction at the joint, the pipeline will fail.

Starting from Hooke's Law, the formulas for calculating the maximum static friction and sliding friction of gasketed joints can be deduced. Hooke's Law:

$\Delta L = \frac{FL}{EA}$, considering radial compression of rubber

gasket per unit length, then $\Delta L = d_3 - \frac{t_1 - t_2}{2}$,

compression area $A = k\pi d_3$, pressure on rubber gasket

per unit length $F = 4kE\pi(d_3 - \frac{t_1 - t_2}{2})$, static friction

coefficient μ between rubber gasket and the pipeline is introduced, and the calculation formula of maximum axial tension of gasketed joint of pipeline can be obtained after organizing, as shown in formula (1).

$$P = k\mu E\pi^2 t_2 (d_3 - \frac{t_1 - t_2}{2}) \quad (1)$$

k: Related to compression ratio of rubber gasket,

μ : Static friction coefficient between rubber gasket and the pipeline,

E: Elastic modulus of rubber gasket,

t1: Inner diameter of socket,

t2: Outer diameter of pipeline,

d3: Diameter of rubber gasket.

2.2 Analysis of bending mechanical properties

The socket joint of ductile iron pipeline is connected by rubber gasket and sealed by super-elastic property of rubber material. Therefore, the joint can be seen as a flexible chain of rigid connection, thus the sectional pipeline can bear certain bending strain under ground displacement or vibration. The bending capacity depends on the bending rigidity of the joint material itself and the compression deformation capacity of the rubber gasket. Depending on the pressure generated by the compressed rubber gasket, the force at the joint is in a balanced state. The shape of the compression gasket

and the elastic modulus of the rubber are known, and the maximum resistance bending moment of the joint can be calculated by formula (2).

$$M = \frac{4\pi t_2 E f^3}{9(t_1 - t_4)} \theta \quad (2)$$

According to the existing domestic standards, after the socket enters the spigot through the compression rubber gasket, they only contact with each other through the rubber gasket with a gap between them. The bending of the joint depends to a large extent on the geometric clearance of the pipe joint design. Unilateral clearance

$\Delta t = \frac{t_3 - t_2}{2}$, rubber gasket compression thickness

$\Delta d = d_3 - \frac{t_1 - t_2}{2}$, under the action of vertical load,

assuming that the pipe socket bends at the same time,

there is $\tan \theta = \frac{\Delta t}{f}$, then $\theta = \arctan \frac{\Delta t}{f}$.

θ : Bending angle of the joint,

f: Socket insertion depth,

M: The maximum bending moment of the joint (kN·m),

t4: The inner diameter of the socket end.

According to the formulae above, the maximum bending angle of pipe socket and spigot before collision can be deduced. **Table 1** gives the clearance angles of several common pipe diameters. As can be seen from **Table 1**, for current rubber gasketed joints on ductile iron pipes, the maximum safe angle of socket and spigot clearance is slightly larger than 3°, which is fully taken into consideration. That is to say, when the safe angle is exceeded, the metal collision between socket and spigot will occur, and the higher metal collision stress will be generated when bending continues, which greatly causing the failure probability of the joint.

Diameter (mm)	t1 (mm)	t2 (mm)	f (mm)	Angle (°)	Notes
100	123.4	118	88	3.5	
150	175.3	170	94	3.2	
200	227.8	222	100	3.3	All larger than 3°
300	332.1	326	110	3.2	
600	642.6	635	120	3.6	

Table 1. Socket and spigot clearance angles of several common pipe diameters

3. Stiffness analysis on gasketed joints of sectional pipes

3.1 Simplified Calculation Model of gasketed joints

In practical engineering, buried pipelines can be simplified calculated through elastic foundation beam model because the overall stiffness of them is consistent. However, the rigidity of the sectional pipe joint is much

lower than that of the pipe body. The maximum joint displacement and maximum joint angle are two important parameters for pipe failure, and the calculation model is relatively complex. Therefore, there are less researches on mechanical properties of sectional pipeline interface currently, and there is greater blindness and risk in the safety design of the interface. Figure 2 shows the schematic diagram of sectional pipes.

