APPENDIX 9D3

# Calculation of Loss Coefficients for Bridge Piers

# APPENDIX D3

# CALCULATION OF LOSS COEFFICIENTS FOR BRIDGE PIERS

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**FIGURES**

# D3-1 INTRODUCTION

## D3-1.1 Background

D3-1.1.1 The Mainland section of Hong Kong-Zhuhai-Macao-Bridge (HZMB), the Hong Kong Link Road (HKLR) and the southern marine viaduct for the Tuen Mun Chek Lap Kok Link (TM-CLKL) will be supported on piles which could impact on tidal flows to some extent as a result of the reduction in flow area and additional friction losses.

D3-1.1.2 The typical dimensions associated with the bridge piers and piles are of the order of 1m-2m and much smaller than the resolution of the model grid (~50m-100m). In order to allow for the effects of the bridge piers on tidal flows, therefore, the Delft3D-Flow model allows for the addition of a quadratic friction term in the momentum equations which is applied in each model grid cell containing bridge piers (Reference 1).

D3-1.1.3 This approach to simulating the impact of bridge piers on tidal flows has now been employed in several studies in Hong Kong including the feasibility study for additional cross border links (Reference 1) and the loss term takes the form:

$$\text{Loss term}_{,u} = \{ C_{loss,u}\, U\, |\langle U\rangle| \} / \{ \Delta x \}\ [m/s^2]$$
$$\text{Loss term}_{,v} = \{ C_{loss,v}\, V\, |\langle U\rangle| \} / \{ \Delta y \}\ [m/s^2] \qquad \text{(Eq 1)}$$

Where:

$\langle U\rangle$ = Velocity vector (u,v) [m/s]
$|\langle U\rangle|$ = Magnitude of the velocity vector $\sqrt{(u^2+v^2)}$ [m/s]
$\Delta x\ \Delta y$ = Grid distances in the u and v coordinate directions [m]
$C_{loss,u}$ = Loss coefficients in the u coordinate direction
$C_{loss,v}$ = Loss coefficients in the v coordinate direction

D3-1.1.4 This additional friction term influences the horizontal flow distribution in each model layer according to the water speeds in each model layer and so indirectly affects the vertical turbulent exchange as well.

D3-1.1.5 The piles also reduce the flow area which will result in local accelerations in the water speeds. This effect is taken into account by calculating the effective flow area, $A_{eff}$, given by the original total flow area , $A_{tot}$, minus the area blocked by the piles and using the ratio of the original total flow area to the effective area to obtain the increased approach velocity $\langle U_{eff}\rangle$:

$A_{eff}$ = $A_{tot}$ – area blocked by piles as seen by the flow
$a$ = $A_{tot}/A_{eff}$
$\langle U_{eff}\rangle$ = $a \times \langle U\rangle$

D3-1.1.6 The forces due to the flow on a vertical section $\Delta z$ of one pile are described by:

$$F_u = \tfrac{1}{2} C_d\, \rho\, D\, u_{eff}\, |\langle U_{eff}\rangle|\, \Delta z$$
$$F_v = \tfrac{1}{2} C_d\, \rho\, D\, v_{eff}\, |\langle U_{eff}\rangle|\, \Delta z$$

Where:

$F_u$ the drag force in u-co-ordinate direction on a pile [N];
$F_v$ the drag force in v-co-ordinate direction on a pile [N];
$C_d$ the drag coefficient (≈1 in the case of a cylinder in a tidal regime);
$\rho$ the density of water [kg/m$^3$];
$<U_{eff}>$ the effective approach velocity vector $(u_{eff}, v_{eff})$ [m/s];
$|<U_{eff}>|$ magnitude of the effective approach velocity $\sqrt{(u_{eff}^2 + v_{eff}^2)}$ [m/s];
D the diameter of a pile [m]; and
$\Delta z$ the length of the vertical section [m].

