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Oscillatory Flow Induced Hydrodynamic Forces upon a Pipeline near Erosive Sandy Seabed

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ABSTRACT

An experimental study of the properties of hydrodynamic forces upon a marine pipeline is presented in this paper, in the equilibrium scour conditions for various Keulegan-Carpenter numbers and various initial relative gaps between pipeline and the erosive sandy seabed. The tests are conducted in a U-shaped oscillatory water tunnel with a sand box located at the bottom of the test section. According to the experimental results, the maximum horizontal forces on the pipelines with an initial gap to seabed will decrease to some extent due to scouring process. For engineering appliances, it seems safer to estimate wave induced forces on pipelines under the assumption that seabed is plane. However, it should be noticed that great changes would be brought to the frequency properties of lift forces because of the sandy scour beneath the pipeline, which occurs for certain KC numbers.

KEY WORDS: Scour; submarine pipeline; hydrodynamic forces; sandy seabed; oscillating flow.

INTRODUCTION

Under the complicate ocean environments with variable waves, currents and erosive seabed, to evaluate properly the hydrodynamic force on submarine pipelines is a key problem in designing pipeline systems. Actually, the periodical vortex shedding and the recip-rotating movements of wakes may induce sunken pits in the seabed around the pipeline, and remarkable changes may be brought to the relative positions between pipeline and bed by the action of scour. Some pipelines installed upon seabed can probably become suspended above the seabed. All those may result in the complicate properties of hydrodynamic forces on the pipelines and even jeopardize the safety of the pipelines.

To meet the requirement of the engineering design of marine pipelines, numerous theories are developed for calculation of the hydrodynamic forces on a pipeline. The most well-known one is Morison's equation (Morison et al, 1950). This formula treats the wave force in the horizontal direction as drag force proportional to the square of the water velocity and the inertia force proportional to acceleration of the water. By introducing drag force coefficient C_D, inertia force coefficient C_M and lift coefficient C_L, the hydrodynamic force can directly link to the velocity and acceleration of the water. Usually, the drag force coefficient C_D and the inertia force coefficient C_M can be obtained through model experiments. Recently, some improvements of modeling the hydrodynamic forces presented by Lambrakos et al (1987), Neill and Hinwood (1998), and Koterayama and Hu (1996), Dutsch et al (1998). These models can include the influence of the shallow water, the added inertia force caused by wake flow downstream of the pipeline, the *KC* number and Reynolds number, and so on. But under the conditions of oscillating flow, the changes of the environmental conditions around pipelines will make the state of forces on pipeline change in a marked way. In the field, the gaps between pipeline and seabed always exist. Sarpkaya (1981) summarized available results for the relationships between wave force coefficients and Keulegan-Carpenter number, initial relative gaps and pipeline etc. The effect of a plane boundary on oscillatory flow around pipeline and on the properties of hydrodynamic forces upon pipeline was studied experimentally by Sumer et al (1991). In the above studies, the seabed was assumed plane, i.e. the sand scour was not considered. In fact, the scour of seabed around submarine pipeline may also have great influence on hydrodynamic forces upon pipeline and its on-bottom stability. The investigation of pipeline accidents have shown that the fatigue failure cases caused by pipeline vibrations at kinds of joints and cross-sections occupy a considerable proportion of the total cases, and these vibrations are mainly brought by the seabed scouring. Many researches on scour around pipeline focus on the equilibrium scour depth and width below pipeline, including Sumer and Fredsøe (1990), Pu and Li (1999), Sumer et al (2001) etc. However, the effect of sand scour on hydrodynamic forces upon pipeline has not yet been revealed. Therefore, the proper evaluation of the hydrodynamic forces upon pipelines near erosive seabed is very important for the safe design of pipelines.

The present paper aims at investigating experimentally the properties of hydrodynamic forces upon the pipeline laid on an erosive seabed for various Keulegan-Carpenter numbers and initial relative gaps between pipeline and seabed. Based on the experimental results, the influences of sand scour on the properties of hydrodynamic forces, including hydrodynamic force coefficients and the frequency characteristics of hydrodynamic forces, are analyzed.

