Alternative designs of pier-scour protection for the Gupo and Subway Bridge on the Lower Nakdong River

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## **CHAPTER 1. INTRODUCTION**

The Nakdong River is located in the southeastern region of South Korea and flows 510 km from the Taebaek Mountains to the East Sea. The Nakdong River is the second largest river in Korea and flows through the major cities such as Daegu and Busan. A hydraulic structure, the Nakdong River Estuary Barrage (NREB), was built in the river mouth to prevent salt water intrusion and the Old Gupo Bridge, New Highway Gupo Bridge (Gupo Bridge) and Subway Bridge are located in about 15km upstream of NREB on the Lower Nakdong River. The Nakdong River has a drainage area of about 23,384 square kilometers with frequent typhoons and floods from June to September. Among the annual typhoons, the Typhoon Maemi of September 12, 2003 was the worst typhoon to hit South Korea for more than a decade and the old Gupo Bridge partially collapsed with the loss of a pier due to high velocities by the large flood and bridge pier scour by the Typhoon Maemi. In the United States, Wardhana and Hadipriono (2003) collected and analyzed 503 cases of bridge failures are flood and scour.

The Gupo and Subway Bridge are an artery road connected between the Busan and southern area. Due to the highway construction for the Dadae Harbor in the leftbank side of the Gupo and Subway Bridge, the rightbank floodplain should be excavated to ensure the flow channel area. Bridge piers affected by the excavation are Pier 11 and 12 of the Subway Bridge and Pier 15 and 16 of the Gupo Bridge. These piers are located in the floodplain without local scour before excavating. However, the bridge-pier scour will be occurred by the flowing water after excavating. Therefore, an appropriate protection must be considered for these piers.

The main objectives of this research are to:

- 1) calculate the scour depth and the scour-hole width around the bridge-pier.
- 2) propose three alternative plans to prevent the bridge-scour.
- 3) design and examine the most feasible plan among three alternatives.

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#### **CHAPTER 2. LOWER NAKDONG RIVER**

### 2.1 Background information and site description

The Lower Nakdong River has a drainage area of about 23,384  $km^2$  and spans 510 km from the north across South Korea. The average width of the Nakdong River is approximately 45 *m* and reaches 250 *m* in the Lower Nakdong River. Based on the Mulgum station (Figure 2-1), the average water depth is 2 - 3*m* on the Lower Nakdong River (from the NREB to Samryangjin). The Lower Nakdong River has a very mild bed slope ( $S_0$ ) of approximately 0.0001 to 0.0002 *m/m* and has one tributary, the Yangsan River.



Figure 2-1. Nakdong River basin and Lower Nakdong River

The mean annual precipitation of the Nakdong River is 1,186 mm and the mean annual temperature ranges from 12 to  $16 \,^{\circ}C$ . The flood discharge used in the scour calculation and scour protection design is 19,370cms, 200 year flood discharge of the Gupo Bridge. The flow velocity and depth of 200 year flood discharge are based on the results of the one dimensional numerical modeling by Busan city report in May, 2005, which is  $2.26 \, m/s$  of the flow velocity and 6.62 *m* of the flow depth.

The average particle size distribution of bed material is shown in Figure 2-2. The median grain size of bed material at the Gupo Bridge is 0.25mm of fine sand.



Figure 2-2. Bed material distribution of the Gupo Bridge area

## 2.2 Bridge-pier information of the Gupo and Subway Bridge

The Gupo and Subway Bridge are primary road of connection between the Busan and southern area. Due to the highway construction for the Dadae Harbor in the



Figure 2-3. Gupo and Subway Bridge area



Figure 2-4. General layout of Gupo and Subway Bridge piers

leftbank area of the Gupo and Subway Bridge, the rightbank floodplain should be excavated to ensure the flow channel area (Figure 2-3). Bridge piers affected by the excavation are the Pier 11 and 12 of the Subway Bridge and the Pier 15 and 16 of the Gupo Bridge. The 7m depth from the top of the concrete footing will be excavated.

General layout of piers (Pier 11, 12, 15 and 16) is shown in Figure 2-4. The widths of concrete footings are ranged from 8 to 10.2 m with 2.5 to 3 m depths. Piles under the footing will be exposed by 7 m depth excavation.

