*China Ocean Engineering*, Vol.15, No.1, pp.129– 137
© 2001 China Ocean Press, ISSN 0890– 5487.

# Scour of the Seabed Under A Pipeline in Oscillating Flow *

PU Qun (浦群), LI Kun (李坤)
and GAO Fuping (高福平)

*Institute of Mechanics, Chinese Academy of Sciences, Beijing 100080, China*

**ABSTRACT**

The scour of the seabed under a pipeline is studied experimentally in this paper. Tests are carried out in a U-shaped oscillatory water tunnel with a box imbedded in the bottom of the test section. By use of the standard sand, clay and plastic grain as the seabed material, the influence of the bed material on the scour is studied. The relationship between the critical initial gap-to-diameter ratio above which no scour occurs and the parameters of the oscillating flow is obtained. The self-burial phenomenon, which occurs for the pipeline not fixed to two sidewalls of the test section, is not observed for the fixed pipeline. The effect of the pipe on sand wave formation is discussed. The maximum equilibrium scour depths for different initial gap-to-diameter ratios, different *Kc* numbers and different bed sands are also given in this paper.

**Key words:** *scour*; *pipeline*; *oscillating flow*; *seabed*

## 1. Introduction

The scour around a pipeline may influence the in-place stability of the marine pipeline, so it is important for the safety and economy of submarine pipeline design (Herbich, 1981; Bruschi and Vitali, 1994). The scour phenomenon around a pipeline is very complex because the scour can be influenced by many environmental elements such as flow, topography and soil. This phenomenon is substantially a result of coupling actions between fluid, solid and seabed. The scour below a pipeline exposed to waves is related to oscillating separated vortex flow. Because of the seabed erosion and the dynamic seabed boundary, the boundary will change and the seabed material will enter the water, which will cause difference between the separated vortex flow around a pipeline above an erodible bed and that above a plane bed (Sumer *et al.*, 1991). On the other hand, start and transportation of sediment in an unsteady flow is a frontier problem in sediment research (Plate, 1994). In addition, there is complicated interaction between multiple separated vortices in the process of oscillating flow. Furthermore, if the effect of the vortex-induced oscillation of the pipeline on the flow field and the transportation of sediment is taken into account, the problem will be even more complex. For the above reason, it is almost impossible to completely simulate the actual situation. Therefore, it is necessary to conduct studies on correlation of parameters that influence scour and scour mechanism. Many studies on scour in waves, although not as many as in currents, have been conducted and some engineering formulas have been proposed (Herbich, 1981; Sumer and Fredsoe, 1990; Gokce and Gunbak, 1991; Cevik and Yüksel, 1999). Most of these studies focus on sand bed. In fact seabed is composed of various soil materials. There is clay bed in many continental shelves and coastal water areas. So the

* The project was supported by the National Natural Science Foundation of China (19772065) and the Key Project (KZ951–A1–405) of "Ninth Five-year Plan" of Chinese Academy of Sciences

study of the effect of different soil materials on scour under pipelines is important both in engineering design and in academic investigation. Because the oscillating flow is a simplified form of waves, present tests are carried out in a U-shaped oscillatory water tunnel with a soil box imbedded in the bottom of the test section. The influence of the bed material on the scour and the self-burial phenomenon are studied. The relationship between the critical initial gap-to-diameter ratio above which no scour occurs and the $Kc$ number is obtained. The maximum equilibrium scour depths for different initial gap-to-diameter ratios, different $Kc$ numbers and different sand beds are obtained.

## 2. Experimental Setup and Procedure

### 2.1 Experimental Setup

A schematic diagram of the U-shaped oscillating water tunnel is shown in Fig. 1. By use of an air blower with a butterfly-value which periodically opens and closes the top of a limb of the water tunnel, the water in the tunnel accomplishes simple harmonic oscillation:

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

where $A_m$ is the amplitude of the oscillating flow, $\omega$ is the circular frequency $\omega = 2\pi / T$, and $T$ is the natural period of the oscillating water and it equals 2.59 s. The amplitude can be varied up to 0.2 m. The size of the test section is $0.2 \times 0.2 \times 0.8$ m$^3$. A bed box of $0.035 \times 0.2 \times 0.6$ m$^3$ is embedded in the bottom of the test section. The undisturbed bed top surface is at the same level as the bottom of the test section. By use of the contour elbow, the flow velocities at the inlet and outlet of the test section are uniform.

