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Simulation of Deformation Transfer Coefficient of Pipe Bend Buried Based on Shaking Table Test and Goodman Contact Element

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Abstract. Due to the large difference of stiffness between pipe and soil, the movement of the two can not be coordinated under seismic. Therefore, the deformation transfer between pipe and soil is a very important research content in the study of pipe failure. At present, scholars have done less research on the pipe-soil deformation transfer of elbow. In this paper, the fitting formula of deformation transfer coefficient of buried elbow under seismic action was obtained by scale shaking table test of pipe bend and 3D finite element model based on Goodman contact element. Then, the test results are compared with the calculation results of the fitting formula and the simulation results of the finite element method to verify the rationality of the fitting formula and analyze the change law of the deformation transfer coefficient at the elbow of the pipe, including the influence of different pipe diameters, buried depth, wall thickness, soil properties, and elbow angles. It is confirmed that these factors have a great influence on the deformation transfer between the pipe and soil, which indicates that the fitting formula of the deformation transfer coefficient at the elbow is of huge significance to the earthquake resisting design of pipe.

Keywords: Deformation transfer coefficient, elbow, shaking table test, goodman contact element, interaction of pipe and soil, earthquake resisting design of pipe

1. Introduction

Water supply and gas supply pipeline networks are an important part of the city's lifeline. In many seismic investigations, it is found that the damage of underground pipe network may damage water supply pipelines, fire-fighting devices and natural gas facilities. Moreover, earthquakes may also cause urban drainage problems and many secondary disasters, and bring great disasters to human life and production [1]. Hanshin Earthquake (M=7.3), more than 20,000 natural gas pipelines leak occurred in Osaka, most of which occurred in places where rivers are prone to liquefaction and welded steel pipe elbows in the 1995. In terms of water supply pipelines, only 900,000 households in Kobe city had no water supply, 23 elbows near the Shenqi River were damaged, and the sewage and rainwater discharge pipeline network in Kobe City was also severely damaged,

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reaching nearly 3m/ha [2]. In the 2008 Wenchuan earthquake (M=8.0), water supply and gas supply facilities including underground pipe network in nearly 20 cities and counties in Sichuan Province were seriously damaged. For example, the gas facilities and drinking water companies in Mianzhu, Beichuan, Dujiangyan and other cities have not been damaged, while the buried water and gas supply networks have been damaged, and the connections between pipelines have been seriously damaged, which can not be used normally and is difficult to repair [3]. Therefore, in the network design, the pipeline system in the city is the key facility to ensure people's livelihood.

In the earthquake, for the simple pipe-soil interaction, the buried pipeline will be damaged by the force generated by the pipe-soil interface interaction, in which the ground movement, wave propagation or permanent ground displacement (PGD) will cause damage to the buried pipeline [4]. The permanent ground deformation includes landslide, fault, lateral expansion and settlement, and the movement is not coordinated due to the deformation of the soil, resulting in uneven deformation of local surface of the pipeline. Therefore, the pipe-soil deformation transfer has a greater impact on the narrow failure of the pipeline network [5]. The local damage of the pipe network, such as the damage to the elbow and the damage of the pipe network nodes, is bound to bring greater challenges to the repair of the whole pipe network.

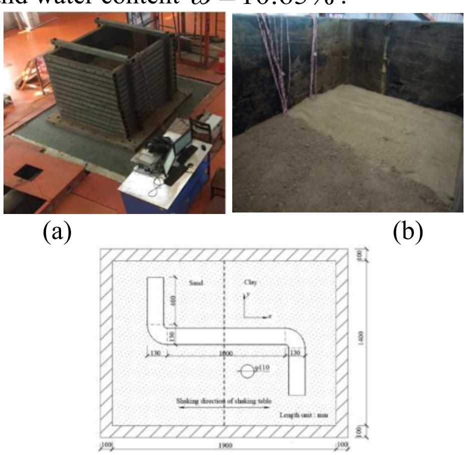
Currently, scholars' research on underground pipeline bending is limited to two aspects. The first is the reliability for network topology and network connection in disaster situations. These studies were based on the idea of probability, only pay attention to the damage probability of underground pipeline network, but do not study the mechanical mechanism of elbow damage [6-9]. Other aspect is the research on the safe operation and risk assessment of the pipeline network under earthquake conditions. This aspect is the deduction of the algorithm based on the monitoring data. These studies are the evaluation of the seismic performance of the existing underground pipeline network and the evaluation of the safe operation of the pipeline network through the data fusion of sensors, but they are not involved in the mechanical failure model of the pipeline network [10-19]. From the above analysis, it can be observed that many scholars no longer study single pipe, but study the underground pipe network involving bends. Their research is aimed at the probability analysis and algorithm research for pipelines, and the mechanical mechanism of bend failure is not mature.