EXPERIMENTAL SETUP, MODELS AND PROCEDURE

Laboratory experiments were carried out in a U-shaped oscillatory water tunnel (Fig.1). The working section of the tunnel is $0.2\times0.2\times0.8$ m^3, and the soil box below the working section is $0.035\times0.2\times0.6$ m^3. Periodical oscillatory flows can be achieved in the water tunnel by cyclical air extraction controlled by a butterfly valve, which periodically opens and closes at the top of a limb of the water tunnel. The water in the tunnel thereby can accomplish a simple harmonic oscillation, i.e.

$$A_0 = A_m \sin\omega t, \tag{1}$$

where A_m is the amplitude of the oscillating flow, ω is the cycle frequency, T is the natural period of the oscillating water and equals $2.59s$. The amplitude can be increased up to $0.2m$. The streamlined curve section at the ends of horizontal part was adopted in the design work, which assures the evenness of flow velocity in the cross-sections of exits and entrances of working section.

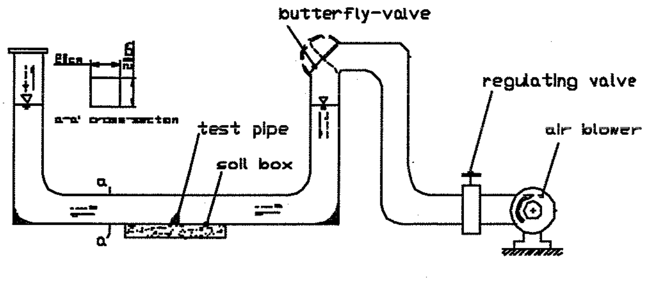


Fig.1. Schematic drawing of the U-shaped water tunnel

The pipeline models are made of aluminum alloy with circular cylindrical shape of 19mm and 29mm in diameters. The axis of the model laid vertically to the oscillatory flow direction. Cantilever beam type hydrodynamic force balance was equipped to measure the hydrodynamic force on the model during experiments. The balance was fixed with the model at one end and with the experimental section wall of the oscillatory water tunnel at the other end. The maximum measurement scope of the balance is 2.9 mV in horizontal direction and 2.1mV in vertical direction with a tolerance of less than one-thousandth in both directions.

Bed models were scour-curve shaped and made of foam plastics and these models were adhered together with steel plates so that they could be easily replaced according to different control values of the gap-to-diameter ratio *e/D* and *KC* numbers. The *e/D* is the initial non-dimensional gap between pipeline and bed, and the *KC* number of oscillatory flow is defined by

$$KC = \frac{U_m T}{D} \tag{2}$$

where T = oscillatory flow period; D = pipe diameter; and U_m = maximum water particle velocity on the bed in the absence of the pipe; i.e., $U = U_m \sin\omega t$, where U is the flow velocity, t the time, and $\omega = 2\pi / T$ is the angular frequency of flow.

The scour-curve shapes of beds are the shapes of equilibrium scour beds achieved in scour experiments making use of model sand with corresponding *e/D* and *KC* values. Bed models were placed in water tunnel, and measurement of forces was made for certain *e/D* and *KC* values. The hydrodynamic forces of pipelines were measured under frozen equilibrium scour bed conditions in this paper.

The measurements of the properties of hydrodynamic forces were carried out by self-design full-bridge strain balance with double beams and double components of the hydrodynamic force on the model. Compared with the single beam case, the appliance of double beams increased the self-vibration frequency of balance with the same measuring scope and sharply decreased the probability of coupling vibrations when the measurements were carried out in near-bed regions.

Waterproof measures to balance were taken with special wax and glue coating. Before formal tests, special waterproof tests and static demarcation in air to balance were carried out. The amplitudes of oscillatory flows were measured with a pressure-difference sensor. And the synchronous collection of the amplitudes of water flows and the data of hydrodynamic forces on pipelines were taken making use of a computer with an *AD* board. In each period, 360 sampling points were collected. The period of the oscillatory flow is 2.59s, and the sampling frequency is 139Hz. Some numerical methods were taken to ensure the accuracy of the data, such as level and smooth to reject the bad points and FFT (Fast Fourier Transformation) to filter the high-frequency disturbance. Good results have been achieved in this way.