D3-1.1.7 For several piles in the same model grid cell, assuming the worst case where the piles under consideration are not in the shadow of each other, results in a total force on the flow equal to:

$$F_{tot,u} = ½\, n \times C_d\, \rho\, D\, u_{eff}\, |<U_{eff}>|\, \Delta z$$
$$F_{tot,v} = ½\, n \times C_d\, \rho\, D\, v_{eff}\, |<U_{eff}>|\, \Delta z.$$

Where:

n = The number of piles in the control grid cell;
$F_{tot,u}$, $F_{tot,v}$ = The total force in the (u,v) coordinate directions [N]

D3-1.1.8 Division of the forces by the mass in the control volume (=$\rho\ \Delta x\ \Delta y\ \Delta z$) yields the following term in the u-momentum equation and the v-momentum equation respectively:

$$\text{Loss term}_{,u} = \{½\, n \times C_d\, D\, u_{eff}\, |<U_{eff}>|\ \} / \{\ \Delta x \times \Delta y\ \}$$
$$\text{Loss term}_{,v} = \{½\, n \times C_d\, D\, v_{eff}\, |<U_{eff}>|\ \} / \{\ \Delta x \times \Delta y\ \} \qquad \text{(Eq 2)}$$

D3-1.1.9 Comparing equations (1) and (2) allows the loss coefficients to be calculated in terms of the pile dimensions and the model grid size as:

$$C_{loss,u} = \{½\, n \times C_d\, D \times a^2\ \} / \{\ \Delta y\ \}$$
$$C_{loss,v} = \{½\, n \times C_d\, D \times a^2\ \} / \{\ \Delta x\ \}$$

D3-1.1.10 Where piles of different dimensions are contained within a model cell, the loss coefficients are calculated using the sum of all the pile diameters and the loss coefficients can be written as:

$$C_{loss,u} = \frac{1}{2}\left(\sum n * D\right) * C_d * a^2 / \Delta y$$
$$C_{loss,v} = \frac{1}{2}\left(\sum n * D\right) * C_d * a^2 / \Delta x$$

D3-1.1.11 Using these expressions, the loss coefficients, for each type of bridge pier have been calculated and are presented below.

## D3-2 TUEN MUN CHEK LAP KOK LINK BRIDGE PIERS

### D3-2.1 Bridge Pier Layout

D3-2.1.1 The bridge pier (**Figure 1**) consists of six piles 1.8m in diameter with a further eight piles 0.6m in diameter to support the ship protection dolphins.

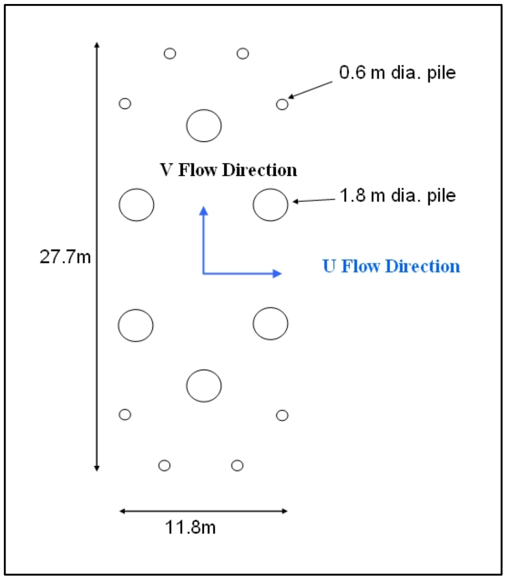


**Figure 1 TM-CLKL Bridge Pier Arrangement**

D3-2.1.2 The loss coefficients depend on the model grid size and, to the east of Chek Lap Kok, two representative grid sizes of 70m and 100m have been considered.

### D3-2.2 70m Model Grid

D3-2.2.1 For a 70m model grid and a 60m pier spacing, some grid cells may contain a single pier or almost two piers (two piers less 1.8m width of ship protection island). However, if the grid cell contains the major part of a second pier, it will be assumed that both piers lie in the same cell and no part of the pier lies in the adjacent grid cell. The calculations of the loss coefficients for the cases of a single pier and two piers in a single cell are detailed below.

***Single Pier : V Flow Direction***

D3-2.2.2 As ‘seen’ by the flow, there will be a reduction in cross-sectional width due to 3 piles of 1.8m diameter and 2 piles of 0.6m diameter, and the ratio of the total area to the effective area, a, will be:

$$a = 70/(70-3*1.8-2*0.6)$$
$$= 1.10$$

D3-2.2.3 Each pier will consist of 6 piles 1.8m diameter exposed to the flow and eight piles of 0.6m diameter. The loss coefficient, $C_{loss,v}$ for this pier will be:

$$
\begin{aligned}
C_{loss,v} &= \frac{1}{2}\left(\sum n * D\right) * C_d * a^2 / \Delta x \\
&= \frac{1}{2}(6 * 1.8 + 8 * 0.6) * 1 * 1.10^2 / 70 \\
&= 0.14
\end{aligned}
$$

