Scour Around Submarine Pipeline in Clayey Soil

By

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ABSTRACT

Experimental investigations on scour due to waves under the submarine pipeline resting on the clay soil bed for different consistency index of the soil were carried out. Based on the scour measurements for few hours of wave action, the ultimate scour depth is estimated using hyperbolic model. The equilibrium scour depth below the pipeline is estimated as 45% of the pipe diameter for consistency index of 0.17 and is 35% of the pipe diameter for consistency index of 0.23. Investigations on wave pressures around the submarine pipeline (exposed, half buried and fully buried) are also carried out. It is found that the pressure is reduced by about 40%, if the pipeline is just buried in clay soil. It is also found that the consistency index of the soil significantly affects the wave-induced pressure.

[**Key words**: Submarine pipeline, Scour, Ocean waves, Wave pressure, Clayey soil, Consistency index, Pipe burial**]**

INTRODUCTION

The search for oil under deep-sea bed has led into extensive theoretical and experimental investigations in the field of offshore oil exploration and exploitation. The discovery of large deposits of oil and gas in many deep-water offshore regions has resulted in the construction of large production and drilling platforms. Since 1940's, the tendency to build the fixed offshore structures in deep waters has progressed steadily. Once the production platforms are erected in the sea, the next immediate task is to transport the oil and natural gas from the production site to onshore terminal facilities. Submarine pipeline offers an efficient mode of transportation of oil and gas continuously from offshore to onshore. Though the pipeline appears as a simple structure, interaction of submarine pipeline with waves is a complex phenomenon. Many foundations of water front structures built on sandy soils have suffered extensive damage due to scour. Even the foundations built in clayey soil beds are not free from scour effects. There are many thick under-consolidated marine clayey deposits located in several coastal areas and the scouring of foundations in such soft cohesive sediments can be quite significant. The review of existing literature reveals that studies on wave induced scour, pressures and uplift forces on submarine pipeline, **especially in cohesive soils** is in the developing stage as compared to the studies in sandy soils. Therefore, the present study has been focused on wave-induced scour and pressures around submarine pipeline in soft marine clayey soil. One of the important questions in the selection of burial of a submarine

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pipeline is "WHAT IS THE OPTIMUM DEPTH OF BURIAL FOR ACHIEVING SUFFICIENT STABILITY AGAINST SCOUR?". The effect of consistency index of the clayey soil on wave induced scour and pressures are also not known clearly and this aspect also is considered in the present investigation. Scour around the submarine pipeline results in spanning problems, flow induced vibrations and resonance, which leads to failure of pipelines.

LITERATURE REVIEW

Comparatively, not much of work is carried out on structures resting on cohesive soils. In most of the previous investigations, the resistance of the soil to erosion was related to soil and hydraulic properties. Some of the important investigations are mentioned in the following:-

Partheniades (1965) investigated the influence of shear stress, suspended cohesive sediments concentration and shear strength of bed on the erosion rate of cohesive bed in an open channel. From the flume experiments, it was found that the erosion rates were independent of the bed shear strength. **Kamphusis and Hall (1983)** studied the initiation of motion of consolidated cohesive sediments under a unidirectional flow (up to a velocity of 3.5 m/s) for clear water conditions in a flume-tunnel. It was found that critical shear stress and critical velocity were found to increase with compressive strength, vane shear strength, plasticity index, clay content and consolidation pressure. **Mitchener and Torfs (1996)** attempted to characterise the erosion behaviour of mixed sediments. It was found that the critical shear stress for erosion increased and erosion rates decreased when mud was added to sand and a maximum value had reached at a sand content in the ratio of 50% - 70 % by weight. **Civik and Yiiksel (1999)** carried out experimental investigation on scour around submarine pipeline in cohesionless soil due to regular wave actions. Based on the experimental data it was found that the relative scour depth increased with increase in wave height, wave period and pipe diameter.

Macpherson (1978) derived an analytical solution from the potential theory for the wave induced pressure distribution in the sandy soil bed surrounding a buried pipeline and the dynamic seepage force exerted on the pipeline was computed. **McDougal et. al. (1988)** developed an analytical model for estimating the pore water pressure in the sandy soil and the resulting pressure force on the submarine pipelines. The analytical solutions were compared with the results of both small and large-scale tests. Reasonable agreement is obtained for the small-scale tests. **Magda (1997)** performed comprehensive numerical studies of the hydrodynamic force acting on a submarine pipeline buried in compressible seabed sediments by using the Boundary Integral Equation method.

In cohesionless sediments, the submerged density of the soil and gravity forces provides the main resistance to erosion, but in clays essentially the physico-chemical properties plays a dominant role. The scour rate in cohesive soil is much lower than the sandy soil. Due to laboratory mechanical limitations, it could not be possible to run the wave maker continuously for long duration. Because of this reason, tests were conducted for few hours in the present study. Since the scour depth obtained at the end of the test is not the ultimate value, there is a necessity to use theoretical models like the "Hyperbolic model" to extrapolate the observed data to arrive at the ultimate scour depth.

EXPERIMENTAL INVESIGATIONS

Test Facility

The present experimental investigations were carried out in a 30m long, 2.0m wide and 1.7m deep wave flume in the Department of Ocean Engineering, Indian Institute of Technology Madras, Chennai, INDIA. Piston type wave maker is used for generation of waves. The wave height and period to be generated are controlled by a personal computer. The other end of the flume is provided with a rubble mound absorber to effectively dissipate the incident wave energy. The details of the flume, position of the model and the wave gauges used to register the wave elevations in front of the model are shown in **Fig.1.**

Experimental Set-Up

The sizes and materials for the model pipes were chosen on the considerations of normal sizes of pipeline adopted in the field and surface characteristics of field pipeline. It has been brought by **Summer et. al. (1993)** that the hydrodynamically smooth surface can contribute a good amount of scouring. **PVC** (Poly vinyl chloride) pipes can be considered as fairly smooth and hence, PVC pipe of 160 mm outer diameter and 1.96 m length were selected. The submarine pipeline model is fitted with three numbers of inductive type pressure transducers placed with equal angular spacing of 120^o on the circumference of the pipe. The measuring ranges of two pressure transducers are of 0.5 bar and one with 0.2 bar. A test section of silty clay bed of size, 2.0 m×2.0 m×0.6 m is formed at a distance of 13m from the wave maker. Uplift force are measured by using bellow type load cell of 20 kg capacity, which is connected to the model by angle section at one end and another end is fixed to the rigid frame which is placed at the top of the flume. But in this paper only the results of scour and some aspects of the wave pressures around submarine pipeline is provided. The detailed results of wave pressures and forces can be obtained from **Vijayakumar et. al. (2002).** The water depth, 'd' of 0.3m and consistency indices of the soil, I_c of 0.17 and 0.23 and pipeline resting on soil bed is adopted for scour measurement around pipeline. The clay bed is meticulously prepared to achieve these consistency indices. For scour measurement, a scale is used whose least count is 1 mm. The (x, y) co-ordinates on the scour bed are identified by using steel mesh of size 2.0 m × 1.2 m with grids of size of size 50 mm × 50 mm. Wave height of 0.2 m and wave period of 1.5 sec was used for scour study. The co-ordinate detail of scour measurements is shown in **Fig.2**.

