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THE NUMERICAL SIMULATION AND PHYSICAL MODEL TEST OF PIPELINE UNDER WAVE ACTION

*Yucheng Li[1], Guozhang Lai[2], Bing Chen[3], Ge Wang[4]
Dalian University of Technology
Dalian, China
J.L.J. Marchal[5], Ph.D. Rigo[6]
The University of Liege, Liege
Anast, Belgium

ABSTRACT

Two scale physical model tests of wave forces on pipeline have been done in this study, and the results of two tests are compared. The comparison shows that the scale effect can not be ignored in predicting the wave forces acting on pipeline. The physical model tests of regular waves are compared with the results from numerical simulation, which is based on Large Eddy Simulation method. The results coincide each other quite well.

INTRODUCTION

Physical model test is widely used in predicting the wave forces acting on pipeline in engineering. As we know, physical model test can not satisfy Froude Law and Reynolds Law in the same time. That is, while the Kc number of physical model test and real condition is the same, the Re number of them will be different. While the forces acting on pipeline by waves are mainly caused by viscous effect, namely surface friction, flow separation, wake and vortex shedding effect. In such case, Re number is an important factor for model test and usually by small scale model test the results can not directly used to the case of real condition. It require more study to resolve the problem of predicting wave forces in real condition based on the results of small scale model test. The purposes of our study are: firstly to run physical model tests in two different scale (and in different facility) as to know more the scale effect; secondly to compare the results from numerical simulation with model test data in the same condition as to know the accuracy of numerical simulation. This is a joint research project between The University of Liege in Belgium and Dalian University of Technology in China.Results of a model scale (1/60) were provided by University of Liege, and the model test with scale 1:30 and numerical simulation were conducted in Dalian University of Technology.

MODEL TEST CONDITION AND FACILITY

Model Test in The University of Liege

The results of the 1/60 model scale provided by Anast of University of Liege were obtained in a towing tank of 1m width. The model of pipeline was fixed through load cell on the side wall of towing tank as a cantilever. The surface elevation, horizontal and vertical force components were measured during the experiment.

Table 1 Model test condition

	e/D=0.0		e/D=0.2	
d(m)	Hs(m)	Tp(s)	Hs(m)	Tp(m)
0.165	0.066	1.55	0.068	1.55
0.165	0.065	2.06	0.067	2.06
0.231	0.101	1.56	0.101	1.56
0.231	0.102	2.07	0.102	2.07
0.298	0.096-0.099	1.59	0.096-0.099	1.59
0.298	0.134-0.136	2.13	0.134-0.136	2.13

Model test in Dalian University of Technology

The model scale is 1:30, which was conducted in the wave-current flume in the State Key Laboratory of Coastal and Offshore Engineering, Dalian University of Technology. The dimension of the wave-current flume is 69m in length, 2m in width and 1.8m in depth. The flex pipeline model (0.8m in length) was connected with two-dimensional load cells at both end. and the load cells were fixed on the two supporters. On the other side of supporters, there were two individual dummy pipe models which were used to eliminate "end effect". During the test, surface elevation, horizontal and vertical force components were measured. Both regular and irregular waves were run. the irregular waves data can be compared with the results from The University of Liege, and regular waves data can be compared with the results from numerical simulation. The test condition of irregular waves are listed in Table 2.

In regular wave tests, average wave height is equal to significant wave height Hs of irregular waves, and average wave period is equal to

1)Professor 3)Master 5)Professor
2)Professor 4)Doctor 6)Doctor

peak period Tp of irregular waves. Other condition is the same as that in irregular wave tests.

Table 2 Irregular wave test condition

	e/D=0.0			e/D=0.2		
d(m)	code	Hs(m)	Tp(s)	code	Hs(m)	Tp(s)
0.333	J31E0	0.126	2.19	J31E2	0.129	2.19
0.333	J32E0	0.133	2.92	J32E2	0.134	2.92
0.467	J33E0	0.179	2.19	J33E2	0.188	2.19
0.467	J34E0	0.190	2.92	J34E2	0.200	2.92
0.6	J35E0	0.189	2.19	J35E2	0.199	2.19
0.6	J36E0	0.253	2.92	J36E2	0.276	2.92