***Single Pier : U Flow Direction***

D3-2.2.4 For flows perpendicular to the main axis of the pier, the flow area will be reduced by 4 piles of 1.8m diameter and 4 piles 0.6m diameter. The ratio of the total area to the effective area, a, will be:

a = 70/(70-4*1.8-4*0.6)
= 1.16

D3-2.2.5 Each pier will consist of 6 piles 1.8m diameter exposed to the flow and eight piles 0f 0.6m diameter. The loss coefficient for this pier will be:

$$
\begin{aligned}
C_{loss,u} &= \frac{1}{2}\left(\sum n * D\right) * C_d * a^2 / \Delta y \\
&= \frac{1}{2}(6 * 1.8 + 8 * 0.6) * 1 * 1.16^2 / 70 \\
&= 0.15
\end{aligned}
$$

***Two Piers: V Flow Direction***

D3-2.2.6 The ratio of the total flow area to the effective flow area is used to allow for the local acceleration in water speed due to local reduction in flow area caused by the bridge pier. However, if two bridge piers are separated by 60m or more and are aligned along the flow direction, the reduction in flow area would be overestimated if the width of both piers is used to calculate this area ratio. However, if the piers are not aligned with the main flow direction, the magnitude of the overestimate should reduce. In order to ensure that the loss coefficients are not underestimated, therefore, it will be assumed the flow width is reduced by the maximum width of two bridge piers.

D3-2.2.7 If the grid cell contains 2 piers, the area ratio calculation gives:

a = 70/(70-2*(3*1.8-2*0.6))
= 1.23

D3-2.2.8 Two piers will consist of 12 piles 1.8m diameter exposed to the flow and sixteen piles 0.6m diameter. The loss coefficient for this pier will be:

$$
\begin{aligned}
C_{loss,v} &= \frac{1}{2}\left(\sum n * D\right) * C_d * a^2 / \Delta x \\
&= \frac{1}{2}(12 * 1.8 + 16 * 0.6) * 1 * 1.23^2 / 70 \\
&= 0.34
\end{aligned}
$$

*Two Piers: U Flow Direction*

D3-2.2.9 If the grid cell contains 2 piers, the area ratio calculation gives:

a = 70/(70-2*(4*1.8 – 4*0.6))
= 1.38

D3-2.2.10 Each pier will consist of 4 piles 1.8m diameter exposed to the flow and one pile with an effective diameter of 20m. The loss coefficient for this pier will be:

$$
\begin{aligned}
C_{loss,u} &= \frac{1}{2}\left(\sum n*D\right)*C_d*a^2/\Delta y \\
&= \frac{1}{2}(2*6*1.8+2*8*0.6)*1*1.38^2/70 \\
&= 0.42
\end{aligned}
$$

## D3-2.3 100m Grid

*V Flow Direction*

D3-2.3.1 For a grid size of 100m, each cell will have 2 piers and the ratio of the total area to the effective area will be:

a = 100/(100-2*(3*1.8 – 2*0.6)))
= 1.15

D3-2.3.2 The loss coefficient will then be:

$$
\begin{aligned}
C_{loss,v} &= \frac{1}{2}\left(\sum n*D\right)*C_d*a^2/\Delta x \\
&= \frac{1}{2}(2*6*1.8+2*8*0.6)*1*1.15^2/100 \\
&= 0.21
\end{aligned}
$$

*U Flow Direction*

D3-2.3.3 Similarly, in the U flow direction the ratio of the total area to the effective area will be:

a = 100/(100-2*(4*1.8 – 4*0.6))
= 1.24

D3-2.3.4 The loss coefficient will then be:

$$
\begin{aligned}
C_{loss,u} &= \frac{1}{2}\left(\sum n*D\right)*C_d*a^2/\Delta y \\
&= \frac{1}{2}(2*6*1.8+2*8*0.6)*1*1.24^2/100 \\
&= 0.24
\end{aligned}
$$

# D3-3 HONG KONG LINK ROAD

## D3-3.1 Section A-A

D3-3.1.1 The HKLR will include bridge piers in the sea immediately to the west of the Sea Channel, as shown as Section A-A **Figure 2** and detailed in **Figure 3** below.

