

# Time Variations of Scour Below Submerged Skewed Pipelines

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**Abstract.** The presence of pipe across river initiates the piping effect combined with the stagnation eddy and vortex system in the vicinity of the pipeline. The main objective of the research is to investigate the physics of scour below skewed pipeline in river crossing as well as the time variations of the scour development. In this study, the experiments were conducted for four different angles of pipe (30°, 45°, 60° and 90°) across a channel and placed on the sediment bed with  $e/D = 0$ . The scour development for flow shallowness  $y/D = 3$  and  $y/D = 4$ , initiated at downstream side of the pipe, where the bed sediment appeared to be ejected from the bed due to the piping effect process. At the initial stage, the scour process for 150mm flow depth enlarged rapidly. Whilst, the scour process for 200 mm flow depth slowly developed and after certain time, the sediment bed scoured rapidly. The scour depth increased considerably at development stage and the suspended load near the bed especially below the pipe decreased significantly compared to the initial stage. The rate of sediment eroded from the sediment bed decreased at the stabilization phase. The equilibrium phase of the scour depth considered achieved as the dimensions of the scour hole do not change significantly.

**Keywords:** Pipeline scour, piping, scour mechanism, skewed pipeline, flow mechanism.

## 1. Introduction

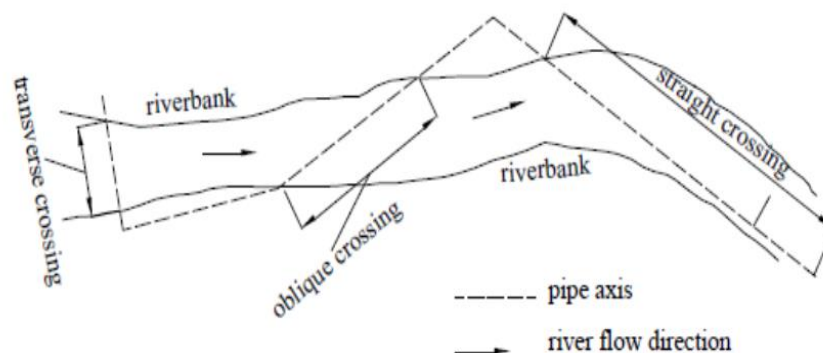
The presence of the pipeline in the river or stream obstructed the flow pattern within the structure may cause erosion or scour that can be divided into general scour and local scour. The changes in flow characteristics lead to a change of sediment transport capacity, hence affecting the equilibrium and the stability of the actual sediment transport capacity. The hydraulic conditions eventually are adjusted to a new state of equilibrium through scour process [1]. The impact of the structure on the flow in the river directly creates the local scour that is relatively has a shorter time scale than the general scour. The onset scour phenomenon is attributed to the seepage flow underneath the pipeline, which is caused by a large jump in the pressure or a different relative pressure coefficient ( $C_p$ ) between the upstream and downstream sides [2]. Dey and Singh[3] concluded that the maximum scour depth below the pipelines with upward seepage through the bed was smaller than that without seepage. The three-dimensional flow field around the pipeline is extremely complicated due to the separation and multiple vortices that occur around the pipes. The difference of the pressure causes tunnel erosion which is affected by the seepage process. The increasing length of the seepage flow along the streamlines can reduce the pressure gradient as well as the seepage effect. The piping effect occurs when the pressure



gradient exceeds the flotation gradient of the bed sediment and the associated upward flow. Tunnel erosion does not occur when the ratio of the flow depth to the pipe diameter exceeds 3.5 and when the embedded ratio is too high [4].