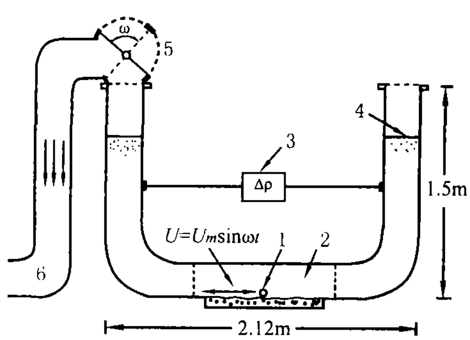


**Fig. 1.** Schematic diagram of the U-shaped water tunnel.
1. Test cylinder; 2. Working section; 3. A differential pressure transducer
4. Water level; 5. A butterfly value; 6. Wind tunnel connected with an air blower.

### 2.2 Pipeline Model

The pipe models of diameters $D = 28.9$ and 19.1 mm are made of plexiglass and are fixed to two sidewalls of the test section. For the pipelines directly installed on the seabed, the pipe models of outer diameter $D = 14$ mm and inner diameter $D_i = 12$ mm are made of aluminium, the length being 190 mm. Different model pipes with different submerged weights are at different initial burial depths.

### 2.3 Preparation of the Soil Sample

Four soil samples are used in the tests for fixed pipeline models: standard sand, clay and two kinds of plastic grain with different mean diameters. The characteristics of the standard sand are $d_{50}$= 0.20 mm, specific gravity $\gamma$ =2.59, and saturated unit weight $\gamma_{sat}$= 10.24 kN / m$^3$. The characteristics of the clay are $d_{50}$= 0.0047 mm, $\eta = \sqrt{d_{75}/d_{25}}$ = 2.86 and percentage of fine grains 72%. The plastic grain is of $d_{50}$= 0.47, 0.68 mm and specific gravity $\gamma$ = 1.42. The clay is from 5~ 7 m depth of the Dongying port area, China. The clay sample in the bed box used in the present tests is obtained from the clay with the same initial unit weight, after four days' sedimentation in a tank. Then its unit weight is measured. For observation of the scour phenomenon around a pipeline in oscillating flow and investigation of the effect of sand diameter on bed scour, the plastic grain is used as the soil sample.

The standard sand of $d_{50}$= 0.38 mm, $D_r$= 0.37, and $\gamma_{sat}$= 19.0 kN / m$^3$ is used as bed material in the tests of the unfixed pipe model.

The grain size distribution curves of the standard sand and the plastic sand are given in Fig. 2. To ensure that the soil sample is sufficiently saturated, the sand is filled in the bed box under the water in a sedimentary tank.

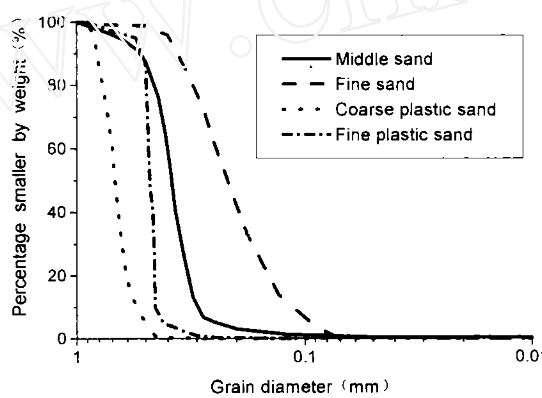


**Fig. 2.** Grain size distribution curves.

### 2.4 Test Procedure

The development of scour in each test is monitored by a CCD video camera located in front of the sidewall of the test section. The oscillation amplitude is gradually increased. When the bed sand starts to move, the critical state of scour is obtained. At a certain oscillation amplitude the test is continued until the movable bed is in dynamic equilibrium. Then the maximum equilibrium scour depth and the wavelength of the sand wave are measured. For the clay bed the sediment start is determined by sudden change of greyness of the water above the bed. Because the water becomes opaque when scour occurs the CCD camera can only record the initial scour process. After two hours' experiment the bed box is taken out and the bed surface pattern is obtained.