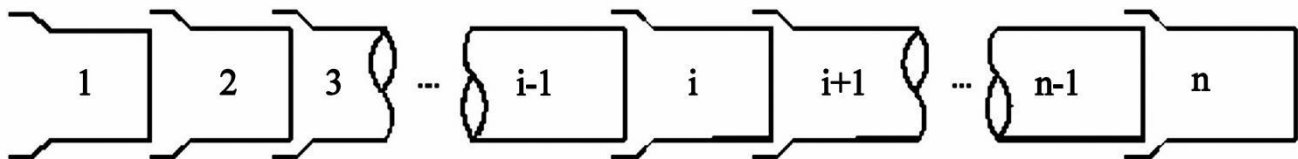
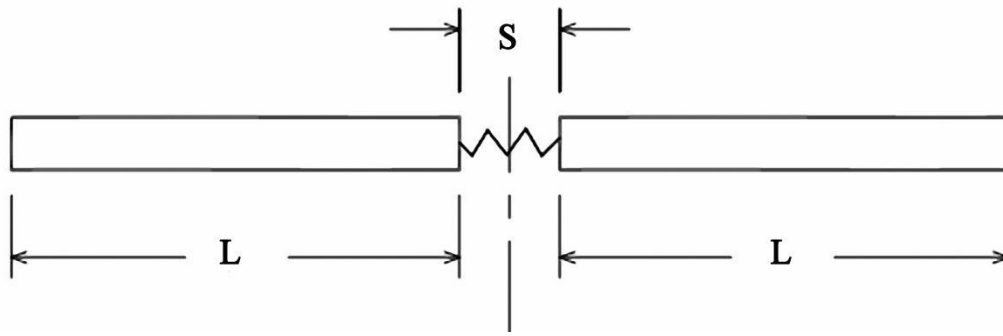


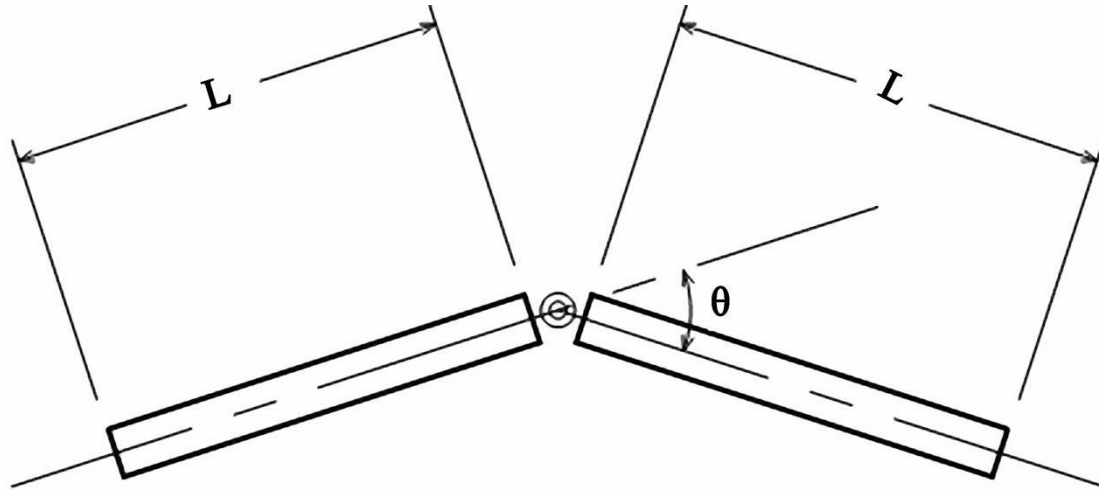
Figure 2. Schematic diagram of sectional pipes

Considering complexities of the interface stress and limitations of this study, only the interface stiffness under axial pullout and transverse bending stress modes is discussed in this paper. Most of the strain is borne by the pipe joint, while a small part is absorbed by the pipe body with the action of various loads. In order to simplify the calculation, it can be assumed that the pipe

body is infinitely rigid and the strain is considered to be fully borne by the interface. Rubber gasketed joints can bear certain axial and bending deformation, thus the axial direction of the joint can be simplified as a spring connection with resistance, and the joint also has certain bending deformation capability. The joint simplified calculation model is shown in Figure 3.