Previous research confirmed that the scour hole below submerged pipelines could be regarded as a function of the Froude number and of a dimensionless clearance between the pipe and the undisturbed bed [5]. Kjeldsen et al. [6] found that scour depth,  $d_s$  is affected by the approach flow velocity,  $U$  and pipe diameter,  $D$  but the effect of flow depth,  $y$  and the sediment size  $d_{50}$  is not included. Mao [7] identified that there are two cases of scour process, (a) jet period, which decides the maximum scour depth, and (b) wake period, which decides the location of scour depth. He also observed that for  $d_s/D < 1$ , the scour depth,  $d_s$  is a weak function of the flow Shields parameter. Sumer et al. [8] compared the effective Shields parameter with the time-averaged value to assess the influence of lee wake on the scour profile downstream of the pipelines. The onset of scour below pipelines occur due to the piping effect and no scour takes place if the ratio of the approach flow depth to the pipe diameter exceed 3.5, and flow shallowness,  $y/D < 3.5$  for the pipelines that laid on the sediment bed.

Chiew [4] investigated the influence of the gap discharge,  $q_g$  in estimation of the scour depth and proposed an iterative method with an empirical function that relate,  $y/D$  with the gap discharge,  $q_g$ . The investigation of the scour characteristics of submerged pipelines continues to be a concern for hydraulic engineers. Most of the common practices for pipeline cross-river in Malaysia are transverse crossing modes (Figure 1). None of the aforementioned studies examined the influence of skew pipelines cross-river under clear-water scour condition. Deng et al. [9] analyzed and presented some pertinent protective measures based on the principle of hazard mitigation. They also presented the relation between pipe axis and river flow direction. The cross-river pipeline construction projects are the key projects in long-distance pipeline construction. Based on years of geological hazard investigation and washout protection in Zhongxian-Wuhan Pipeline and Lanzhou-Zhengzhou-Changsha Oil Pipeline, scouring and erosion as well as change in the river's course are the main dynamic factors in river washout [9].

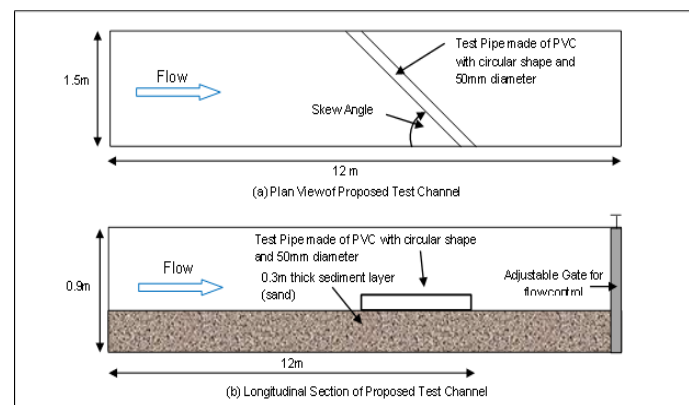


**Figure 1.** Relation between the pipeline axis and river flow direction [10]

Boyd et al. [11] suggested that the designed of pipelines across Musselshell River need to avoid meander bends and braided channels as well as buried the pipeline as deep as possible under the river bed. If the river bed does not have sufficient natural armoring, carefully construct a graded rock apron that extends far enough upstream and downstream from the buried siphon to assure the channel bed over the siphon fits the overall river channel gradients. Therefore, the main objective of this research is to conduct experimental and simulations of scour caused by submerged skew pipelines across the river.

## 2. Materials and methods

The experiments will use a 12 m long concrete (mortar finish) rectangular flume with a width of 1.5 m and a depth of 0.9 m. A PVC pipe with a 50 mm diameter is used in the experiment. The pipe will be placed crossing the flume at 30°, 45°, 60° and 90° and on the sediment bed as shown in Figure 2. A sand bed will be used in these experiments. The 12 meter test flume was divided into three sections which were the false floor, sediment recess and sediment basin. The false floor was constructed to maintain the same bed level of the sediment recess in the channel. After the false floor, the sediment recess section is filled with 0.3 m long, 1.5 m wide and 0.3 m deep of gravel. The gravel functioned as scour protection for the bed after the false floor. A sediment recess was 7m long, 1.5 m wide and 0.3 m deep, and located after the false floor. The sediment basin was located at the downstream part to cater the sediment that was transported through the channel. The sediment recess is raised 0.3 m from the bottom floor with a slope,  $S = 1:1000$ . The sediment particle that is used in the experiment can be classified into very coarse sand with mean sediment size,  $d_{50} = 0.58$  mm. The water from the three interconnected tanks was supplied to the channel through the centrifugal pump. After entering the channel through the sump section, the water was allowed to flow into the main sump again where the water was recirculated. Water was allowed to stay over the bed for some time to remove the air voids and fill it with water.