The Keulegan-Carpenter number $Kc$ is defined by

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

where $U_m = \omega A_m$ is amplitude velocity of the incoming flow, and $D$ is the pipe diameter. The Reynolds number is defined by

$$Re = \frac{U_m D}{v} \tag{3}$$

where $v$ is kinematic viscosity coefficient of water. The Shields number corresponding to the incoming oscillating flow is defined by

$$\theta = \frac{f \cdot U_m^2}{(\gamma - 1) \cdot g \cdot d_{50}} \tag{4}$$

where $g$ is acceleration of gravity, $f$ is the friction coefficient for the wave-boundary layer, which is given by Fredsoe (1984).

## 3. Experimental Results and Analysis

### 3.1 Scour Process Around the Pipeline

The scour phenomenon for gap-to-diameter ratio $e/D = 0$ is dissimilar to that for $e/D \neq 0$. When $Kc$ increases, flow separation and vortex shedding occur. For $e/D = 0$, the flow around a pipe is a forward separated flow at the corner between the lower pipe surface and the bed surface and is a separated and reattached flow behind the pipe. This flow undergoes an acceleration and deceleration process. Whatever the bed material is, the tests show that scour occurs at the forward corner of the pipe at first. Sediment moves backwards away from the pipe and reaches the vicinity of the separating point B as shown in Fig. 3(a). For standard sand bed, the reattached flow behind the pipe is observed. The sediment moves towards two opposite directions away from the reattaching point C, as shown in Fig. 3(a). Point C is farther away from the pipe than point B. With the scour development sediment stacks up near point B. The gap between the pipe and the bed occurs after a scour process, and the flow pattern changes. For $e/D \neq 0$, the flow pattern is different from that for $e/D \neq 0$. When $e/D$ is small, sediment reciprocates near point A and then stacks up a little (see Fig. 3(b)), whether the bed is made of standard or plastic sand. When $e/D$ is larger than a certain value, for example $e/D = 0.45 \sim 1.0$ for standard sand bed, reciprocation of sediments are observed at points A, D and E, as shown in Fig. 3(b). The larger the $e/D$, the larger the distance between A and D or E. This is dependent on the action of the shedding vortex of the wake on the sand bed. With the increasing velocity, transfiguration of the bed surface is observed for standard and plastic sand bed. When the velocity is a little larger than the critical value, there is only one main sand valley formed underneath the pipe. When the velocity increases, the second and third sand waves occur successively on both sides of the main sand valley. The larger the distance from the sand wave to the pipe, the lower the peak of the sand wave. The sand bed far from the pipe is undisturbed. It seems that there is propagation and consumption of wave energy in the liquefied sand bed. The scour hole of the standard sand bed is steeper than that of the plastic sand bed. This may be interpreted by their different rest angles.