For wave pressures around the submarine pipeline, regular waves with wave height, H ranging from 0.05m to 0.25m with an interval of 0.05m is used. For each wave height, six different wave periods, T ranging from 1.0 sec to 2.25 sec with an interval of 0.25 sec is used. The water depths, 'd' adopted for the tests are 0.3m, 0.4m and 0.5m. The consistency index of the cohesive soil, I_c used was 0.18, 0.24 and 0.33. Tests were carried out for 3 different conditions based on the position of model with reference to the bed:

1. Pipeline resting on the bed
2. Pipeline Half buried and
3. Pipeline fully buried.

Scour Measurement

The clay bed was prepared for the required consistency and initial bed level was measured. For the purpose of reference, four concrete cubes of size 150 mm are placed at four corners of the pit and two-channel section of 2.5 m length is placed over the concrete cubes. Now steel mesh was placed over the channel section to measure the level of bed by using scale with 1 mm as least count. After taking all the measurements, the above set up was removed and the model was placed over the soil bed. The water level was raised to a depth of 0.3 m. The scour testing was carried out for a total of about 7200 wave cycles (about 3 hours) to ensure a good progressive rate of scour at the end of the tests. It may be noted that to reach ultimate conditions of scouring in this type of soil, it has been established earlier **(Rambabu (2000)**) in this laboratory that it is required to continue the testing for more than three days. Due to the limitations in the wave maker equipment, it was not possible to extend this testing beyond 3 – 4 hours. In view of this, the test duration was limited to 3 hours for about 7200 cycles of waves. At this stage, a good progressive rate of scouring was observed. After every 1 hour test run, the water level was lowered and the magnitude of scour depth (clay bed topography) was measured around the submarine pipeline by following the same procedure as explained above. This measurement at a particular point, after subtraction from the initial measurement gives the scour depth at that particular co-ordinate.

Test Bed And Soil Placement

A test section with soil bed of size 2.0 m × 2.0 m × 0.6 m was formed at distance of 13m from wave maker. The fine-grained soil, silty clay from a local deposit was brought and used in this investigation. Fairly homogeneous and saturated clay bed was formed using the technique adopted by the earlier investigators **(Mallikarjuna Rao, 1992)**. The soil brought was first air dried and mixed with water to get the desired water content and this soil was placed layer by layer in the test pit. The index property tests like liquid limit (LL) and plastic limit (PL) were conducted as per IS 2720 (part 5) - 1985. The grain size distribution of the soil was established through hydrometer test conducted as per IS 2720 (part 4)-1985. The different properties of the soil measured were presented in **Table. 1.** It is generally known that the fine-grained soil is less prone for scouring. However, if these soils are deposited with higher moisture contents, significant scouring in these deposits is possible. In order to get in to these conditions, soil bed was formed at higher moisture contents. Moisture content can be expressed in terms of consistency index, I_c. As the soil bed was formed at higher moisture contents, there was no difficulty in the formation of homogeneous bed **(Prasad and Narasimha Rao, 1994)**.

RESULTS AND DISCUSSIONS

Scour Around Submarine Pipeline

The stability of many structures in ocean environment is very much controlled by wave activity. In the first instance, waves can cause significant amount of scouring around these structures, which are founded on / in seabed, affecting seriously the stability of foundations. In few cases, along with the scour, the increase in the magnitude of forces on the structures leads to structural failures. From the results presented in the previous sections, it is clear that with change in burial depth of submarine pipeline, there are enormous difference in the forces and pressures. It is known that pipeline resting on the seabed induces significant scour compared to buried pipeline (Sumer & Fredsoe, 1990) in sandy soil. In view of this an attempt has been made to get the spatial and temporal variation of scour depth for submarine pipelines resting on the seabed. From the limited measured scour depth data, ultimate values are predicted using an established observational hyperbolic method (Kondner (1963)).

Hyperbolic Model

According to this model by Kondner (1963), the scour depth (S) can be expressed as function of time 't' as

$$S = t / (A + B t) \quad (1)$$

$$S_u = \lim_{t \to \alpha} S = (1/B) \quad (2)$$

The constant 'A' and 'B' depends on soil and hydraulic conditions. The slope of the best line fit i.e.'1/B' gives the ultimate scour depth. This is essentially the model suggested by **Kondner (1963)** to validate stress-strain relationship in soils. The following example illustrates the estimation of the ultimate scour depth from the data of measured scour depth and time duration. The time development of scour depth for a particular diameter (D=160 mm) at different locations around pipeline with two different consistency index of soil is shown in **Table 2**. The effect of time of wave action, t on development of scour depth, S at four different relative locations at the upstream side of the pipeline (y/D = -0.31, -0.62, -0.94 and –1.25) for two different consistency index of the soil (I_c = 0.17 and 0.23) is brought out in **Figs.3.** A similar plot for the down streamside of the submarine pipe for y/D = 0.0, 0.31, 0.62 and 0.94 is provided in **Fig.4**. Here 'y' is the distance of the scour measurement point upstream (-ve) or downstream (+ve) from the centre of pipe. The scour measurement was carried out after every 1 hour wave action on the submarine pipe-clay bed. From these plots it is observed that the scour rate is higher in the initial stages. It is observed that the time development of scour depth reduces with increase in consistency index of soil. This is due to the fact that the increase in the consistency index of the soil is associated with increase in the strength of the soil. It is generally established in the field of geotechnical engineering that as the consistency index of the clay soil changes from a very soft to soft one, there is a tendency for the reduction in the scour depth. At the end of 3 hours of wave action, the measured scour for I_c = 0.17 below the centre of the pipe (y/D=0.0) was 34 mm, which is not the ultimate scour depth for these conditions. The plots of scour depth "S_i" with time "t" appears to resemble the rectangular hyperbolae and if this is valid, the transformed plots between 't/S_i' and 't' should be of linear fits.