For the purpose of comparison with the results in the case of erosive seabed, the hydrodynamic forces on pipelines in plane bed case with relevant *e/D* and *KC* numbers were measured in the experiment as well.

THERETICAL BASIS

According to the Morison formula, the hydrodynamic force on a cylinder exerted in a wave field can be calculated by:

$$F_H(t) = \frac{\pi}{4}\rho D^2 C_M \frac{du(t)}{dt} + \frac{1}{2}\rho D C_D |U_C + u(t)| [U_C + u(t)], \tag{3}$$

$$F_V(t) = \frac{1}{2}\rho D C_L [U_C + u(t)]^2, \tag{4}$$

where $F_H(t)$ is the hydrodynamic force on a pipeline of a unit length in horizontal direction, so called the horizontal force, $F_V(t)$ is the hydrodynamic force on a pipeline of a unit length in vertical direction, namely, the lift force, ρ is the density of the fluid, D is the diameter of the pipe, *Uc* is the velocity of flow, and *u(t)* is the velocity of water particle in the wave field. C_M, C_D and C_L are called inertia force coefficient, drag force coefficient and lift force coefficient. The drag force coefficient C_D and the inertia force coefficient C_M can be obtained by least–square fitting

$$C_D = [\sum AB \cdot \sum BF_{xp} - \sum AF_{xp} \cdot \sum B^2] / [(\sum AB)^2 - \sum A^2 \cdot \sum B^2], \tag{5}$$

$$C_M = [\sum A^2 \cdot \sum BF_{xp} - \sum AB \cdot \sum AF_{xp}] / [\sum A^2 \cdot \sum B^2 - (\sum AB)^2], \tag{6}$$

where

$$A = \frac{1}{2}\rho \cdot D \cdot u(z,t) \cdot |u(z,t)|, \quad B = \frac{\pi \cdot D^2}{4}\rho \frac{\partial u(z,t)}{\partial t}, \tag{7}$$

F_{xp} is the wave force in horizontal direction measured in experiments. The maximum lift force coefficient is defined by

$$C_{L\max}^{\ +} = F_{V\max}^{+} / \frac{1}{2}\rho \cdot u_{\max}^2 \cdot D \cdot L, \tag{8}$$

$$C_{L\max}^{\ -} = F_{V\max}^{-} / \frac{1}{2}\rho \cdot u_{\max}^2 \cdot D \cdot L. \tag{9}$$

in which, the upper indices "+" and "-" stand for the upwards lift and downwards lift respectively, L is the length of the pipe. The maximum horizontal force coefficient is defined as

$$C_{f\max} = F_{H\max} / \frac{1}{2}\rho \cdot u_{\max}^2 \cdot D \cdot L, \tag{10}$$

where $F_{H\max}$ is the maximum horizontal force within one period.

RESULTS AND DISCUSSION

In the experiments, two kinds of pipes are used, one is with D=0.019m, the other is D=0.029m. For D=0.019m and e/D=0.262, the measurements of hydrodynamic forces on pipelines in scour bed cases were carried out at KC=14.0, 18.9, 23.6 and 25.6 respectively, and those in plane bed cases were taken at KC=13.5, 23.7 and 25.6 respectively. When D=0.029m and e/D=1.003, the hydrodynamic forces on pipelines in scour bed cases were measured at KC=7.1, 10.9, 14.6, 17.7 and 18.4 respectively, and those in plane bed cases were measured at KC=6.9, 11.0, 14.3, 17.7 and 18.4 respectively. However, when D=0.029 and e/D=0, only the measurement of the hydrodynamic forces on pipelines in scour bed cases were conducted at KC = 3.9, 8.9, 15.4 and 18.2. The main results obtained are given below. Fig.2 presents the typical measuring results of the variation of horizontal forces with time. From the figure, we can see that the symmetry of the horizontal forces is not destroyed by changing KC number. With the increase of KC, horizontal forces remain single frequency consistent with the frequency of oscillatory flow, but its amplitude is enlarged. From the figure, we can also get that with the increase of e/D, the horizontal forces are decreased obviously. Those are true both for plane bed and scour bed.