#### **CHAPTER 3. BRIDGE PIER SCOUR**

Scour is the removal of material from the bed and banks of a channel by flowing water (May et al., 2002). Generally, scour which may occur at a structure classifies into three types; long-term general scour, contraction scour, and local scour. Long-term general scour including bed degradation and lateral channel movement may not be significant during the design life of a bridge if the rate of scour development is relatively slow (Melville, 2000). Contraction scour can occur in confined section of a channel due to a bridge or other structures. Local scour results from the direct impact of the structures such as a bridge-pier and abutments. Especially, Pier scour is caused by the interference of piers with the flow. The obstruction of a bridge-pier results in significant changes in the flow pattern and causes pier scour. In this research, pier scour is only considered for scour depth and scour hole width computation.

#### 3.1 Pier scour equation

The pier scour has been studied extensively for more than 100 years in the laboratory. Numerous equations are suggested to estimate the depth of pier scour. Melville (2000) selected and summarized some of the better known and recent equations. Several equations selected by Mellville (2000) and recently proposed equations such as the FHWA's HEC-18 equation are given in Table 3-1. The detail descriptions of these equations are not noted in this paper. Brief descriptions of these equations are as follows.

The Laursen (1958 and 1963) equations are consistent with the basic equation of Melville (1997), which is as following.

$$y_s \propto \sqrt{By}$$

Where, B = foundation width

 $y_s =$  scour depth

y = flow depth

Reference	Equation	Standard format (for comparison)	Notes
Laursen (1958)	$\frac{b}{y} = 5.5 \frac{y_s}{y} \left[ \left( \frac{y_s}{11.5y} + 1 \right)^{1.7} - 1 \right]$	$\frac{y_s}{b} \approx 1.11 \left(\frac{y}{b}\right)^{0.5}$	applies to live-bed scour b = pier width
Laursen (1963)	$\frac{b}{y} = 5.5 \frac{y_s}{y} \left[ \frac{\left(\frac{y_s}{11.5y} + 1\right)^{7/6}}{\left(\frac{\tau_1}{\tau_c}\right)^{0.5}} - 1 \right]$	At the threshold condition, $\frac{y_s}{b} \approx 1.11 \left(\frac{y}{b}\right)^{0.5}$	applies to clear-water scour
Neill (1973)	$y_s = K_s b$	$\frac{y_s}{b} = K_s$	
Richardson et al. (1975) CSU	$\frac{y_s}{y} = 2.0K_s K_\theta \left[\frac{b}{y}\right]^{0.65} Fr^{0.43}$	$\frac{y_s}{b} = 2.0K_s K_\theta \left[\frac{b}{y}\right]^{0.35} Fr^{0.43}$	
Jain (1981)	$\frac{y_s}{b} = 1.84 \left(\frac{y}{b}\right)^{0.3} Fr_c^{0.25}$	At the threshold condition, $\frac{y_s}{b} = 1.84 \left(\frac{y}{b}\right)^{0.3}$	for circular pier
Breusers and Raudkivi (1991)	$\frac{y_s}{b} = 2.3K_y K_s K_d K_\sigma K_\theta$	$\frac{y_s}{b} = 2.3K_y K_s K_d K_\sigma K_\theta$	
Ansari and Qadar (1994)	$y_s = 0.86b_p^3$ $b_p < 2.2m$ $y_s = 3.60b_p^{0.4}$ $b_p > 2.2m$	$\frac{y_s}{b_p} = 0.86b_p^2 \qquad b_p < 2.2m$ $\frac{y_s}{b_p} = 3.60b_p^{-0.6} \qquad b_p < 2.2m$	$b_p$ =projected width of pier
Melville (1997)	$y_s = K_{yb} K_I K_d K_s K_\theta$	$y_s = K_{yb} K_I K_d K_s K_\theta$	
Richardson et al. (2001) FHWA- HEC18	$\frac{y_s}{y} = 2.0K_s K_\theta K_b K_a K_w \left[\frac{b}{y}\right]^{0.65} Fr^{0.43}$	$\frac{y_s}{b} = 2.0K_s K_\theta K_b K_a K_w \left[\frac{b}{y}\right]^{0.35} Fr^{0.43}$	modification of the CSU equation

 Table 3-1. Selected pier scour equations

Neill (1973) considered the coefficient of pier shape ( $K_s$ ) to calculate the scour depth, which is  $K_s = 1.5$  for round-nosed and circular piers and  $K_s = 2.0$  for rectangular piers. However, some of equations such as the Laursen's and Neill's equations do not include velocity factors (normally in the form of a Froude number in other equations).