The variation of the ratio of time to the scour depth (t/S_i) with the time 't' for the different experimental conditions is shown in **Figs.5 and 6** for the above refered experimental conditions. The best line fit suggest linear plots, thereby confirms the application of hyperbolic model. In view of this, it is possible to predict the ultimate scour depth from the measured slope of the linear fit. The predicted values of ultimate scour depth by using the hyperbolic model are given in **Table 3**. For the tests with I_c = 0.17 and for y/D = 0.0 (below the centre of the pipe), the ultimate scour depth is found to be 72 mm.

A typical spatial variation of normalised ultimate scour depth, S_{uc} for Ic of 0.17 and 0.23 for both upstream and downstream side of the pipeline is shown in **Fig.7.** It is found that the maximum S_{uc}/D below the centre of the pipeline is 0.45 and 0.35 for Ic=0.17 and 0.23 respectively. For similar hydrodynamic conditions, the S_{uc}/D for sandy soil is about 0.67 (Sumar and Fredsoe (1990)). From the limited results available it is clear that I_c significantly influences the scour depth below the pipeline resting on the seabed in clayey soil.

Wave Induced Pressure Around Submarine Pipeline

In the field, selection of minimum burial depth of the submarine pipeline is one of the important factors from stability point of view. Deeper the burial, expensive is the pipeline installation. The optimum depth of burial depends on the stability of pipe from scour, floatation and hence on pressures and uplift forces. Due to the variation of moisture content in clay, the consistency index of the soil also varies. In many places the consistency index of marine clay is generally very much less than the values observed for clays on land. At several places on the West Coast of India (Kandla and Cochin) and in East Coast of India (Krishna – Godavari basins), large tracts of marine clays are found with $I_c = 0.1$ to 0.3. The effect of burial of the pipeline and consistency index of the soil on local water particle velocity and hence the wave induced pressure around submarine pipeline is required. The variation of pressure around submarine pipeline is indirectly an influencing parameter on the magnitudes of scour under the submarine pipeline.

The variation of wave pressure for different consistency index of the soil around submarine pipeline at different location for e/D = 1.0 (i.e. fully buried), d/a = 6.25 and ka = 0.148 is shown in **Fig.8.** It is observed that, when the pipeline is fully buried, the pressure at point P_3 is high as compared to other two points. This marginal difference in pressure is due to the damping effect of soil. The variation of pressure around submarine pipeline for $I_c = 0.24$, d/a = 6.25, H/D = 0.64 and for different burial depths is given in **Fig.9.** It is observed that the normalised pressure is decreased, when the pipeline is buried in to the seabed.

The effect of relative burial depth, e/D on the variation of normalised wave induced pressures $\{P/[\rho g(H/2)(1/\cosh kd)]\}$ on the submarine pipeline for H/D = 0.64 & 0.94 are presented for d/a = 5.0 and $I_c = 0.33$ in **Fig.10.** The results show that the increase in e/D results in a general decrease in the normalised pressure. This plot also indicates that the normalised pressure at point P_1 and P_2 are reduced by about 45% and at point P_3 it is reduced by about 26%, when the pipe is just fully buried compared to the pipeline resting on the seabed. Due to the limitation in the experimental set up, tests could not be conducted with pipeline buried at greater depths of embedment. It is observed that, when the pipeline is resting on the seabed, the pressure at point P_2 facing to waves is high as compared to other two points. This marginal difference in pressure is due to difference in the levels of the still water at that instance due to stagnation effects. Further, it can be observed from the above figures that the normalised pressure increases with increase in wave height ratio, H/D.

The effect of consistency index of soil, I_c on the variation of normalised pore water pressure $\{P/[\rho g(H/2)(1/\cosh kd)]\}$ around the submarine pipeline for d/a of 5.0 and 6.25 for e/D = 1.0 with constant H/D of 0.94 is shown in **Fig.11.** In any parametric study, it is normally considered to be satisfactory, if the investigation is carried out for more values of that parameter. But with the clay kept in contact with water, it is very difficult to keep the I_c at a value greater than 0.35. In view of this, the variation in Ic is considered not much. From these plots it is observed that the normalised pore water pressure decrease by about 26% when the consistency of the soil increases from 0.18 to 0.33. The increase in the consistency index of the soil is associated with increase in the strength of the soil. It is generally established in the field of geotechnical engineering that as the consistency index of the clay soil changes from a very soft to soft one, there is a tendency for the reduction in the pore water pressure **(Bishop and Henkel, 1962)** with a consequent increase in effective stress and this accounts for improved strength.

CONCLUSIONS

Based on the present experimental investigations on scour and wave pressures around the submarine pipelines in clayey soil, the following conclusions can be drawn: -

1. The maximum scour depth under the submarine pipeline resting on the cohesive seabed is 45% D for $I_c = 0.17$ and 35.4% D for $I_c = 0.23$. For similar hydrodynamic condition, for sandy bed, the value of S_{uc}/D is about 0.67 (Sumer and Fredsoe (1990)).
2. The normalised significant wave induced pressure around the submarine pipeline is decreased by 30% to 52%, when the position of the submarine pipeline is shifted from e/D=0.0 (resting on the bed) to e/D=1.0 (just fully buried) in clayey soil.
3. The normalised significant wave induced pressure around submarine pipeline in clayey soil is decreased by 20% to 30%, when the consistency index of the soil is increased from 0.18 to 0.33.

