

PHYSICAL MODELING STUDY ON SCOUR AND SCOUR COUNTERMEASURE FOR SEA-CROSSING BRIDGE PIERS

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There are significant engineering challenges in placing the sea-crossing bridge piers in more or less shallow coastal waters because, as well as having to withstand storm-force waves and tidal currents, the bridge piers have to remain stable on a sea bed that may be continuously changing. One of the major challenges faced by designers is how to predict, and prevent, scour of the seabed sediments around the sea-crossing bridge piers. This paper describes a physical model study on scour and scour countermeasure for sea-crossing bridge piers. A 1:49 scale movable bed model tests were carried out in the Near-shore Wave Basin (NSWB, 27m x 19m) at the Tainan Hydraulics Laboratory, National Chang Kung University (NCKU), Tainan, Taiwan, with the sea-crossing bridge piers in the test area. Three series of physical model tests were performed in this study. The aim of the first test series is to investigate the maximum scour depth for the initial construction of bridge piers with only one pier model. Then the second test series were conducted to investigate the greatest magnitude of local scour and potential scour area in the sand bed around the sea-crossing bridge group piers with no scour protection. Based on the analysis from the former NSWB experimental results, the suitable scour countermeasure for sea-crossing bridge piers would be proposed and validated its function of preventing scour in the third test series.

Keywords: sea-crossing bridge; scour; scour protection, physical modeling

INTRODUCTION

Kinmen is a small archipelago of several islands administered by the Taiwan: Greater Kinmen, Lesser Kinmen, and some islets. The island was the site of extensive shelling between the People's Republic of China (PROC) and Republic of China (ROC, Taiwan) forces during the first and second Taiwan Strait Crisis. Therefore, Kinmen was originally a military reserve. The island was returned to the civilian government in the mid-1990s, after which travel to and from it was allowed. Before the mid-1990s, development on the island was extremely limited due to its military importance. However as a result of political situation change between PROC and ROC, Kinmen is now a popular weekend tourist destination for Taiwanese. Furthermore, it is recognized as one of the national parks in Taiwan. Therefore, now the Kinmen's economy is mainly based on tourism and services due to its proximity to mainland China. Owing to the governmental policy aiming to achieve balanced regional development and integrate local tourism resources, the Kinmen sea-crossing bridge (Fig. 1) is planned to be completed by June 2016. The Kinmen Bridge is a 5.4km long sea-crossing bridge connecting Kinmen Island (Greater Kinmen) and Lieyu. The bridge is constructed over tidal flats and up to 22 depth of water. The estimated constructing cost of this bridge is up to US\$250 million. This bridge is an integration of several special featured bridges and the major part of the bridge consists of five continue towers of ridgeback bridge. This marine ridgeback bridge will have the largest span of 280m in the world when completed. Kinmen Bridge is currently under final design stage. Foundation design of the Kinmen Bridge P29 foundation is shown in Fig. 2. It is well known that local scour around bridge piers is one of the major causes of bridge failure. Local scour depths are usually determined using empirical formulas and field monitoring is conducted in construction stage to verify the estimated results. However, in an offshore environment, it is difficult to acquire scour data due to tide and waves. In this study, a three-dimensional scour laboratory study is conducted to measure scour contour for sea-crossing bridge piers. Through experiment, it is shown that the developed physical model simulation can accurately measure the potential scour depth and the extent of scour of target bridge piers.

Scour is a natural phenomenon caused by erosive action of the flowing water on the bed and banks of alluvial channel. There is also scour occurring at the coastal regions as a result of the passage of wave and current. Meanwhile, scour phenomenon is of high practical importance from the point of view of marine and river structures, such as offshore platforms, subsea templates, bridges, etc., as excessive scour at piles is detrimental to the structures. Several recent scour-related bridge catastrophes

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through out the world have obtained general attention (Lagasse et al. 1995; Johnson and Dock 1996). Many bridges failed around the world because of extreme scour around piers. Failure of bridges due to scour at their foundations, which consist of abutments and piers, is a common occurrence. Researchers from all over the world have studied extensively the problem of local scouring from different points of view and under different conditions. The subject of scour at piles under steady current has been studied (in the context of scour at bridge piers) extensively by many investigators (Melville and Sutherland 1988; Dey et al. 1995; Melville 1997; Dey 1999; Melville and Chiew 1999; Oliveto and Hager 2002). On the other hand, Chiew 1989, Sumer et al. 1992, 1993, Kobayashi and Oda 1994, and Sumer and Fredsøe 2001 explored scour at piles under waves. Review of the important experiments and field studies on scour at piers or piles under waves and currents was put forward by Dey 1997, Whitehouse 1998, Melville and Coleman 2000, Richardson and Davis 2001, and Sumer and Fredsøe 2002. There is also an immense interest in finding different methods of scour reduction. These countermeasures for local scour at piles or bridge piers can be divided into two categories: Armoring devices and flow-altering devices. Armoring techniques include riprap (Zarrati et al. 2006), cable-tied blocks, tetrapods, etc., placed at the pier or pile base (Lagasse et al. 2001). Flow altering devices that have been used to protect piers against local scour include sacrificial piles placed upstream of the piers (Melville and Hadfield 1999), submerged vanes (Odgaard and Wang 1987), and flow deflectors attached to the pier, such as slot through piers (Chiew 1992, Kumar et al. 1999).



Figure 1. Sketch of the Kinmen sea-crossing bridge connected Greater Kinmen and Lieyu.

The objective of this study is to improve understanding of scour behavior and to aid the design of scour protection systems for sea-crossing bridge foundation with group piers located on sandy seabed in shallow water by physical modeling simulation. A 1:49 scale movable bed model tests are carried out in the Near-shore Wave Basin (NSWB, 150m x 60m x 1.5m) at the Tainan Hydraulics Laboratory (THL), National Cheng Kung University (NCKU), Tainan, Taiwan, with model of sea-crossing bridge foundation in the test area. Three series of physical model tests are performed in this study. The aim of the first test is to investigate the maximum scour depth for the initial stage of bridge construction with only one pier model exposed to wave and current. Then the second test is conducted to investigate the greatest magnitude of local scour and potential scour area around sea-crossing bridge group piers with no scour protection. In order to prevent the local scour from the second test result, the suitable scour-reduction countermeasure with armoring devices is also proposed and validated its efficiency in the third test.