For example, the CSU equation includes the flow velocity upstream of the pier by including the Froude number (*Fr*). The CSU equation add the correction factor for flow angle of attack ( $K_{\theta}$ ) as well as pier shape.

Jain (1981) compared the potential predictors of the maximum clear-water scour with the experimental data and presented another formula to predict the maximum clearwater scour for circular piers considered the limitations of potential predictors.

Breusers and Raudkivi (1991) used five specific parameters in the pier scour equation, which include characteristics of the sediment, the flow and the geometry of a pier and a channel. The Breusers and Raudkivi's equations consider the effect of sediment grading ( $K_{\sigma}$ ), pier and sediment size ( $K_{d}$ ), flow depth ( $K_{y}$ ), pier alignment ( $K_{\theta}$ ), and pier shape ( $K_{y}$ ).

Ansari and Qadar (1994) proposed a design equation for estimating ultimate depth of local scour at bridge piers which is based on the envelope curves drawn to published field data covering a wide range of variables. This equation includes the projected width of a pier.

Melville's design method rests on the following relation for the depth of local scour (Melville, 1997):

$$y_s = K_{yb} K_I K_d K_s K_\theta$$

Where,  $K_{vb}$  = depth-foundation size

 $K_I =$  flow intensity

The flow intensity represents the differences between clear-water and live-bed scour and the  $K_{yb}$  represents flow shallowness which has the effect of the flow depth in relation to the pier width.

The FHWA's HEC-18 equation is a modification of the CSU equation resulting from additional research and field data since 1975. This equation is recommended to determine the ultimate scour depth for both live-bed and clear-water scour. The FHWA's HEC-18 equation has a coefficient that decreases scour depth when bed materials have large particles. The FHWA's HEC-18 equation predicts the maximum pier scour depth and the form is as following.

$$\frac{y_s}{y} = 2.0K_s K_\theta K_b K_a K_w \left[\frac{b}{y}\right]^{0.65} Fr^{0.43}$$

Where,  $K_b =$  Correction factor for bed condition

 $K_a$  = Correction factor for armoring by bed material size  $K_w$  = Correction factor for pier width

Richardson el al. (2001) indicate that existing equations, including the CSU equation, overestimate scour depth by flume studies on scour depth at wide piers in shallow flows and field observations of scour depths at bascule piers in shallow flows. The  $K_w$  can be applied when the ratio of flow depth (y) to pier width (b) is less than 0.8; the ratio of pier width to the median diameter of the bed material ( $d_{50}$ ) is greater than 50; and the Froude number of the flow is subcritical.

The FHWA's HEC-18, Melville's, Ansari and Qadar's, Breusers and Raudkivi's, CSU and Neill's equations are used to calculate and compare the pier scour depth for the Gupo and Subway Bridge on the Lower Nakdong River. These equations are selected based on the better known and recent equations after 1970s. The Jain's equation is excluded because it can be applied for only circular piers.

#### 3.2 Width of scour hole

Richardson and Abed (1999) proposed the following equation to estimate top width of a scour hole in cohesionless bed material from one side of a pier or footing.

$$W = y_{s}(K + \cot \theta)$$

Where, W = top width of the scour hole from each side of the pier or footing

 $y_s =$  scour depth

K = bottom width of the scour hole as a fraction of scour depth

 $\theta$  = angle of repose of the bed material and ranges from about 30° 44°

If the bottom width of the scour hole is equal to the scour depth  $y_s$  (K = 1), the top width of cohesionless sand would range from 2.07 to 2.08  $y_s$ . For the reverse case, the top width would vary from 1.07 to 1.8  $y_s$ . Conclusively, the top width could range from 1.0 to 2.8  $y_s$ . Richardson et al (2001) suggest 2.0  $y_s$  for practical application, which is also used for the Gupo and Subway Bridge.