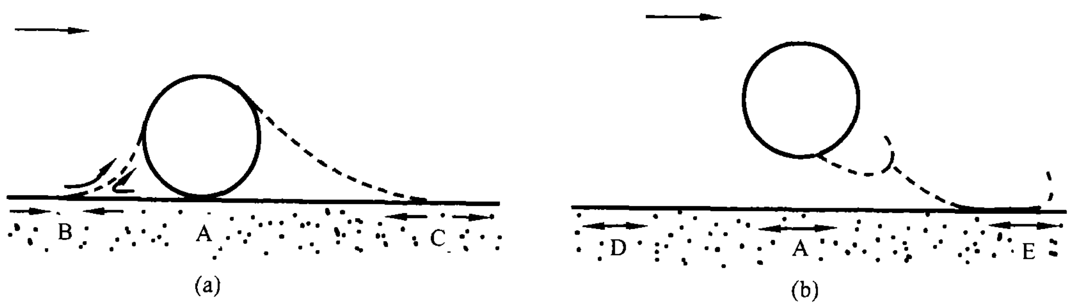


**Fig. 3.** Schematic diagram of sand start for different gap-to-diameter ratios.

### 3.2 Critical Scour Parameters

For onset of scour, there is a minimum velocity for given $e/D$ and one kind of bed soil. This is called the critical state for onset of scour. The test results for the critical state for different $e/D$, different $Kc$ and different bed soils are given in Fig. 4. It is discovered that the experimental results for different bed soils are located on a series of oblique lines with the same slope in the logarithm coordinates, as shown in Fig. 4, although the characteristics of the sand bed and clay bed are very different and the start mechanisms for them are also different. On the basis of investigation by Pu and Li (1999) the correlation expression is given by

$$\left(\frac{e}{D}\right)_{cr} = 2.2 \lg Kc - B \tag{5}$$

where $B$ is a constant related to the bed material characteristics. This conclusion is convenient in practice to determine whether the scour of the bed will take place for different bed soils. It shows also that the $Kc$ number is a main parameter among many similar parameters of flow that influence the onset of scour. In Fig. 4 the experimental results for fine plastic sand bed fall near the fitted straight line for coarse plastic sand bed given by Pu and Li (1999), indicating that the grain size has no obvious effect on critical scour under the present experimental conditions.

### 3.3 Sand Wave Formation

When there is no pipe on the bed, the start and scour of the sand bed also takes place as the oscillating velocity increases. The scour process for plastic and standard sand bed develops as follows: at first, part of the sand grains on the surface of the bed rocks at the original location with the oscillating frequency, but they do not jump from the bed; then they jump a little distance from the bed and move forth and back with the oscillating flow and the sand grains nearby begin oscillatory motion; in succession some streaming grooves distribute randomly on the surface of the bed. When the velocity is large enough, regular sand waves form on the bed surface as mentioned by Pu and Li (1999). With the velocity increasing, the length and the height of the sand wave increase. In a certain range of velocity, for example at $U_m = 10.3 \sim 14$ cm / s for fine plastic sand, the length-to-height ratio does not vary, and equals approximately to 10, and the ratio $A_{mcr}/k$, for coarse and fine plastic sand is nearly the same, where $A_{mcr}$ is the minimum oscillation amplitude at which sand waves occur and $k$ is the roughness of the bed. $A_{mcr}/k$ for the standard sand is larger than that for the plastic sand. After the sand wave takes place on the standard sand bed, the oscillation amplitude decreases obviously. It means that as a result of sand wave formation the drag of the sand bed increases.

When the pipe is present on the sand bed, the scour of the bed takes place as mentioned above. When the oscillation amplitude is larger than a critical value, regular sand waves also take place on the bed surface far away from the pipe. The $A_{mcr}/k$ for the sand bed with a pipe is a little smaller than that without a pipe. This is the same for the standard or plastic sand bed. The present experiment shows that the critical oscillation amplitude for the same bed soil and different $e/D$ and $D$ is almost the same and the length of the sand wave is also the same. No matter whether the pipe is present or not, a series of streamwise thin grooves is seen distributed along the pipe axis direction on the sand wave valley surface.