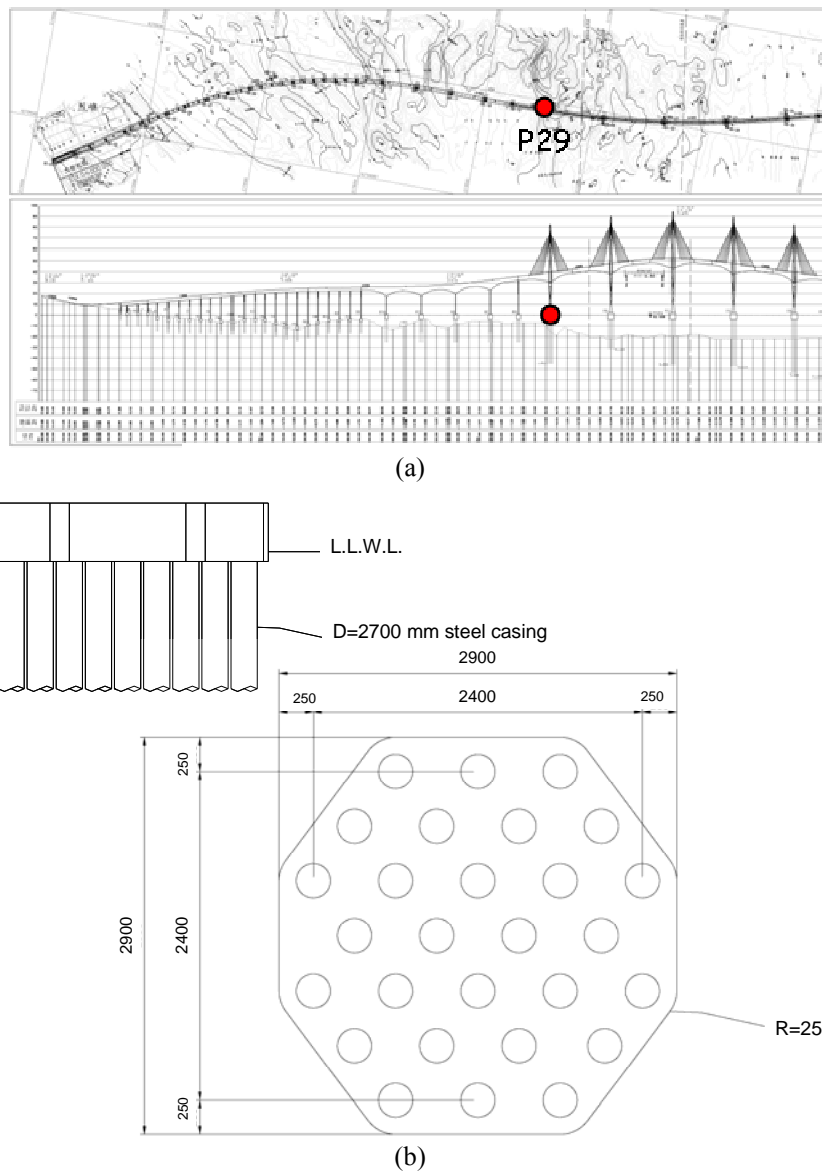


Figure 2. (a) Location and (b) sketch of foundation design of the Kinmen bridge for P29 foundation.

HYDRODYNAMIC AND MORPHOLOGIC BACKGROUND

The selected foundation P29 of the Kinmen sea-crossing bridge for physical simulation is located at water depth 15m with mild slope bottom (slope=1/150~1/200). The sediment around the foundation P29 in-situ is fine sand of a median diameter of $d_{50}=0.2\text{mm}$. An important parameter for seabed mobility is the Shields parameter $\theta=\tau/[(\rho_s-\rho)gd_{50}]$, where τ is the bed shear stress, g is the gravitational acceleration, ρ_s and ρ are the sediment grains and water densities, and d_{50} is the median grain size of the sediment by mass. Although the design life of the Kinmen sea-crossing bridge is 50 years, however due to the consideration of extreme wave loading (especially for the currently severely global climate change), the model has to be performed for 1:100 year return period typhoon wave for short-term impact on the local scour around the sea-crossing bridge foundation piers. Based on the simulation result of wave climate analysis, the maximum 1:100 return period typhoon wave of the water channel between Greater Kinmen and Lieyu can be up to the significant wave height $H_s=2.0\text{m}$ and the significant wave period $T_s=11.9\text{sec}$. From the result of tidal current simulation, the maximum current speed near the foundation P29 is almost up to 1.5m/sec (to see Fig. 3), this is a depth average current for both tidal and wind driven current. The angle between the incident wave and current is 90° . Due to high tidal range of the studied area, different water level is also considered for every test. The

simulated sea-crossing bridge foundation models include one pier for the initial stage of construction, group piers without scour protection for the completed stage of construction, and group piers with scour protection for the assessment of scour protection efficacy. All the test conditions (6 test runs) are shown in Table 1.

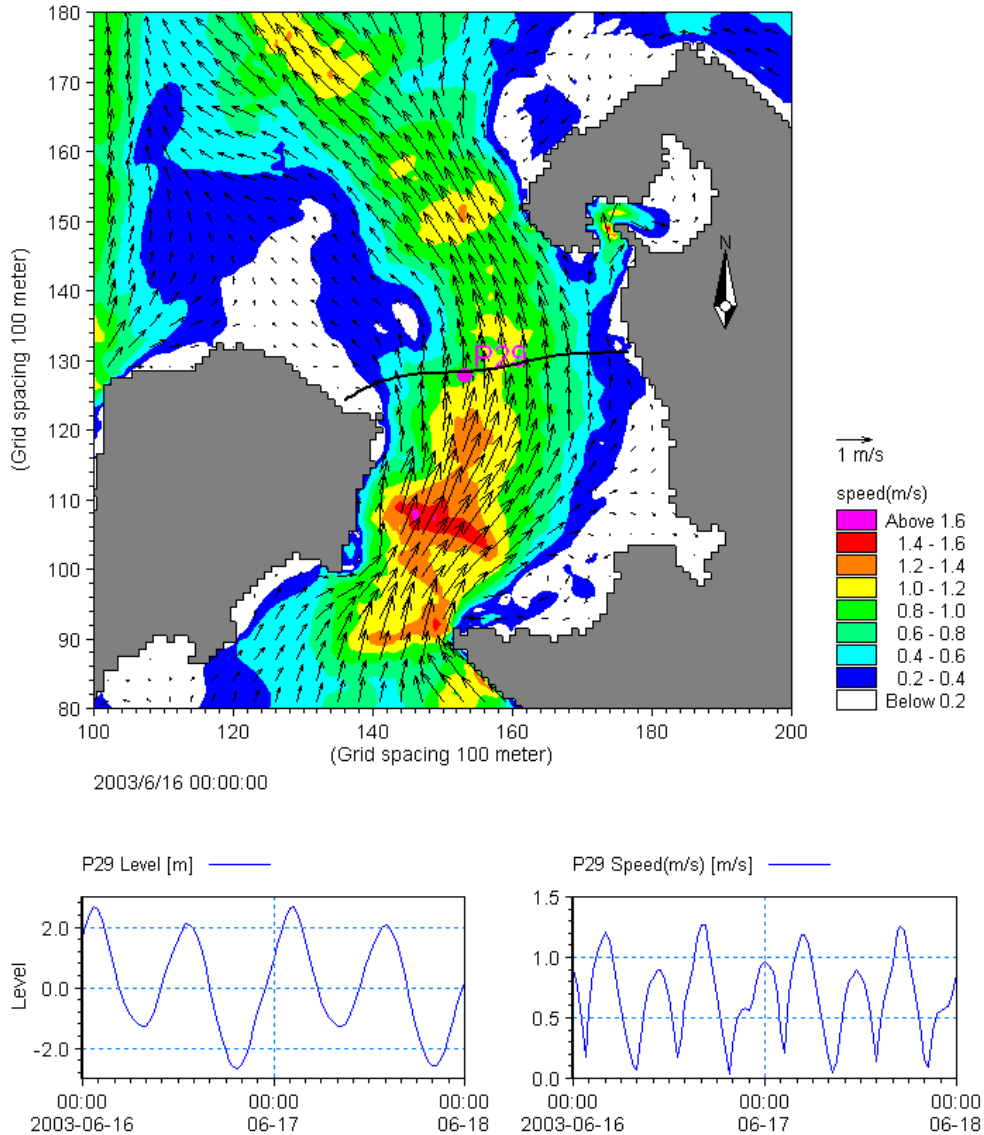


Figure 3. Flow field simulation for Kinmen water channel (the maximum current speed near P29 foundation is around 1.28 m/sec).