For this study, shaking table test and finite element simulation based on Goodman contact element were utilized to study the coefficient of deformation transfer under seismic, and the formula was fitted according to the influencing factors. Then, change law of deformation transfer coefficient was discussed through comparison, which provided a theoretical basis for design of the bend.

2. Design of the Test

Due to the limitation of existing conditions, PVC-U pipe (unplasticized polyvinyl chloride pipe) was used to simulate iron pipe. PVC-U pipe is a rigid plastic pipe. According to the influence of model scale, the pipeline is not easy to be damaged by seismic wave and is always in the elastic stage. Therefore, the internal force and deformation trend of PVC-U pipe areas of iron pipe. Through the similarity of elastic modulus, PVC-U pipe can be utilized to simulate iron pipe. Figure 1 (c) below shows the form, layout, and dimensions of the elbow. The internal dimension of the shear box is 1900 × 1400mm, with a diameter of 100mm (75mm and 50mm in comparison test), a wall thickness t of 2.0mm (3.0mm and 4.0 mm in comparison test), an elastic modulus of 4000 MPa, a density of 1400 kg/m3, a Poisson's ratio of 0.3 and a buried depth of 0.3 m (0.2 m and 0.4 m in the comparative test).The elbow angle is 90 degrees (45 degrees and 135 degrees in the comparative test). The elbow was inserted into the straight pipe and coated with PVC-U special glue. Because the bonding strength of the special glue can reach the strength of the pipe itself, this form can simulate the welding of iron elbow. In the test, the end of the pipe was sealed with rubber to prevent the soil from entering the pipe and weaken the influence of shear box.

In this test, sand and clay were loaded into the laminated shear box on both sides. The shear box as shown in Figure 1(a) and compacted layer by layer as shown in Figure 1(b). The compacted height of the soil is 15cm for each layer. This test uses the volume and quality of each layer of soil to control the density of the filled soil. Therefore, it is slightly soft for the soil, according to the state, the shear wave velocity of the soil is about 120 m/s. After filling and tamping, a soil sample is collected from the shear box, and the physical parameters of the soil are measured with a pycnometer and a ring knife. For sand, the following physical parameter values were measured: density $\rho = 1692\ \text{kg/m}^3$, specific gravity $G_s = 2.62$, the internal friction angle $\varphi = 32^{\text{o}}$, cohesion $c = 0$ and water content $\omega = 0.18\%$. The corresponding values for the clay were: density $\rho = 1430\ \text{kg/m}^3$, specific gravity $G_s = 2.45$, the angle of internal friction $\varphi = 20^{\text{o}}$, cohesion $c = 5\ \text{kPa}$, and water content $\omega = 10.65\%$.



(a) (b)

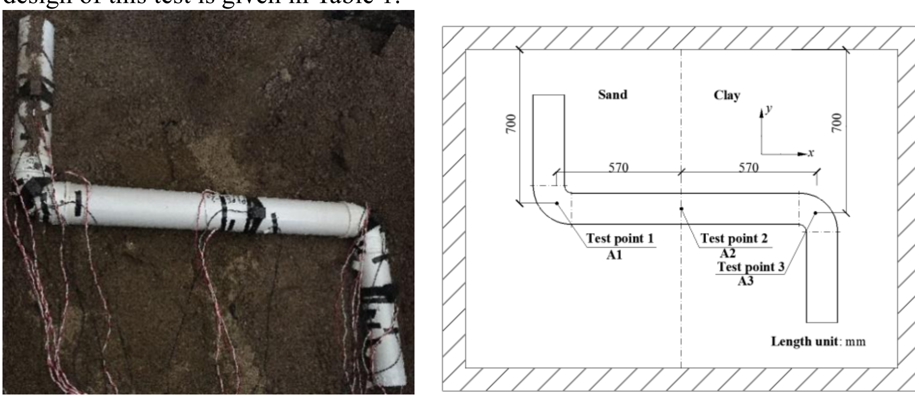
(c)

Figure 1. Design of test shear box, soil and pipe bend. (a) Laminated shear box. (b) The division of sand and clay. (c) Schematic diagram of pipe laying.

The acceleration measurement adopted the acceleration sensors that were produced at B&K in Denmark, with a measurement accuracy of 0.1 m/s^2. The acceleration sensor was installed in a closed iron box and fixed to the pipe to prevent interference from the outside soil, as shown in Figure 2(a). The arrangement of the accelerometers has been shown at A1, A2, and A3 in Figure 2(b), which were used to measure the acceleration of the first (Test point 1), second (Test point 2) and third section (Test point 3). Test point 1 and Test point 3 were located at the elbow. A DH5922N data acquisition system from the Donghua test company was adopted for data acquisition, with a sampling frequency of 1000 Hz.

