Effects of Bridge Pier Friction on Flow Reduction in a Navigation Channel

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Abstract- **The Rambler Channel is an 8-kilometer long navigation waterway. A number of bridges are built on piers over the channel; the presence of bridge piers changes the nearby flow regime and induces friction in the ambient tidal currents. This paper presents a hydrodynamic model to study the effects of bridge pier friction on flow reduction in the Rambler Channel. Energy losses due to the bridge piers are estimated by introducing additional quadratic friction terms into momentum equations. Comparisons of the tidal flow patterns, changes in flow rate through the channel, and flow paths in the surface water layer by drogue tracking simulations for situations with and without bridges are presented.**

Keywords- Pier Friction; Flow Reduction; Hydrodynamic Model; Drogue Tracking

I. INTRODUCTION

The Rambler Channel is located to the northwest of Hong Kong Island, separating the Kowloon Peninsula and Tsing Yi Island. The channel is a busy waterway for use by various commercial vessels. In recent decades, reclamation was conducted along the southern section of the channel to form new land for container port facilities. The width of the channel now varies from 1 km to less than 300 m, and the length of the channel is approximately 8 km.

There are ten water control zones in Hong Kong; the Rambler Channel is located in the Western Buffer Water Control Zone. A set of water quality objectives specifying permissible concentrations of pollutants in marine water is applied in this water control zone. The water near the southern end of the channel is influenced by discharge from Stonecutters Island Sewage Treatment Works, which employs a chemically enhanced primary treatment process with relatively high *E. coli* levels (110 – 3,000 count/100mL in 2013). Polluted discharge from two box culverts near the middle of the channel causes water pollution. Dispersion of pollutants is highly dependent on the prevailing tidal movement in the channel.

II. THE BRIDGES

There are seven bridges which cross the channel: Ting Kau Bridge, Tsing Yi North Bridge, Tsing Lai Bridge, Cheung Tsing Bridge, Tsing Yi South Bridge, Kwai Tsing Bridge and Stonecutters Bridge. Figure 1 shows the locations of the seven bridges. Amongst all these bridges, Tsing Lai Bridge is the only rail bridge for Mass Transit Railway and Airport Express; all of the others are road bridges. The two most recently completed bridges, including Stonecutters Bridge (2009) and Ting Kau Bridge (1998) are cable-stayed bridges. Stonecutters Bridge is 1,600 m in length, and Ting Kau Bridge is 1,177 m in length. Tsing Yi North Bridge opened in 1987 and is a pre-stressed cantilever bridge, which spans 160 m across the channel. Tsing Yi South Bridge opened in 1974 and is approximately 610 m wide. Kwai Tsing Bridge is a duplication of Tsing Yi South Bridge and was built in parallel, reducing the traffic load on the Tsing Yi South Bridge. Cheung Tsing Bridge is located to the immediate north of Tsing Yi South Bridge, connecting Cheung Tsing Tunnel and Tsing Kwai Highway. Tsing Lai Bridge was completed in 1997 and has a length of 1.1 km, providing a railway link to Tsing Yi Island and the Hong Kong international airport at Chek Lap Kok.

All the bridges are supported by bridge piers; both caissons and reclaimed islands were used as foundations for the bridge piers. Stonecutters Bridge is one of the longest cable-stayed bridges in the world and its bridge piers, which support the deck over Rambler Channel, are constructed on both sides of the reclaimed land. The bridge itself does not cause disturbance to the tidal flow in the channel. However, the bridge piers of the other bridges are constructed in the channel, blocking the movement of tidal flow. In this study, a hydrodynamic model is used to investigate the influence of the bridge piers of individual and groups of bridges on the tidal exchange in the Rambler Channel. Energy losses due to bridge piers are estimated by introducing quadratic loss terms into momentum equations. This paper presents a prediction model to investigate the changes in tidal flow rate, flow pattern and the movement of surface water in the channel.

III. MODEL SETUP

A. Hydrodynamic Model

The dredging of marine sediments to deepen the seabed level to provide adequate water depth for container vessels and reclamation to provide new land were conducted on the southern section of Rambler Channel. There was no identified area of

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high ecological value within the channel. The existing beneficial uses of the channel are the bathing beaches on the northern part, and cooling water intakes along its length.

