170 Journal of Ocean Engineering and Technology, Vol. 6, No. 2, pp. 170~180. 1992.

⊙ 論　文

Scour development around an artificial cylinder on tidal sand ridge in Gyeonggi bay, Korea

J. H. Choi*

(1992년 8월 21일 접수)

京畿灣 潮流性 砂堆위에 設置한 圓筒物體 周邊 浸蝕 및 堆積現象

崔　振　爀

Key Words : Scour Pit(浸蝕 構造), Burial(埋沒), Tidal Sand Ridge(潮流性 砂堆), Lee-side Erosion(後流 浸蝕), Secondary Flow(二次流)

요　약

강조류하의 인공 구조물 주변 해저 침식 및 재퇴적 현상을 연구하기 위하여 1987년 8월 24일부터 9월 26일까지 경기만에 발달한 조류성 사퇴위에서 현장 실험을 실시하였다. 인공 구조물(원통 물체) 주변에 발달한 침식 구조는 전체적으로는 타원형으로 접시모양을 하고 있으며, 후류 및 이차류에 의한 복합 침식작용에 의한 것으로 분석되었다. 아울러 연속적인 침식구조 크기 측정자료를 이용 산술적으로 침식율(1.5~20m^3/day) 및 재퇴적율(0.13~0.18 gr/cm/sec)을 추정하였다.

Introduction

As soon as placing underwater structures on the sea floor, scour(or erosion) of bottom sediments around the foundation of structures on sea bottom has bothered marine geologists and ocean engineers.

Niedoroda and Dalton1) presented a review of the fluid mechanics of ocean scour and discussed the processes of scour hole formation in marine and river environments. Herbich et al.2) summarized informations on scour around seafloor-founded structures to provide detailed state-of-the-art guidance for predicting and mitigating sediment scour around them. There were considerable researches of iceberg scouring3, 4), scour under pipelines5, 6), erosion around artificial islands7), and scour around bridge piers8).

Most of these studies were about scour and

---

* 국방과학 연구소

scour protection around relatively large underwater structures. A relatively few studies have been carried out on the scour problem around relatively small submerged objects(blocks as anchors, mines, reefs, etc.) and on the infilling (burial) of scour pit. Kurata and Hirai[9] studied the scour phenomenon caused by unidirectional flow around two submerged cylinders, and presented the relations of cylinder gaps and submerged cylinder heights to the scour dimensions.

The present study was undertaken to measure the scouring and infilling(burial) phenomena of the scour pit around an artificial object(cylinder) under the strong tidal currents. Scouring and infilling rate were also estimated from the sequential measurements of dimensions of the scour pit. For field experiments, a tidal sand ridge in the southern part of Soijak Do and Taeijak Do in Gyeonggi Bay, Korea was selected (Fig. 1). The tidal sand ridge developed in NE-SW direction is located between the East and West Waterways, and is approximately 15km long and 2~4km wide. Average water depth on crest of the ridge is about 20m.

Tidal currents on the crest are semi-diurnal and flow largely in east-northeastward for flood and west-southwestward for ebb[10, 11]. The mean and maximum speed in near bottom(1.5m above bottom) are 43.5cm/sec and 92.5cm/sec during flood, and 43.8cm/sec and 95.3cm/sec during ebb, respectively[11]. Bottom sediments on the crest of the tidal sand ridge are composed of well sorted sand, which are unimodal in peakedness, and have mean grain size of 1.57ϕ(0.334mm)[10, 12].

Field Experiments and Results

Field Experiments

An artificial cylinder was laid down on the relatively flat crest of the tidal sand ridge(Station A1 of Fig. 1), and visual observation and video recording of the scour development around it were conducted(Table 1). Table 1 shows the intervals, activities and summarized results of field experiment during each visit. The cylinder was laid normal to flow direction at 12 : 00, 24 August, 1987. The flatness of the crest of sand ridge was confirmed from echo sounding and side scan sonar survey on 24 September, 1987[10]. The cylinder used has a dimension of 0.5m in diameter and 1.6m in overall length. Weight of the cylinder is 534kg in air and 250kg in water. 6 poles of 2m in length marked with 20cm grid intervals were also placed around the cylinder as a reference to check the change of bottom level.