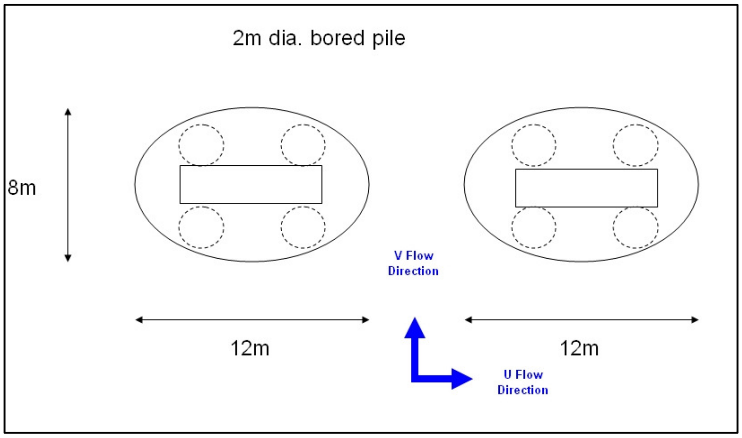


**Figure 3 Hong Kong Link Road Marine Bridge Piers Outside the Sea Channel**

D3-3.1.2 It is assumed that the flow directions are as indicated in **Figure 3**. At high water, the pile caps may be partially submerged by up to ~1m which would result in a small reduction in the flow area in the model's surface layer and introduce some additional drag in the surface layer. The pile caps may also be clear of the water at other times during the tidal cycle.

D3-3.1.3 In order to model this situation, the drag coefficients for the surface layer would need to be time dependent and linked to the tidal water levels. However, by ignoring the fact that some of the piles lie within the shadow of the leading piles with respect to the flow direction, the calculated loss coefficients should not underestimate the drag which will be generated by the piers. For the purposes of calculating the loss coefficients, therefore, it will be assumed that the pile caps remain above the sea surface level.

D3-3.1.4 Below the sea surface level, a total of eight 2m diameter piles will reduce the effective flow area and result in additional drag. It is also assumed that the grid size in the area containing these bridge piles is 70m.

*V Flow Direction*

D3-3.1.5 Based on these assumptions, the ratio of the total flow area to the effective flow area, a, is given by:

$$a = 70/(70-4*2)$$
$$= 1.13$$

D3-3.1.6 Each pier will consist of 8 piles 2m in diameter exposed to the flow. The loss coefficient for this pier will be:

$$\begin{aligned} C_{loss,v} &= \frac{1}{2}\left(\sum n * D\right) * C_d * a^2 / \Delta x \\ &= \frac{1}{2}(8*2)*1*1.13^2/70 \\ &= 0.15 \end{aligned}$$

***U Flow Direction***

D3-3.1.7 Similarly, in the U flow direction, the ratio of the total flow area to the effective flow area, a, is given by:

a = 70/(70-2*2)
= 1.06

D3-3.1.8 Each pier will consist of 8 piles 2m in diameter exposed to the flow. The loss coefficient for this pier will be:

$$\begin{aligned} C_{loss,u} &= \frac{1}{2}\left(\sum n * D\right) * C_d * a^2 / \Delta y \\ &= \frac{1}{2}(8*2)*1*1.06^2/70 \\ &= 0.13 \end{aligned}$$

### D3-3.2 Section B-B : In The Airport Sea Channel

D3-3.2.1 The HKLR will include rectangular piles in the Sea Channel, as shown as Section B-B in **Figure 2** and detailed in **Figure 4** below.

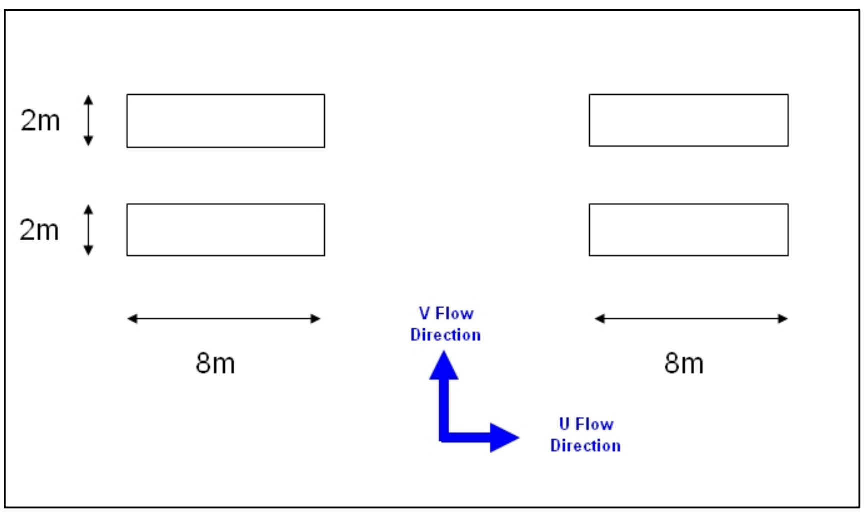


**Figure 4 Hong Kong Link Road Marine Bridge Piers Inside the Sea Channel**

D3-3.2.2 It is assumed that the flow directions are as indicated in **Figure 4** and that the pile caps are buried below seabed level.