Test case	Water depth (m)	Wave height (m)	Wave period (sec)	water level (m)	Tidal current (m/s)	note
SMC	15.0	---	---	M.W.L. (+0.00)	1.5	one pier
SHTC	15.0	2.0	11.9	H.H.W.L. (+3.16)	1.5	one pier
GMC	15.0	---	---	M.W.L. (+0.00)	1.5	pier groups
GHTC	15.0	2.0	11.9	H.H.W.L. (+3.16)	1.5	pier groups
GMCP	15.0	---	---	M.W.L. (+0.00)	1.5	scour protection
GHTCP	15.0	2.0	11.9	H.H.W.L. (+3.16)	1.5	scour protection

EXPERIMENTAL SETUP

Three series of physical model tests are performed in this study. The aim of the first two test series is to investigate the greatest magnitude of local scour and potential scour area in the sand bed around the sea-crossing bridge pier/group piers with no scour protection. The third series of tests is aimed at

the level of protection for proposed scour mitigation under design wave and current conditions and to assess the extent of scouring around the sea-crossing bridge foundation with scour protection. Layout of 27m x 19m wave-current basin in the NSWB for scour experiments is shown in Fig. 4. The wave flume passes from right to left and the current-generation flume circulate from downside to upside. The test area with the sea-crossing bridge foundation is at the junction of these two flumes. The physical modeling is carried out in this wave-current basin at the Tainan Hydraulics Laboratory (THL) with a scale of 1:49. The model law of this movable-bed experiment is followed by the Shields parameter. Therefore, the bed material used in this experiment is light density (specific gravity, $\gamma=2.02$) coal of a median grain size of $d_{50}=0.18\text{mm}$ and the model sand bed is 0.35m deep, 7.0m long and 3.0m wide. The equipments and measurement system used in this experiment include irregular wave maker, current-generation system, electrical capacitance wave gauges, ADV current meters and ultrasonic bottom profiler moved by the carriage table (7m x 3m). The calibration of the experimental target wave and current test condition are respectively shown in the Fig. 5 and Fig. 6. Before and after the wave-current action for several runs in each test, the bottoms of model sand bed are scanned line by line along the carriage table. Then the topography evolution sea bottom and the scour around the sea-crossing bridge foundation can be analyzed from the measurement data of ultrasonic bottom profiler carried by X-Y carriage table system.

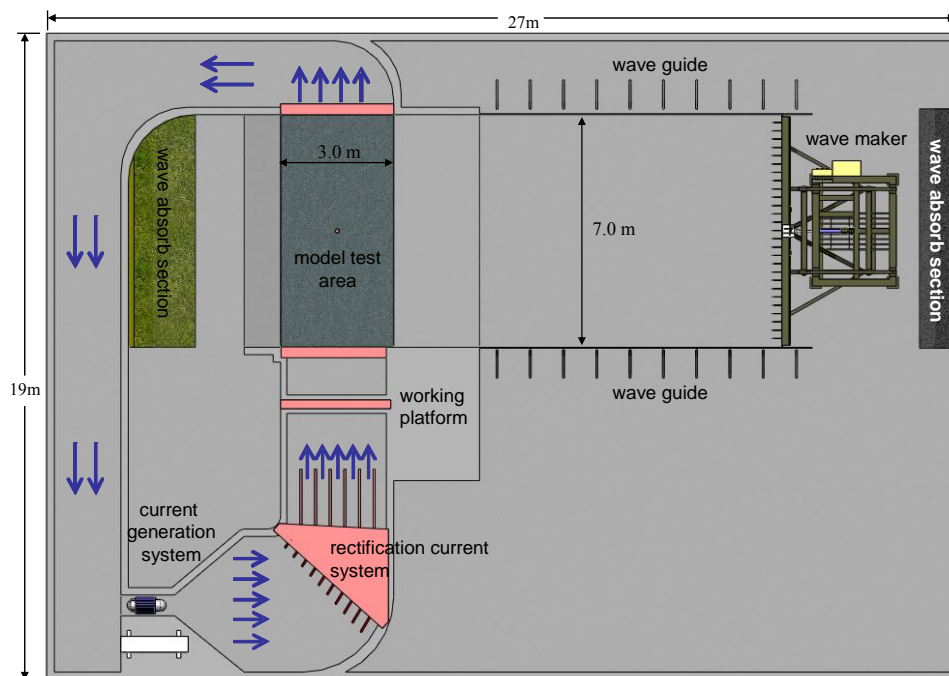


Figure 4. Experimental setup for scour around sea-crossing bridge.

ONE PIER MODEL FOR SIMULATION INITIAL CONSTRUCTION STAGE

In order to investigate the maximum scour and potential scour area during the initial construction stage, one pier model is firstly simulated. From the former experience, scour around a pier is caused mainly by the following three effects : (1) horseshoe vortex combined with the downflow in front of the pier; (2) vortex shedding at the back of the pier; and (3) contraction of streamlines at the side edges. The horseshoe vortex (combined with the downflow) and the contraction of streamlines are the key elements for scour in the case of a steady current. In the case of the combined waves and current, the scour depth is a function of the KC number and the parameter. Here, KC is defined by

$$KC = \frac{U_m T}{D} \quad (1)$$

in which U_m =maximum value of the undisturbed orbital velocity at the sea bottom just above the wave boundary layer; T =wave period; and D =pier diameter. The other important dimensionless parameter is

$$U_{cw} = \frac{U_c}{U_c + U_m} \quad (2)$$

in which U_c =undisturbed current velocity at the distance $y=D/2$ from the bed representing the near-bed current velocity.

The evolution equilibrium scour depth and potential scour area obtained from the present one pier experiments are shown in Fig. 7 and Table 2 for the current-alone case and combined-wave-and-current case. The maximum scour depths(S) around one pier are $S/D=0.99$ for current-alone case and $S/D=0.94$ for combined-wave-and-current case, respectively. It is estimated the length of the scour hole around one pier is approximated up to 1.6~2.0 times the pier diameter ($1.6D\sim 2.0D$) for current-alone case and $2.3D\sim 3.6D$ for combined-wave-and current case. Compared with the results from the current-alone case and combined-wave-and-current case, the scour depth seems to be uninfluenced when wave action added. However combined the wave action, the potential scour area seems to be increased (to see Fig. 8).