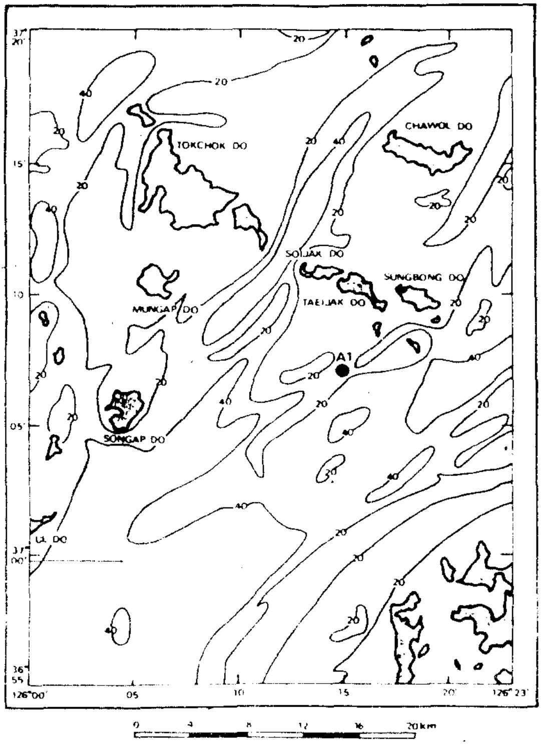

Fig 1. A map showing the experimental site (Station A1) on the crest of the tidal sand ridge in Gyeonggi Bay, Korea.

Table 1. Intervals, activities, and summerized results of field experiment during each visit to the study area.

Visits	Periods	Activities	Field Results
1st Visit	8/21−8/29	· Cylinder laying · Reference poles placing (2m long) · Still photographying · Video recording · Diving measurements	· Station Al was selected · About 50 divings · Severe erosion around cylinder · Sketching the scour pit dimension on 28 August · Extremely low visibility due to suspended material
2nd Visit	9/3−9/5	· 4 miniatures laying · Still photographying · Video recording	· 4 divings on 4 september · Intense bursting around the miniatures
3rd Visit	9/9−9/11	· 4 miniatures laying · Still photographying · Video recording	· 8 divings on 10 September · Full burial of cylinder · Full burial of miniatures in $3^1/_2$ hours after laying
4th Visit	9/14−9/17	· 4 miniatures laying · Still photographying · Video recording	· 6 divings on 16 September · Almost no change of burial state · Severe sand transport · Exposure of reference pole does not changed · Good video recording
5th Visit	9/23−9/28	· Miniatures laying · Still photographying · Video recording · Recovery of all materials	· 12 divings on 25−27 September · Almost no change of burial state · Severe sand transport

From the second visit, four miniatures(two cylinders and two hexahedrons) made of steel were laid near a large cylinder to observe the whole views of scour development and secondary flows around the miniatures(Table 1). The dimensions of cylindric miniatures were 5cm (diameter)×15cm(length) and 10cm×30cm, respectively.

The hexahedral miniafures had the dimensions of 10cm×10cm×10cm and 10cm×10cm×20cm, respectivvely.

With the aid of SCUBA divers, direct observation, measurement and photography of scour pit around the cylinder were performed five times during 24 August~28 September, 1987 (Table 1). Dimension(width, depth, etc.) of the scour pit was measured several times by divers during every visit to the site. The slope angles of the scour pit were approximated on board from the measured width and depth of the scour pit. Still photographs were taken with conventional underwater cameras. Video recording by MINIROVER ROV(Remotely Operated Vehicle) was firstly taken around the cylinder, and then around the miniatures at the fixed position using steel frame for half tidal cycle(about 6 hours) (Plate 1). Due to the high speed of tidal current at mid-tide, diving operations were restricted for about 2 hours around slack tide.