DATA ANALYSIS METHOD AND RESULTS OF PHYSICAL MODEL TESTS

Data analysis method

Horizontal force coefficient C_{fx} and vertical force coefficient C_{fz} are used to analyze the measured forces acting on pipeline model. The definition of force coefficients are as follows:

$$C_{fx} = \frac{(Fx)_{1/10}}{0.5\rho D U_{max}^2} \tag{1}$$

$$C_{fz} = \frac{(Fz)_{1/10}}{0.5\rho D U_{max}^2} \tag{2}$$

where D is the diameter of pipeline model, U_{max} is the amplitude of significant local undisturbed horizontal velocity of fluid particle. As significant wave height Hs and peak period Tp are known variables, U_{max} can be calculated by Airy Wave theory:

$$U_{max} = \frac{\pi Hs}{Tp}\frac{\cosh[k(e+D/2)]}{\sinh(kd)} \tag{3}$$

The definition of Re number and Kc number are:

$$Re = \frac{\rho U_{max} D}{\mu} \tag{4}$$

$$Kc = \frac{U_{max} T_p}{D} \tag{5}$$

Based on the data analysis, Eq.(6) is supposed to give the best simulation of the relation between C_{fx}, C_{fz} and Re, Kc.

$$C_f = \left(\frac{a}{\log Re}\right)^b Kc^c \tag{6}$$

in which a, b and c are constants to be determined by regression analysis. Because the parameter e/D, also has substantial influence on the flow behavior around the pipeline, it is reasonable to divide the data from these two models into two groups, e/D=0.0 and e/D=0.2. Table 3 gives the regression results. The relative errors of the regression results are also calculated. It seems that all the regression analysis are quite successful.

Table 3 Regression results of force coefficients

		$C_f = (a/\log Re)^b Kc^c$				Re	Kc
e/D	C_f	a	b	c	r	Max/Min	Max/Min
0.0	C_{fx}	5.7772	5.9306	-0.1527	0.130	38411/4928	22.65/3.43
0.0	C_{fz}	11.1858	1.9867	-0.1761	0.206	38411/4928	22.65/3.43
0.2	C_{fx}	5.9296	4.7363	-0.08199	0.102	38437/5164	20.05/3.44
0.2	C_{fz}	24.4805	1.1519	-0.3324	0.124	38437/5164	20.05/3.44

Comparison between the results of two scale physical model tests

Table 4 and Table 5 give the comparison of measured forces between these two models.

Table 4 Comparison of the forces between the two models when e/D=0.0

code	Fx			Fz		
	Model2 (N/m)	Model1 (N/m)	$(Fx)_2/(Fx)_1$	Model2 (N/m)	Model1 (N/m)	$(Fz)_2/(Fz)_1$
J31E0	19.6	7.02	2.79	17.8	7.10	2.51
J32E0	20.9	7.12	2.94	23.1	7.81	2.96
J33E0	22.2	8.17	2.72	25.7	6.92	3.71
J34E0	22.4	9.22	2.43	32.8	8.71	3.77
J35E0	17.4	5.50	3.16	18.6	4.25	4.38
J36E0	21.2	10.49	2.02	34.7	8.28	4.19
average			2.68	average		3.59

Table 5 Comparison of the forces between the two models when e/D=0.2

code	Fx			Fz		
	Model2 (N/m)	Model1 (N/m)	$(Fx)_2/(Fx)_1$	Model2 (N/m)	Model1 (N/m)	$(Fz)_2/(Fz)_1$
J31E2	14.4	6.44	2.24	10.0	4.90	2.04
J32E2	14.9	6.77	2.20	13.2	4.78	2.76
J33E2	19.8	7.65	2.62	18.2	5.61	3.24
J34E2	21.1	9.28	2.27	19.4	6.49	2.99
J35E2	14.7	5.16	2.85	16.9	3.70	4.57
J36E2	24.2	9.86	2.45	22.3	6.43	3.47
average			2.44	average		3.18

In the Table 4 and 5, the subscript "1" means the results of model test of scale 1:60.5, the subscript "2" means the results of model test of scale 1:30.

According to Froude Law, The scale values of wave forces by two models should be equal to 4.0. But as indicated by Table 4 and Table 5, The real horizontal force scale values $(Fx)_2/(Fx)_1$ are far less than 4.0. While the vertical force scale values $(Fz)_2/(Fz)_1$ are little higher, but still less than 4.0. This is the viscous effect, which means if we calculate the wave forces acting on real pipeline directly from the data of small scale model test according to Froude Law, we would over estimate the forces caused by viscosity. In this study, the average viscous effect coefficients are 0.67 and 0.61 for horizontal forces of e/D=0.0 and e/D=0.2, respectively, the average viscous effect coefficients of vertical forces are 0.90 and 0.80, respectively.