Fig. 3 gives the typical measuring results of the variation of lift forces with time. The figure indicates that KC number has a significant effect on lift forces. Different from the horizontal force, the asymmetry of lift forces is enhanced with the increase of KC number and the doubling frequency occurs when KC number reaches some value. With the further increase of KC number, the main frequency comes out, and the variation of lift forces with time is mainly at doubling frequency. As to the relative gap ratio e/D, its influence on lift forces is much large than on horizontal forces. The increase of e/D not only decreases the amplitudes of lift forces, but also changes the distribution of the main frequency and secondary frequency.

From the experimental data of hydrodynamic forces, the hydrodynamic force coefficients can be calculated using Eqs (3)~(10). Fig. 4 gives the variation of horizontal force coefficient $C_{f\,\max}$ with KC numbers. The results both for plane bed and scour bed are given in the figure. The maximum horizontal force coefficients in scour bed cases are smaller than those in corresponding plane bed cases, and their differences decrease with the increasing of e/D. Therefore, it is safer to estimate the horizontal forces in relevant plane bed conditions for engineering applications. Fig. 4 also presents that the results are very similar both in scour bed cases and in plane bed cases when e/D are close to 1, and the influences of bed are gradually reduced with the increasing of e/D. The results are also compared with those obtained by Pu (1999). Furthermore, we may see that the variation of horizontal force coefficients with e/D is not monotonous for the scour bed cases.

Fig. 5 shows the variation of lift force coefficient $C^{+}_{L\,\max}$ with KC and e/D. The variation of maximum lift force coefficients at e/D = 0.045 and 0.29 both in plane bed and scour bed is given in the figure with a wide range of KC numbers. And the experimental results given by Wang (1999) at e/D = 0 and 0.2 in wave tunnel and given by Pu (1999) at e/D = 0 and 0.262 in oscillating water tunnel in plane bed cases related in paper are also presented in this figure to make some comparison. As can be seen from this figure, at the same bed condition and gap magnitude, the maximum lift coefficient trends towards decrease with the increase of KC numbers, and at the same gap magnitude and same KC number, bed condition exerts a significant influence on maximum lift coefficient. With the increase of the gaps between the pipeline and bed from zero, the maximum lift coefficient increases at the beginning then decrease at some gap magnitude. That is to say, during the scouring process, the pipeline will undergo the action of maximum lift force from the scouring until the scouring equilibrium is reached.

Fig. 6 gives the variation of lift force coefficient $C^{-}_{L\,\max}$ with KC and e/D values. The conditions of KC and e/D values remain unchanged as in figure 5. From the figure, we can see that the basic changing tendency of $C^{-}_{L\max}$ is similar to that of $C^{+}_{L\max}$. Fig. 5 and Fig. 6 also show that there are not obvious influences caused by scour to the maximum lift force coefficients after KC > 10. And the changing tendency of the maximum lift force coefficients with the change of KC number in scour bed cases is consistent with that in plane bed cases, while the two kinds of lift forces, $C^{+}_{L\max}$ and $C^{-}_{L\,\max}$ in plane bed conditions are much larger than those in scour bed conditions. From the above discussion, it may be concluded that it is practicable and safe to estimate lift forces on pipelines in plane bed conditions for engineering application.

In scour bed case with e/D = 0, it can be seen that the changing tendency of frequency properties of lift forces with KC numbers is very similar to that in plane bed cases with e/D = 0.262. It may be considered that because the gap between pipeline and bed is brought about by scour, but the gap is so small that the reciprocating movements of separating vortex are restricted.