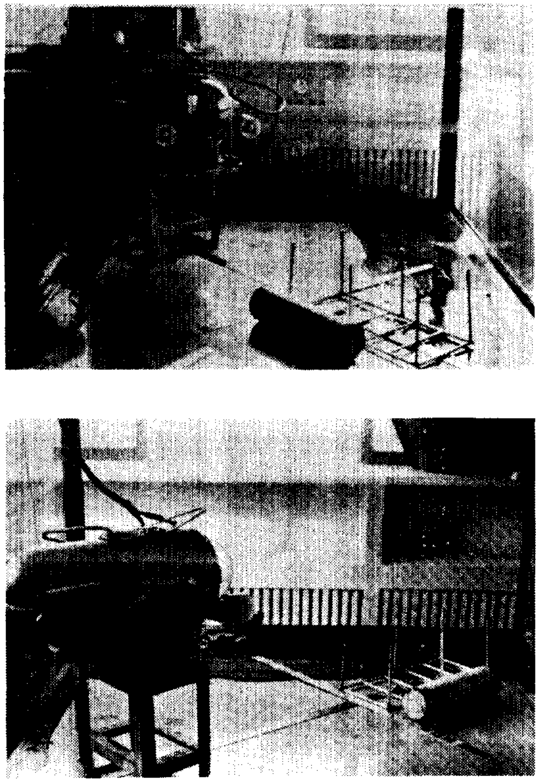

Plate 1. MINIROVER(ROV) video recording system and the frame fabricated for underwater observation of the scour phenomena. The system is reconstructed in laboratory for scale correction and photography.

Results

The development process of the scour pit around a cylinder laid horizontally on sand bed is schematically sketched from the time of first laying to the time of full burial of cylinder(Fig. 2). The scales between diagrams and in each diagram are non-dimensional to emphasize the change of scour pit dimension.

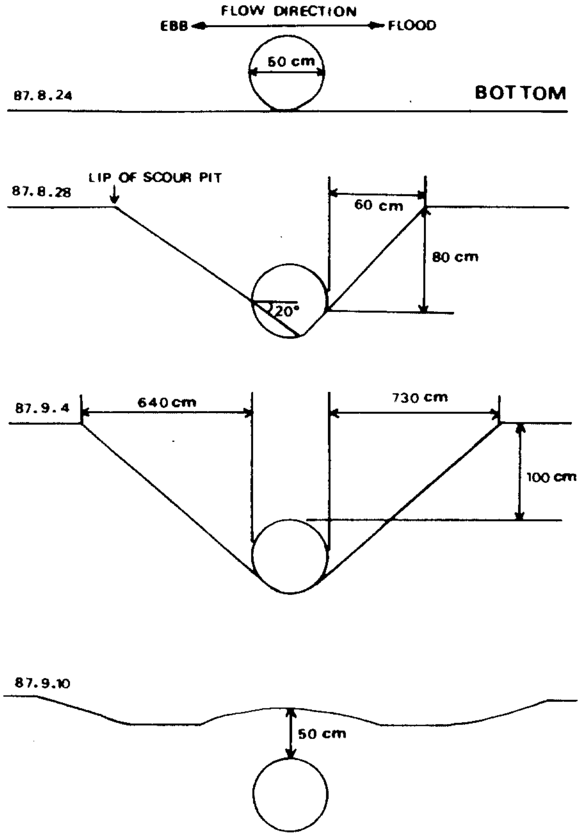

Fig 2. Schematic diagrams showing development stages of the scour pit around cylinder from the time of first laying to the time of full burial during field experiment. Scales are non-dimensional.

During the first visit, the dimension of the scour pit was measured at 14 : 00, 28 August when the flood tide began. The shape of the scour pit was dish-like and had a rather gentle slope in ebb side(left) than flood side(right) (Fig. 2). The slope of the scour pit was approximated to be 35°~40° in the flood side, which was close to the angle of repose of sand[13].

This steep slope of the flood(right) side seems to be due to the slumping of sand transported as bedload during ebb tide before observation time (14 : 00, 28 August)[14].

At 15 : 00, 4 September during the second visit, it was founded that the size of the scour pit was much larger than that observed during the first visit, but the dish-like shape was still maintained (Fig. 2). Both sides(flood and ebb side) of the scour pit showed the slope angles of about 10°. Although the time of observation was at the early stage of ebb tide, there was no discernible difference between the slope angles of both sides, which was different from the shape of the scour pit observed on 28 August. The depth to the top of cylinder from the original seabed was about 100cm(two times of cylinder diameter) (Fig. 2).

During the third visit, it was observed at 13 : 00, 10 September(at the beginning of flood tide) that the cylinder had been fully buried (Fig. 2). The depth to the top of the cylinder was approximately 50cm from the seabed just above the buried cylinder. The seabed above the buried cylinder was approximately 50cm below the surrounding original seabed. The level of surrounding seabed checked by the reference poles was not changed by visual inspections by divers. During the subsequent 4th and 5th visits, it was observed that the burial state of the cylinder was almost the same as before, i.e., the cylinder was not exposed again.

