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Evaluation of Some Proposed Methods for Protecting Bridge Substructure Using Physical Models

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ABSTRAK

Jambatan yang dibina di atas tanah yang mudah terhakis menyeberangi aliran sungai adalah terdedah kepada bahaya banjir terutama di kawasan pelabuhan dan landasan. Akibatnya, lubang aliran air akan terbentuk pada substruktur jambatan. Lubang aliran air itu boleh ditafsirkan dengan kedalaman lubang air yang dipanggil kedalaman lubang aliran air tempatan dan saiz kawasan aliran. Pengalaman lepas telah menunjukkan kadar kedalaman lubang air yang meningkat di kawasan substruktur jambatan, menyebabkan kelemahan pada asas struktur dan menjelaskan jambatan. Pencegahan mengelakkan aliran air pada asas substruktur jambatan perlu bagi mengurangkan risiko keruntuhan. Formasi lubang aliran air pada substruktur jambatan dianggap kompleks dan fenomena ini melibatkan proses pengiraan kedalaman lubang air yang kurang tepat. Model fizikal mengekalkan perkakas utama sebagai pengukur saiz aliran lubang air pada substruktur jambatan. Dalam kajian ini, keberkesanan lima jenis kaedah yang dicadangkan, diuji dengan menggunakan sebuah model fizikal. Kaedah-kaedahnya adalah kaedah tumpang kolar, tumpang pelbagai kolar, tumpang berslot, cerucuk depan tumpang dan penggunaan 'riprap'. Model fizikal terdiri daripada saluran menyerong (5 m panjang, 76 mm lebar dan 250 mm tinggi) dengan pasir di atas tapak semaian (bersaiz nominal: 35 mm) dan sebuah tumpang berbentuk silinder yang diperbuat daripada kayu jati yang keras (berdiameter 16 mm). Sebuah kolar yang diperbuat daripada besi berdiameter 40 mm dilekatkan pada model tersebut. Dimensi sebuah slot 7 mm × 20 mm (lebar × dalam) dibuka di bahagian atas tumpang. Beberapa batang paku berdiameter 3 mm digunakan bagi menyerupai cerucuk. Pasir kasar yang digred, digunakan sebagai 'riprap'. Data yang diambil daripada model fizikal menunjukkan penggunaan tumpang pelbagai kolar memberikan 88% pengurangan pada kawasan aliran manakala pengurangan maksimum kawasan aliran berjarak dari 73% kepada 64%, bergantung kepada kadar aliran pada saluran. Pencegahan 'riprap' pada substruktur jambatan juga efektif dalam mengurangkan kawasan aliran maksimum dan pengurangan jarak dari 100% kepada 68%. Walau bagaimanapun, pengurangan kawasan aliran berjarak dari 100% kepada 83%. Pengurangan tersebut bergantung kepada kadar aliran.

ABSTRACT

Bridges constructed across streams with erodable beds are normally subjected to serious scouring during the flood at piers and abutment sites. As a result, scour holes will be formed at the bridge substructure. The scour hole can be described by its maximum vertical scour depth which is called local scour depth and by the size of its projected scour area. Experience has shown that progressive depth of scour holes at the site of bridge substructures could undermine the foundation and result in bridge failure. Protection against scouring for constructed bridges is necessary to minimize the risk of failure. The formation of the scour hole at the bridge substructure is considered as very complex and this phenomenon is so involved that only very limited success has been made to predict the size of the scour hole computationally. Physical model remains the principal tool employed for estimating the size of scour hole at the site of bridge substructure. In this study, the efficiency of five different proposed methods of protecting the bridge substructure were tested using a physical model. These methods are piers with collar, pier with multiple collars, pier with slot, piles in front of piers, and using riprap. The physical model comprises a tilted flume (5 m long, 76 mm wide and 250 mm high) with sand on its bed (nominal size = 0.35 mm) and a single circular cylindrical pier model which was made of hard teak wood (diameter =16 mm). A collar form steel with a diameter of 40 mm was attached to the pier model. A slot of a dimension 7 mm x 20 mm (width x depth) was opened in the upper side of the pier. Steel nails 3 mm in diameter each were used to simulate the piles. Coarse graded gravel was used as a riprap. Data collected from the physical model showed that using multiple collars around the pier can give 88% reduction in the scour area while the reduction in the maximum scour depth ranges from 73% to 64%, depending on the flow rate in the flume. It was observed that the riprap protection at the bridge substructure is also effective in reducing the maximum scour depth and reduction ranges from 100% to 68%. However, the reduction in the scour area ranges from 100% to 83%. The reduction was also dependent on the flow rate.