The displacement sensor used in this test is LVDT (linear variable differential transformer), and its measurement accuracy is 0.1mm. Since the sensor measures the distance from the solid surface through expansion and contraction with the solid surface, it can only be arranged on the outer surface of the solid. It is arranged on the outer surface of the shear box and at the same height as the pipe, represented by DS. Because the size of the soil box is small, the displacement of the soil around the pipeline is approximately equivalent to that of the shear box, as shown in Figure 2 (b).

This experiment used dimensional analysis to identify similar relationships. Length l, elastic modulus E, and acceleration a were basic physical quantities. In multi-media coupling dynamic test, the similar relationship between the foundation soil and the pipeline structure should be kept as consistent as possible, and the soil should be tamped to be consistent with the actual site as far as possible. For the shaking table test, the similar design was mainly pipe structure. In the design of similarity ratio, the table size, dynamic performance, load-bearing tonnage and other supporting equipment performance of the test system should need to be fully considered. The similarity ratio design of this test is given in Table 1.



(a) (b)

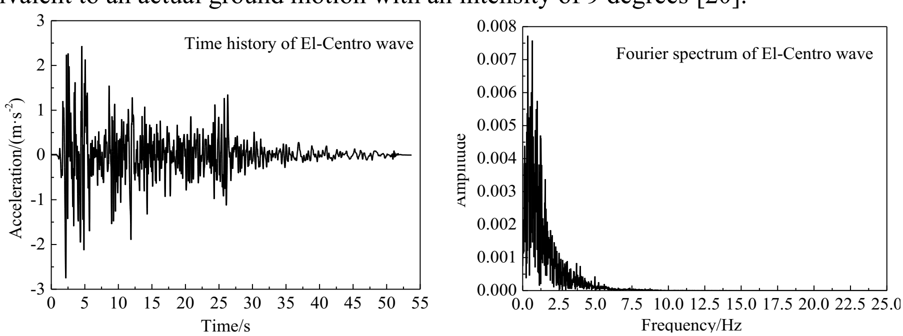
Figure 2. Sensors layout for pipe bend. (a) The sensors layout at pipe bend. (b) The design of sensors layout for pipe bend.

Table 1. Similarity ratio design of shaking table test.

Groups	Physical parameters	Similar relations	Similar ratio
Geometric parameters	Length l	S_l	0.10
	Area S	$S_S = S_l^2$	0.01
	Linear displacement u	$S_u = S_l$	0.10
	Angular displacement θ	$S_\theta = S_\sigma / S_E$	1.00
Material properties	Elastic Modulus E	S_E	0.02
	Stress σ	$S_\sigma = S_E$	0.02
	Strain ε	$S_\varepsilon = 1$	1.00
	density ρ	$S_\rho = S_E / (S_l S_a)$	0.10

Load performance	quality m	$S_m = S_\sigma S_l^2 / S_a$	1.00×10^{-4}
	Concentrated force F	$S_F = S_E S_l^2$	2.00×10^{-4}
	Linear load q	$S_q = S_E S_l$	2.00×10^{-3}
	Surface load p	$S_p = S_E$	0.02
	Moment M	$S_M = S_E S_l^3$	2.00×10^{-5}
Dynamic characteristics	Time t	$S_t = S_l^{0.5} S_a^{-0.5}$	0.22
	Frequency f	$S_f = S_l^{-0.5} S_a^{0.5}$	4.47
	Velocity V	$S_v = S_l^{0.5} S_a^{0.5}$	0.45
	Damping c	$S_c = S_\sigma S_l^{1.5} S_a^{-0.5}$	4.47×10^{-4}
	Acceleration a	S_a	2.00

Due to the limitations of the test equipment, when seismic waves were loaded, the seismic station only moves horizontally in one dimension. Consider the most unfavorable seismic wave input direction when designing the experiment. This paper uses El-Centro wave as the input prototype wave in Figure 3(a). The predominant frequency of Fourier spectrum corresponding to seismic wave is 1Hz in Figure 3(b). Because of the similarity ratio of the test, the seismic wave shape input by the shaking table must be tailored according to the similarity condition, that is, the prototype wave must be adjusted according to the time similarity ratio. In the shaking table test for bend in this paper, the pipeline moves along the x direction of Figure 1(c), and its peak value was converted to 0.8 g according to the similarity relationship. Intensity of this ground motion is equivalent to an actual ground motion with an intensity of 9 degrees [20].



(a) (b)

Figure 3. Prototype curves of seismic wave loaded. (a) The curve of time history. (b) The curve of Fourier spectrum.