During every visit from the sceond visit(Table 1), severe wake flumes were recorded at the rear of cylinder(Plate 2). Plate 2 shows the photo graphs taken 1/30 second intervals from the video record, and shows the rapid change of turbulent wake flumes behind the miniatures with the lapse of time.

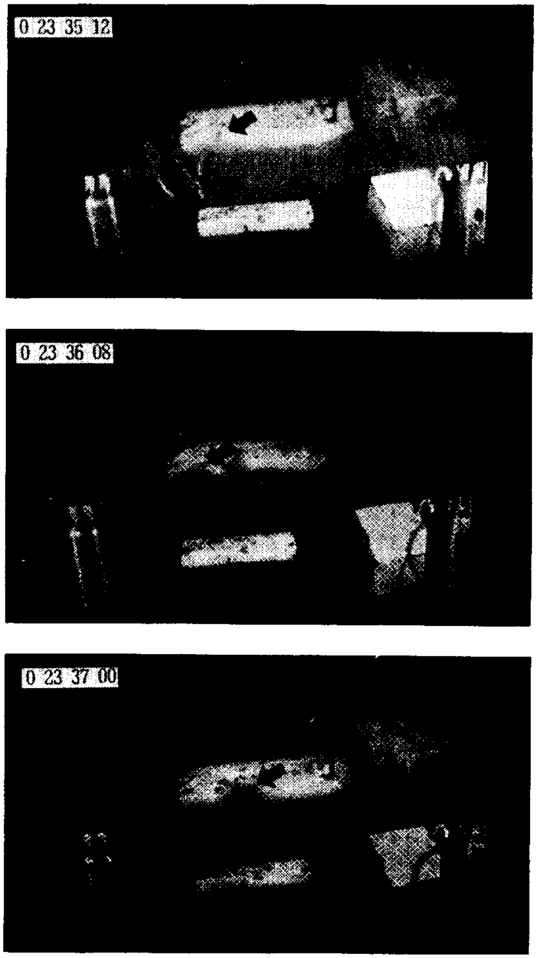

Plate 2. Change of turbulent wake flumes behind the miniatures with lapse of time. Current flows from large cylinder to small cylinder. Arrows indicate the change of wake flumes at the rear of cylinder(see text).

Discussions

Development Processes of the Scour Pit

Fig. 3 schematically shows the top and side views of the scour pit observed during the second visit. Direction of the tidal current is up and down(C—D direction on top view) and the scales are also non-dimensional as Fig. 2. Viewing from the direction of tidal current, the length of cylinder(1.6m) can be considered as an object diameter because the cylinder was laid normal to the flow direction.

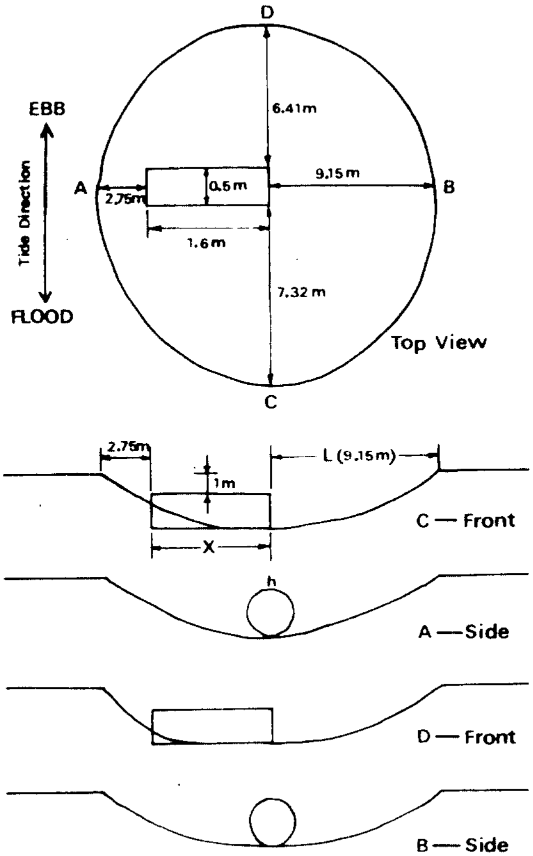

Fig 3. Top and side views of the scour pit around cylinder observed on 4 September, 1987. Scales are non-dimensional.