#### **CHAPTER 4. COUNTERMEASURES FOR BRIDGE PIER SCOUR**

Pier protections against local scour can be classified generally in two methods; armoring methods and flow changing methods such as sacrificial piles, Iowa vanes, and flow deflectors. The examples for the armoring methods are riprap, tetrapods, terahedrons, grout-filled mats, gabions, mattresses, cable-tied blocks, etc. There is also a debris catcher constructed upstream of bridge piers to prevent the problem of debris accumulation. This chapter mainly deals with protection methods selected in alternative designs for the pier retrofitting of the Gupo and Subway Bridge.

#### 4.1 Riprap protection

The riprap layer is the most commonly and widely used method to protect the pier from the scour. The extensive studies including experiments and field studies have been conducted. Also, many equations for the riprap size to protect bridge piers against scour have been proposed. Especially, Melville (2000) compared the published equations and concluded that the Parola (1993, 1995) and Lauchlan (1999) equations lead to conservatively large riprap relatively to the other equations. For the pier protection design of the Gupo and Subway Bridge, the Parola (1993, 1995), Richardson and Davis (1995) and Lauchlan (1999) equations are selected for the riprap size calculation and summarized in Table 4-1.

Melville (2000) summarized the following recommendation of other design criteria for riprap protection at bridge piers (Figure 4-1).

- Thickness of riprap layer,  $t_r = 2d_{r50}$  to  $3d_{r50}$
- Lateral extent of riprap layer, 3b to 4b
- Grading of riprap to satisfy,  $0.5d_{r \max} < d_{r50} < 2d_{r15}$
- Synthetic filter: the lateral extent should be about 75% of the lateral extent of the riprap layer.
- Stone filter layers: as an alternative to synthetic filters
- Thickness of stone filter layers,  $t_f = d_{r50}$

- Grading of filter layer: 
$$\frac{d_{15}(riprap)}{d_{85}(bed)} < 5$$
,  $4 < \frac{d_{15}(filter)}{d_{15}(bed)} < 20$ ,  $\frac{d_{50}(filter)}{d_{50}(bed)} < 25$ 

Reference	Equations	Notes
Richardson and Davis (1995)	$\frac{d_{r50}}{y} = \frac{0.346f_1^2 f_2^2}{S_s - 1} Fr^2$	$d_{r50}$ = median size of riprap $S_s$ = 2.65 $f_1$ = factor for pier shape; 1.5(round-nose) and
		1.7(rectangular) $b_p$ = projected width of pier f = factor for pier shape:
Parola (1993, 1995)		0.71(round-nose if aligned) and 1.0(rectangular) $f_3$ = pier size factor;
	$\frac{d_{r50}}{y} = \frac{f_1 f_3}{S_s - 1} Fr^2$	$f_3 = 0.83  4 < \frac{b_p}{d_{r50}} < 7$
		$f_3 = 1.0$ $7 < \frac{b_p}{d_{r50}} < 14$
		$f_3 = 1.25$ $20 < \frac{b_p}{d_{r50}} < 33$
Lauchlan (1999)		$S_f$ = safety factor, with a
	$\frac{d_{r50}}{v} = 0.3S_f \left(1 - \frac{Y_r}{v}\right)^{2.75} Fr^{1.2}$	minimum recommended value = 1.1
	у (У)	$Y_r$ = placement depth below bed level

 Table 4-1. Selected riprap size equations



Figure 4-1. The example of recommendations for riprap replacement at bridge piers

Recommended gradations of the riprap from the U.S. Army Corps of Engineers are presented in Table 4-2, which is used for the alternative designs for retrofitting and protecting the Gupo and Subway Bridge piers.

% finer by weight	Sieve diameter (×d50)
0	0.25
10	0.35
20	0.5
30	0.65
40	0.8
50	1
60	1.2
70	1.6
90	1.8
100	2

Table 4-2. Riprap gradations of the riprap from the U.S. Army Corps of Engineers

The riprap thickness should not be (1) less than 12 inches (30 cm), (2) less than the diameter the upper limit of  $d_{100}$ , or (3) less than the 1.5 times the diameter of the upper limit  $d_{50}$  (Julien, 2002). Also, the thickness increased by 50% would be used for the submerged portion of the riprap.