3. Test Results and Formula of Deformation Transfer Coefficient

3.1. Test Results of the Pipe Bend

The acceleration of the pipe could be measured by the acceleration sensor A1 (D = 0.1 m, H = 0.3 m, t = 2.0 mm, θ = 90°) in the soil box of the site shaking table, as shown in Figure 4(a), and the displacement could be obtained by integrating twice, seeing Figure 4(b). The maximum displacement was 45.912 mm, and the corresponding time was 7.875s. When loading, the maximum value for the sensor DS measuring the soil displacement was 140.607 mm, and the corresponding time of the maximum displacement was 7.876 s, which indicated that the time of the maximum pipe-soil displacement was almost the same, as shown in Figure 5.

With the above method, the measured accelerations of A1 and A3 under different working conditions of four factors were integrated from 0 to 16.0 s, the displacement of the first 16.0 s was obtained, and the actual displacement of Test points 1 and Test point 3 was obtained, and the maximum displacement was found out. Then found out the maximum value of the soil displacement from the data recorded by the displacement sensor corresponding to each working condition, and utilized equation (1) to calculate the deformation transfer coefficient [21] of the elbow under each working condition, as shown in Table 2.

$$\beta = \frac{\Delta_{\mathrm{p}}}{\Delta_{\mathrm{s}}} \tag{1}$$

where Δ_{p} is the actual absolute displacement of the elbow; Δ_{s} is the actual absolute displacement of the soil.

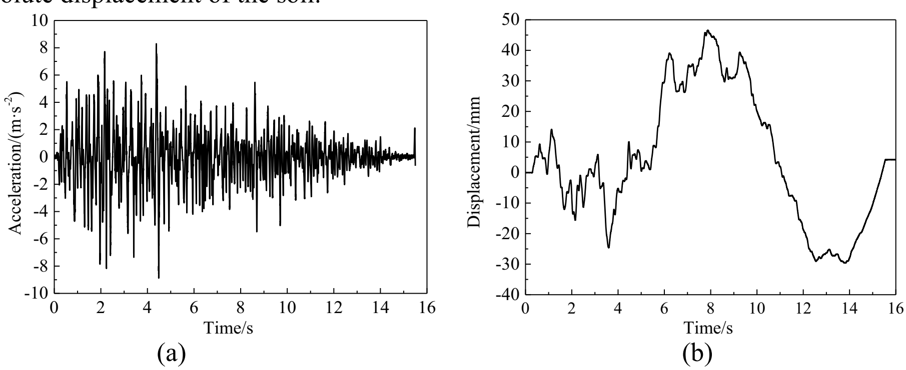


Figure 4. Time history curve of acceleration A1 and displacement curve obtained by integration. (a) Acceleration A1 time history. (b) Displacement integral time history.

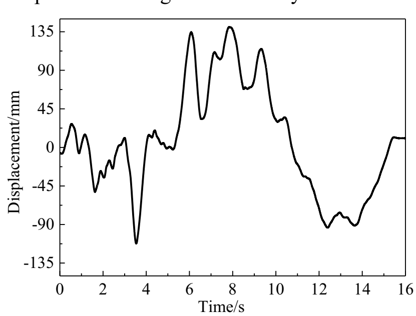


Figure 5. Displacement curve of soil around elbow with time.

Table 2. Comparative test results of displacement and pipe-soil deformation transfer coefficient.

Pipe diameter /m	Buried depth /m	Wall thickness /mm	Angle /°	Pipe displacement /cm		Soil displacement /cm	Deformation transfer coefficient	
				Sand	Clay		Sand	Clay
0.050	0.3	2.0	90	5.53	6.63	11.26	0.49	0.59
0.075	0.3	2.0	90	5.66	6.89	13.70	0.41	0.50
0.100	0.3	2.0	90	4.59	6.39	14.06	0.33	0.45
0.100	0.2	2.0	90	5.08	6.81	17.38	0.29	0.39
0.100	0.3	2.0	90	4.59	6.39	14.06	0.33	0.45
0.100	0.4	2.0	90	5.06	6.41	12.58	0.40	0.51
0.100	0.3	2.0	90	4.59	6.39	14.06	0.33	0.45
0.100	0.3	3.0	90	3.56	4.42	13.03	0.27	0.34
0.100	0.3	4.0	90	2.83	3.40	13.92	0.20	0.24
0.100	0.3	2.0	45	5.12	6.92	11.60	0.44	0.60
0.100	0.3	2.0	90	4.59	6.39	14.06	0.33	0.45
0.100	0.3	2.0	135	2.50	3.79	12.79	0.20	0.30

Note: at this time, the seismic wavelength is 2 m; the elastic modulus of the pipe is 4000 MPa; the foundation coefficient is 5 MPa for clay and 3 MPa for sand; the pipe-soil friction coefficient is 0.4.

