A Shaking table test on soil-pipe dynamical interface displacement research under inconsistent seismic excitation

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Abstract:
The research about the underground-pipes excited by dynamical seismic wave is still blanket all over the world. By the two layered-equipped shear boxes fixed on the shaking table, embedding the steel pipes, and inputting the intervening seismic waves, describes the interaction between the embedded pipes and the soil, discusses the mechanism of the interaction between the pipes and the soil under the condition of uniform and non-uniform seismic excitation, while the evolution of the mechanism is also included.

Key Words: underground pipes; shaking table test; Non-uniform Earthquake Wave Excitation; interface slippage; intervening seismic waves

1. Introduction

During the daily research and practice, people realize that vibration in earthquake can not be perfectly described under the hypothesis of inputting the uniform seismic wave excitation, as the difference between the theoretical result and the fact is too obvious to be neglected in the analysis of structure in earthquake, therefore the effect of non-uniform seismic wave excitation is taken into consideration. The paper studies the mechanism and the evolution of the interaction between the pipes and the soil by the two layered-equipped shear boxes fixed on the shaking table and the embedded steel pipes. The experimental testing also provides helpful materials for the theory research.

2. Experimental design of similarity ratio

Experimental design of similarity ratio is based on the demand of the standard of the structure due to the complicity of the site which the experiment is simulating. For the limit of the maxim load of the shaking table and the difficulty of adding the artificial mass on the model whose scale is large or the one with big dimensions, the effect of the gravity is neglected.

Table 1: Model similarity ratio

Physics	Geometry	Density	Strain	Stress	Acceleration	Time	Frequency
Expressions	S_L	S_ρ	S_ε	S_σ	$S_a = S_E/(S_\rho \cdot S_L)$	$S_t = S_L / S_E^{1/2}$	$S_f = 1/S_t$
Similarity ratio	0.167	1	1	1	6	0.167	6

3. Experimental testing preparations

3.1 Model soil

The silty clay whose internal friction angle is 27.9 degree and the cohesive force is 24.4 kPa is chosen from the upper section of Yangtze River in Chongqing which is situated at the basic earthquake intensity of VI Area. Based on the Criterion of site soil and the site categories, the overburden in Chongqing is medium-soft site soil and the bedrock is stiff site soil.

3.2 The shear box

The basic frequency test of the empty-box under motive power is carried out. And the basic frequency turned out to be 1.75Hz by inputting flat noise。The basic frequency of the box full of soil in the following test turns out to be 6Hz which is far away from 1.75Hz; it means that the effect of the empty box should not be negative in the test.

Figure 1：Frequency test of empty box

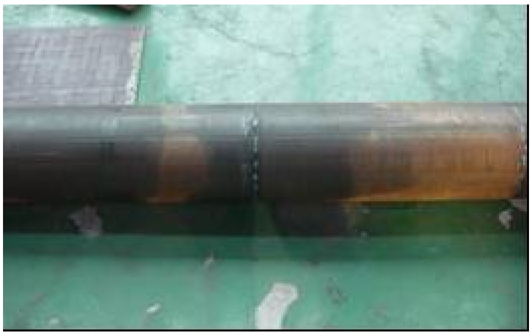


Figure 2：Welding line of pipe

3.3 Shaking table

The experimental testing is carried out in the structure dynamic laboratory of bridge in Chongqing Research and Design Institute. The experimental equipment is constituted by two platforms with the dimension of 3m×6m and the ultimate load of 35t. The fixed platform is named A, and the other is named B which can be moved along a railroad.

3.4 Steel pipes

The specification of the steel pipes for the experiment is φ219-3.25mm, and the length is 6000 mm.

Table2： pipe capability index

Specification	Diameter (mm)	Yielding stress (MPa)	Tension stress (MPa)	Stretchy ratio
8”	219	235	420	24%

4. Input of the earthquake waves

The EL-Centro wave is chosen as the initial earthquake waves to synthesize two intervening earthquake waves which are inputted for the two shear box.