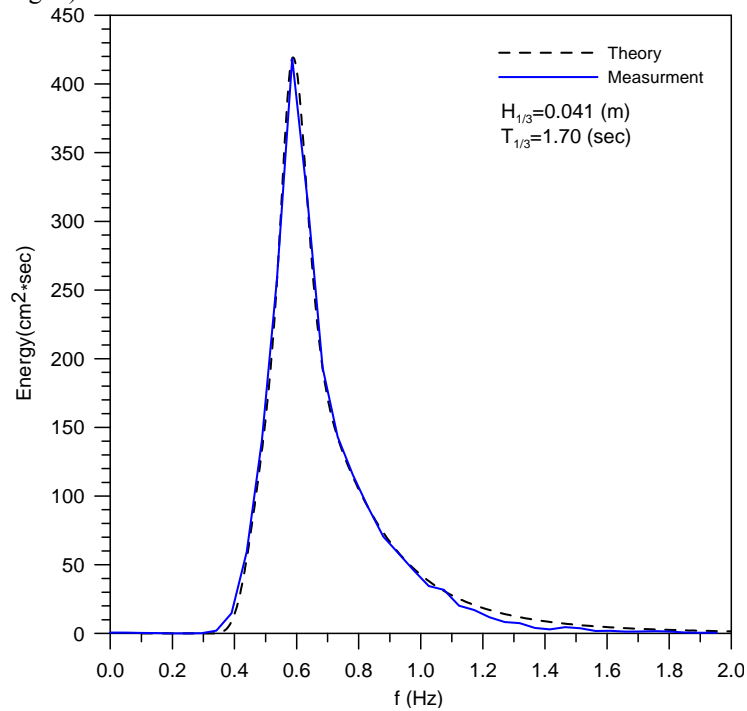
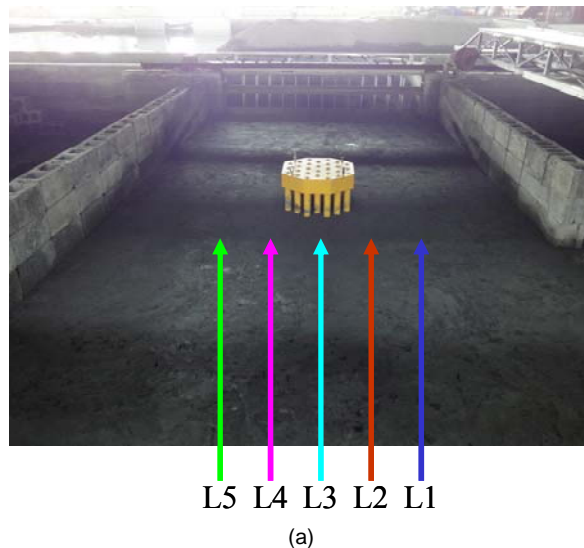


Figure 5. The calibration of the experimental target wave test condition ($H_{1/3}=0.041$ m, $T_{1/3}=1.7$ sec).



(a)

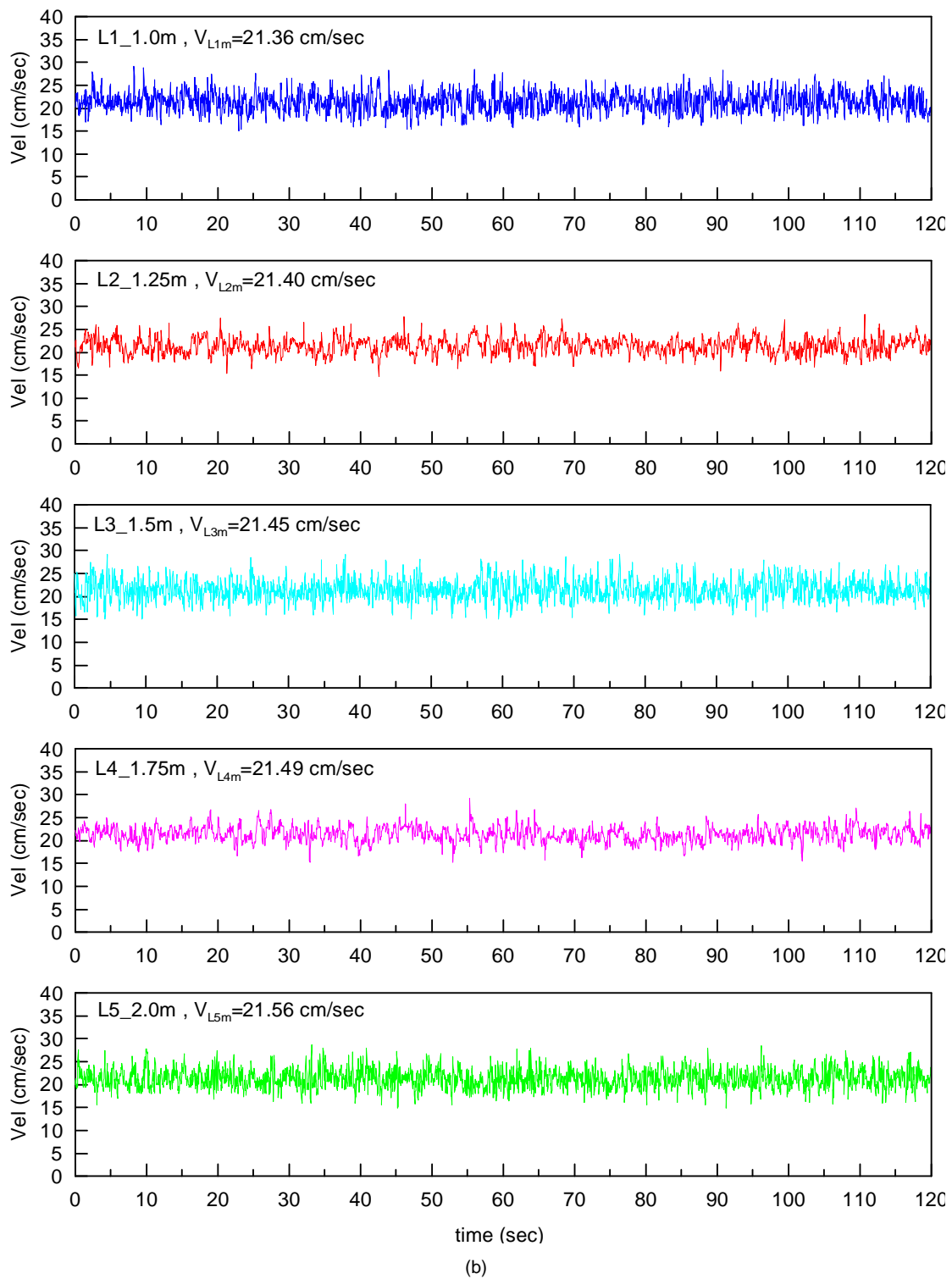


Figure 6. (a) The calibration of the experimental target current test position (b) The current test time series ($V_0=21.43$ cm/sec).

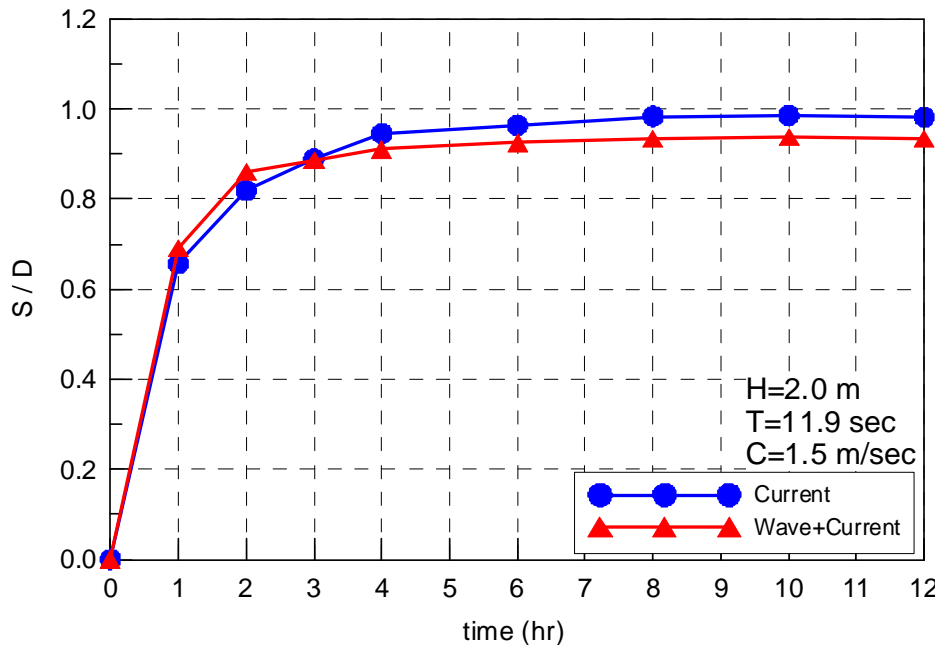


Figure 7. The evolution of maximum scour depth around one pier for the current-alone case and combined-wave and current case.