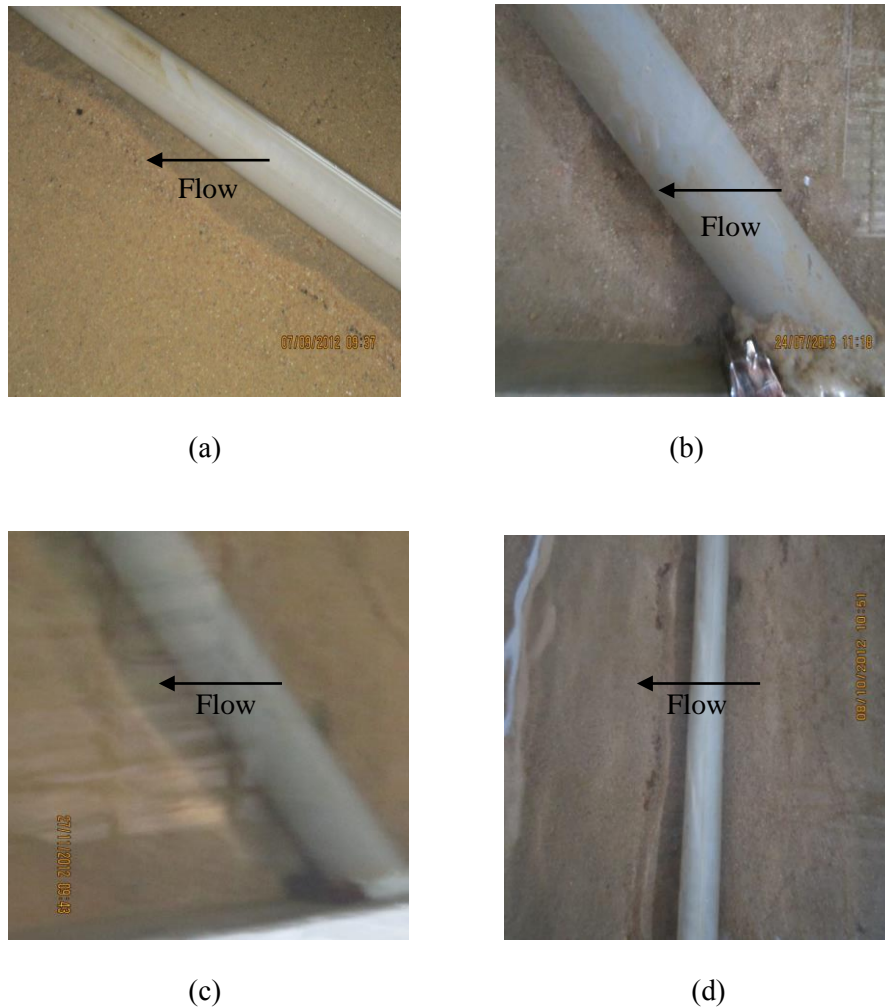
**Figure 2.** Test channel dimension and setup.

The pipeline model particularly PVC circular pipe was installed carefully in the middle of sediment recess and will be adjusted according to the desire angle of attack which are 30°, 45°, 60° and 90°. The water was allowed to flow through the test section and the scouring process was observed from the side walls. The arrangement was made such that if the experiment stopped due to any reasons, the water remained in the channel. This arrangement helped in resuming the experiment from the same point, where it was stopped without any disturbance to the scour hole developed. Water was allowed to flow at a specific flow depth for specific time duration. The experiments were conducted for initial flow depths of 150 mm and 200 mm. At the end of each experiment, the water was drained out of the test section as well as scour hole. Scour profile was measured for depth, width and length of scour hole. The equilibrium scour depth achieved when the scour hole did not change for quite some of time. The maximum scour profile achieved at that particular point.