Keywords: Bridge substructure, scour hole, pier, protection, physical model

INTRODUCTION

Bridges constructed across streams with erodable beds are normally subjected to serious scouring at piers and abutment sites during floods. As a result, scour holes will form at the bridge substructure. The scour hole is a result of the interference of the bridge substructure with flowing water. This interference will result in a considerable increase in mean velocity of the flowing water in the stream section at the bridge site. Scouring vortex will be developed when the fast moving flow near the water surface (at the location of the maximum velocity in the channel section) strikes the blunt nose of the pier and is deflected towards the bed where the flow velocity is low. Portion of the deflected surface flow will dive downwards and outwards. *Fig. 1* shows this mechanism. This will act as a vacuum cleaner and suck the soil particles from area around the pier site. The scoured hole formed at the site of bridge substructure has a random geometrical shape. Normally, one simple or compound scour hole will form around one pier. Qadar (1981) proved through experimental work that the local scour at the pier site occurred due to the effect of vortices. The scour hole can be described by its maximum vertical scour depth which is called local scour depth and by the size of its projected scour area. The pattern of scour at the bridge substructure will depend on river

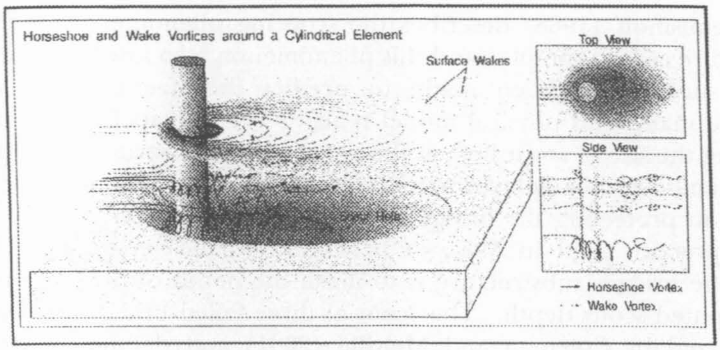

Fig.1: Three-dimensional schematic drawing showing the mechanism of scour hole forming at a site of bridge pier

discharge, bed slope, bed material, direction of flow, alignment of pier, pier's shape, pier's size and the number of piers used. Protection against scouring for constructed bridge is necessary to minimize the risk of failure.

Experience has shown that progressive depth of scour hole at the site of bridge substructure could undermine the foundation and result in bridge failure. Many bridges failed around the world because of extreme scour around pier and abutment, for example during the spring floods of 1987, 17 bridges in New York and New England, USA were damaged or destroyed by scour. In 1985, floods in Pennsylvania, Virginia, USA destroyed 73 bridges. A total number of 383 bridges failed in the USA, caused by catastrophic floods and 25% of these bridges failed due to the damage to the pier's foundation, while 72% failed due to damage to the abutment's foundation (Federal Highway 1991). Another extensive study conducted in 1978 indicated that the number of failed bridges due to the damage to the pier's foundation was almost equal to the number of failed bridges due to the damage to the abutment's foundation. Chiew (1992) studied the effect of making a slot with different dimensions in the pier body on the reduction in scour depth. A reduction of 20% was obtained when he used a pier with a slot having a width equal to a quarter of the pier diameter and a height greater than twice the pier diameter.

Many researchers proposed to use a collar with a pier as a method of protection against scour. However, the earliest proposal was made by Thomas (1967). In general, the use of collar with a bridge pier appears to be effective in reducing the scour depth at the pier site. However, when the bed material at the pier site which is protected by the collar is removed and transported by the flowing water, the pier beneath the collar will be exposed and under such a condition, it losses its effectiveness (Chiew 1992).

Chiew (1996) proposed a semiempirical method to size the stones for riprap protection. Chiew and Lim (2001) proposed a semiempirical equation to compute the maximum depth of the riprap degradation. Lauchlan and Melville (2001) proposed an empirical equation to estimate the size of riprap protection for a given size of the pier substructure.

Cheremisinoff (1988) describes the scouring phenomenon at the bridge substructure as very complex and this phenomenon is so involved that only very limited success has been made to predict the size of the scour hole computationally, and physical model remains the principal tool employed for estimating the size of scour hole at the site of bridge substructure. In this paper a physical model was employed to investigate the efficiency of different proposed methods in protecting the bridge substructure from scouring.

The practice used in Malaysia by Public Works Department (PWD), to protect the bridges substructure is to make the depth of piles cap more than the computed scour depth. The scour at three failed bridges in New Zealand was analyzed by Coleman and Melville (2001) and defined as degradation scour, bend scour and local scour. Finally, the foundation geometry also affects the dimension of the scour hole as mentioned by Melville and Raudkivi (1996).