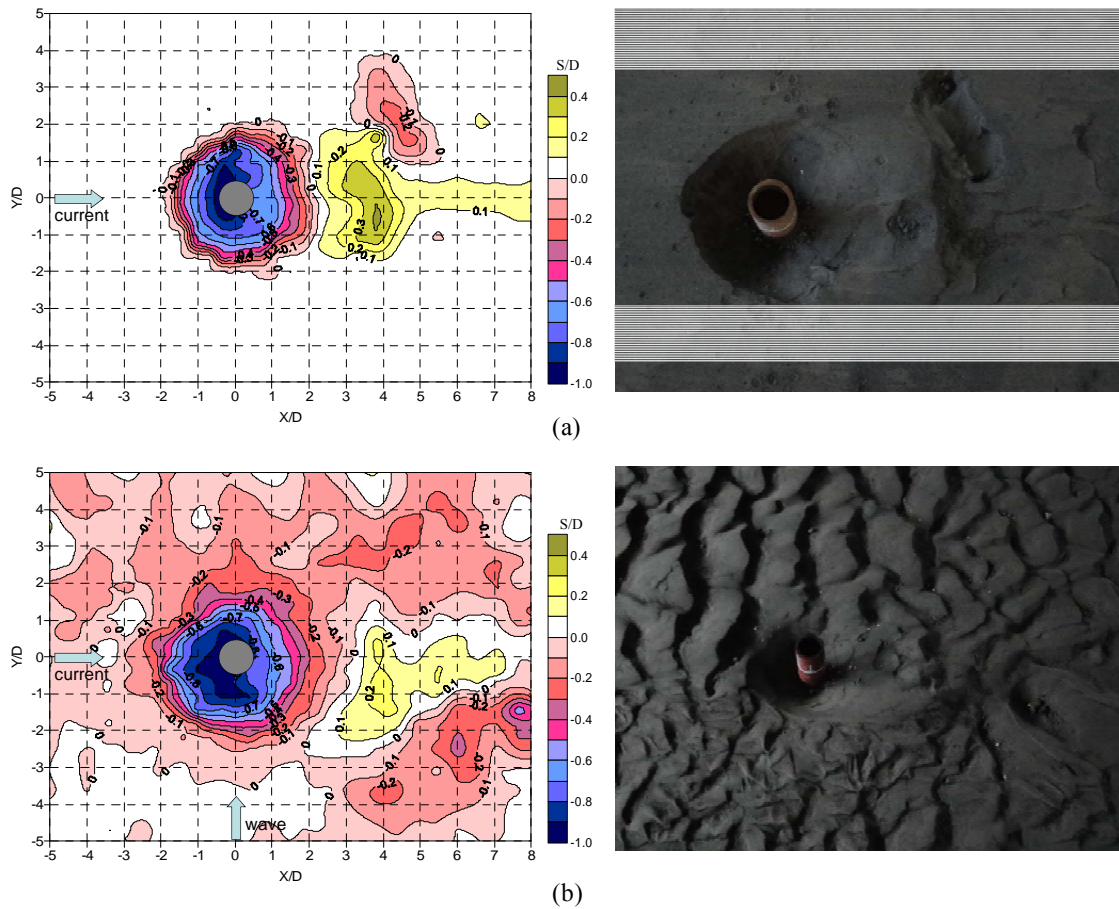


Figure8. (a) The potential impact erosion area and scour around one pier for the current-alone case; (b) The potential impact erosion area and scour around one pier for the combined wave and current case.

test case	scour direction	impact area of the different scour depth (D)			
		>0.2D	>0.4D	>0.6D	>0.8D
SMC	current-front	1.7	1.5	1.2	0.8
	current-back	1.9	1.6	1.2	0.4
	wave-front	1.8	1.6	1.6	0.9
	wave-back	1.8	1.7	1.5	1.3
SHTC	current-front	2.4	2.0	1.8	1.4
	current-back	2.4	1.8	1.2	0.6
	wave-front	2.3	1.9	1.6	1.3
	wave-back	3.2	1.6	1.3	0.9

SCOUR AROUND BRIDGE PIER GROUPS OF SEA-CROSSING BRIDGE

This section presents an experimental study on local scour around pier groups of sea-crossing bridges subject to combined wave and current. Local scour around bridge piers is one of the major causes of bridge failure. Scour washes away bed materials around the foundations of a bridge, which causes a reduction in the load capacity of the foundations. Pier groups are widely used in the field to support bridges and marine structures. Clearly scouring at the piling is of importance in connection with the stability of the structure since the extensive scour may reduce the stability of the structure and leads to its failure, Sumer et al. 1992.

There are 28 piers for P29 foundation of the Kinmen sea-crossing bridge. Fig. 9(a) shows the bed configuration of scour holes around twenty-eight pier groups subject to current. From the result of Fig. 9(a), it shows that the shape of the scour hole around the pier groups remained almost unchanged with respect to time. This shape can be approximated by an inverted cone having a circular base. Deposition occurs downstream the pier groups, the area of deposition increases with increasing the time.

The maximum scour depth around these 28 pier groups is $S/D=1.88$ for current-alone case. Meanwhile for this current-alone test case, the severe scour happens in the gap area between the second now to fourth now of the groups pier from the up-coming current side. The average scour depth can be up to $1.6D \sim 1.8D$. It is clear that the scour depth more increases than that around one pier. This is firstly due to the vortices created around the piers will interact with each other, and secondly, the flow accelerated owing to contraction created by the adjacent pier (the "jet" effect). This obviously results in a very high sediment transport induced by the gap flow, and hence contributes substantially to the scour depth. Compared to current-alone case, more vortices among the gap of pier groups will be induced by combined wave and current loading. The bed configuration of scour hole around this twenty-eight pier groups under combined wave and current loading is shown in Fig. 9(b). Table 3 shows the potential impact erosion area around the pier groups of sea-crossing bridge under different hydrodynamic conditions. It is obvious that when bridge pier groups of sea-crossing bridge under combined wave and current loading there will be more severe scour generated. The maximum scour depth around this 28 pier groups can be up to $S/D=3.6$, almost two times larger than that of current-alone test case (to see Fig.10). In Fig. 10 we also compare the present results for one pier case with the experimental result from Sumer and Fredsøe 2001. The KC number is 2.7 and U_{cw} parameter is 0.71 under the present experiment of wave propagating perpendicular to current. It shows that the present results are consistent with that of Sumer and Fredsøe's experiments 2001.