The process is as follows：First, the auto-power spectral density function S(ω) of the acceleration process is calculated by the EL-Centro wave, and the cross-power spectral density function S(ω) of the acceleration between the 2 points can be calculated by the formula as follow :

$$s_{jk}(\omega,d)=\sqrt{s_j(\omega)s_k(\omega)}\rho(\omega,d)e^{-i\omega\frac{d}{v_a(\omega)}} \tag{1}$$

Within the rang of 100Km, the change of the intensity of the vibration of the ground is not very obviously, so it is possible to treat the auto-power spectral density function of the acceleration the same in every point of the pipe, therefore, the cross-power spectral density function can be calculated by the formula as follow :

$$s_{jk}(\omega,d)=s(\omega)\rho(\omega,d)e^{-i\omega\frac{d}{v_a(\omega)}} \tag{2}$$

The Harichandran and Vanmareke (1986) model is employed as the coherent model:

$$\rho(\omega,d)=Ae^{-\frac{2d}{\alpha\theta(\omega)}(1-A+\alpha A)}+(1-A)e^{-\frac{2d}{\theta(\omega)}(1-A+\alpha A)} \tag{3}$$

In which: $\theta(\omega)=K[1+(\frac{\omega}{\omega_0})^b]^{-\frac{1}{2}}$, $A=0.736,\alpha=0.147,K=5210,\omega_0=6.85,b=2.78,d=100$

$v_a(\omega)$ is the seen velocity of earthquake waves.

According to the mutual-spectrum model of earthquake and the power-spectrum matrix, the time interval process of steady ground vibrations at multi-points can be created by the formula of the multi-point earthquake model and IFFT method. Intercepting a 30s-long steady process for consideration, the un-steady stochastic process of artificial earthquake could be created by multiplying the sample process which has been compressed by the ratio of 1/6 by the envelope function. The function is adopted as follows, which the steady part constituted 60% of the whole process:

$$f(t)=\begin{cases}(t/A)^2 & 0\le t\le A\\ 1 & A\le t\le B\\ e^{-a[t-(A+B)]} & B\le t\le C\end{cases} \tag{4}$$

$$A=0.5,B=3.5,C=1,a=1.5$$

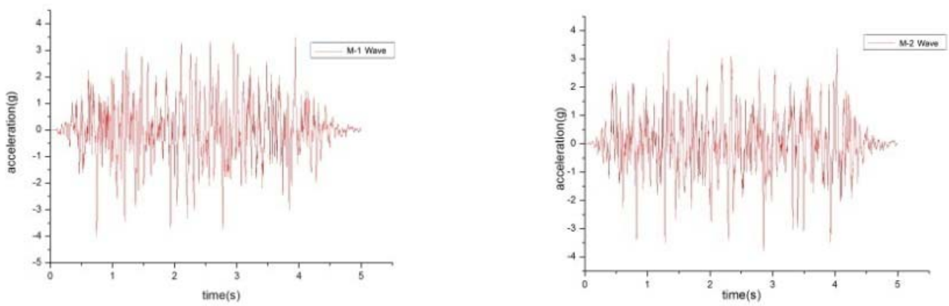


Fig.3 ： Input of intervening seismic waves

The input of the earthquake waves is shown in Fig.3. In the experimental testing, the un-uniform excitation of earthquake wave is followed by the uniform one.

Table 3: The load of the earthquake waves

	No.1Un-uniform Excitation				No.2 Uniform Excitation		
Oder	Input	A	B	Oder	Input	A	B
1	0.1g	M-1	M-2	7	0.1g	M-1	M-1
2	0.3g	M-1	M-2	8	0.3g	M-1	M-1
3	0.4g	M-1	M-2	9	0.4g	M-1	M-1
4	0.6g	M-1	M-2	10	0.6g	M-1	M-1
5	1.0 g	M-1	M-2	11	1.0 g	M-1	M-1
6	1.2 g	M-1	M-2				