(a) Simplified model of axial direction of the joint



(b) Simplified model of bending deformation of the joint

Figure 3. Simplified calculation model of rubber gasketed joints

3.2 Analysis on joint stiffness matrix

According to the calculation model diagram, the pipeline brings about s of axial displacement and θ of bending deformation with the action of seismic wave, bearing axial tension F and transverse moment M . Under the coupling effect of the two loads, it is assumed that the joint's load-deformation relation is a quadratic polynomial, as shown in equation 3.

$$\begin{Bmatrix} F \\ M \end{Bmatrix} = \begin{bmatrix} K_{11} & K_{12} \\ K_{21} & K_{22} \end{bmatrix} \begin{Bmatrix} s \\ \theta \end{Bmatrix} + \begin{bmatrix} K_{11} & K_{12} & K_{13} \\ K_{21} & K_{22} & K_{23} \\ K_{31} & K_{32} & K_{33} \end{bmatrix} \begin{Bmatrix} s^2 \\ s\theta \\ \theta^2 \end{Bmatrix} \quad (3)$$

As the coupling effect is a highly nonlinear comprehensive problem, this paper only discusses the single stress mode, ignoring the joint coupling effect for the moment. In this case, joint controlling is deduced in equation 4.

$$\begin{Bmatrix} F \\ M \end{Bmatrix} = \begin{bmatrix} K_{11} & K_{12} \\ K_{21} & K_{22} \end{bmatrix} \begin{Bmatrix} s \\ \theta \end{Bmatrix} \quad (4)$$

4. Stiffness matrix of rubber gasketed joints based on test data

Based on the test of axial tensile and transverse bending^[16-18] on rubber gasketed joints of ductile iron pipes with three diameters of DN150, DN200 and DN300, stiffness coefficient of the rubber gasketed joints of ductile iron pipes is given in this paper, and joint stiffness matrix is established, among which $K_{12}=K_{21}=0$, K_{11} and K_{22} are obtained from experimental data.

4.1 Stiffness coefficient of axial direction

According to analysis on the previous experimental data of gasketed joints' axial tensile test, the curve of axial tensile force and interface displacement is simplified to two straight lines (Figure 4). The OB line segment is a completely linear elastic stage; the corresponding pulling force and displacement of the B point are F_0 and s_0 respectively; the slope of the OB line segment is K_{11} , the axial stiffness; BC line segment is the interface displacement sliding stage; and the pulling force is the maximum sliding friction force, which is

considered unchanged with zero rigidity.