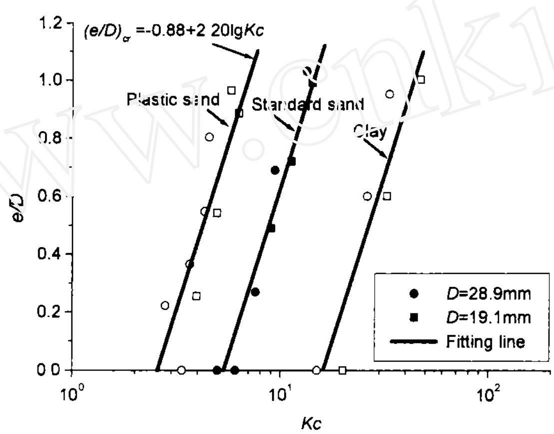


**Fig. 4.** Critical gap-to-diameter ratio vs. $Kc$ number.

### 3.4 Self-Burial Phenomenon

The pipe models used in the self-burial test are not fixed to the sides of the test section. The submerged weights of the pipe models are 0.68, 0.94 and 1.19 N / m and the initial burial depth are 0, 3.6% and 7.1% respectively. The light pipe model rolls away from the original position at $U_m = 0.09$ m / s. There is not any trace on the bed surface. But for the heaviest pipe model, as the velocity increases gradually, the scour of the bed at both sides of the pipe takes place at a certain velocity and the sediment stacks up near the separating point B. This is similar to that for the fixed pipe. But this is different from the fixed pipe case in that, due to the sag of the pipe into the scour valley, the gap between the pipe and the bed cannot take place. When the amplitude increases slowly a scour hole forms gradually near point P outside the separation region. Bed sand grains move along the dash line as shown in Fig. 5. Following the flow, the sand grains sedimentated at the top of the pipe shake left and right. As a result of the above process, the pipe is self-buried gradually. The stability of the self-burial pipe increases. The middle weight pipe model shakes a little in the scour hole at a certain velocity, but does not move away from the original place. When the flow amplitude increases drastically the pipe would roll up. It is seen in the experiment that the formation of the self-burial phenomenon of the pipe is related to the accelerating process of the flow. A slow acceleration of flow leads to the self-burial phenomenon, while a sudden acceleration of flow would cause the instability of the pipe, especially after shaking of the pipe. The self-burial phenomenon is also related to the pipe weight and the initial burial depth. For the same accelerating process the heavier of the pipe weight or the deeper of the burial depth, the more easily the self-burial phenomenon will take place. It is also observed in the experiment that the characteristics of sediment transport near the separating point are major factors affecting self-burial formation. The self-burial phenomenon does not occur in the tests for fixed pipe models.

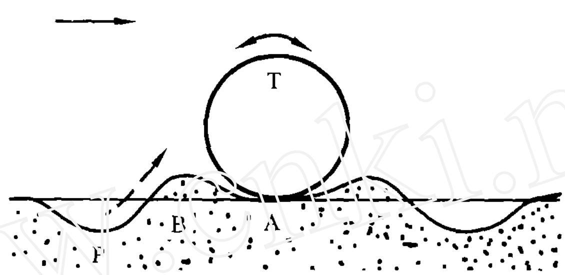


**Fig. 5.** Schematic diagram of self-burial process.

### 3.5 Maximum Equilibrium Scour Depth

The experimental results of the maximum equilibrium scour depth are obtained at $e/D = 0 \sim 1.0$ for the fixed pipe of $D = 2$ and 3 cm. The experimental parameters are listed in Table 1.

**Table 1** Experimental parameters for different bed materials

| Bed material | $Kc = \frac{U_m T}{D}$ | $Re = \frac{U_m D}{\nu}$ | $\theta = \frac{f \cdot U_m^2}{(\gamma - 1) \cdot g \cdot d_{50}}$ |
|---|---|---|---|
| Fine plastic grain | 4.30 ~ 22.20 | $0.9 \times 10^3 \sim 4.0 \times 10^3$ | 0.052 ~ 0.273 |
| Coarse plastic grain | 3.91 ~ 31.90 | $1.3 \times 10^3 \sim 6.5 \times 10^3$ | 0.049 ~ 0.395 |
| Standard sand | 6.07 ~ 32.57 | $1.3 \times 10^3 \sim 4.9 \times 10^3$ | 0.030 ~ 0.245 |