The top view of the scour pit of the present study has roughly circular(elliptical) shape(Fig. 3), and is different from the horseshoe shape under unidirection flow[13, 15, 16]. The ratio of the diameter of the scour pit to the object diameter (length of cylinder) is more than 4. The depth to the top of cylinder from seabed is two times of the cylinder diameter(1m).

From flume experiments under various wave conditions, it was shown that the ultimate depth of the scour pit depends on the pile diameter and mean current velocity, and approaches asymptotically to the value of little less than one pile diameter[2, 14, 17, 18]. Herbich et al.[2] and Palmer [14] showed that the ratios of the pit diameters to the object diameters were approximated to be 2 in equilibrium maximum developement stage of scour pit on the tidal flat(Fig. 4). And they[2, 14] presented that "secondary flows" such as turbulences, vortexes, and increased flow velocities at the side of the pile(Fig. 5) were responsible for such dimensions of the scour pit.

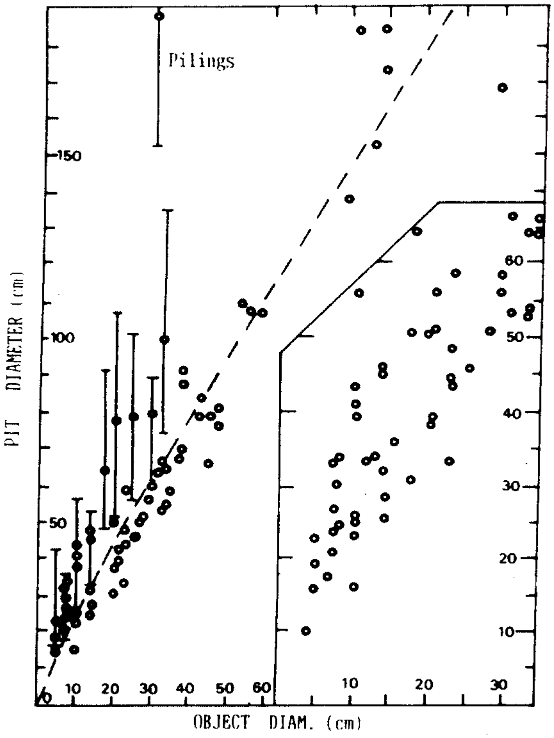

Fig 4. The ratios of a pit diameters to the diameters of test objects at the maximum development stage(After Palmer, 1970).

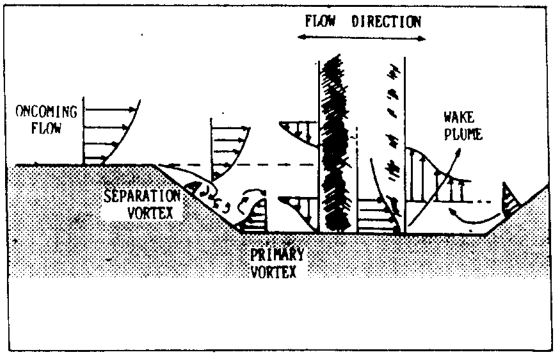

Fig 5. Schematic flow regime around a cylindrical obstruction(After Palmer, 1970). Length of arrow is non-dimensionally related to the velocity of fluid. Note the development of two vortices facing flow and the wake plume behind the obstruction in the scour pit.

By the detailed cross-section study over the scour depression around pipeline(one feet diameter) under strong tidal currents in Dutch North Sea, Hulsbergen[19] found that the top of the pipeline was finally buried little more than two diameters below the original seabed level. And he [19] also discovered that the depression had more than 15m width and side slope as gentle as 1 to 15(angle of about 4°). To explain such gentle slope, wide pit diameter, and large buried depth of the scour depression, he[19] suggested erosional process, so-called "leesideerosion" by reattachment of the separated stream lines over the top of pipeline(Fig. 6). Under the alternating tidal current directions, leeside-erosion will occur on both sides of the pipeline, and creates a rather extended gentle depression around the pipeline with local pipe sagging[19] (Fig. 6).