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Table:1. Properties of soil used for the present study

S.No	Property	Magnitude
1	Clay fraction(<0.002mm)	57%
2	Silt fraction (0.002 to 0.075mm)	35%
3	Sand fraction (0.075 to 4.75mm)	8%
4	Liquid Limit(LL)	52%
5	Plastic Limit(PL)	32%
6	Plasticity Index(PI)	20%

Table:2. Spatial variation of scour depth measurements (mm) w.r.t time

Co-ordinates (0,y/D)	$I_c = 0.17$			$I_c = 0.23$		
	1 hour	2 hour	3 hour	1 hour	2 hour	3 hour
(0,0)	17	29	34	15	25	29
(0,-0.31)	15	24	29	13	22	25
(0,-0.63)	13	21	24	11	18	20
(0,-0.93)	10	16	19	9	15	17
(0,-1.25)	7	11	14	6	10	12
(0,0.31)	13	20	25	11	19	22
(0,0.63)	11	18	21	9	16	18
(0,0.93)	8	14	16	7	12	14

Table:3. Spatial variation of ultimate scour depth (mm w.r.t consistency index of the soil, I_c

Co-ordinates (0,y/D)	$I_c = 0.17$	$I_c = 0.23$
(0,0)	71.4	55.5
(0,-0.31)	55.5	45.4
(0,-0.63)	41.6	35.7
(0,-0.93)	35.7	28.6
(0,-1.25)	28.6	24.4
(0,0.31)	50	38.4
(0,0.63)	40	32.3
(0,0.93)	33.3	28.6