For every bed material the test results can be related by a series of oblique lines in the logarithm coordinates of $S/D$ and $Kc$, $S$ being the maximum equilibrium scour depth. For different $e/D$ the intercepts of the oblique lines are different, but their slopes only differ a little. The average of these slopes taken, the normalized test results are given in Fig. 6, Fig. 7, and Fig. 8 in the logarithm coordinates of $S/(DA)$ and $Kc$, for fine, coarse plastic sand and standard sand bed respectively. Here A represents the intercepts of the oblique lines with the average slope and is a function of $e/D$ and $D$, as seen in Fig. 6(b), Fig. 7(b) and Fig. 8(b). It must be pointed out that most results for plastic sand are obtained at live-bed case, but most results for standard sand are taken where sediment far away from the pipe does not move. A does not change with $e/D$ much in Fig. 6(b) and Fig. 7(b) but it changes obviously in Fig. 8(b). From Figs. 6 and 7, and Fig. 8 the following relationship between $S/D$ and $Kc$ can be given by

$$\frac{S}{D} = A \cdot Kc^{m} \tag{6}$$

where $m$ is a constant of bed material.

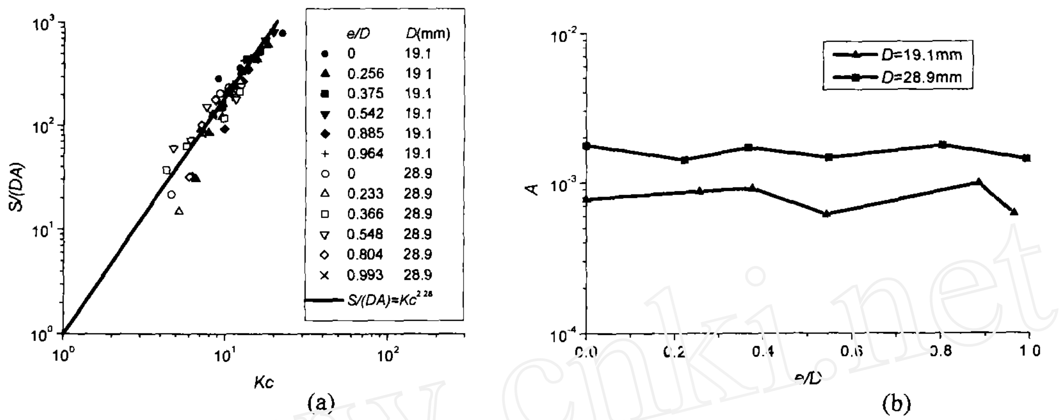


**Fig. 6.** Dimensionless scour depth vs. $Kc$ for fine plastic sand bed.

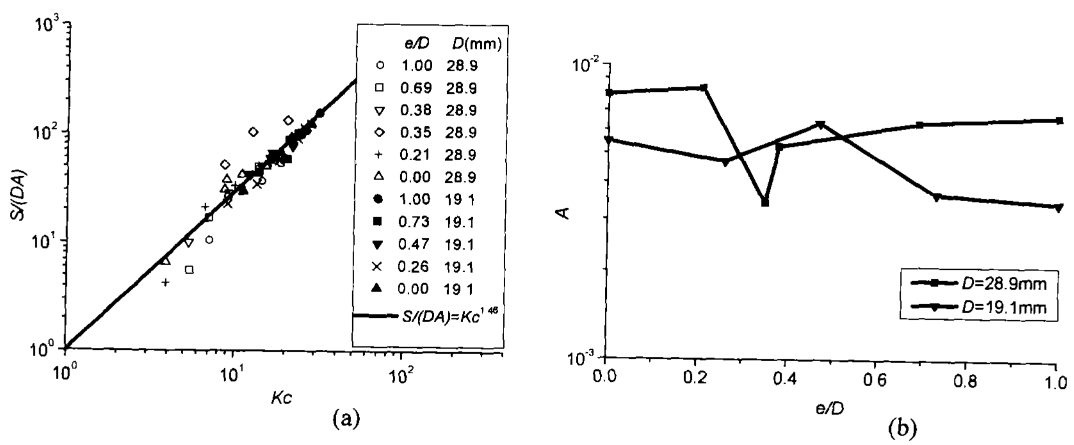


**Fig. 7.** Dimensionless scour depth vs. $Kc$ for coarse plastic sand bed.

## 4. Conclusions

The following conclusions are drawn from the present experiments.