Furthermore in order to estimate the maximum scour depth around these 28 pier groups under current and wave, the maximum possible estimation of scour depth using Hyperbolic Model is conducted. For example, GHTC test case combined wave and current, the relevant parameters are described in Fig. 11. Assuming maximum scour depth and pile diameter ratio (S/D) of the asymptotic line as S_{max} , initial erosion rate is V_s , then the longitudinal axis of the item changed to $t/(S/D)$ to be drawn. Fig. 12 shows that the data points of pier groups GMC and GHTC test cases after conversion. Then different test cases followed point by point, thus the linear regression line will be obtained from the analysis. The maximum possible scour depth and pile diameter ratio S_{max} , initial erosion rate V_s , extrapolated the slope of the linear regression line b and intercept a . The relationship can be obtained as follows:

$$t / (S/D) = a + b \times t \quad (3)$$

$$S_{max} = 1/b \quad (4)$$

$$V_s = 1/a \quad (5)$$

From the test results and the estimation of Hyperbolic Model for the maximum possible scour depth, the S_{max} was 2.12 of GMC test case (current-along), and the GHTC test case combined with wave and current, S_{max} reached up to 3.78. The maximum scour depth predicted results seem to be more conservative as a design reference.

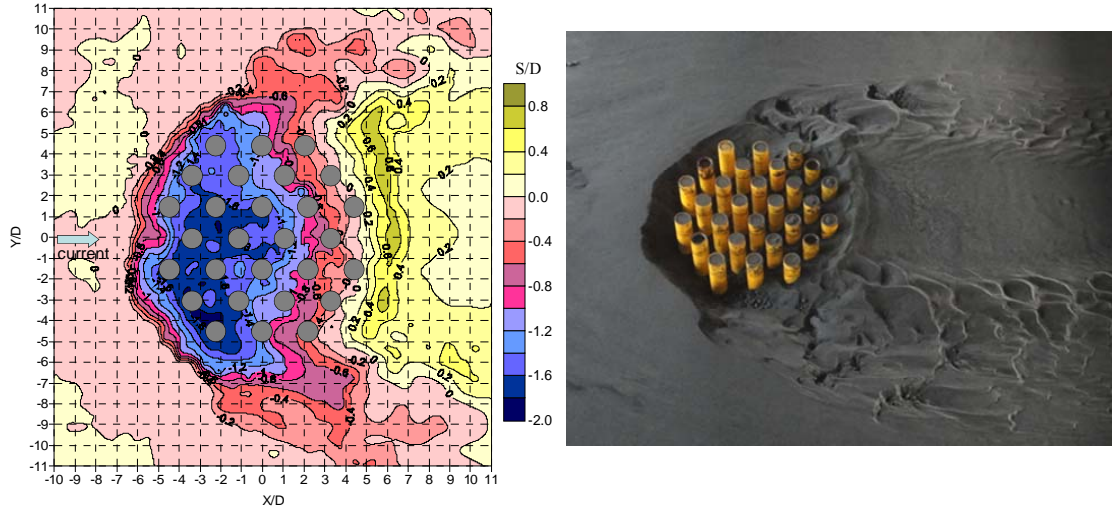


Figure 9(a). The bed configuration of scour holes around twenty-eight pier groups subject to current.

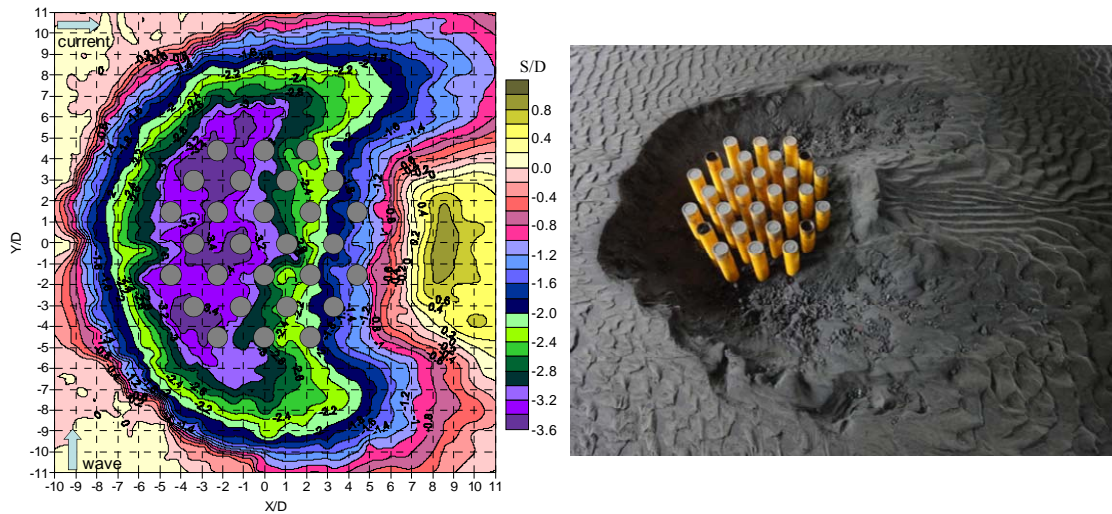


Figure 9(b). The bed configuration of scour holes around twenty-eight pier groups under combined wave and current .

Table 3. The potential scour area obtained from the pier groups experiments.							
test case	scour direction	impact area of the different scour depth (D)					
		>0.4D	>0.8D	>1.2D	>1.6D	>2.0D	>3.0D
GMC	current-front	1.5	1.2	0.7	0.1	---	---
	current-back	-0.4	-2.3	-3.5	-4.2	---	---
	wave-front	5.0	2.0	1.5	0.6	---	---
	wave-back	4.8	1.5	1.3	-1.2	---	---
GHTC	current-front	4.8	4.4	3.9	3.5	2.6	1.0
	current-back	8.0	7.0	4.9	3.0	1.0	-3.4
	wave-front	7.6	6.2	5.4	4.8	4.1	2.0
	wave-back	7.2	6.2	5.2	4.5	3.9	2.0

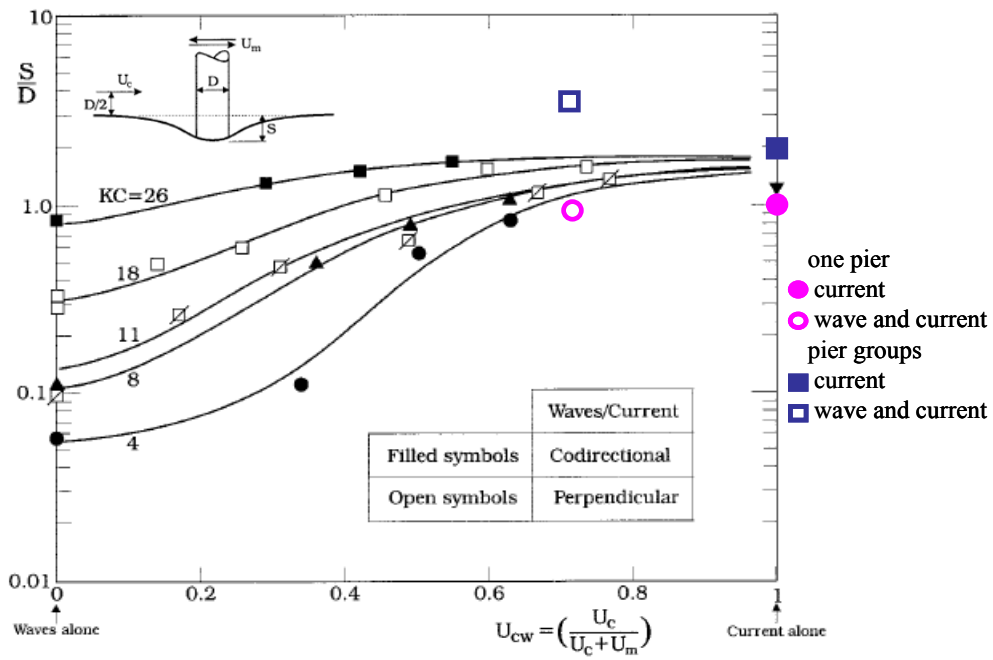


Figure 10. Experiment results from this paper compared with that of Sumer and Fredsoe (2001).