3.2. Formula Fitting of Pipe-Soil Deformation Transfer Coefficient of Pipe Bend

According to the elastic foundation beam model [21], the pipe-soil deformation transfer coefficient β is:

$$\beta = \frac{1}{1+\frac{EA}{K}(\frac{2\pi}{L})^2} \tag{2}$$

where E is pipe's elastic modulus, A is pipe's cross-sectional area, L is seismic wave length, and K is foundation coefficient, which is the reaction force of the foundation soil on the unit length of the pipe when the foundation soil and the pipe are relatively displaced. When equation (2) is used to calculate the value of β, it is first applicable to straight pipe. And then it is applicable to the case that the angle between pipe direction and shear wave direction is 45°. The difficulty is to determine the value of K. In general, the value of K should be determined by in-situ experimental measurement. According to the Japanese anti-seismic criteria for chemical equipment, the value of K can be expressed as:

$$K = 3G = \frac{3\gamma_s}{g} V_s^2 \tag{3}$$

where G is soil's shear modulus, γ_s is bulk density of soil, g is acceleration of gravity, V_s is shear wave velocity.

Takada [22] conducted an experimental study on the axial restoring force between the pipe and the soil, and found that the pipe-soil friction under dynamic loading is about 70% of that under static loading, which can be taken as 1 MPa, 5 MPa and 10 MPa, corresponding to soft, medium and hard sites respectively.

In the 1970s, Japanese scholars used the theory of beam on elastic foundation and simple harmonic wave to put forward the analytical model of pipe-soil interaction, namely the response displacement method. The displacement transfer coefficient was divided into axial β_1 and transverse β_2 directions, as shown in the equation (4).

$$\beta_1=\frac{1}{1+\left(\frac{2\pi}{\sqrt{2}L}\right)^2\frac{EA}{K}},\ \beta_2=\frac{1}{1+\left(\frac{2\pi}{L}\right)^4\frac{EI}{K}} \tag{4}$$

Based on the previous pipe-soil deformation transfer theory and the seismic response test results of buried elbow in Table 2, considering the influence of wall thickness, pipe diameter, buried depth, soil properties, angle and other factors on the seismic resistance of elbow, and according to dimensional analysis and equation (4), with the method of control variable fitting, a calculation formula for estimating the pipe-soil deformation transfer coefficient at the maximum strain of buried elbow was put forward, as shown in the equation (5). And its correlation index is 0.95. Compared with the existing transfer coefficient formula of straight pipe, the influence of buried depth, wall thickness and elbow angle was considered in equation (5). Only El-Centro seismic wave was considered in this formula, so on this basis, Kobe seismic wave (predominant frequency 2.5 Hz) and artificial wave (For the artificial wave synthesized, the return period was 50 years, while its duration was 40 s with maximum and minimum periods of 4 s and 0.01 s, respectively. The dominant frequency of Fourier spectral curve for this wave is 4 Hz,) were loaded for the test. The peak value of wave was 0.8 g . Compared with the calculated value of equation (5), the relative error of the deformation transfer coefficient for the elbow obtained by applying Kobe wave and artificial wave was less than 20%, which indicated that the influence of seismic wave frequency on the deformation transfer coefficient at the elbow was small.

$$\beta=\frac{1}{1+0.005\frac{EDt}{K}(\frac{2\pi}{L})^2u^{4.01}(\frac{H}{L})^{-0.64}\cdot 1.72^{1.005-1.78\cos\theta}} \tag{5}$$

where β is the pipe-soil deformation transfer coefficient at the maximum strain of the buried elbow; K is the foundation coefficient, the soft, medium and hard sites can be taken as 1 MPa, 5 MPa and 10 MPa respectively; in this paper, the clay was taken as 5 MPa, and the sand was taken as 3 MPa; L is the seismic wave length/m, the soil characteristic period was taken as 0.3 s, and the shear wave velocity mentioned above was about 120 m/s, and two thirds of the actual shear wave velocity was taken in this paper [21]. Therefore, for the actual situation, the seismic wave length was taken as 24 m, through the similarity ratio transformation, taken as 2 m for the test; D is pipe's diameter/m; t is pipe's wall thickness/mm; H is pipe's buried depth/m; θ is the elbow angle/°; u is the pipe-soil friction coefficient, taking 0.4 in this paper. The research showed that [23] the selection of pipe-soil interface friction coefficient is related to soil physical and mechanical properties, soil type and pipe wall roughness. When the friction coefficient of pipe-soil interface is equal to 0.4, the axial force, circumferential strain and pipeline shear stress are the smallest, and the seismic effect of pipeline is the best. Xiao and Huang [24] studied the friction coefficient at the pipe-soil interface. During earthquake, when the pipe-soil contact material is polyethylene and the sand has 0 ~ 16% water content, the dynamic friction coefficient at the interface is in the range of 0.4 ~ 0.6. Similarly, for clay, when the water content is 10% ~ 50%, the friction coefficient at the interface is in the range of 0.37 ~ 1.10. For the above pipeline dynamic test, the interface friction coefficient of sand and clay was taken as 0.4. Therefore, in the finite element calculation model built in this paper, the tangential friction coefficient of the interface was set to 0.4.