MATERIAL AND METHODS

A tilted glass-sided flume (5 m long, 76 mm wide and 250 mm high) with erodable material was put in its bed. Sand with an average particle size of 0.35 mm was used in the flume bed as an erodable material. A hard teak wood pier model (16 mm diameter) was fixed firmly at the center of the flume cross section. The protection methods which were tested in this study included a collar around the pier, multiple collar, pier with slot, piles in front of the pier, and riprap around the pier. A 40 mm diameter circular steel plate with a thickness of 5 mm was used as collar with the pier model. A slot with a dimension 7 mm x 20 mm (width x height) was made in the pier below the water surface. Long nails of 3 mm diameter were used to simulate the piles and were located in front of the location pier model. Course graded gravel was used as a riprap. For a measured flow rate, the size of the scour hole was measured with and without protection. The data collected is shown in Table 1 while *Fig. 2* shows the profiles of various protection methods used in the experiments.

RESULTS AND DISCUSSION

The simulation of scouring at bridge substructure was conducted by using a single circular cylindrical pier model (diameter =16 mm) which was fixed in a glass sided flume (5 m long, 76 mm bed width, and 250 mm total depth) with a sand bed (d_{50}= 0.35 mm). The range of the flow rate which was used to run the experiments was between 0.5 to 1.5 L/s. Five different methods of protecting the bridge substructure were tested in the present study. These methods are collars around the pier, multiple collars around the pier, piers with slots, piles in front of piers, and using riprap. *Fig. 2* shows various protection methods used in the experiments. The scour hole dimension was recorded with time and it was observed that after 1 h there was no appreciable change to this dimension. Based on the collected data, a comparison is made between the various studied methods of protection (Table 2, *Fig. 3* and *Fig. 4*).

TABLE 1
Data collected from the experiments

Description	Flow Rate (L/S)	Projected Area of Scour (Cm^2)	Maximum Depth of local Scour (mm)	Remarks
Pier model without protection	0.5	39.6	26	
Protection with collar	0.5	30	18	
Protection with multiple collars	0.5	4.9	7	The measurements were taken one hour from the commencement of each run.
Protection with slot	0.5	33	20	
Protection using piles in front of pier	0.5	35	24	
Protection using riprap	0.5	0	0	
Pier model without protection	1.0	40.7	28	
Protection with collar	1.0	34	20	
Protection with multiple collars	1.0	4.90	10	
Protection with slot	1.0	36	22	
Protection using piles in front of pier	1.0	37	26	
Protection using riprap	1.0	3.8	3	
Pier model without protection	1.5	40.7	28	
Protection with collar	1.5	34	22	
Protection with multiple collars	1.5	4.90	10	
Protection with slot	1.5	36	23	
Protection using piles in front of pier	1.5	37	26	
Protection using riprap	1.5	7.06	9	

The results showed that the method of riprap protection and the method of protection using multiple collars are the best among the other studied methods of protecting bridge substructure. Using riprap method, a reduction of 100%, 90% and 83% were recorded in the scour area for flow rates of 0.5 L/s, 1 L/s and 1.5 L/s respectively. However, the reductions in the scour depth were 100%, 89% and 68% for the flow rates of 0.5 L/s, 1 L/s, and 1.5 L/s respectively. A constant reduction of 88% was observed in the scour area and for all values of flow rates when a multiple collar protection method was used. However, reductions in the scour depth were 73% and 64% for flow rates of 0.5 L/s and 1 L/s respectively. A reduction of 64% in scour depth was observed when the flow rate was increased to 1.5 L/s.

In the study, with a slot of dimensions of 0.44D X 1.25D (width x depth) located at the top part of the pier model and 10 mm below the flowing water surface, the recorded reduction in the maximum scour depth using this type of protection ranges from 23% to 18% for different values of flow rates. In the present study a collar with a diameter equal 2.5 times the pier diameter (2.5D) was used and an average reduction of 20% was recorded.