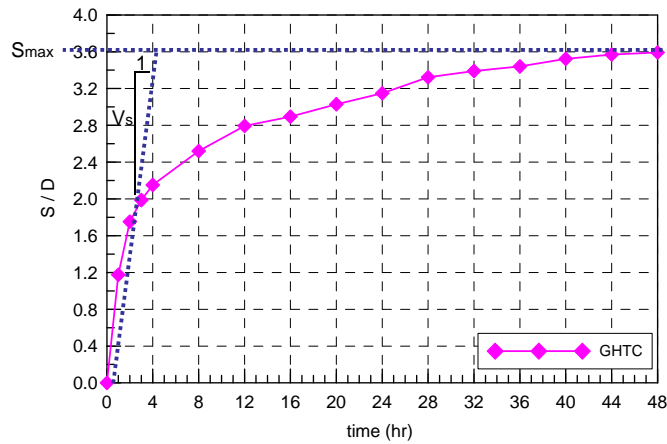


Figure 11. The Hyperbolic Model S_{max} and V_s of schematic.

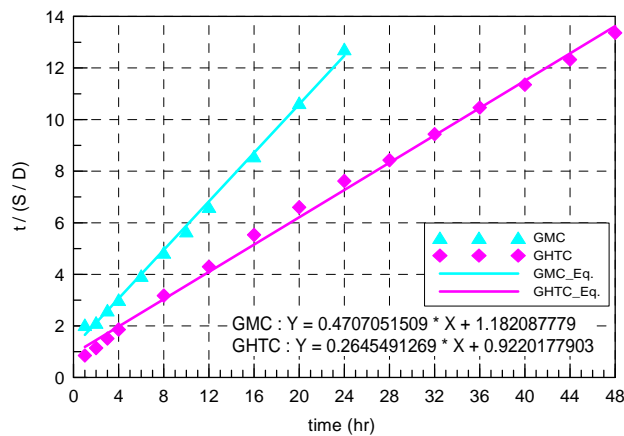


Figure 12. The maximum possible scour depth estimation schematic diagram of using hyperbolic model.

SCOUR PROTECTION FOR BRIDGE PIER GROUPS OF SEA-CROSSING BRIDGE

When placing the bridge pier groups of sea-crossing bridge on an unprotected seabed with non cohesive sediments in shallow coastal waters, a scour hole will develop due to the changes in the flow pattern, caused by the sea-crossing bridge foundation. In order to circumvent this problem, scour must be prevented by means of an appropriate scour protection. However, one of the significant engineering challenges faced by designers is how to predict, and prevent, scour of the seabed sediments around sea-crossing bridge foundation. In order to circumvent this problem, scour must be prevented by means of an appropriate scour protection. Most commonly rocks, large enough to be stable under these design conditions, are used as a scour protection around the mono pile. Recently several authors (Sumer and Fredsøe 2002; Whitehouse 1998 and Jensen et al. 2006) reported on scour around mono pile. May et al. 2002 suggested guidelines for the design of scour protections for bridge piers in rivers (a current only climate). However, little research is available that links the dimensions of the scour protection to the flow parameters in wave-dominated flow or in a combined wave-current climate (den Boon et al. 2004). The key issue is to determine the required stone size, the plan view extent and the thickness of the protection layer. Shields criterion for the threshold of the motion at the surface of the stone layer determines the critical bed shear stress and the required stone size.

To consider the critical bed shear stress and the scour holes around the twenty-eight pier groups of sea-crossing bridge foundation from the results of Fig. 9 and Table 3, the scour protection around this foundation is proposed as Fig. 13. The proposed scour protection consists of three layers as followed:

- (1) C block stone: 300~500kg, with layer thickness of 1.5m.
- (2) Core stone: grain size 10~30cm, with layer thickness of 0.6m.
- (3) Filter stone: grain size 4~10cm, with layer thickness of 1.5m.

Meanwhile, the edge of the scour protection attains a slope of 1V:2H. The experimental setup of scour protection around the P29 bridge foundation is shown in Fig. 14. The initial bed levels and scour protection block stone level are checked with bed profiles taken using a calibrated automatic bottom profiler. Pre-and-post-test profiles are used to identify any settlement and stability in the each three layer and scour in the surrounding seabed. From Fig. 15 and Fig. 16, the results show that the protection of the three layer stone maintained the initial level and kept stable. But, there are local scouring of the bed at the current lee-side of outside scour protection two corner by up to 1.3m (0.5D). However, a three-layer scour protection is tested and found to be effective in preventing scour around this twenty-eight pier groups of sea-crossing bridge foundation.

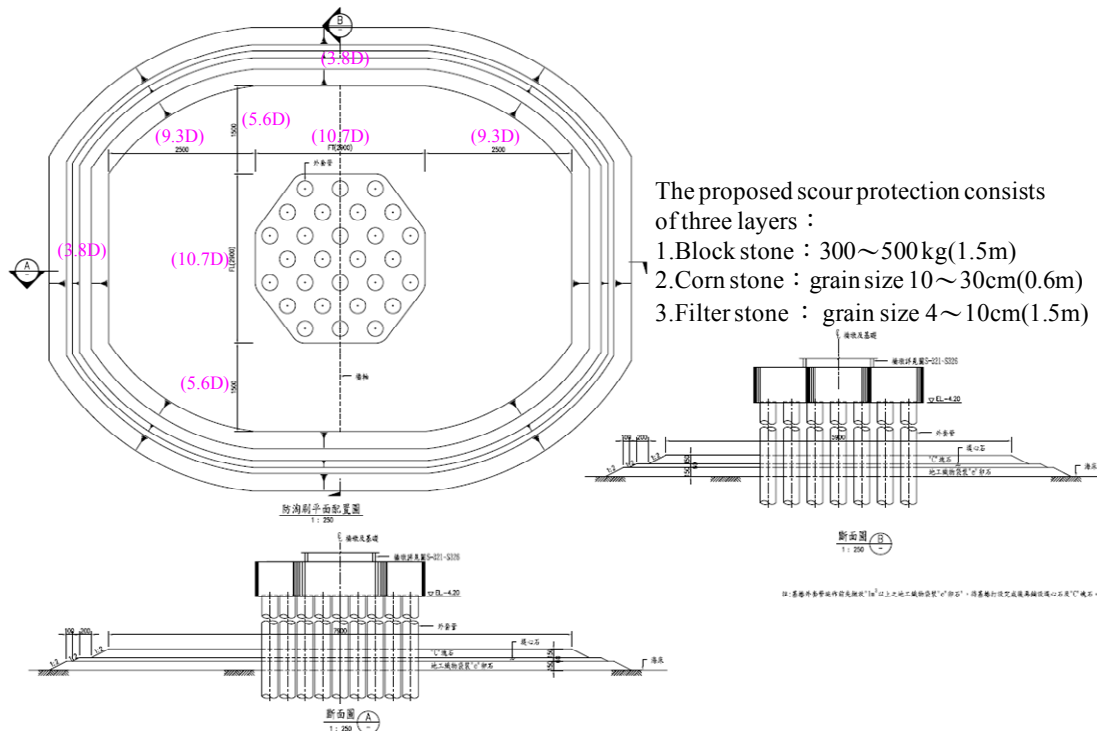


Figure 13. Sketch of the proposed scour protection around the sea-crossing bridge pier groups foundation.