5. The arrangement of the sensors

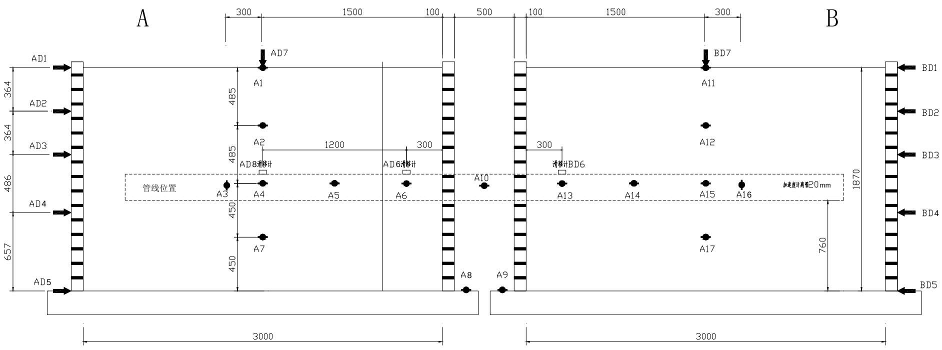


Figure 4： Accelerometers and displacement of arrangement

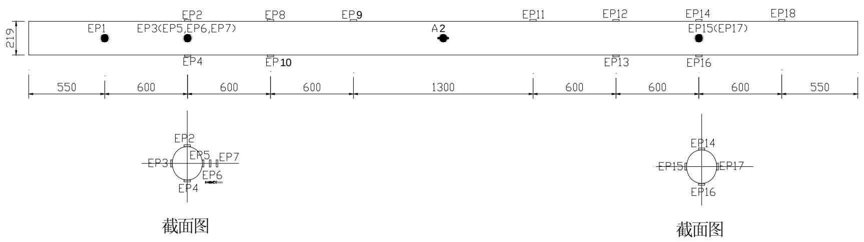


Figure 5： Dynamic earth pressure sensors arrangement

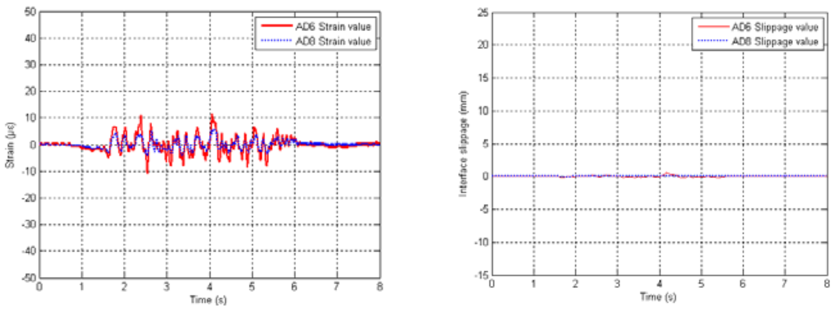
Many instruments such as accelerometer sensor, guyed displacement sensor, laser displacement sensor, break ground manometer, strain gauge are used in the experimental test to record the reaction of the structure and the soil. In additional, Dr. Shi Xiao Jun designed a corner displacement sensor to record the displacement of the interface between the pipe and the soil. The first letter of the serial number means the name of the box, the second letter stands for the type of the instrument, and the last one is the number of the instrument.

6. The analysis of the experimental test results

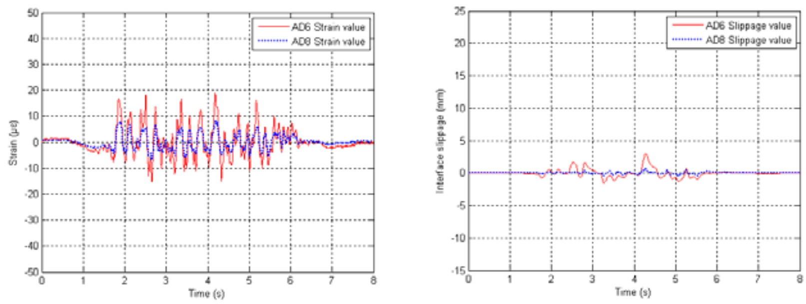
6.1 The analysis for the time interval process of the slippage between the pipe and the soil

The cause of the greater shear stress in the interface between the pipe and the soil is the un-matching deformation between the two kinds of the material. During the earthquake, the soil passes the effect of the seismic to the pipes by shear, and the transmission creates the major part of the load applied on the pipes. The one side of the interface is soil which is a kind of loose medium, therefore the effect of the deformation of the soil caused by the pressure can discount the pass ratio of the shear, as a result, the shear applied along the interface is not homogeneous, so does the relative displacement on the interface. YinZongZe has ever performed the experiment for the direct shear on the interface between the soil and the pipes with large scale sample, the distribution of the relative displacement is observed directly. This paper discusses the distribution and the developing trend of the strain along the soil-pipe interface under the condition of earthquake by measuring the slippage.