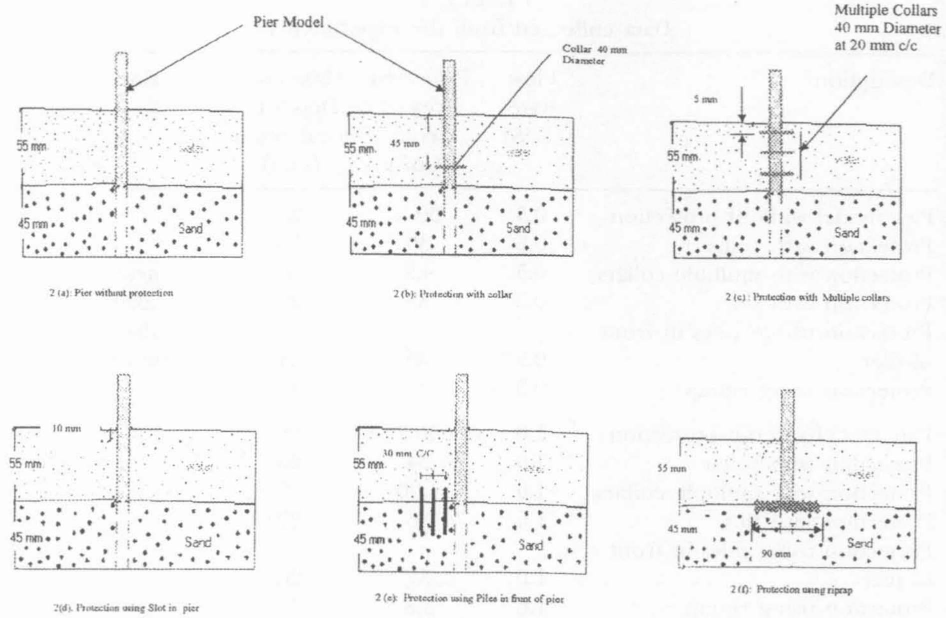

Fig. 2: Various methods of protecting bridge substructure from local scouring

TABLE 2
Reduction in maximum scour depth and area of scour at the pier model

Method of Protection	Flow Rate (L/s)	Reduction in Scour Depth (%)	Reduction in Scour Area (%)
Collar around the pier		30	24
Multiple collars around the pier		73	88
Slot at the top of the pier	0.5	23	17
Piles in front of the pier		8	12
Riprap around the pier		100	100
Collar around the pier		29	16
Multiple collars around the pier		64	88
Slot at the top of the pier	1	21	12
Piles in front of the pier		7	9
Riprap around the pier		89	90
Collar around the pier		21	16
Multiple collars around the pier		64	88
Slot at the top of the pier	1.5	18	12
Piles in front of the pier		7	9
Riprap around the pier		68	83

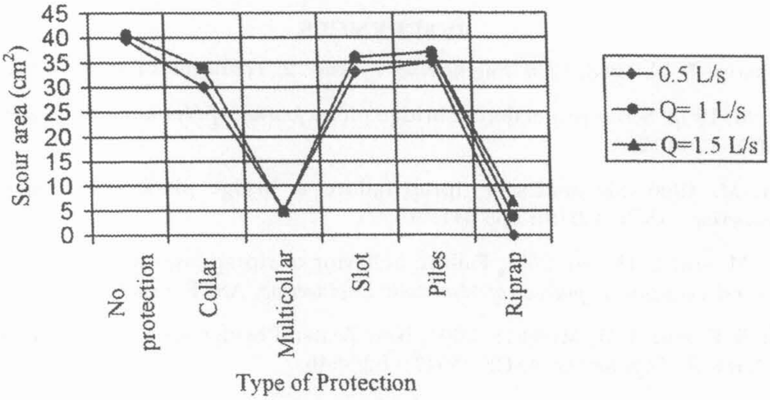

Fig. 3: Scour area around the pier model

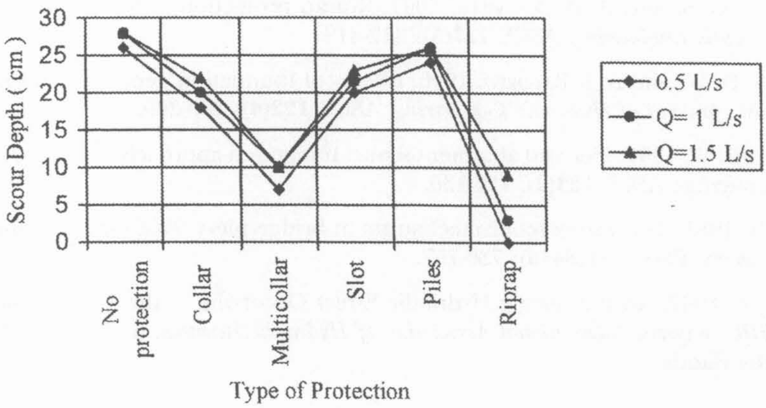

Fig. 4: Maximum scour depth at the site of pier model

CONCLUSIONS

Among the five methods tested to protect the pier model, it was found that using multiple collars around the pier can give 88% reduction in the scour area recorded before this protection. The reduction in the maximum scour depth ranges from 73% to 64% depending on the flow rate of the flume. It was observed that the riprap protection at the bridge substructure was also effective in reducing the maximum scour depth, a reduction from 100% to 68% was observed depending on the flow rate. The reduction in the scour area ranged from 100% to 83% depending also on the flow rate.

The collected data from the physical model showed that the method of riprap gives best protection against scour at flow rates of 0.5 L/s and 1 L/s while at the flow rate of 1.5 L/s, the method of multiple collar and method of riprap both have almost the same effectiveness in scour protection.

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