Numerical simulation method

For numerical simulation of this project, it is a problem of finding numerical solution of Navier-Stokes Equation. The Large Eddy Simulation (LES) method we used is a powerful and less artificial assumption method in simulating turbulent flow developed in recent years.

The dimensionless N-S equation can be written as follows:

$$\frac{\partial u_i}{\partial t}+u_j\frac{\partial u_i}{\partial x_j}=-\frac{\partial p}{\partial x_i}+\frac{1}{Re}\frac{\partial^2 u_i}{\partial x_j^2}+\frac{\partial}{\partial x_j}(\tau_{ij}) \quad (7)$$

$$\frac{\partial u_i}{\partial x_i}=0 \quad (8)$$

where $$\tau_{ij}=\gamma_s\left(\frac{\partial u_i}{\partial x_j}+\frac{\partial u_j}{\partial x_i}\right) \quad (9)$$

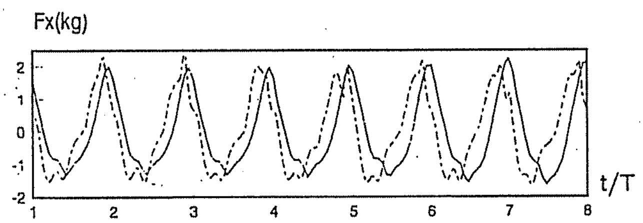
$$\gamma_s=(c\Delta_{ij})^2\left\{2\left[\left(\frac{\partial u}{\partial x}\right)^2+\left(\frac{\partial v}{\partial y}\right)^2\right]+\left(\frac{\partial u}{\partial y}+\frac{\partial v}{\partial x}\right)^2\right\}^{\frac{1}{2}} \quad (10)$$

C is the Smagorinsky constant, we take C=0.1

Δ_{ij} is the characteristic length of calculated grid, we take $\Delta_{ij}=\sqrt{S_{ij}}$, in which S_{ij} is the area of the calculated grid, u_i and p are dimensionless velocity and pressure.

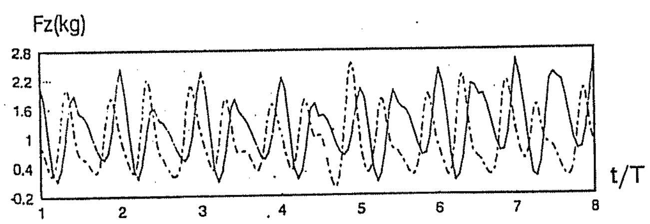
Comparison between the results of numerical simulation and regular wave model test

From Fig.1 to Fig.3 give the time history of horizontal forces, vertical forces and resultant forces of LES numerical model and measured by physical model tests.



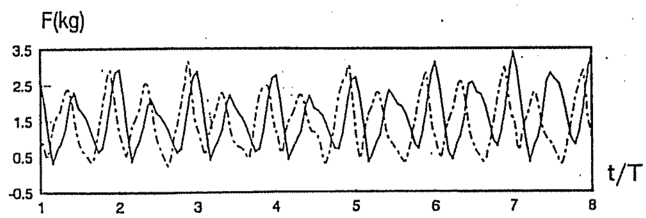
(R31E01) solid line:measured dashed line:calculated

Fig.1 Comparison between calculated and measured horizontal force



(R31E01) solid line:measured dashed line:calculated

Fig.2 Comparison between calculated and measured vertical force



(R31E01) solid line:measured dashed line:calculated

Fig.3 comparison between calculated and measured resultant force

It is indicated by these figures : (1) The calculated horizontal force agree quite well with the test data. The amplitude of the horizontal forces agree very well, there are only a small phase shift between the maximum calculated horizontal forces and the maximum measured horizontal forces;(2) The time history of the calculated vertical forces are very similar to those of the measured vertical forces It means that they have the same frequency and reach its maximum or minimum values at almost the same phase (but only a small phase shift) ; (3) The calculated resultant forces agree quite well with the measured test data. The maximum resultant forces in one wave period for calculated and measured agree quite well, but there a small phase shift between them.

CONCLUSION

The numerical simulation by Large Eddy Simulation of flow around pipeline is successfully developed. The results by numerical simulation are quite close to the model test data (scale of 1:30).

Two scale model test showed that by the influence of viscous effect the wave forces acting on pipelines would not follow the Froude Law. Based on our test data, the average viscous effect coefficients are 0.61 ~ 0.67 for horizontal forces and 0.80 ~ 0.90 for vertical forces, which depend on Reynolds number.

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