***V Flow Direction***

D3-3.2.3 A total of two 8m wide piles will reduce the effective flow area and all 4 8m wide piles will result in additional drag. It is also assumed that the grid size in the area containing these bridge piles is 70m.

D3-3.2.4 Based on these assumptions, the ratio of the total flow area to the effective flow area, a, is given by:

a = 70/(70-2*8)
= 1.3

D3-3.2.5 Each pier will consist of 4 piles with an effective diameter of 4.5m exposed to the flow. The loss coefficient for this pier will be:

$$\begin{aligned} C_{loss,v} &= \frac{1}{2}\left(\sum n * D\right) * C_d * a^2 / \Delta x \\ &= \frac{1}{2}(4 * 4.5) * 1 * 1.3^2 / 70 \\ &= 0.22 \end{aligned}$$

***U Flow Direction***

D3-3.2.6 For flows in this direction, 2 piles 2m wide will reduce the effective flow area and all 4 piles with an effective diameter of 4.5m will again introduce some additional drag. The ratio of the total area to the effective flow area and the loss coefficients will be given by:

a = 70/(70-2*2)
= 1.06

$$\begin{aligned} C_{loss,u} &= \frac{1}{2}\left(\sum n * D\right) * C_d * a^2 / \Delta y \\ &= \frac{1}{2}(4 * 4.5) * 1 * 1.06^2 / 70 \\ &= 0.14 \end{aligned}$$

### D3-3.3 Section D-D – Navigation Span

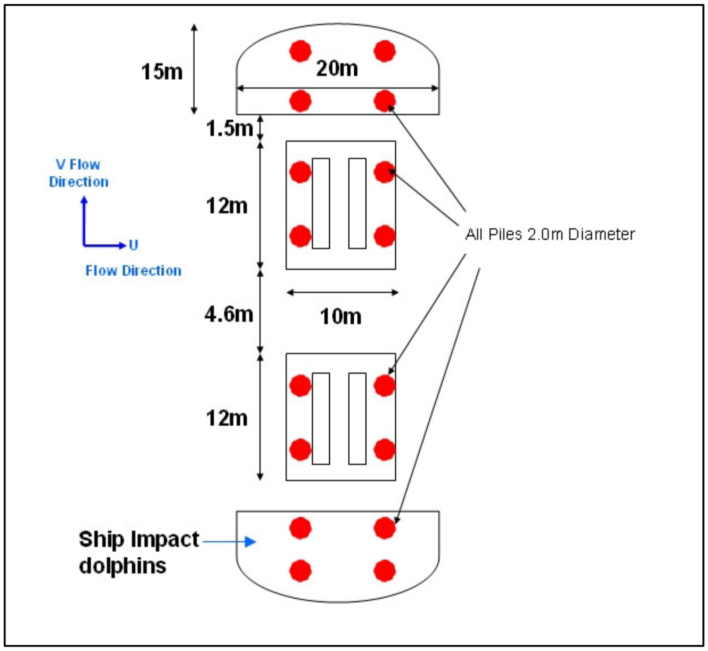


**Figure 5 Hong Kong Link Road – Bridge Piers at the Navigation Channel**

D3-3.3.1 In the vicinity of the navigation channel (Section D-D, **Figure 2**), a bridge span of 150m will be used with ship protection for the bridge piers as show in **Figure 5**. In this area, it will be assumed that the model grid size is 100m and that no more than one bridge pier lies in any one grid cell. The bridge pier consists of 8 piles 2m in diameter and 8 piles 2m in diameter to support the ship protection dolphins.