It should be mentioned here that the hydrodynamic force exerted on the pipeline depends mainly on the scouring state under the pipe and vortex motion in the flow field around the pipe. During the scouring process, the gap between the pipe and seabed becomes larger and larger until the scour equilibrium state is reached, and the flow state within the gap will also vary according to the magnitude of the gap, typically jet flow when e/d is small or vortex flow when e/d is large. Conversely, the flow state will also influence the scouring profile and speed. Their interaction may play an important role in the hydrodynamic forces upon the pipeline on seabed. Therefore, it is necessary to make further investigations on vortex motion properties of flow field with the coupling effects between water and soil.

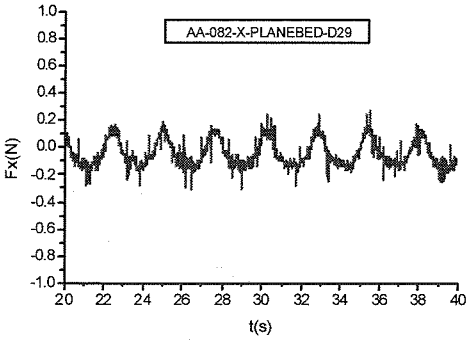
CONCLUSIONS

From the preceding experimental results and their analysis, the following conclusions can be drawn:

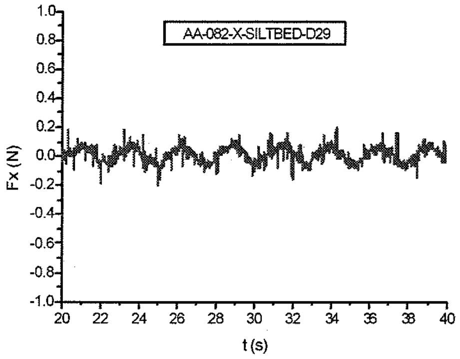
(1) With the increase of KC number, the amplitude of horizontal force increases, and its frequency property also remains unchanged. The maximum horizontal forces on pipelines are found to decrease obviously to some extent due to seabed scour.

(2) KC number has a significant effect on lift forces. When KC number increases, lift forces become asymmetry, doubling frequency occurs at a certain value of KC number. The increase of e/D not only brings the decrease of the amplitudes of lift forces, but also may change the properties of main frequency and secondary frequency of lift forces.

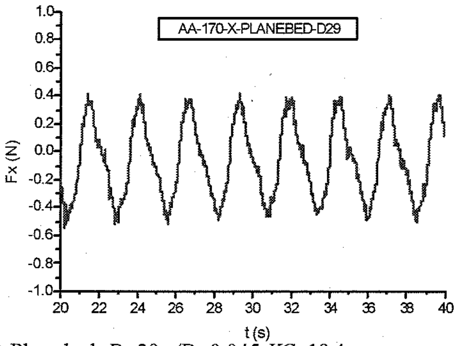
(3) For engineering application, it is safer to estimate the amplitudes of hydrodynamic forces on pipelines by using plane bed conditions. However, it should be noticed that the frequency properties of lift forces may be significantly influenced by scour process.



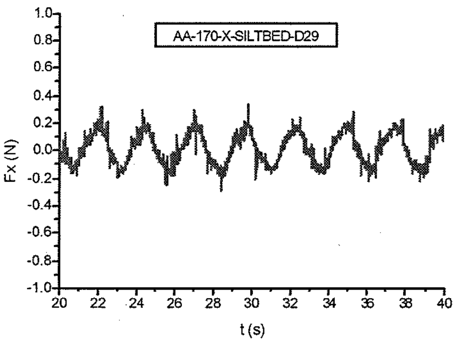
(1) Plane bed, D=29, e/D=0.045, *KC*=8.9.



(2) Scour bed, D=29, e/D=0.045, *KC*=8.9.