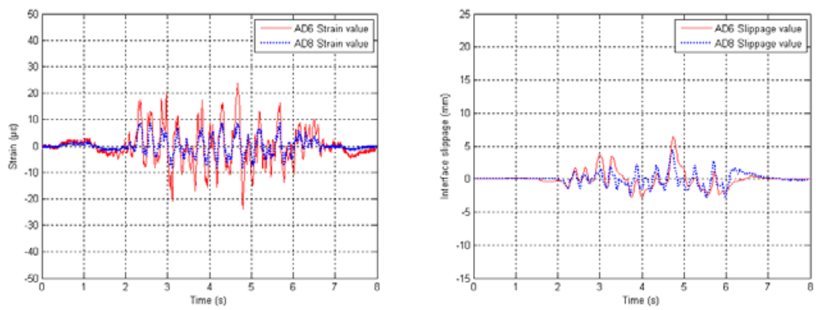
Fig.6 shows the value of the steel pipe strain and the slippage on the interface at the points AD6 and AD8 as the different ultimate wave value is inputted. In the graphic, the sensor plotted at different place is used to detect the whole damage process of the soil-pipe interface and the state of the developing trend after the damage



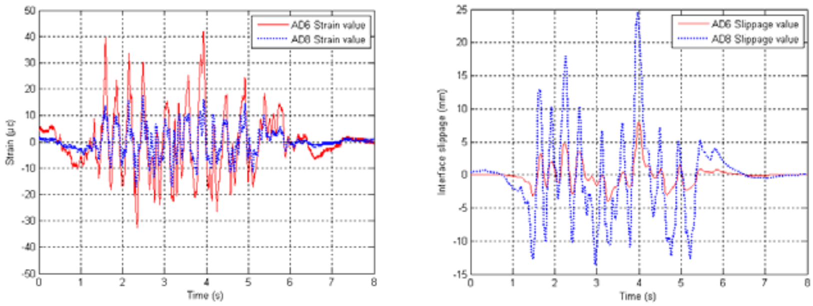
(a) PGA = 0.1g



(b) PGA = 0.3g



(c) PGA = 0.6g



(d) PGA = 1.2g

Figure 6：Time interval process of strain and slip on point of survey

It can be seen that the displacement is not obvious at the beginning, which suggests that the interface has not been damaged. While the value of the ultimate wave inputted grows up to 0.3g, a tiny slippage appears on the interface at the inner part of the box, and the ultimate value turns out to be 0.5mm, while the value at the outer part of the box turns out to be 3mm around. The strain is developing meanwhile, the strain at the outer point reaches 18με, so is 8με at inner point. The structure is still elastic due to the appearance of the tiny displacement of the interface at inner part, while the slippage at outer part begins to develop linearly. It can be judged by figure of the ultimate value of the strain that stress on the steel pipe is growing linearly slowly at the same time. While the input reaches 0.6g, the growth of the slippage at the inner part gradually exceeds the outer part, but they are still at the same level. The analysis above says that the damage on the interface is accumulating gradually, while the inputting of the earthquake waves. Until reaching some degree, the interface at the outer points is damaged thoroughly, while the greater ultimate slippage appears. After above 0.6g, the velocity of the growth of the slippage at the inner part is much faster, therefore, it can be thought to be in the plastic-flow stage. The slow growth of the strain on the pipes suggests that the interface of the soil and the pipe is completely free from now on, so the adhesive force between the soil and the pipes on the interface is damaged, only exits the steady transmission of the friction. The ratio of the transmission of the shear is constant which fit with the forecasty.

The conclusions can be drawn based on the result of the experimental testing as follows: The relative-slippage occurs at the outer part of the pipes first, but the same thing doesn’t happen at the inner part. While the ultimate value of the vibration is growing, the relative-slippage at the outer part is developing at the same time, and the slippage appears at the inner part too, which suggests that the damage of the interface is a process which develops from the outer part to the inner part gradually. On the other hand, the appearance and the development of the slippage basically has the same step with the strain of the pipe, while the ultimate value of the two mentioned above can be reached nearly at the same time, which is due to the expanding of the area damaged by the shear gradually.