***V Flow Direction***

D3-3.3.2 The ratio of the total area to the effective flow area will be given by:

a = 100/(100-2*2)
= 1.04

D3-3.3.3 Each pier will consist of 16 piles each with a diameter of 2m exposed to the flow. The loss coefficient for this pier will be:

$$C_{loss,v} = \frac{1}{2}\left(\sum n * D\right) * C_d * a^2 / \Delta x$$
$$= \frac{1}{2}(16*2)*1*1.04^2/100$$
$$= 0.17$$

***U Flow Direction***

D3-3.3.4 The ratio of the total area to the effective flow area will be given by:

a = 100/(100-8*2)
= 1.19

D3-3.3.5 Each pier will consist of 16 piles each with a diameter of 2m exposed to the flow. The loss coefficient for this pier will be:

$$\begin{aligned} C_{loss,u} &= \frac{1}{2}\left(\sum n * D\right) * C_d * a^2 / \Delta y \\ &= \frac{1}{2}(16 * 2) * 1 * 1.19^2 / 100 \\ &= 0.23 \end{aligned}$$

# D3-4 HONG KONG ZHUHAI MACAU BRIDGE (HZMB)

## D3-4.1 Introduction

D3-4.1.1 The whole length of the HZMB will be included in the Delft3D model and it is assumed that the main bridge sections across the Pearl Estuary have similar bridge piers along its length as shown in **Figure 6**. It will also be assumed that the bridge will have a span of 70m although it is appreciated that the span length could vary in different sections.

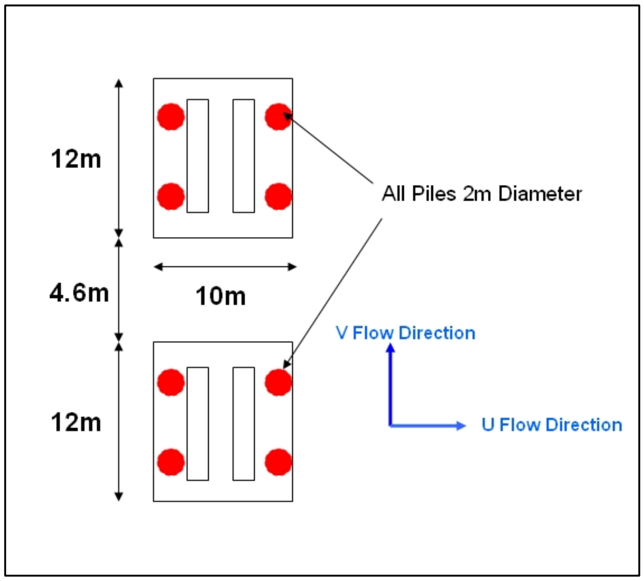


**Figure 6 Mainland Section of Hong Kong Zhuhai Macau Bridge Piers**

D3-4.1.2 The model grid size in the southern part of the Pearl Estuary will varies from the order of a few hundred metres to over 1,000m and could contain up to 15 bridge piers. The loss coefficients relevant to each grid cell will be calculated and following sample calculations of the loss coefficients are for a grid size of 1,000m and a bridge span of 70m.

## D3-4.2 V Flow Direction

D3-4.2.1 In the V flow direction, the flow area will be reduced by 2 pile diameters for each of 15 piers and the ratio of the total area to the effective area will be given by:

$$a = 1000/(1000-15*2*2) = 1.06$$

D3-4.2.2 Each of the 15 piers will consist of 8 piles each with a diameter of 2m exposed to the flow. The loss coefficient for these pier will be:

$$
\begin{aligned}
C_{loss,v} &= \frac{1}{2}\left(\sum n * D\right) * C_d * a^2 / \Delta x \\
&= \frac{1}{2}(15 * 8 * 2) * 1 * 1.06^2 / 1000 \\
&= 0.13
\end{aligned}
$$

### D3-4.3 U Flow Direction

D3-4.3.1 In the U flow direction the total area will be reduced by 4 piles of 2m diameter and the ratio of the total area to the effective area will be given by:

a = 1000/(1000-4*2)
= 1.008

D3-4.3.2 Each of the 15 piers will consist of 8 piles each with a diameter of 2m exposed to the flow. The loss coefficient for these piers will be:

$$
\begin{aligned}
C_{loss,u} &= \frac{1}{2}\left(\sum n * D\right) * C_d * a^2 / \Delta y \\
&= \frac{1}{2}(15 * 8 * 2) * 1 * 1.008^2 / 1000 \\
&= 0.12
\end{aligned}
$$

## D3-5 REFERENCES

1 Feasibility Study for Additional Cross Border Links, Stage 2 Water Quality Impact Assessment Working Paper WP2. Mouchel Asia 1999.

**Figure 2 Hong Kong Link Road**

## Assumptions for Water Quality Impact Assessment