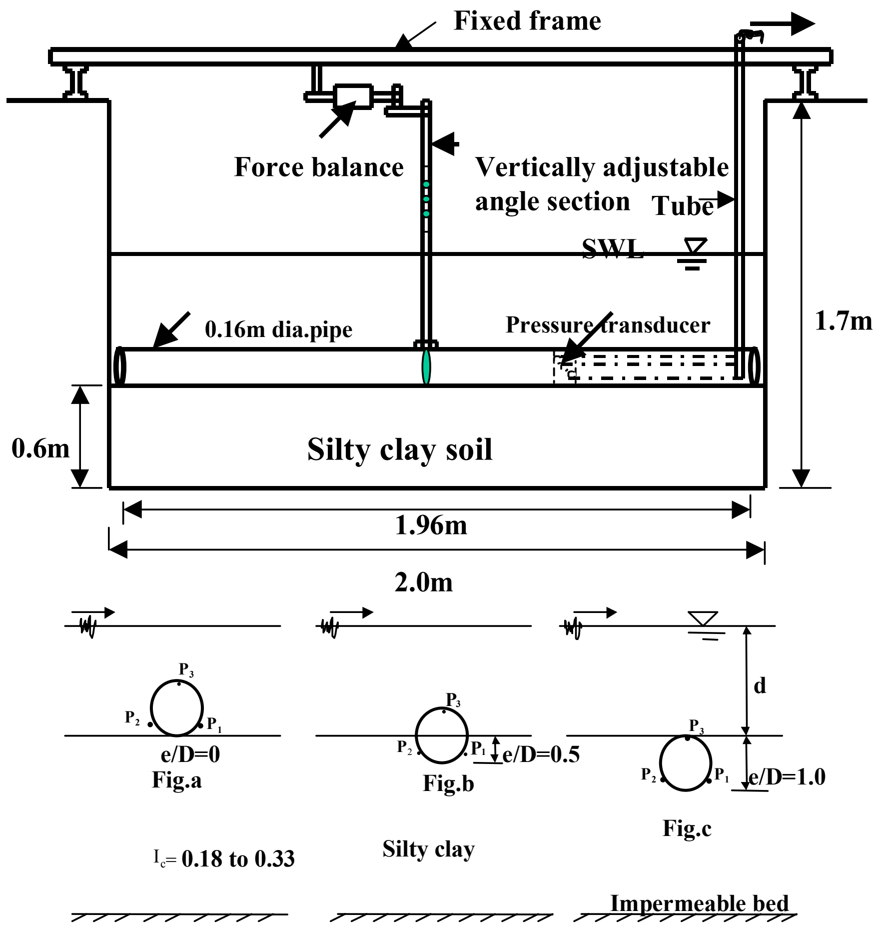

Fig.1 Experimental set-up for the present study

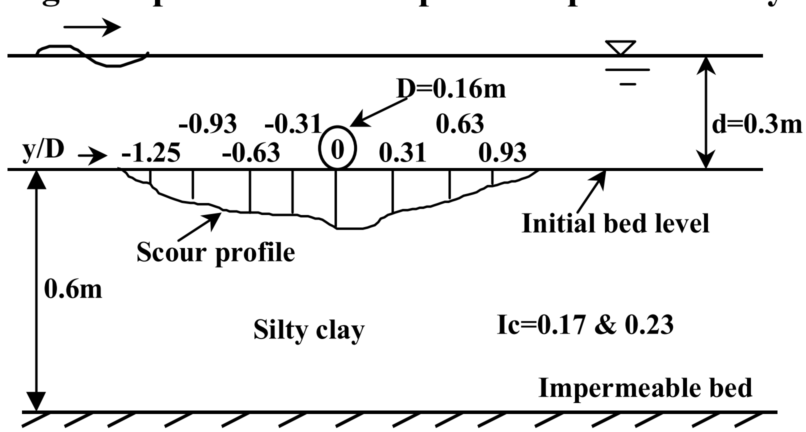

Fig.2 Scour measurements

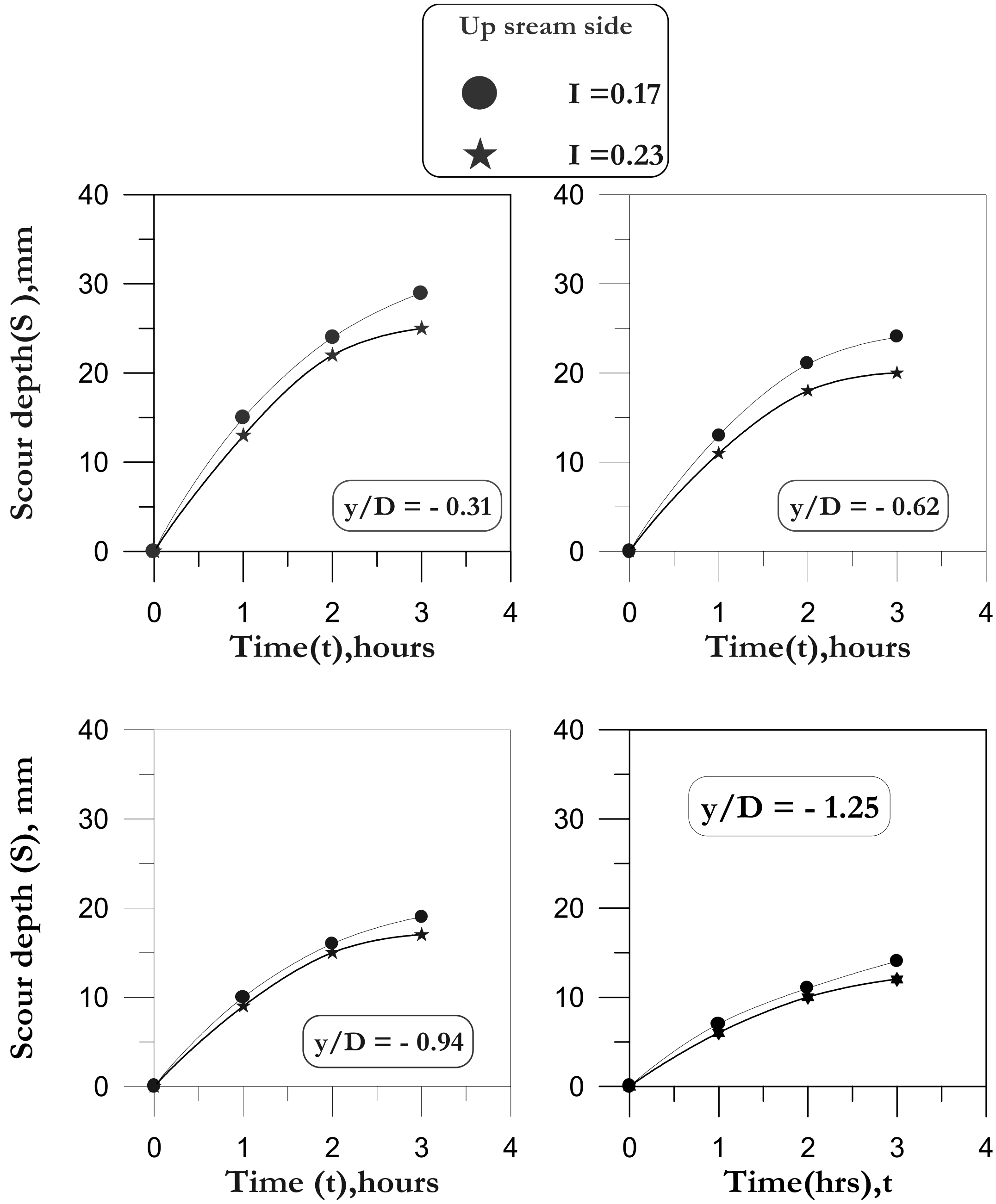

Fig.3 Effect of I_c on the variation of time development of scour depth on the upstream side of the pipeline.

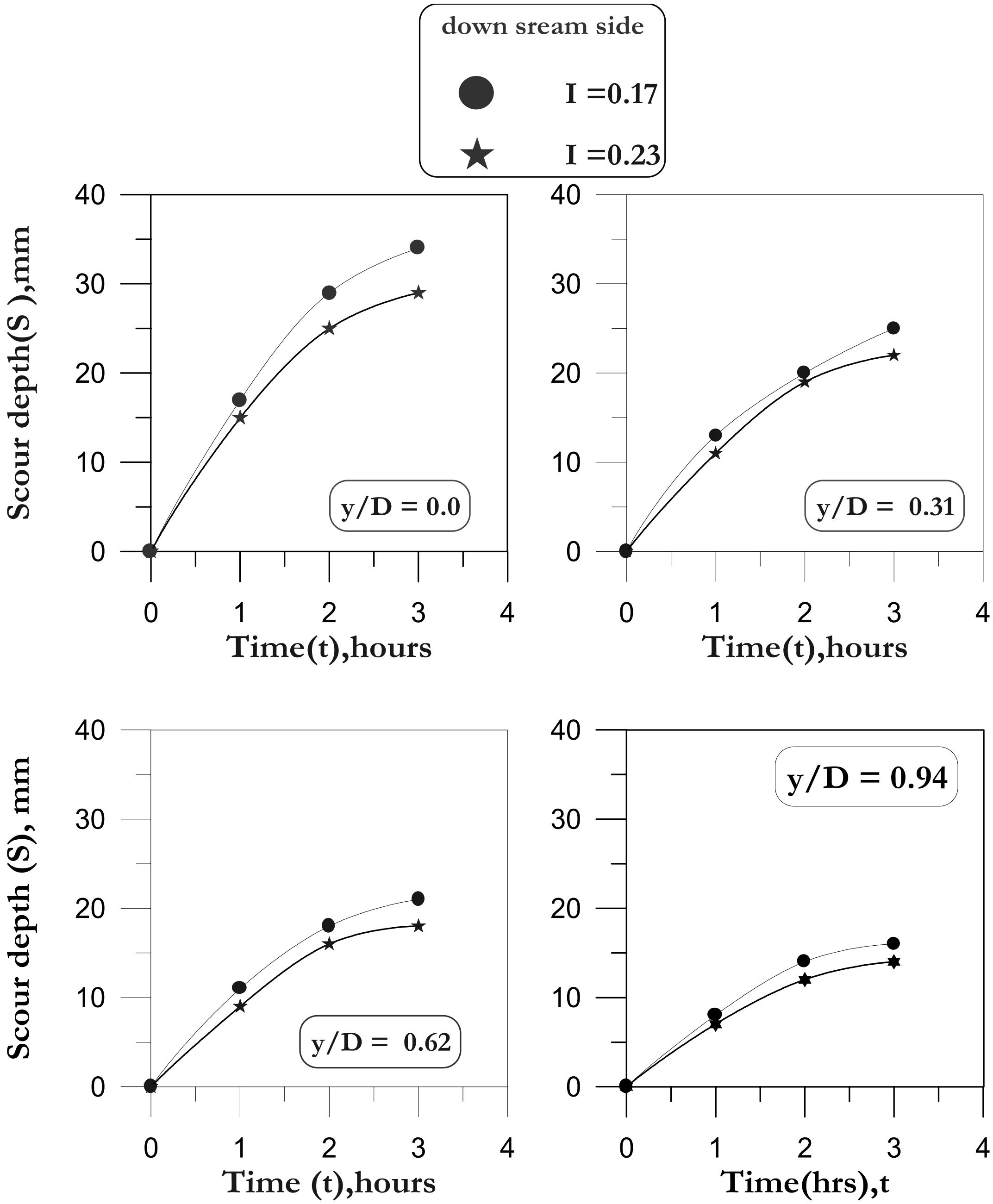

Fig.4 Effect of I_c on the variation of time development of scour depth on the down stream side of the pipeline.