Equation (5) is applicable to the calculation of pipe-soil deformation transfer coefficient at the elbow of buried cast iron elbow. When the pipe diameter is 0.5~1.5 m, the buried depth is 1~4 m, the wall thickness is 10~40 mm, and the elbow angle is greater than 30° of the pipe, the equation (5) has strong applicability to estimate the pipe-soil deformation transfer coefficient. It was found that when the elbow angle θ was 180° and the pipe-soil friction coefficient u was 0.4, the buried depth H was 0.3 m and the shear wave length L was 2 m, the equation (5) could be simplified as equation (6):

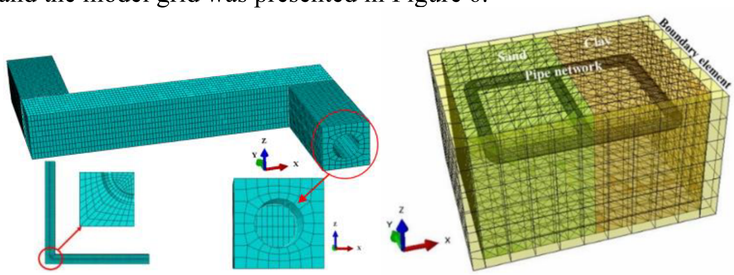
$$\beta=\frac{1}{1+2\times\left(\frac{2\pi}{L}\right)^2\frac{EDt}{K}} \tag{6}$$

This equation is exactly the axial transfer coefficient β_1 from equation (4), but the wall thickness t of the pipe is in m.

4. Numerical Simulation Design Based on Goodman Contact Element

In the analysis of this paper, the three-dimensional model calculation results of ABAQUS finite element software were compared with the experimental calculation results. Taking the buried steel elbow as the research object, the pipe is API 5L X60 steel pipe. 210 GPa is for elastic modulus, 7800 kg/m^3 is for density, and 0.25 is for Poisson's ratio of the pipe. Ramberg Osgood's model was used to describe its nonlinear behavior. The specific size of the pipe was the same as that of the test converted by similarity ratio, and two groups of comparison models were added for each factor, as shown in Table 4. The physical parameters of the soil were the same as the test. In the simulation analysis, the Drucker-Prager model was used to describe the constitutive relationship of the soil, and the seismic wave input was also El-Centro wave.

Taking the bend diameter D = 1.0 m as an example, in the numerical modeling, a bend with a radius of 0.5 m was drawn in the form of axis sweeping. S4R shell element was used for the elbow, 8 seeds were arranged along the circumferential direction of the pipe, and 2112 elements were divided into grids. At the pipe ends, a ring of viscoelastic boundary element was set to simulate the effect of rubber. In order to compare with the test, 19×14×12 m cube soil was cut and extended 1 m along the normal direction on its four sides and bottom surface. A uniform viscoelastic artificial boundary was established to simulate the infinite foundation. The soil around the pipe of 2 m×2 m centered on the pipe axis was selected for mesh refinement. Firstly, the soil around the pipe was partitioned along the straight pipe section. Then, the soil around the pipe was partitioned along the elbow axis. Finally, the structured mesh division of the soil around the pipe was realized, with a total of 15360 elements. The soil around the pipe was also partitioned, and this part of a structured grid implemented was separated into 15604 elements by global seeding. Research showed that [25] the number of soil elements is about 30000, and the convergence of the element is the best. The mesh size of the artificial boundary was 0.2×0.2×0.2 m, with 584 elements. C3D8R solid element was used for soil and boundary, and the model grid was presented in Figure 6.



(a) (b)

Figure 6. Finite element model for pipe bend buried. (a) Finite element mesh of soil around pipe. (b) Stereogram of finite element mesh.

Goodman contact element model [26]: Goodman proposed that the contact surface was completely consistent before the force was applied, and the thickness of the element at the contact surface was zero. For the ABAQUS software, only the frictional contact characteristics of the contact surface were considered, and the sliding deformation was transformed into two directions, namely parallel and vertical directions [27], as shown in Figure 7(a). If the interaction of shear stress in two directions is considered, the constitutive relationship of the contact surface is:

$$\begin{Bmatrix} \Delta\tau_1 \\ \Delta\tau_2 \end{Bmatrix} = \begin{bmatrix} k_{s1} & 0 \\ 0 & k_{s2} \end{bmatrix} \begin{Bmatrix} \Delta\gamma_1 \\ \Delta\gamma_2 \end{Bmatrix} \tag{7}$$

and k_{s1} and k_{s2} can be expressed as:

$$k_{s1} = \left(1 - R_f \frac{\tau_1}{\sigma_n \tan\delta}\right)^2 K_1 \gamma_w \left(\frac{\sigma_n}{p_a}\right)^n \tag{8}$$