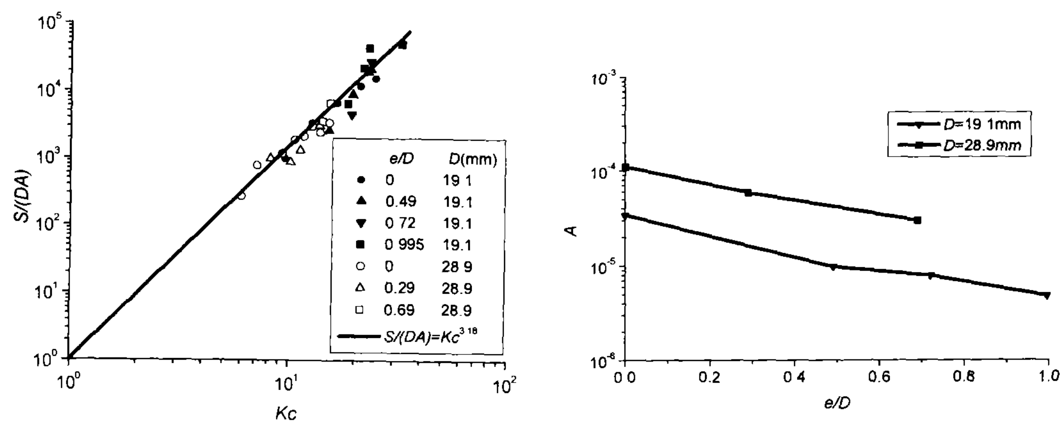


**Fig. 8.** Dimensionless scour depth vs. $Kc$ for standard sand bed.

—The onset of scour is mainly influenced by $Kc$ number. The relationship between the critical initial gap-to-diameter ratio $(e / D)_{cr}$ above which no scour occurs and the $Kc$ number can given by $(e / D)_{cr} = 2.2 \log Kc - B$, $B$ being a constant of bed material.

— The presence of a pipe can result in a reduction of the dimensionless critical amplitude $A_{mcr}/ k$, above which the sand wave forms on the surface of the bed.

— The self-burial phenomenon is observed for the pipe directly installed on the bed but not for the fixed pipe. The self-burial phenomenon is related to the flow accelerating process, the pipe weight, and the initial burial depth.

— The relationship between dimensionless maximum equilibrium scour depth $S/ D$ and $Kc$ number can be given by the expression $S / D= A \cdot Kc^{m}$, $m$ being a constant of bed material.

## References


Bruschi, R. and Vitali, L., 1994. Recent advances in offshore pipeline technology, *Proceeding of the 4th Int. Offshore and Polar Engineering Conf.*, Osaka, Japan.

Cevik, E. and Yüksel, Y., 1999. Scour under submarine pipelines in waves in shoaling conditions, *J. Waterway, Port, Coastal and Ocean Engineering*, ASCE, **125** (1): 9~19.

Fredsoe, J., 1984. Turbulent boundary layer in wave-current motion, *J. Hydraulic Engineering*, ASCE, **110** (8): 1103~1120.

Gokce, K. T. and Gunbak, A. R., 1991. Self burial and stimulated self burial of pipelines by waves, *1st Int. Conf. on Offshore and Polar Eng.*, ISCOPE, Edinburgh, 308~314.

Herbich John B., 1981. *Offshore pipeline design elements*, MARCEL DEKKER, INC.

Plate, E. J., 1994. The need to consider non-stationary sediment transport, *International Journal of Sediment Research*, IRTCES, **9** (3): 117~123.

PU Qun and LI Kun, 1999. Scour of the sand bed below the pipeline in oscillating flow, *ACTA Mechanica Sinica*, **31** (6): 677~681.

Sumer, B. M., Jensen, B. L. and Fredsoe, J., 1991. Effect of a plane boundary on oscillatory flow around a circular cylinder, *J. Fluid Mech.*, **225**, 271~300.

Sumer B. M. and Fredsoe, J., 1990. Scour below pipelines in waves, *J. Waterway, Port, Coastal and Ocean Engineering*, ASCE, **116** (3): 307~323.