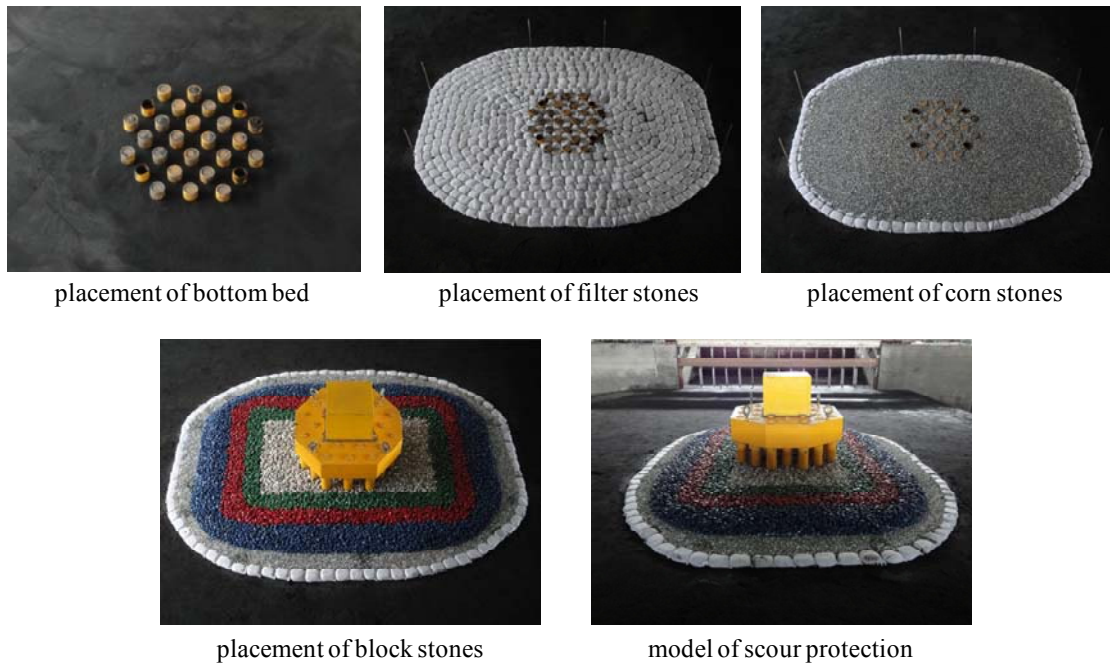


Figure 14. Experimental setup of scour protection around the P29 bridge foundation.

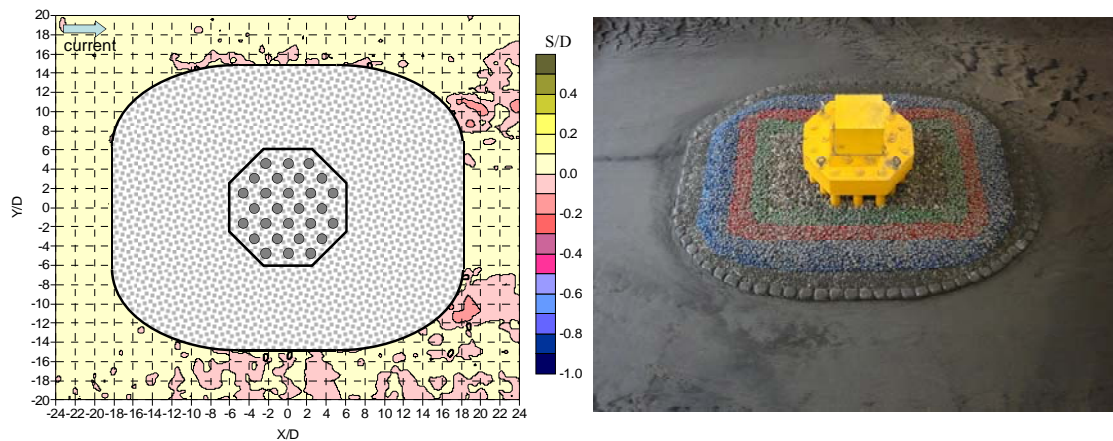


Figure 15. The bed configuration of scour hole around the scour protection for the sea-crossing bridge pier groups foundation subject to current.

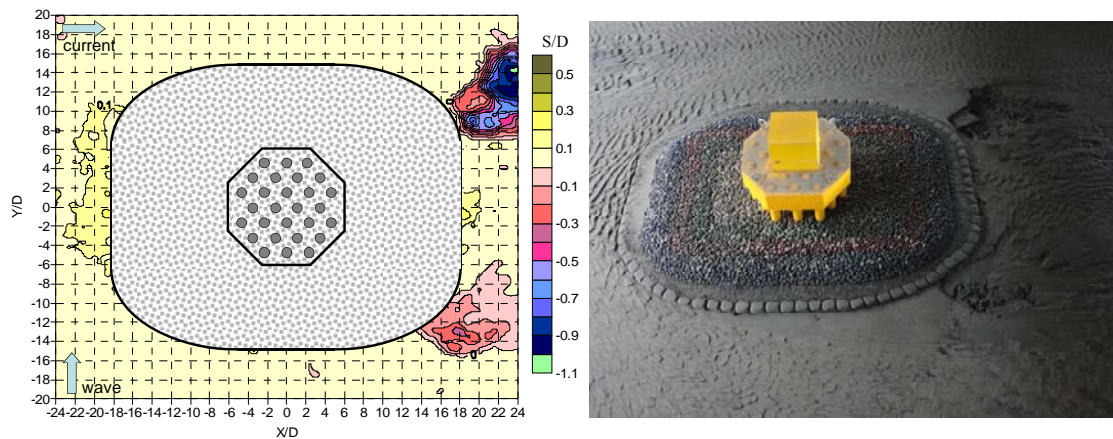


Figure 16. The bed configuration of scour hole around the scour protection for the sea-crossing bridge pier groups foundation under combined wave and current.

CONCLUSION

A clear water scour and hydrodynamic loading experiments were conducted to investigate the characteristics of the scour hole around sea-crossing bridge piers and its dynamic loading under combined wave and current loading. The results of these experimental tests were analyzed and discussed, and the following conclusions could be drawn from the present study:

1. The average scour depth for bridge pier groups more increases than that around one pier. That is due to the vortices created around the piers will interact with each other, and the flow accelerated owing to contraction created by the adjacent pier. Thus, a higher sediment transport induced by the gap of bridge piers hence contributes substantially to the scour depth.
2. The shape of the scour hole around the sea-crossing bridge piers may be approximated by an inverted cone having a circular base, the area of deposition downstream the pier groups increases with time.
3. In order to circumvent the scour problem, scour must be prevented by means of an appropriate scour protection. To consider the critical bed shear stress and the scour holes around the twenty-eight pier groups of sea-crossing bridge foundation from the results of scour experiment for bridge pier groups, three different layers of scour protection including block stone, core stone and filter stone are proposed in this study. Finally, a three-layer scour protection is tested and investigated to be effective in preventing scour around this twenty-eight pier groups of sea-crossing bridge foundation.

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