## 3. Results and discussion

The maximum scour depth and width for the 30° and 60° of pipe installation are lower than 90° of pipe installation. From the physical observations, the scour tendency for the submerged skewed pipe is near the left bank (Figure 3). The hydrodynamic forces which consisted of drag force (in line with the flow direction) and lift force (normal to the flow direction) have been affected by the presence of the

skew pipe. The skew pipe has changed the force direction as well as shifted the location of scour hole. There were also different rate of scour process for flow shallowness,  $y/D = 3$  and  $y/D = 4$ . It can be seen that there was a rapid change of scour development for  $y/D = 3$  compared to  $y/D = 4$ . The time-variation scour depth showed that the rate of scour for  $y/D = 3$  was higher than  $y/D = 4$ .

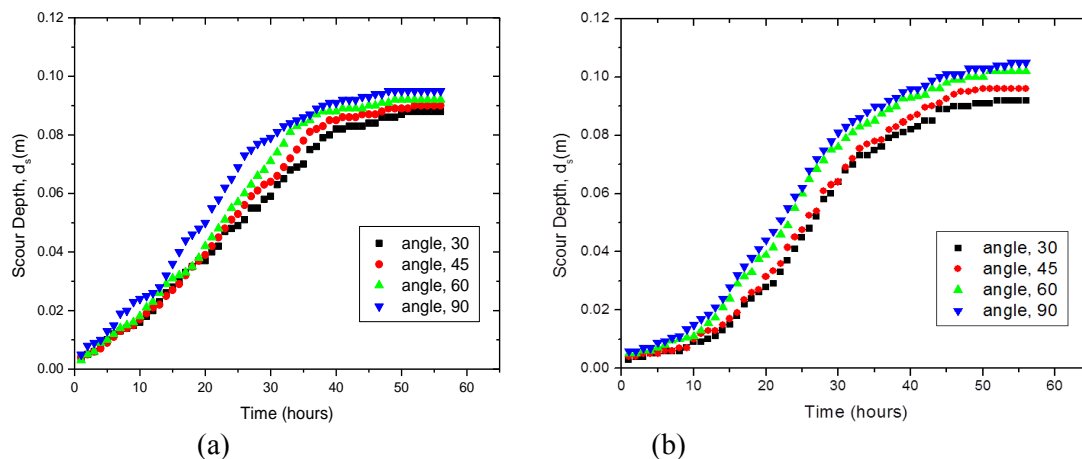


**Figure 3.** Scour depth location below pipe; (a) 30° (b) 45°(c) 60°, and (d) 90°.

The difference pressure between the upstream and downstream the pipe created a small gap below the pipe. At this stage, the jetting flow started to eroded and transported the sediment away from the pipe. The tunnel erosion process continued to erode the sediment until certain stage where the combination of luff erosion and lee erosion started to dominate. The luff erosion occurs at the upstream side which was caused by the eddy formation in front of the pipe while the lee erosion at the downstream of the pipe, caused by the reemergence of main flow and turbulent wake (vortices system) downstream the pipe.

### 3.1 Time variation of scour depth

The temporal development of the scour hole below submerged skewed pipeline on a flat plane showed the tunnel scour for both flow shallowness,  $y/D = 3$  and  $y/D = 4$  initiated at the downstream side of the pipe. The bed sediment appeared to be ejected from the bed, showing that piping could be the cause of failure. Once the sand particles at the downstream side of the pipe were lifted off the bed, they were transported out by the flow. At the same time, the stagnation eddy at the upstream side of the pipe created a small depression, and the sand barrier was quickly breached leading to the formation of a tunnel under the pipe. In the tunnel, the sediment particles were entrained, and vigorous sediment transport occurred in the early stages. The sand that eroded from the tunnel formed a bar downstream of the scour hole, and with time, the sand bar propagated downstream and lee erosion, caused by the turbulent wake and reattachment of the main flow over the pipe began to dominate. Scouring continued until equilibrium was reached, when the temporal shear stress and turbulent agitation near the bed were no longer able to transport bed material from the scour hole. Figure 4 show the scatter plot for the effect of water depth on the scour profile and it can be observed that the scour process for flow depth 150 mm enlarged rapidly with time duration at the initial stage compared to scour development for 200 mm flow depth.