$$k_{s2} = \left(1 - R_f \frac{\tau_2}{\sigma_n \tan\delta}\right)^2 K_2 \gamma_w \left(\frac{\sigma_n}{p_a}\right)^n \tag{9}$$

where K_1, K_2, n, R_f are the non-linear index, δ is the interface friction angle of the contact surface, γ_w is the volume density of water, P_a is the atmospheric pressure, σ_n is the normal contact stress, $\Delta\tau_1$ and $\Delta\tau_2$ are the shear stress increase in two directions, k_{s1} and k_{s2} are the spring stiffness in both directions Direction, $\Delta\gamma_1$ and $\Delta\gamma_2$ are the strain increment in the two directions, τ_1 and τ_2 and are the shear stress in the two directions.

In Table 3, for specific parameter settings, the calculation method of each parameter was carried out by Wang et al. [28] in 2005.

Table 3. The Goodman contact parameters.

K_1	K_2	n	R_f	δ (°)	γ_w (kN/m^3)	P_a (kPa)
2000	2000	0.56	0.74	29.3	10	100

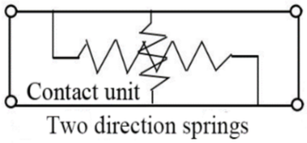


Figure 7. The Goodman contact element model.

5. Verification of the Pipe-Soil Deformation Transfer Coefficient Formula

In order to be consistent with the experimental measurement and analysis process, the displacement of the elbow was not extracted directly, but the acceleration of the elbow was extracted and integrated to calculate the displacement of the elbow. Statistics and calculations were made by the finite element method based on Goodman contact element and equation (5), and the pipe-soil deformation transfer coefficient was obtained, as shown in Table 4. The calculation results of the test were also added to the table, and the curves in Figure 8(a), (b), (c) and (d) were established.

Table 4. Statistics of the deformation transfer coefficient for pipe and soil obtained by two methods.

Pipe diameter /m	Buried depth /m	Wall thickness /mm	Angle /°	Finite element results		Formula calculation results	
				Sand	**Clay**	**Sand**	**Clay**
0.50	3.0	20.0	90	0.482	0.596	0.491	0.616
0.75	3.0	20.0	90	0.396	0.522	0.391	0.517
1.00	3.0	20.0	90	0.321	0.452	0.325	0.445
1.25	3.0	20.0	90	0.259	0.398	0.278	0.391
1.50	3.0	20.0	90	0.245	0.336	0.243	0.349
1.00	1.0	20.0	90	0.207	0.294	0.193	0.284
1.00	1.5	20.0	90	0.252	0.361	0.236	0.340
1.00	2.0	20.0	90	0.288	0.382	0.271	0.383
1.00	3.0	20.0	90	0.321	0.452	0.325	0.445
1.00	4.0	20.0	90	0.365	0.485	0.367	0.491
1.00	3.0	10.0	90	0.493	0.602	0.491	0.616
1.00	3.0	15.0	90	0.382	0.522	0.391	0.517
1.00	3.0	20.0	90	0.321	0.452	0.325	0.445
1.00	3.0	30.0	90	0.237	0.355	0.243	0.349
1.00	3.0	40.0	90	0.198	0.285	0.194	0.286
1.00	3.0	20.0	30	0.536	0.652	0.526	0.649
1.00	3.0	20.0	45	0.481	0.635	0.488	0.614
1.00	3.0	20.0	60	0.429	0.571	0.438	0.565
1.00	3.0	20.0	90	0.321	0.452	0.325	0.445
1.00	3.0	20.0	135	0.188	0.279	0.196	0.289