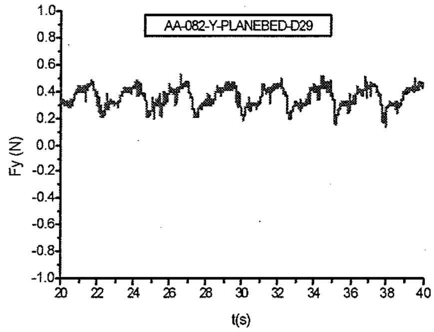


(3) Plane bed, *D*=29,*e/D*=0.045,*KC*=18.4

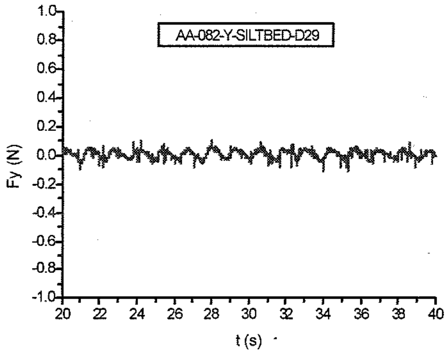


(4) Scour bed, *D*=29, *e/D*=0.045, *KC*=18.4

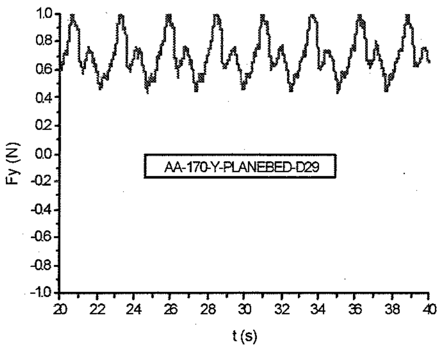
Fig.2. The variation of horizontal hydrodynamic forces with time.



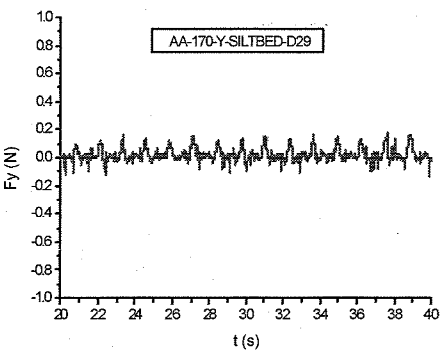
(1) Plane bed, *D*=29,*e/D*=0.045, *KC*=8.9



(2) Scour bed, *D*=29,*e/D*=0.045, *KC*=8.9

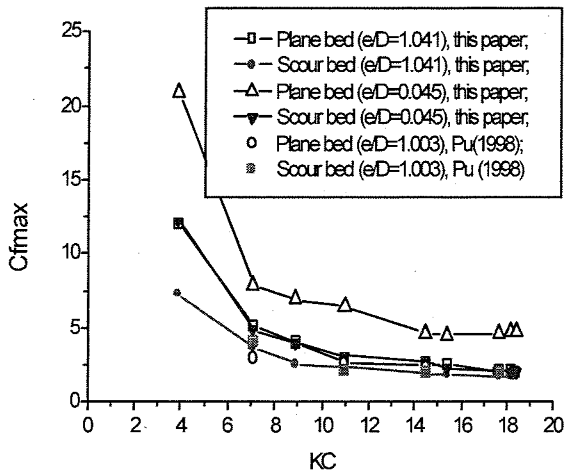


(3) Plane bed, *D*=29,*e/D*=0.045,*KC*=18.4



(4) Scour bed, *D*=29, *e/D*=0.045, *KC*=18.4

Fig.3. The variation of lift forces with time.