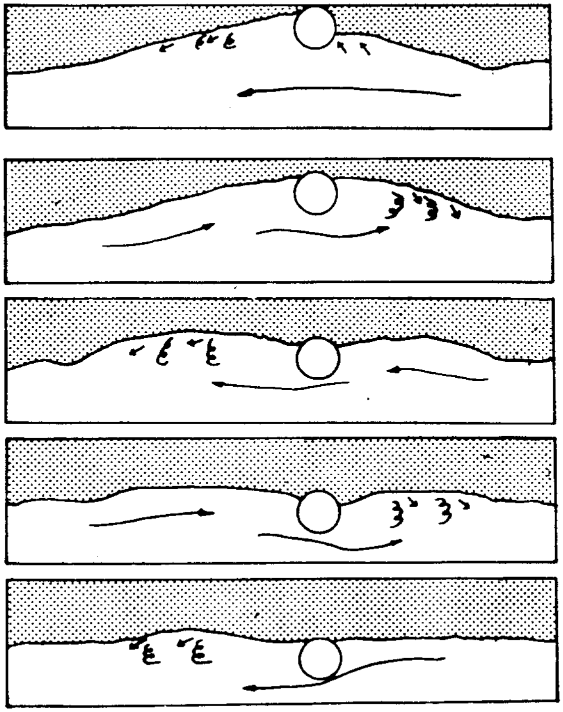

Fig 6. Schematic diagrams representing the alternate "lesside-erosion" processes for the development of a wide, gentle scour depression around the pipeline(After Hulsbergen, 1984).

In summary, the slope of the scour pit in the present study is much lower than the value suggested by Palmer[14], but higher than that suggested by Hulsbergen[19]. And the diameter of scour pit is much larger than that suggested by Herbich et al.[2] and Palmer[14], but smaller than that suggested by Hulsbergen[19]. The depth to the top of cylinder(two times of cylinder diameter) is very close to the final depth suggested by Hulsbergen[19].

Neither "leeside-erosion" suggested by Hulsbergen[19] nor erosion only by secondary flows suggested by Palmer[14] can thoroughly explain the development of the scour pit of the present study. The length(object diameter) of cylinder used in this study is very much shorter than the length of pipeline used by Hulsbergen[19]. Thus, the acceleration of fluid at the side of the cylinder and subsequent wake flume at the rear of the cylinder(Plate 2) occur, and are responsible for excavation of the toe of the scour pit slope. The ripples formed by primary vortex at the base of vertical pile[14](Fig. 5) can be used as the evidence of excavation at the toe of the scour pit slope, and were shown from the experiment using same cylinder at Pohang Harbor in April, 1987 (unpublished ADD data, 1987).

Excavations of the toe of the scour pit slope by secondary flows can be regarded as the main mechanism for the slope angle higher than that suggested by Hulsbergen[19]. Thus, the compound process of "leeside-erosion" and erosion by secondary flows seems to be responsible for the development of such a scour pit of the present study. Solving the detailed mechanisms needs more study in the future.

Scouring Rates

The volume of the scour pit can be approximated by the assumption that the scour pit resembles a half-cut ellipsoid. The calculated volumes of the scour pit are about 6m^3 on 28 August(during first visit) and 150m^3 on 4 September(during second visit). Although there are time variations of volume increment of the scour pit according to the tidal variation, average increasing rates of the pit volume can be approximated to be 1.5m^3/day in the initial stage ('87. 8. 24~8. 28) and 20m^3/day in the later stage('87. 8. 28~9. 4). It can be said that scouring rate in later stage is far greater(order of magnitude) than that in the initial stage.

This time-differential volume increase is presumably ascribed to the low height of the cylinder in contrast to the length of the cylinder. From the observation of scouring rates around vertical piles with various size, Palmer[14] concluded that it took a long time to reach the fully developed state of the scour pit around a pile which had a low height and large diameter. And he[14] also showed that scouring rate increases exponentially in the later stage.

From the exponential increase of scouring rate during later stage and the scour pit dimensions which are different from those reported by other researcher, the scour pit observed on 4 September seems to have reached almost the maximum and equilibrium stage. If the maximum development of the scour pit occurred on someday after 4 September, the volume of the scour pit ought to be much larger than that measured on 4 September due to the exponential increase of the pit volume(about 20m^3/day). In that case, the depth from the original seabed to the top of the cylinder should be larger than that measured on 4 September(about 1.0m). If the maximum development of the scour pit occurred someday before 4 September, it is reasonable to use the pit volume measured on 4 September for the calculation of the infilling rate of the scour pit. Thus, it seems to be reasonable to assume that the scour pit measured on 4 September is very near to maximum development stage.