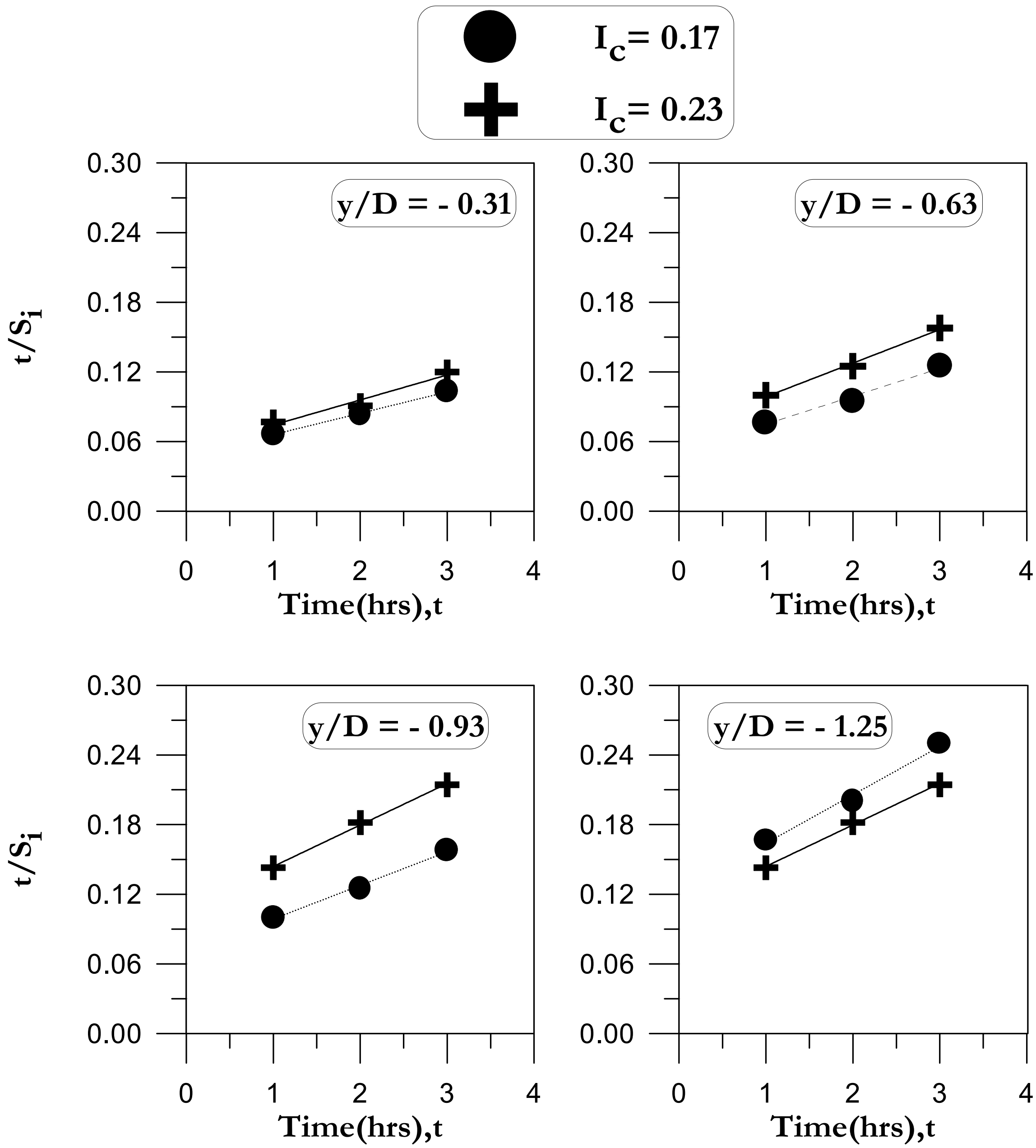

Fig.5 Application of Hperbolic formulation for prediction of ultimate scour depth - An illustration