**Figure 4.** Time variations of scour depth for (a) 150 mm water depth and (b) 200 mm water depth.

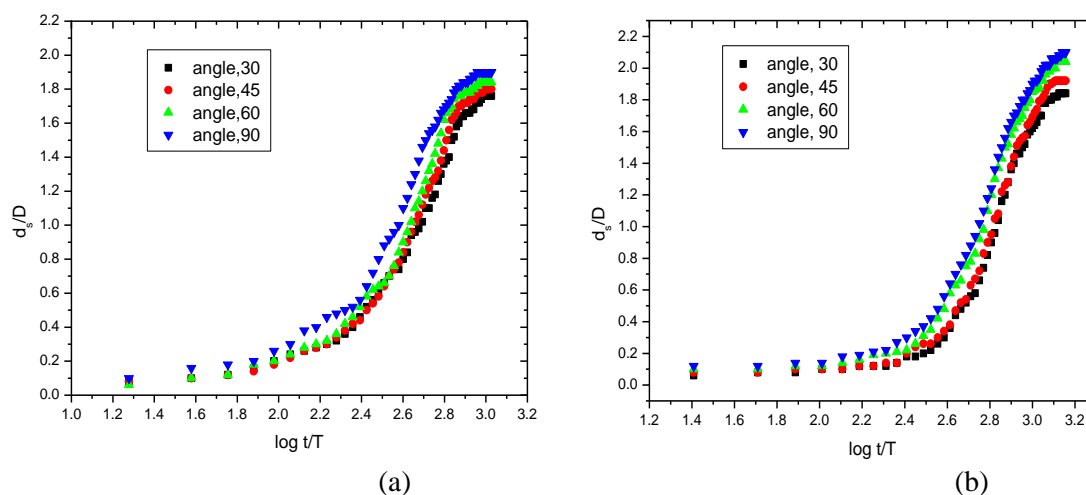
The strong pressurized flow between the upstream and downstream side of the pipeline caused the tunnel erosion effect to occur underneath the pipeline. The upward forces due to the ground-water flow under the pipe inducing instability to the particles and moved away the sediment particles. The vortices due to the pipe obstacles and seepage flow leads to the formation of small opening under the pipe and increased the flow concentration in the gap which augmented the shear stress on the sediment bed below the pipe. At the initial stage, the scour process for 150mm flow depth enlarged rapidly. Whilst, the scour process for 200 mm flow depth slowly developed and after certain time, the sediment bed scoured rapidly. The scour hole enlarged rapidly for 150 mm flow depth due to the jetting of flow underneath the pipeline which creates the lift forces for the sediment to move from the scour hole.

Eventually, a compact secondary armor layer from the non-uniform sediment offering resistance to the smaller sediment particles that inhibited the progress of further scouring. After the armor layer collapsed, lee wake and tunnel erosions prevailed. When the gap below the pipe considerably large at the end of the tunnel erosion, the vortex shedding began and swept the sediment below the pipe as the convection of flow towards downstream. This case mainly prevailed for the flow depth equal to 200 mm as the ratio  $y/D$  exceed 3.5 because the flow not adequate to induce force on the armor layer thus, retarded the scour process at early stage. The evolution of scour phase was divided into four phase: an initial phase, a development phase, a stabilization phase and an equilibrium phase, which was distinguished by previous researchers [12].