6.2 The model of the constitutive relation about the interface

Figure 7 shows the relationship between the ultimate value of the strain of the pipe and the ultimate value of the slippage of the interface at the point where the sensor AD8 is located under different input by the uniform excitation.

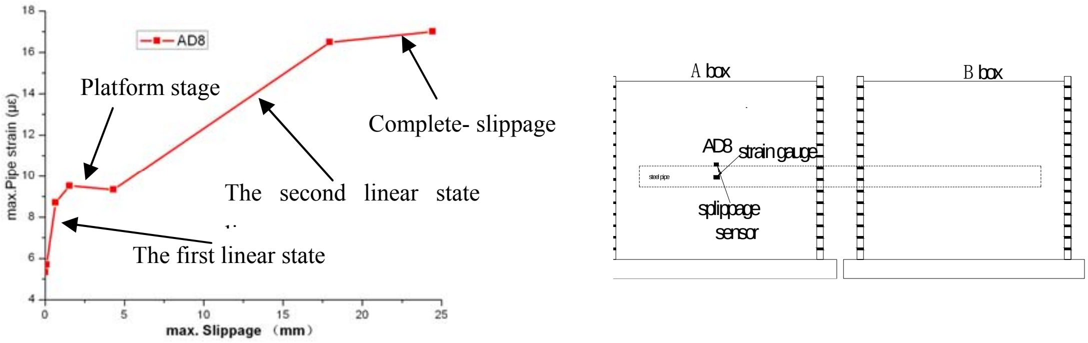


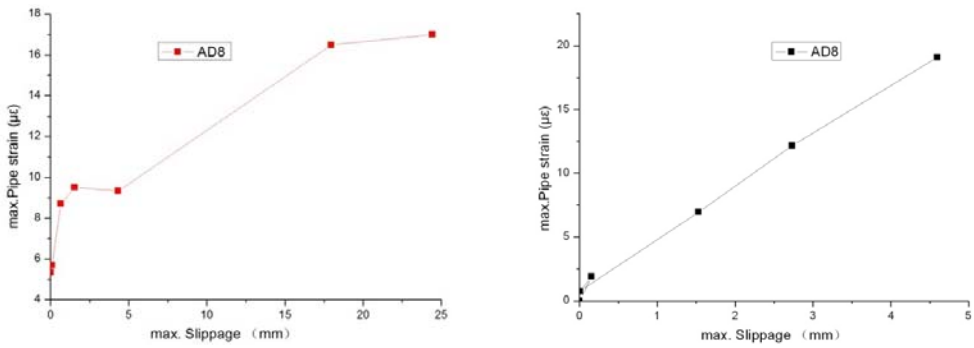
Figure 7: Strain and slippage

Based on the Fig.7, the developing process of the strain and the slip on the interface can be divided into four stages: The first linear stage suggests the interface is still in the elastic state. The platform stage means many tiny slippages appears on the interface, within this stage, the arrangement of soil is re-built due to the vibration, then the s slippage pauses and the state goes in to the next stage, which is called the second linear stage. During this stage, the damage on the interface is developing steadily, and finally totally damaged, and then the complete- slippage stage comes out.

Based on relationship between the relative deformation of pipe and the soil and the force of constraint, the state of the interaction can be simplified into double-linear restrict and plastic restrict. For the point on the interface, while the $\tau<\tau_f$, the slip develops linearly; while the $\tau=\tau_f$, the slippage should develop limitless, but for the constraint of the other points on the surface, it will stop developing.

6.3 The comparison of slippage under the excitation of uniform and un-uniform

The following figure shows the comparison of slippage under the excitation of uniform and un-uniform. The relationship of the slippage and the strain of the pipe at the point where sensor AD8 is located is used to make a graphic.