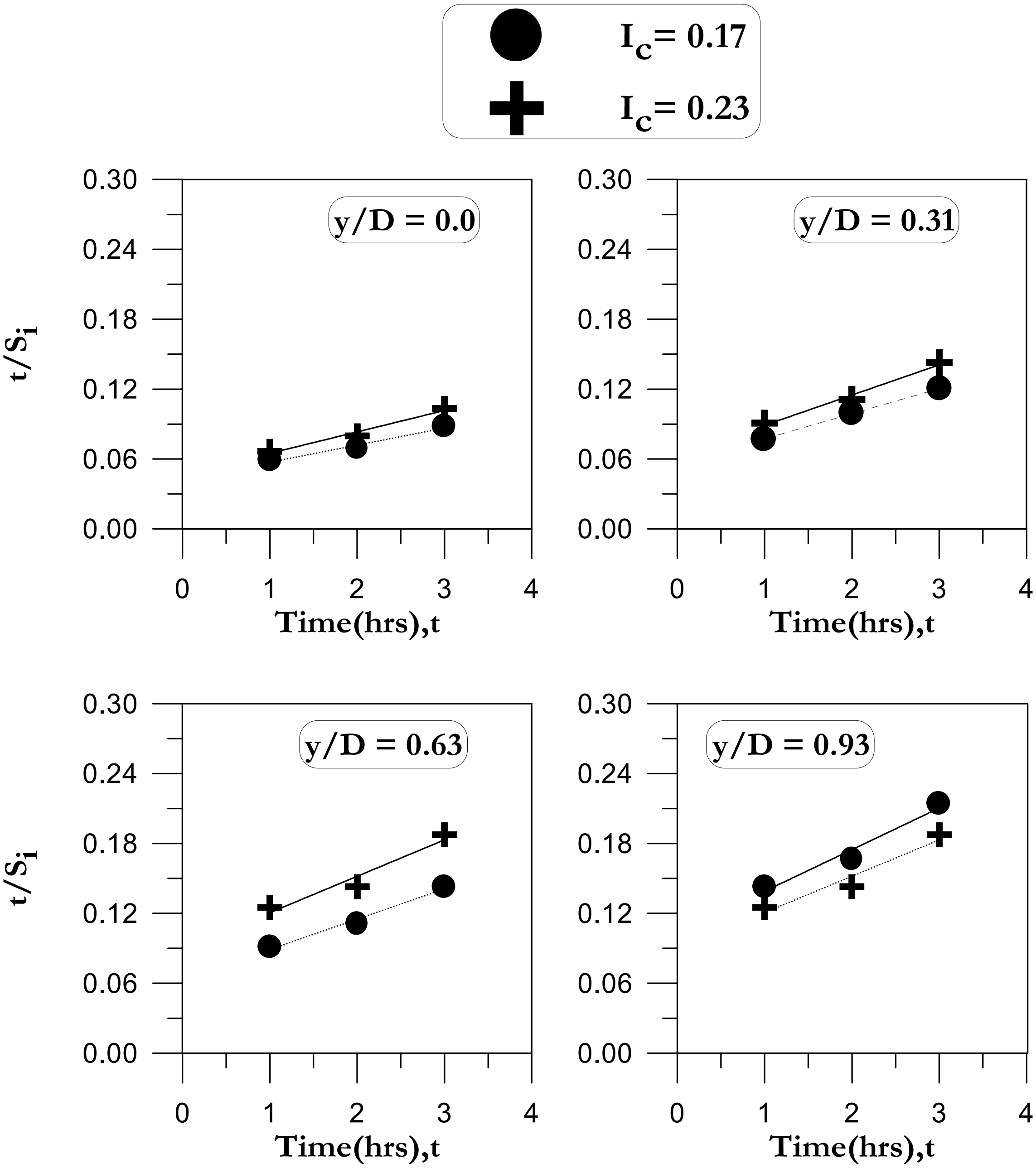

Fig.6 Application of Hperbolic formulation for prediction of ultimate scour depth - An illustration

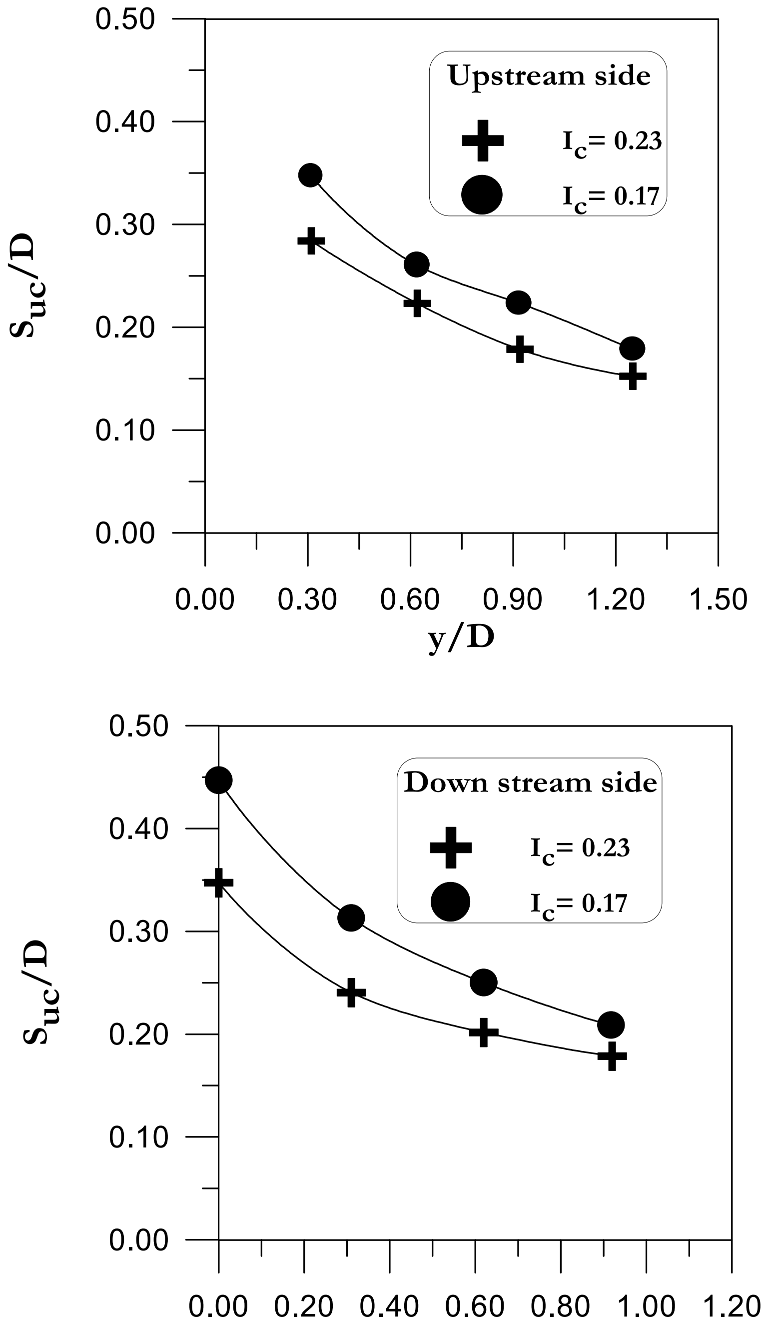

Fig. 7 Effect of I_c on the spatial variation of ultimate scour depth

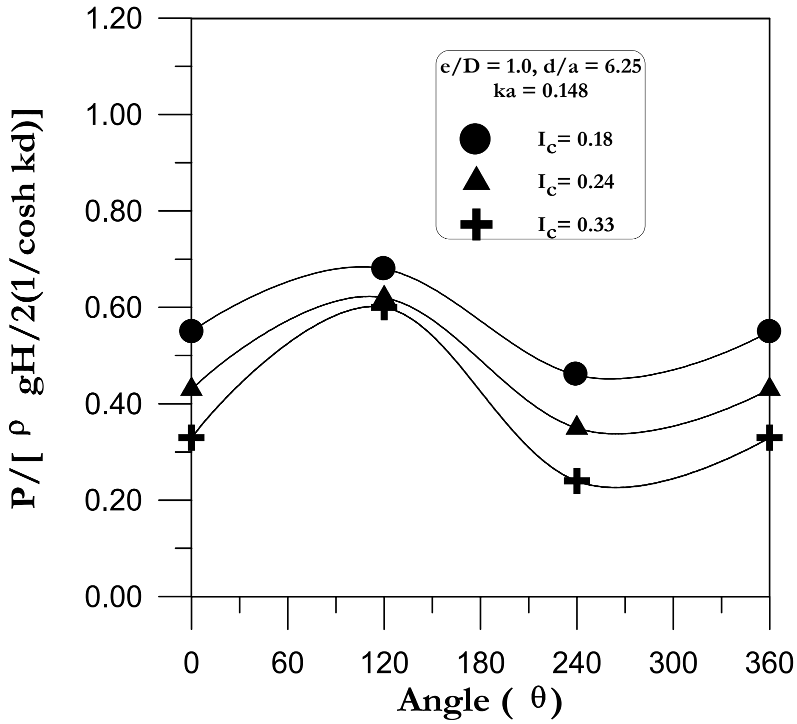

Fig.8 Variation of dimentionless pressure around submarine pipeline for different I_c with e/D =1.0