### 3.2 Effect of approach flow depth relative to pipe diameter on scour depth

Figure 5 show the relationships between the normalized scour depth relative to pipe diameter and the dimensionless time variation of pipeline scour. The pattern of the time variation seems to be in a logarithmic scale as suggested by several researchers. The figures showed that the scour depth ( $d_s/D$ ) increases with the flow shallowness ( $y/D$ ). The final scour depth at high  $t/t_e$  values, may considered as the equilibrium scour depth increases with the approach flow velocities which creates higher flow depth. The approach flow depth considered as the dominant factor for the experiments as the scour depth keep increases with the flow shallowness. Evolution of the scour depth can be divided into three stages; (a) initial stage which the scouring rate increases sharply with time, (b) development stage where the scour process increases steadily with time and (c) equilibrium stage where the scour depth remains unchanged with time relatively. At this point, the scour depth and time are equilibrium, respectively. Alternatively, there was a possible tendency of  $d_s/D$  to be independent of  $y/D$  as the ratio  $y/D > 4$ . Dey and Singh [3] mentioned that the data plot for larger pipe diameter sizes are scattered and tends to be independent for  $y/D > 4$ . This aspect can be justified that the mechanism of scour depth below pipes governed by the three different erosion; (a) luff erosion caused by the eddy formation upstream the pipe (b) lee erosion caused by the vortices system downstream the pipe, and (c) tunnel erosion caused by the increase of flow concentration below the pipe and jetting flow. But, there is little argument on the scour potentials characterized by the near bed or lower flow zone as the approach flow depth beyond five times the pipe diameter [13].



**Figure 5.** Evaluation of scour depth ( $d_s/D$ ) with non-dimensional time dependent,  $\log (t/T)$  for (a)  $y/D = 3$ , and (b)  $y/D = 4$ .

### 4. Conclusion and recommendation

The change of flow direction affected by the skewed pipe obstacle created difference pressure between the upstream and downstream side of the pipe. The presence of the seepage effect created the uplift forces for the sediment underneath the pipe and sediment particles forced to transport downstream. The scour hole enlarged rapidly at the initial stage for flow depth 150 mm due to the tunnel erosion effect while the scour process for 200 mm flow depth increase gradually till reach the equilibrium stages. The hydrodynamic forces which consisted of drag force (in line with the flow direction) and lift force (normal to the flow direction) have been affected by the presence of the skew pipe. The skew pipe has changed the force direction as well as shifted the location of scour hole. There were also different rate of scour process for flow shallowness,  $y/D = 3$  and  $y/D = 4$ . It can be seen that there was a rapid change of scour development for  $y/D = 3$  compared to  $y/D = 4$ . The time- variation scour depth showed that the rate of scour for  $y/D = 3$  was higher than  $y/D = 4$ . The difference pressure between the upstream and downstream the pipe created a small gap below the pipe. At this stage, the jetting flow

started to erode and transported the sediment away from the pipe. The tunnel erosion process continued to erode the sediment until certain stage where the combination of luff erosion and lee erosion started to dominate. The luff erosion occurs at the upstream side which was caused by the eddy formation in front of the pipe while the lee erosion at the downstream of the pipe, caused by the reemergence of main flow and turbulent wake (vortices system) downstream the pipe. The skew pipe also was affected the time scale of scour process where the shorter time of scour process for skew pipe more than  $45^\circ$  ( $60^\circ$  and  $90^\circ$ ). The time scale of scour process for  $y/D = 4$  was shorter than flow shallowness,  $y/D = 3$ , although at the initial stage, it can be seen that the scour hole for  $y/D = 3$  enlarged rapidly. The study found that the initiation of scour below submerged skewed pipeline is predominantly caused by piping as a result of the pressure gradient across the pipeline. Therefore, it is possible to inhibit this failure, thereby eradicating tunnel scour below submerged skewed pipeline completely, if the pressure gradient across the pipe can be kept reduced by increasing the flotation gradient of the bed sediment. Further investigation on others parameters such as grains size, high approach flow and different pipe sizes need to be carried out to ensure the possibility of placing a pipe across channel and minimize the cost of operations.

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