The Civil Engineering and Development Department [1] studied the feasible dredging scenarios which would not cause adverse impact to water quality in order to increase the water depth for Kwai Tsing container basin and its approach channel. A numerical model was used to conduct both hydrodynamic and water quality simulations of the study area, which encompassed the Rambler Channel and adjacent water bodies. Morelissen et al. [2] generated a tidal stream atlas of the stratified tidal flows near Stonecutters Bridge using a three-dimensional numerical model with horizontal large eddy simulation. Complex flow patterns such as tidally driven eddies and recirculations were included to predict water levels and currents in the channel. Pun et al. [3] established a three-dimensional hydrodynamic regional model to study water movement and dispersion characteristics of pollutants in the Rambler Channel. The regional model is used to provide open boundary conditions for the present study to simulate tidal exchange through the channel for situations with and without the effects of bridge piers. The present model has been developed using the Delft3D-FLOW module of the Delft3D model suite. The model grid is refined to increase the resolution in the channel, and there are a total of 3,003 grid cells. The sizes of grid cells within the channel vary from approximately 60 m in the inner portion of the channel to 330 m at the channel entrances. The water column is divided into ten layers to allow for vertical variations in tidal speed, direction, temperature and salinity. The modelling period is between June and July of 2012 and covering a total of 22 days, including a complete spring-neap tidal cycle during the wet season. The first several days of the simulation are used for model spin up. A one-minute time step is adopted to avoid instability in the model simulation.

B. Bridge Pier Friction

The general schematization of the geometry in a numerical model generates various grid sizes in order to cover the entire model domain. The dimension of a bridge pier is generally much smaller than the smallest grid size of the model. One method to model the local resistance of bridge piers is to add quadratic friction terms in both the *x*- and *y*-directions of the momentum equations to approximate the energy losses generated by the bridge piers. Farraday and Charlton [4] established the relationship between flow resistance and the presence of bridge piers. A quadratic friction term at the bridge pier location can be added to the momentum equation to estimate the energy loss. This method requires the determination of a friction loss coefficient. With reference to the Delft3D-Flow User Manual [5], the quadratic friction terms in the *u*- and *v*-coordinate directions (M_u and M_v) of the momentum equations (in m/s^2) can be expressed as:

$$M_u = \frac{c_{Lu}}{\Delta x} u\sqrt{u^2+v^2} \qquad (1)$$

$$M_v = \frac{c_{Lv}}{\Delta y} v\sqrt{u^2+v^2} \qquad (2)$$

where c_{Lu} and c_{Lv} are the energy loss coefficients in the *u*- and *v*-coordinate directions, respectively; *u* and *v* are the velocity components (m/s); and Δ_x and Δ_y are the grid sizes (m) in the *u*- and *v*-coordinate directions, respectively. Multiplication of Eq. (1) and Eq. (2) by the mass of a control volume provides the corresponding drag forces in the *u*- and *v*-coordinate directions.

The loss coefficient for piles or piers of different dimensions within a grid cell is calculated using the sum of all of the pile diameters. The following mathematical expressions represent the loss coefficients in the *x*- and *y*-directions, respectively:

$$c_{Lu} = \frac{(\Sigma nD) c_d a^2}{2\Delta y} \qquad (3)$$

$$c_{Lv} = \frac{(\Sigma nD) c_d a^2}{2\Delta x} \qquad (4)$$

where *n* is the number of piers in the grid cell; C_d is the drag coefficient, which is approximately equal to one for a cylinder in the tidal flow; *D* is the diameter of the bridge pier (m); Δ_x and Δ_y are the grid distances (m) in the *u*- and *v*-directions, respectively; and the parameter *a* (= $A_t / A_e = A_t / (A_t - nD)$) is the ratio of the total cross-sectional area (A_t) to the effective cross-sectional area A_e (= $A_t - nD$).

Fig. 2 presents the configurations and approximate dimensions of the bridge piers of different bridges. Table 1 summarizes the calculated loss coefficients corresponding to the dominant movement direction of the tidal flows. Tsing Yi South Bridge and Kwai Tsing Bridge are located directly next to one another. The bridge piers are considered as a single unit in calculating the loss coefficient. The bridge piers of Stonecutters Bridge are not located in the channel. Effects due to the bridge piers of this bridge are not considered in the hydrodynamic simulation of this study.

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TABLE 1. LOSS COEFFICIENTS OF BRIDGES.