Infilling Rates

Analysing the characteristics of the sand and tidal currents in the study area, it was reported that almost all the sands on tidal sand ridge are transported as bedload following the current directions[10, 12]. The scour pits around the cylinders are ususally infilled by sands transported as bedload from both tidal direction[14, 20]. In the first stage of development of the scour pit, infilling rate of the scour pit is far less than the scouring rate of sea-bed due to the strong secondary flows[2, 14]. As the scour pit develops further, the volume of the scour pit is increased and finally reached to the equilibrium stage, when infilling rate equals to the scouring rate.

After then, the cylinder has negligible influence to the flow regime flowing over it due to the large depth and width of the scour pit, and infilling rate exceeds the scouring rate of the scour pit. Thus, sands which are trapped by the pit gradually infill the scour pit and bury the cylinder.

As previously mentioned, the development stage of the scour pit observed at 14 : 00, on 4 September(during second visit) was assumed to be in maximum stage. Full burial of cylinder was observed at 13 : 00, 10 September(during third visit) (Fig. 2). Dimension of the scour pit measured on 4 September was approximated to be 150m^3. And it was observed on 10 September that the scour pit was partially filled to the depth of about 0.5m below the original seabed level(Fig. 2). Thus, the volume of sands deposited in the scour pit by infilling can be roughly approximated to be 80m^3. Assuming that sand has the density of quartz, the wet density of sand is 1.63 gm/cm^3. And the average porosity of medium sand deposits is about 45%[13)]. Therefore the total wet weight of sands deposited in the scour pit by infilling can be approximated to be 0.7×10^2 tons, and used for arithmetic estimation of infilling rate.

It is impossible to know at present the exact time of the full development of the scour pit due to the field experiment schedules(Table 1). Maximum infilling rate is approximated to be 0.18 gm cm^{-1} sec^{-1} under the supposition that sands in the scour pit have been deposited from 00 : 00 on 5 September to 24 : 00 on 9 September. Minimum infilling rate is approximated to be 0.13 gm cm sec^{-1} under the assumption that sands have been deposited from 00 : 00 on 4 September to 24 : 00 on 10 September. At present it is very hard to calculate the time variation of infilling rate in accordance with the change of tidal current velocity. However, arithmetic estimation of infilling rate can be considered as significant because it can be used as the reference for comparison with the bedload transport rate calculated by equations.

The sands deposited in the scour pit for given period of time are the summation of the infilled sands(transported into) and scoured sands (transported out) during that time. Even though the scouring activity is far less than the infilling activity due to the large width and depth of the scour pit at the maximum development stage, net amounts of sands deposited in the scour pit should be less than the total amount of sands possibly trapped by the pit. Thus, the infilling rate calculated from the amount of infilled sands seems to slightly underestimate the real infilling rate.

Conclusions

Scour and infill processes of the scour pit developed around an artificial cylinder placed on tidal sand ridge in Gyeonggi Bay, Korea were observed by underwater video recorder and divers during 24 August~26 September, 1987.

The top view of the scour pit has roughly circular(ellipitical) shape, which is different from the horseshoe shape under uniderectional flow or from the shape of inverted frustrum under wave condition. Considering the dimension(diameter, scour depth, slope) of the scour pit, compound process of "leeside-erosion" and erosion by secondary flows around the cylinder seems to be responsible.

The volumes of the observed scour pit are calculated to be about 6m^3 on 28 August, and about 150m^3 on 4 September. The volumes of scour pit seem to be increased exponentially from 1.5m^3/day during the initial stage('89. 8. 24~8. 28) to 20m^3/day during the later stage('87. 8. 28~9. 4). Total infilled(deposited) sands in the scour pit during '87. 9. 4~9. 10 are approximated to be $80m^3$. Assuming that sand has the density of quartz and that the average porosity of medium sand deposits is about 45%, the total wet weight of sands deposited in the scour pit by infilling can be approximated to be 0.7×10^2 tons.