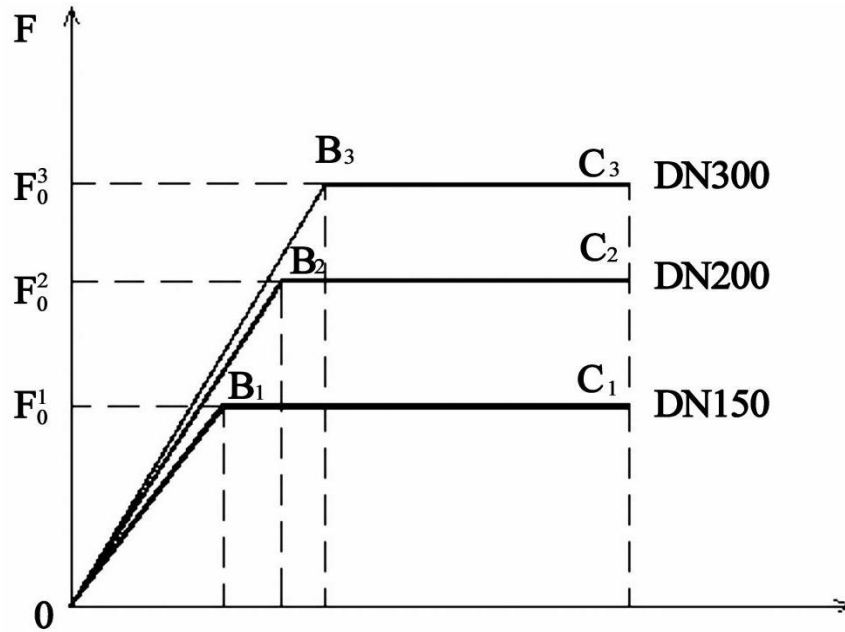


Figure 4. Simplified Model of F-S Curve

Based on the statistical analysis of test data, of three pipe diameters b I (I = 1, 2, 3) are given in Table 2. interface tension, displacement and axial stiffness values

Pipe Diameter	s_0 (mm)	s_{max} (mm)	F_0 (kN)	Axial stiffness value(kN/mm)	
				$s < s_0$	$s_0 < s < s_{max}$
DN150	20.08	24.26	8.16	0.4064	0
DN200	28.52	38.40	13.266	0.4651	0
DN300	30.31	42.52	17.231	0.5685	0

Table 2. Axial stiffness value of gasketed joints

4.2 Bending stiffness coefficient

According to the transverse bending test of the interface, the bending moment and rotation angle curve of the joint is simplified as double oblique lines (Figure 5). In the figure, OB line segment is the linear elastic stage of the compression rubber gasket ; B point is M_0 and θ_0 for bending moment and rotation angle; the slope

of OB line segment is the bending rigidity K_{22} in the linear elastic stage of the flexible joint. BC line segment is the stress intensifying stage of metal collision of pipe socket after the compression limit of rubber gasket. With the continuous increase of load, the stress rapidly intensifies until the interface is damaged. The slope of BC section is the bending rigidity of this stage.

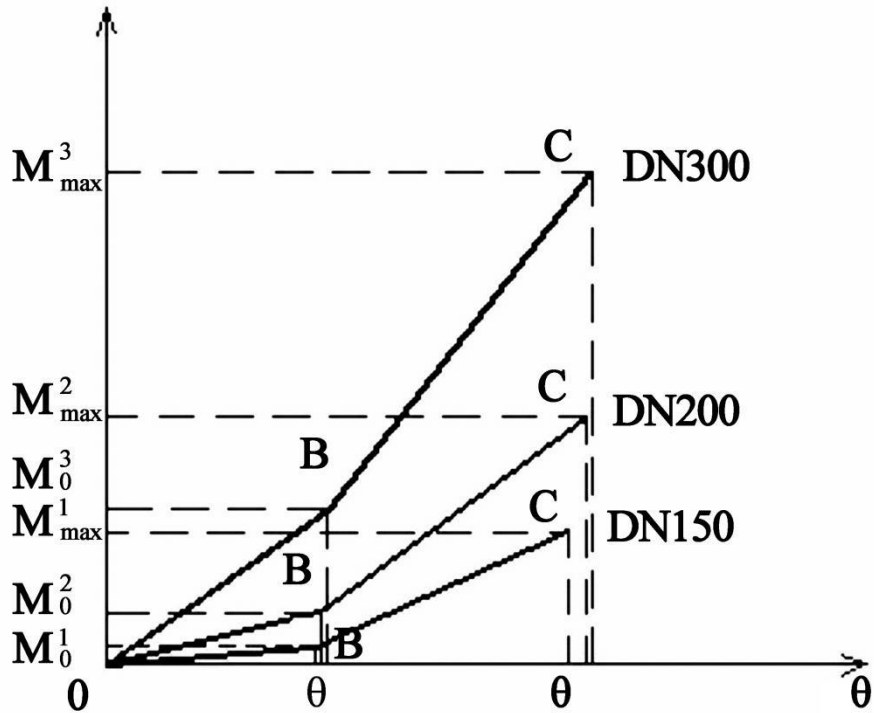


Figure 5. Simplified model of M- θ curve

According to the analysis of experimental data, **Table 3** gives the joint bending moment, rotation angle

and joint bending stiffness values at B points of three pipe diameters.