Bridge	Loss Coefficient
Tsing Yi North Bridge	0.600
Tsing Lai Bridge	0.297
Cheung Tsing Bridge	0.187
Tsing Yi South Bridge and Kwai Tsing Bridge	0.298
Ting Kau Bridge	0.484

IV. MODEL RESULTS AND DISCUSSION

A. Model Verification

Verification of the model in the present study was accomplished by comparing the model results of tide levels, current speeds, directions, salinities and temperatures at locations inside and outside of the channel with those generated by the well-verified regional model established by Pun et al. [3]. The performance of the present model with a higher grid resolution in Rambler Channel was comparable to that of the regional model.

In addition, the predicted tide levels were also compared to the tide data recorded at Kwai Chung tide station. Figure 3 shows that the model prediction matches reasonably well with the field data, but that the predicted high tide levels immediately after the preceding ebb tides are slightly lower at spring tide. Tidal current measurements were conducted at a location adjacent to Tsing Yi North Bridge in June 2012. A propeller current meter was used to measure tidal current speeds at a depth of three meters below the water surface. The duration of measurement was approximately two hours. As demonstrated in Figure 4, the model was able to accurately reproduce the current magnitudes during the period of flow measurement.

B. Hydrodynamic Results

Figures 5 and 6 present velocity vector plots of tidal flows for both flood and ebb tides. During flood tide, tidal flows enter the channel from the southern entrance, where Stonecutters Bridge is located, and leave the channel through the northern entrance near Ting Kau Bridge; the tidal movement reverses during ebb tide. By analyzing the accumulated flow through the channel, there is a net volumetric flux from north to south. Therefore, it can be concluded that a higher volumetric flux associated with ebb tides dominates the tidal movement in the channel. The figures also show comparisons between the velocity vectors for situations with and without the effects of the bridge piers. The magnitudes of tidal current are generally higher in the absence of bridges, particularly at the locations where the bridge piers are present. This phenomenon was also observed at the inner corner of the channel. The bridge piers appear to alter the local flow directions, as can be observed in the region near Tsing Yi North Bridge.

Drogue tracking was conducted as part of the hydrodynamic simulations to examine how the bridge piers affect the path of the surface layer tidal flow. Figures 7 and 8 graphically present the predicted flow paths of a drogue, which was released during flood tide in situations with and without bridges. The recovery time was 29 hours after release of the drogue. The time interval between two consecutive dots is one hour, as shown in the figures. The point of release of the drogue is at the outlet of a storm water box culvert. For many years, the storm water discharged from this box culvert contained organic and inorganic contaminants. The selection of this point for release of the drogue provides an indication of whether such contaminants would be trapped or carried out of the channel by tidal flows. For the situation in which all bridges are present, the drogue circulated in the inner part of the channel and was eventually trapped in the channel. In the absence of all bridges, the drogue moved to the southern entrance of the channel after 26 hours and was eventually carried out of the channel by the flows during ebb tide. The model results clearly demonstrate that the bridge piers reduce the tidal flow speeds in the channel and may limit the removal of contaminants through tidal exchanges.

The model runs address the bridge pier effects from all bridges together, as well as the effects of individual bridges. Figure 9 presents the percentage reduction in tidal flow rate of all examined situations. As shown in the figure, the cumulative effects of Tsing Yi North Bridge, Tsing Lai Bridge, Cheung Tsing Bridge, Tsing Yi South Bridge (and Kwai Tsing Bridge), and Ting Kau Bridge contribute to a 40.8% reduction in tidal flow rate through the channel over a spring-neap cycle.

Individually, Tsing Yi North Bridge causes the highest reduction in tidal flow rate at 28.2%. The bridge is located at the narrowest part of Rambler Channel with a width of approximately 284 m. The two bridge piers with a width of 16 m each reduce the channel width by 11.3%; together with two structures (each 8 m wide x 28 m long) for the protection of bridge piers against ship collision, the results in a higher reduction of the tidal flow rate.