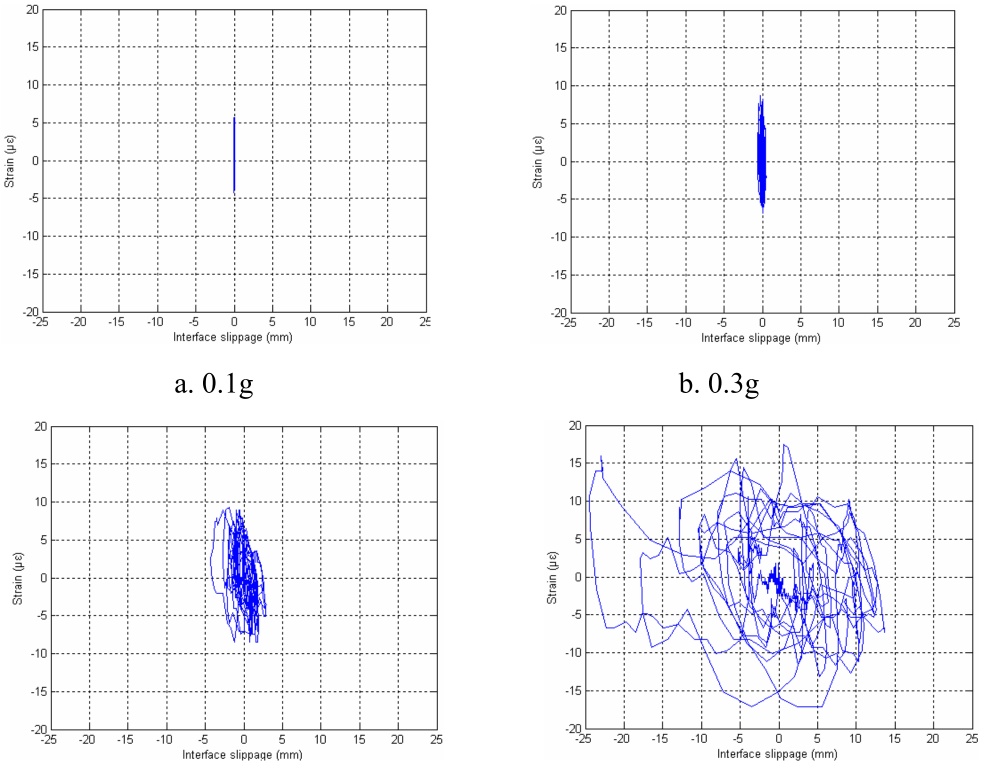
a. Under the un-uniform excitation b. Under the uniform excitation

Figure 8: The relationship between slippage and strain

The conclusion can be drawn that the relationship of the slippage-strain develops gradually from the elastic to the plastic state, and then the complete flowing state is reached. This suggests that the interface can be damaged completely while the increase of the input under the un-uniform of the excitation. While the curve of the relationship between slippage and strain is elastic under the uniform excitation, the interface will not be completely damaged. Judged by the value of the slippage, the value under the un-uniform excitation is much greater than under the uniform excitation, which means the damage of the interface under the uniform damage is tiny, meanwhile, the curve is always in the elastic state.

6.4 The slip-strain curve on the interface

The figure describes the hysteretic relationship of the strain- slippage on the interface under the un-uniform excitation, which is the basis of judging the un-linear process of the interface slippage -strain.



a. 0.1g b. 0.3g

c、0.6g d、1.2g

Figure 9：hysteretic relationship between strain and slippage

While 0.3g, the slippage -strain is totally linear. While 0.6g, the growth of the strain on pipe is tiny, and the slippage is developing obviously, which suggests that the slippage -strain begins to reach the un-linear state. While 1.2g, the slippage -strain is totally un-linear, at the last stage, the slippage develops rapidly while the strain remains the same, which suggests the soil-pipe interface is in the state of slip completely.

7. Conclusion

1. The development of the damage at different points on the soil-pipe interface is not in the same step, the damage can be thought as a process which develops from outer to inner part.

2. Based on the relationship of relative-deformation and force of constraint between the pipe and the soil, the state of interaction can be simplified to double-linear restrict and plastic restrict.

3. The slippage on the soil-pipe interface under un-uniform excitation exceeds the one under uniform excitation very much.

4. The curve of slippage -strain of the interface can reach the state of totally plastic under the un-uniform

excitation, while the curve is always in the linear state under the uniform excitation.

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