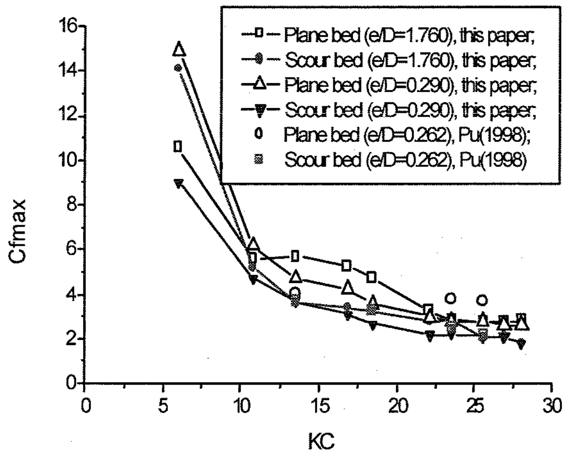
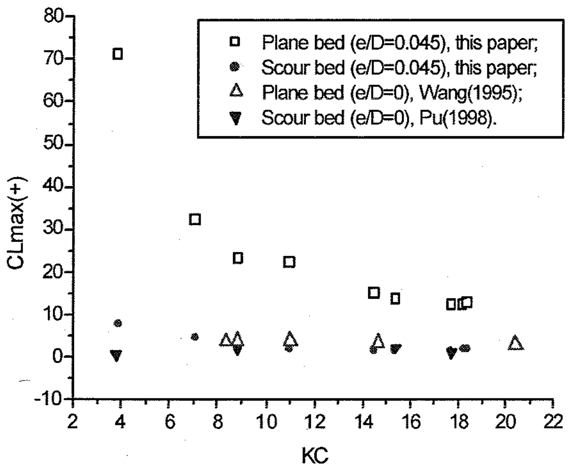


Fig.4. The variation of maximum horizontal force coefficient $C_{f\max}$ with KC number.



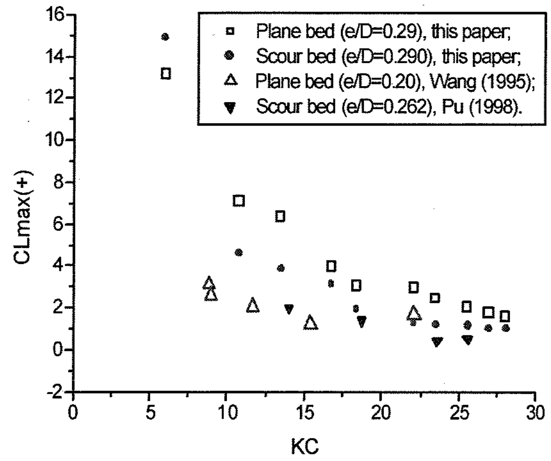
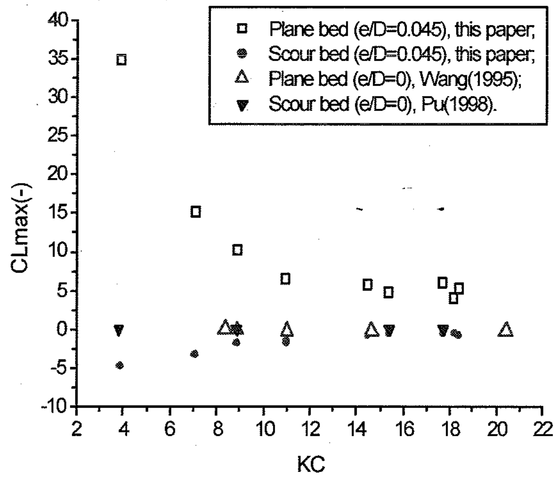


Fig.5. The variation of lift force coefficient $C_{L\max}^{+}$ with KC and e/D.



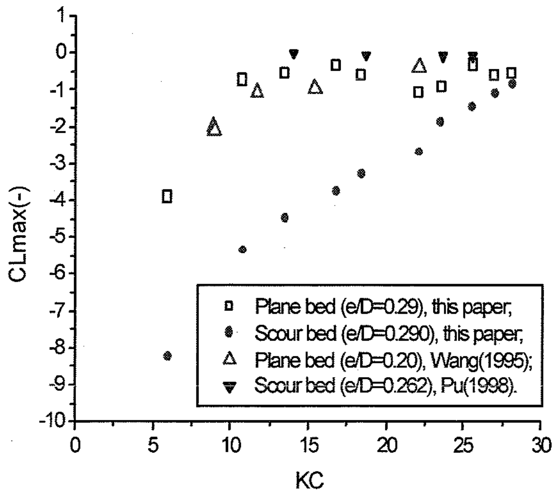


Fig.6. The variation of lift force coefficient $C_{L\max}^{-}$ with KC and e/D.

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