Cheung Tsing Bridge alone generates a tidal flow percentage reduction of 19.3%. This situation is similar to that of Tsing Yi North Bridge as the width of the channel section is only approximately 292 m. There are three bridge piers in the channel to support Cheung Tsing Bridge. The width of each pier is approximately 10 m, leading to a channel width reduction of 10% at this location. Tsing Yi South Bridge is supported by three circular piles, each with a diameter of 14 m. Kwai Tsing Bridge is

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supported by three rectangular-shaped piers with dimensions of 16 m wide x 28 m long. Together, the piers of these two bridges contribute to a 16.1% reduction in tidal flow rate. Tsing Lai Bridge is supported by three irregular hexagon-shaped bridge pier foundations in the channel. There are another three bridge piers: one on the breakwater of the Rambler Channel Typhoon Shelter, and two inside the typhoon shelter. Therefore, only three piers in the channel are included in the model simulation. Different from the other bridges, the alignment of Tsing Lai Bridge makes an angle of approximately 45º to the center line of the channel. The total percentage reduction in the tidal flow rate of Tsing Lai Bridge is 11.3%.

The reclaimed island to support the central tower of Ting Kau Bridge is the largest single obstacle in the channel when compared to the sizes of other bridge piers. This island alone, however, causes a decreased reduction rate of 0.2%. This may be related to the location of the reclaimed island, which is situated at the northern entrance of the channel with a width of 820 m. The ratio of the width of the reclaimed island (~ 80 m) to the channel width is approximately 10%. However, water depths in this region vary from approximately 10 m to 19 m, and are much deeper than the other regions with bridges. For this situation, the presence of a physical barrier in a large water body appears to not cause a significant reduction in tidal flow rate.

V. CONCLUSIONS

A hydrodynamic model was applied to study the influence of the bridge piers of six bridges on the tidal exchange in Rambler Channel. The energy losses due to the bridge pier resistance are estimated by introducing additional quadratic friction terms in the *x*- and *y*-directions of the momentum equations. The model prediction has shown that all the bridges combined contribute to a significant reduction in tidal flow rate, limiting the tidal exchange in the channel. Amongst all the bridges, Tsing Yi North Bridge is the greatest contributor to the reduction in tidal flow rate. The tidal flow path at the surface water layer may also be modified by the bridge piers, causing negative impact to the removal of contaminants from the channel by tidal flows.

In the present study, the sizes of model grid cells are much larger than the sizes of the actual bridge piers. Quadratic friction terms are introduced into momentum equations of the model to produce a reasonable estimate of the reduction in flow rate through the channel. Refinement of the model grid cells to more comparable sizes may improve the accuracy of the model prediction. However, a refined grid model must resolve the problems of complex model grid layout configuration and the increase in computational time for model simulation. Further study in this area is required to address the computational problems.

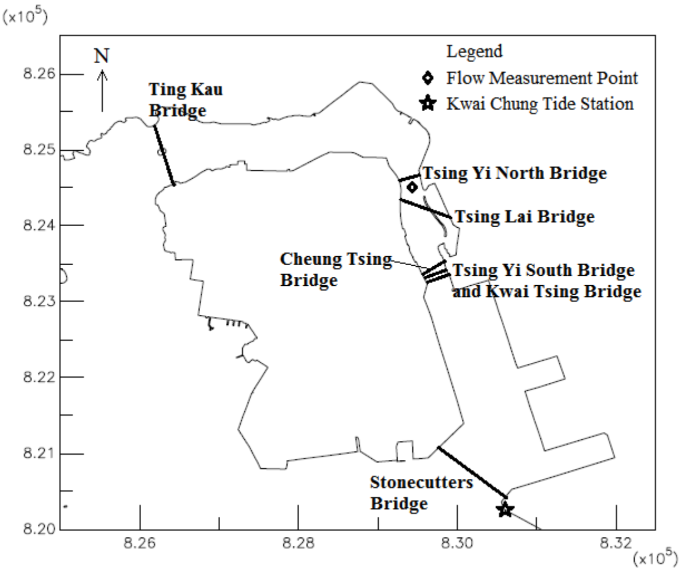

Fig. ,1 Locations of Bridges in Rambler Channel.