Under the assumption that the sands infilled the scour pit(0.7×10^2 tons) have been deposited by bedload transport from 4 September to 10 September, 1987, infilling rates can be arithmetically approximated as 0.13gm/cm/sec (minimum) and as 0.18gm/cm/sec (maximum).

References

1) Niedoroda, A. W. and C. Dalton, "A review of the fluid mechanics of ocean scour", Ocean Eng., Vol. 9, pp. 159-170, 1982
2) Herbich, J. B., R. E. Schiller Jr., W. A. Dunlap and R. K. Watanabe, "Seafloor scour : Design guidelines for ocean-founded structures", Marcel Dekker, Inc., New York and Basel, 1984
3) Chari, T. R. and K. S. R. Prasad, "Analytical and experimental modelling of iceberg scours and pits", 3rd Can. Conf. Mar. Geotech. Eng., Vol. 2, pp. 457-468, 1986
4) Lewis, C. F. M., D.R. Parrott, H.W. Josenhans, J.V. Barrie, C.M.J. Woodworth-Lynas, W. T. Collins and J. I. Clark, "Iceberg scouring : Hazard for seabed development", 3rd Can. Conf. Mar. Geotech. Eng., Vol. 3, pp. 1020-1021, 1986
5) Raven, P. W. J., R. J. Stuart, J. A. Bray and P. S. Littlejohns, "Full-scale dynamic testing of submarine pipeline spans", 7th Ann. Offshore Tech. Conf. Proc., Vol. 3, pp. 395-404, 1985
6) Ibrahim, A., C. Nalluri, J. S. Chung, K. Yoshida, C. P. Sparks and D. T. Tsahalis, "Scour prediction around marine pipelines", Proc. 5th Int. Offshore Mech. and Arctic Eng. Symp., Vol. 3, pp. 679-684, 1986
7) Isaacson, M., "Sediment erosion around artificial islands", 21st Cong. Int. Asso. Hydraulic Res., Vol. 4, pp. 160-165, 1985
8) Melville, B. W., "Live-bed scour at bridge piers", J. Hydraul. Eng. Am. Soc. Civ. Eng., Vol. 110, pp. 1234-1247, 1984
9) Kurata, K. and S. Hirai, "Scour around multiple and submerged circular cylinders", Coast. Eng. Japan, Vol. 25, pp. 287, 1982
10) Choi, J. H., "Scour and infill processes of sand around an artificial cylinder on tidal sand ridge in the Gyeonggi Bay, Korea", Ph. D. Diss., Dept. Ocean., Seoul Nat. Univ., 1990
11) Choi, J. H., 'Estimation of boundary shear velocities from tidal current in the Gyeonggi Bay, Korea", J. Oceanol. Soc. Korea, Vol. 26, pp. 340-349, 1991
12) Choi, J. H. and Y. A. Park, "Textural characteristics and transport mode of surface sediments of a tidal sand ridge in Gyeonggi bay, Korea", J. Oceanol. Soc. Korea, Vol. 27, pp. 145-153, 1992
13) Pettijohn, F. J., "Sedimentary rocks, 3rd ed.", Harper and Row Pub., New York, 1975
14) Palmer, H. D., "Wave-induced scour around natural and artificial objects", Ph. D. Diss., Dept. Geology, Univ. Southern California, 1970
15) Blatt, H., G. Middleton and R. Murray, "Origin of sedimentary rocks", Prentice-Hall, Inc., 1980
16) Allen, J.R.L., "Sedimentary structures : Their character and physical basis. Vol. II", Elsevier Scientic Pub. Co., Amsterdam, 1982
17) Wells, D. R. and R. M. Sorensen, "Scour around a circular pile due to oscillatory wave motion", TAMU-SG-70-208, Rep. No. COE 113. Texas A & M Univ., College Station, Texas, 1970

18) Xie, S. L., "Scouring patterns in front of vertical breakwater", Acta Oceanologica Sin., Vol. 4, pp. 153-164, 1985

19) Hulsbergen, C. H., "Stimulated self-burial of submarine pipelines", OTC paper 4667, pp. 171-178, 1984

20) Reimnitz, E. and E. W. Kempema, "High rates of bedload transport measured from infilling rate of large strudel-scour craters in the Beaufort Sea, Alaska", Cont. Shelf Res., Vol. 1, pp. 237-251, 1983