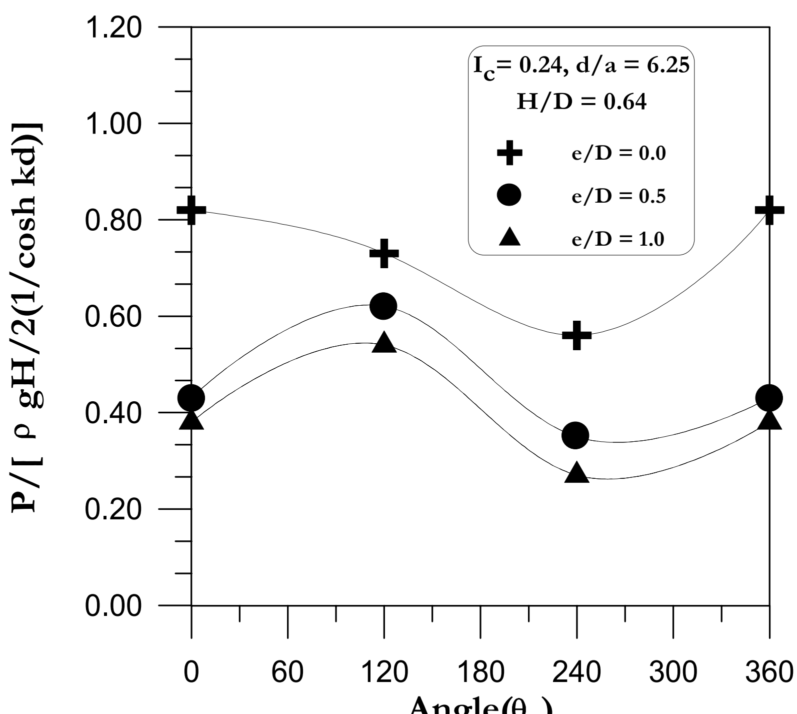

Fig.9 Variation of dimentionless pressure around submarine pipeline for different e/D with I_c= 0.24

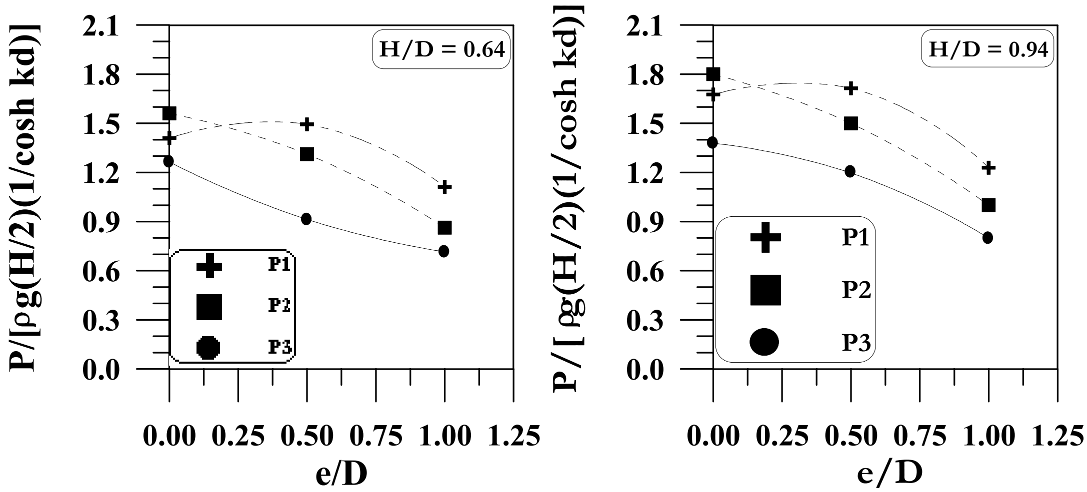

Fig. 10 Effect of H/D on the variation of dimensionless pressure, P/P with relative burial depth, e/D for d/a=5.0 ad I =0.33

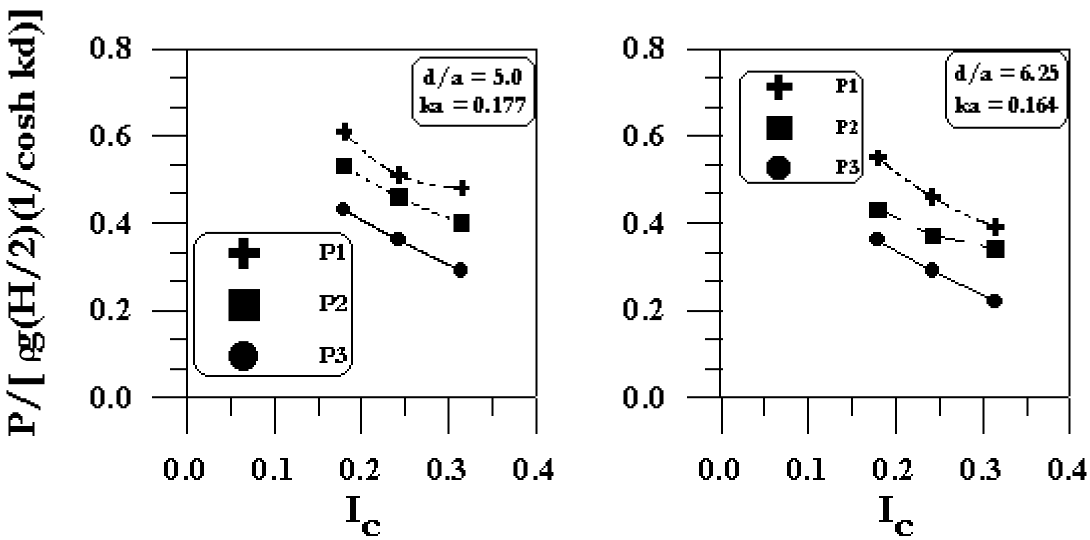

Fig.11 Effect of consistency index on the dimentionless pressure for e/D = 1.0 and H/D = 0.94