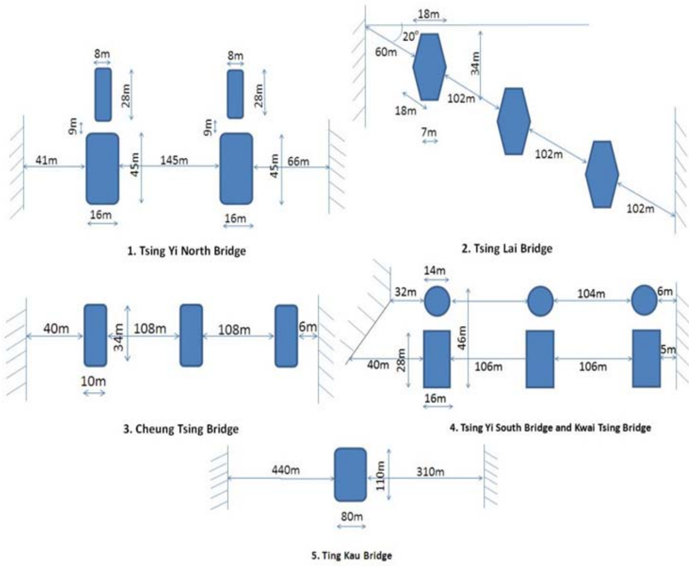

Fig. 2. Configurations and Dimensions of Bridge Piers.

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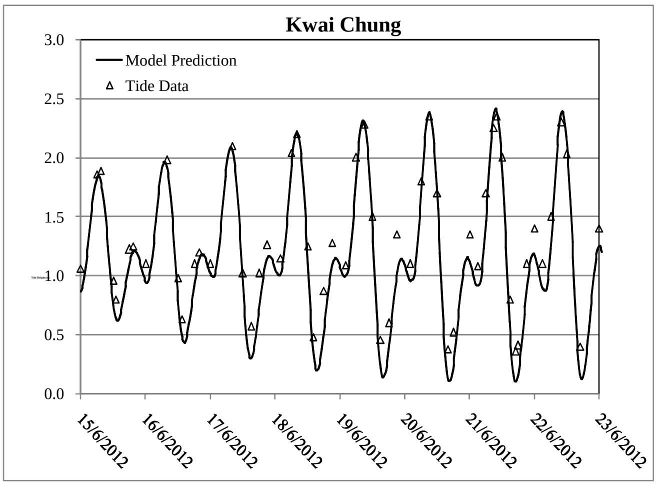

Fig. 3. Comparison of Tide Levels.

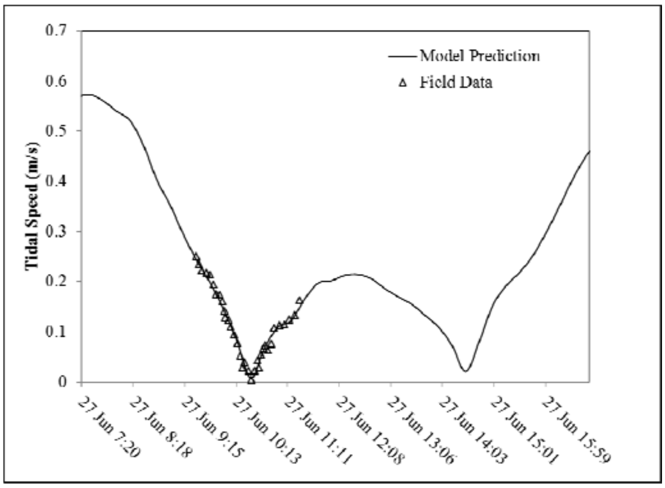

Fig. 4. Comparison of Tidal Speeds.

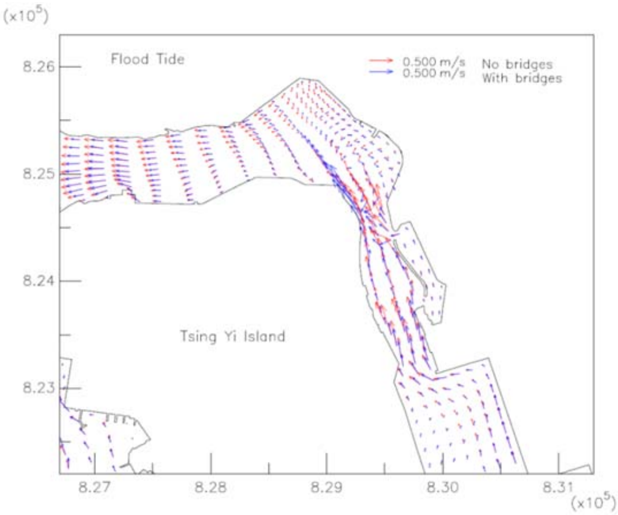

Fig. 5. Velocity Vector Plots for Situations With and Without Bridges – Flood Tide.