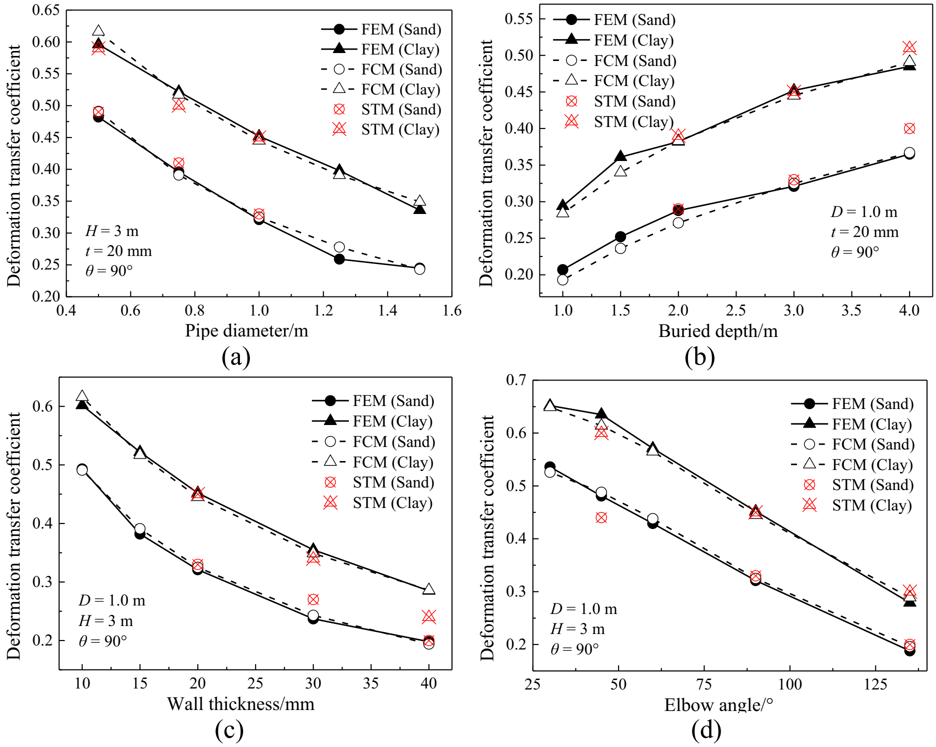


Figure 8. Comparison of finite element simulation (FEM), formula calculation (FCM) and scale test results (STM). (a) Pipe diameter D. (b) Buried depth H. (c) Wall thickness t. (d) Elbow angle θ.

It can be found from Figure 8(a) that the pipe-soil deformation transfer coefficient decreases with the increase of pipe diameter under the condition of different pipe diameters, that is, the corresponding deformation of the elbow decreases when the soil is in large deformation, and the ability of the pipe to resist the deformation of the surrounding soil is enhanced. Therefore, the pipe diameter should be appropriately increased in the seismic design of the elbow. It can be seen from Figure 8(b) that the pipe-soil deformation transfer coefficient decreases with the increase of the buried depth of the elbow, that is, the corresponding deformation of the pipe increases when the soil has large deformation, and the ability of the pipe to resist the deformation of the surrounding soil decreases. Therefore, pipe bend should be buried shallowly in the seismic design of the elbow. As can be seen from Figure 8(c), the pipe-soil deformation transfer coefficient decreases with the increase of the wall thickness of the elbow, that is, the corresponding deformation of the pipe decreases when the soil has large deformation. That is to say, when the soil has large deformation, the corresponding deformation of the pipe decreases, and the ability of the pipe to resist the deformation of the surrounding soil increases; Therefore, the wall thickness should be increased properly in the seismic design of elbow. It can be seen from Figure 8(d) that the pipe-soil deformation transfer coefficient decreases with the increase of elbow angle, that is, when the soil has large deformation, the corresponding deformation of the pipe decreases, and the ability of the pipe to resist the deformation of the surrounding soil increases. Therefore, elbow with large elbow angle should be used as far as possible according to the actual situation of the project in the seismic design of elbow. The angle of the straight pipe is equivalent to

180°, so the seismic capacity of the straight pipe is the strongest. It can also be found from Figure 8 that the deformation transfer coefficient of the elbow in clay is larger than that in sand. The reason is that the foundation coefficient of clay is larger than that of sand. Therefore, the clay has a strong binding capacity to elbow during earthquake, making the elbow relatively dangerous. While the binding capacity of sand to the pipe is relatively weak, the pipe is relatively safe without sand liquefaction.

From table 4, it can be observed that the relative error of the pipe-soil deformation transfer coefficient calculated by the equation (5) and finite element simulation based on Goodman contact element is less than 5% under different working conditions. It indicates that the equation of pipe-soil deformation transfer coefficient proposed in this paper has certain accuracy for the different pipe diameters, buried depth, wall thickness, elbow angles and soil properties.

6. Conclusion

In this paper, shaking table scale test and Goodman contact element methods were used to study the pipe-soil deformation transfer coefficient under seismic and the change law of deformation transfer coefficient under multiple factors, the conclusions were as followed:

- The equation of deformation transfer coefficient of elbow fitting by shaking table test data has strong applicability, and when the elbow angle is 180 degrees, the equation can be simplified to the axial deformation transfer coefficient of existing straight pipe.
- The pipe-soil deformation transfer coefficient of elbow decreases with the increase of pipe diameter, wall thickness and elbow angle, and increases with the increase of buried depth. It shows that increasing pipe diameter, wall thickness and elbow angle and reducing buried depth are beneficial to the aseismic performance of elbow, and reducing soil hardness will also improve the aseismic performance of elbow.
- The relative error of the pipe-soil deformation transfer coefficient calculated by the equation and finite element simulation based on Goodman contact element is less than 5% under different pipe diameters, buried depth, wall thickness, elbow angles and soil properties, which means that the equation fitted of pipe-soil deformation transfer coefficient has certain accuracy.

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