Pipe Diameter	$\theta_0(^{\circ})$	$\theta_{max}(^{\circ})$	$M_0(kN \cdot m)$	$M_{max}(kN \cdot m)$	bend rigidity coefficient ($kN \cdot m/^{\circ}$)	
					$\theta \leq \theta_0$	$\theta_0 < \theta \leq \theta_{max}$
DN150	3.47	7.71	0.32	2.23	0.09	0.45
DN200	3.59	8.00	0.89	4.13	0.25	0.73
DN300	3.70	8.09	2.59	8.19	0.70	1.28

Table 3. Stiffness Value of rubber gasketed joints

4.3 Stiffness matrix of flexible interface

Based on the analysis above, the simplified stiffness matrix of the rubber gasketed joints of ductile iron pipe aprons with diameters of DN150, DN200 and DN300

under axial and bending moment loads can be deduced. According to the different stages of the two loads, there are four forms of joint stiffness matrix of each pipe diameter, as shown in **Table 4**:

Pipe Diameter (mm)	K			
	$s < s_0$	$s < s_0$	$s_0 < s < s_{max}$	$s_0 < s < s_{max}$
	$\theta \leq \theta_0$	$\theta_0 < \theta \leq \theta_{max}$	$\theta \leq \theta_0$	$\theta_0 < \theta \leq \theta_{max}$
DN150	$\begin{bmatrix} 0.4064 & 0 \\ 0 & 0.09 \end{bmatrix}$	$\begin{bmatrix} 0.4064 & 0 \\ 0 & 0.45 \end{bmatrix}$	$\begin{bmatrix} 0 & 0 \\ 0 & 0.09 \end{bmatrix}$	$\begin{bmatrix} 0 & 0 \\ 0 & 0.45 \end{bmatrix}$
DN200	$\begin{bmatrix} 0.4651 & 0 \\ 0 & 0.25 \end{bmatrix}$	$\begin{bmatrix} 0.4651 & 0 \\ 0 & 0.73 \end{bmatrix}$	$\begin{bmatrix} 0 & 0 \\ 0 & 0.25 \end{bmatrix}$	$\begin{bmatrix} 0 & 0 \\ 0 & 0.73 \end{bmatrix}$
DN300	$\begin{bmatrix} 0.5685 & 0 \\ 0 & 0.70 \end{bmatrix}$	$\begin{bmatrix} 0.5685 & 0 \\ 0 & 1.28 \end{bmatrix}$	$\begin{bmatrix} 0 & 0 \\ 0 & 0.70 \end{bmatrix}$	$\begin{bmatrix} 0 & 0 \\ 0 & 1.28 \end{bmatrix}$

Table 4. Stiffness matrix of rubber gasketed joints on ductile iron pipelines

5. Conclusion

On the basis of theoretical and experimental studies on gasketed joints of sectional pipelines at home and abroad, and combined with previous experimental studies, the following conclusions are drawn in this paper:

1) For gasketed sectional pipelines, axial load resistance mainly depends on the friction between the pipeline and rubber gasket; and the bending depends to a great extent on the designed joint geometry clearance.

2) Based on Hooke's Law, the theoretical calculation formulas of the maximum pull force and moment in the the rubber gasketed joints are deduced and safe bending angle is given, which provide a basic theoretical research on the coupling effect of ductile iron pipes under various loads, and play a reference role in the design of gasketed joints on pipes.

3) The simplified curves of axial pull force and displacement, bending moment and angle of rubber gasketed joints on ductile iron pipelines are established, and the stiffness matrix of gasketed joint of this kind of pipelines is given. The variable form of stiffness matrix coefficient mainly depends on the form of the joint and the connection mode, which is convenient for computer simulation and provides theoretical and technical support for numerical simulation research of rubber gasketed joints on pipelines.

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