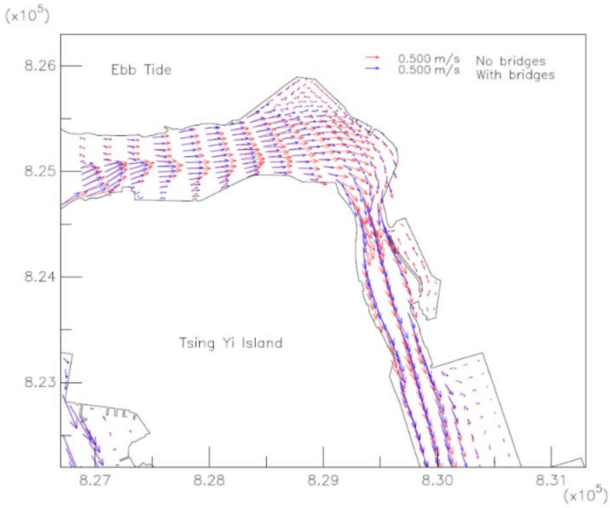

Fig. 6. Velocity Vector Plots for Situations With and Without Bridges – Ebb Tide.

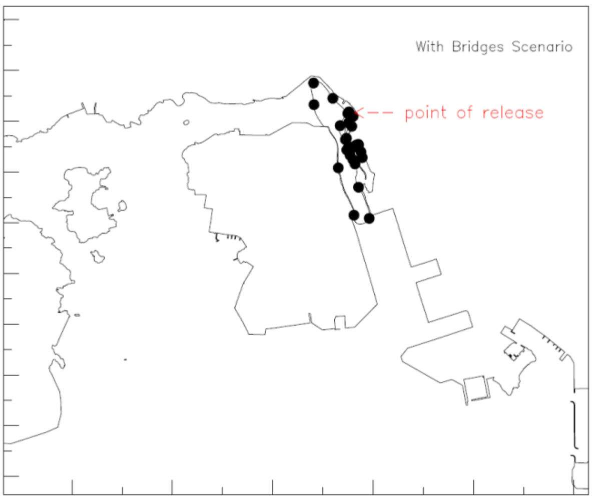

Fig. 7. Drogue Tracking with Bridges.

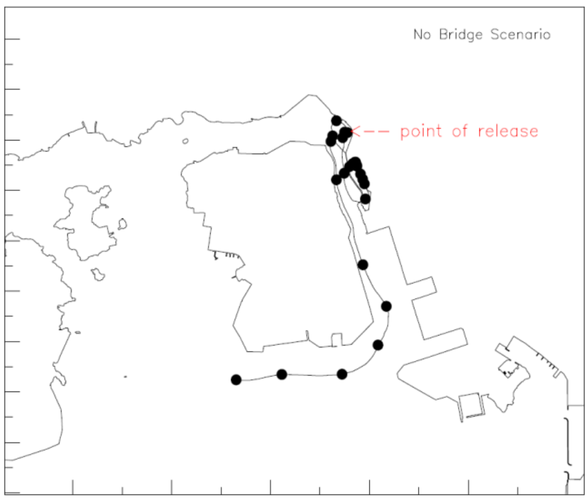

Fig. 8. Drogue Tracking without Bridges.

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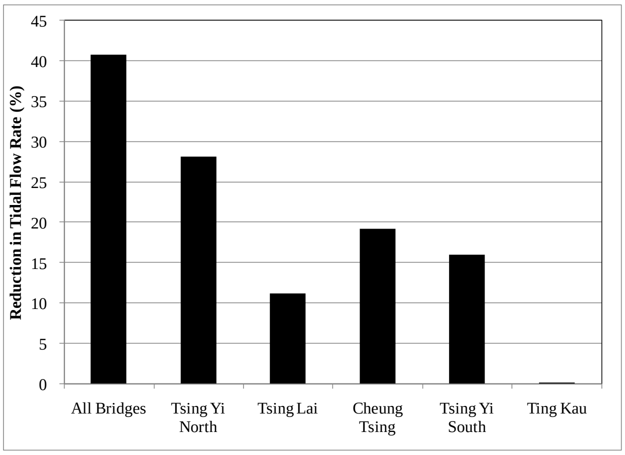

Fig. 9. Percentage Reduction in Tidal Flow Rate.

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