In addition, filters are important to allow to drain water between the riprap layer and bed layer without carrying out soil particles. There are two types of filters: stone filters and synthetic filter. In this study, both of them, stone filters and synthetic filter, are suggested and the calculation method of stone filters follows the same method of the filter design for the riverbank riprap revetment. To determine whether the filter is required or not, the calculation of the criteria for the filter (below) is required.

$$\frac{d_{50}(riprap)}{d_{50}(base)} < 40$$

$$5 < \frac{d_{15}(riprap)}{d_{15}(base)} < 40$$

$$\frac{d_{15}(riprap)}{d_{85}(base)} < 5$$

If the riprap does not contain sufficient fines, filters are required. If the filter is required by the above criteria, the properties of the filter to be placed adjacent to the bed can be defined as follows:

$$\frac{d_{50}(filter)}{d_{50}(bed)} < 40$$
$$\frac{d_{15}(filter)}{d_{15}(bed)} > 5$$
$$\frac{d_{15}(filter)}{d_{15}(bed)} < 40$$
$$\frac{d_{15}(filter)}{d_{15}(bed)} < 5$$

The properties of the filter placed adjacent to the riprap are as follows:

$$\frac{d_{50}(riprap)}{d_{50}(filter)} < 40$$
$$\frac{d_{15}(riprap)}{d_{15}(filter)} > 5$$
$$\frac{d_{15}(riprap)}{d_{15}(filter)} < 40$$
$$\frac{d_{15}(riprap)}{d_{85}(filter)} < 5$$

### 4.2 Riprap design for sloping structure for pier protection

One of the alternative designs for retrofitting and protecting the Gupo and Subway Bridge piers adopt the sloping structure which is similar to the riverbank riprap revetment as shown in Figure 4-2.



Figure 4-2. The example of the sloping structure at bridge piers

The basic equation widely used in the side slope riprap calculation is the U.S. Army Corps of Engineering (USACE) equation and the formula is as follows.

$$D_{30} = S_f C_s C_v C_T d \left[ \left( \frac{\gamma_w}{\gamma_s - \gamma_w} \right)^{1/2} \frac{VL}{\sqrt{K_1 g d}} \right]^{2.5}$$

Where,  $D_{30}$  = characteristic riprap size of which 30 percent is finer by weight

 $S_f =$  safety factor, minimum =1.1

 $C_s$  = stability coefficient for incipient failure

 $C_v$  = velocity distribution coefficient

 $C_T$  = blanket thickness coefficient

d =local depth, use depth at 20 percent upslope from toe for side slopes

 $\gamma_s$  = unit stone weight

 $\gamma_w$  = unit weight of water

VL = local depth-averaged velocity

 $K_1$  = side-slope correction factor

As well as the USACE method, there are the velocity and shear-stress methods. The velocity method refereed in Julien (2002) is used to decide the riprap size of the sloping structure in the alternative design with the USACE equation. Although shear-stress method is prefer at larger flow depths ( $h > 10d_s$ ), the velocity method is selected to determine the riprap size in the alternative design including the sloping structure because the very mild slope (S = 0.0002m/m) of the Lower Nakdong River underestimates the shear stress and the riprap size (Figure4-3).



**Figure 4-3.** The result of the riprap size for the Gupo and Subway Bridge piers using the shear-stress method

The riprap thickness and filter calculations are same as the method already mentioned in Chapter 4.1.

## **CHAPTER 5. APPLICATION FOR THE GUPO BRIDGE PIERS**

## 5.1 Alternative plans for the Gupo Bridge piers

Three alternative designs for retrofitting and protecting the Gupo and Subway Bridge piers are proposed in this study. The Alternative plan I is using the sheet pile and riprap to protect the piers and the Alternative plan II is the wall caisson method grouting the exposed part under the original foundation. The last proposed plan (Alternative plan III) is the sloping structure constructed around piers with the riprap protection. The Figure 5-1 shows the general layout for three alternative plans.



Alternative plan III

Figure 5-1. Proposed three alternative plans

Designs	Strength	Weakness	Methods
Alternative plan I	<ul> <li>very feasible for the Gupo and Subway Bridge piers</li> <li>no exposing and disturbing the supporting piles under the foundation (strong stability)</li> </ul>	- not easy to drive sheet piles around piers and grout partially	Sheet piles and riprap
Alternative plan II	<ul> <li>easy to grout the wall caisson</li> <li>not required additional structures</li> </ul>	<ul> <li>weak in stability due to the exposing and disturbing the supporting piles under the foundation</li> <li>additional load to the supporting piles under the foundation due to the grouted wall caisson</li> </ul>	Wall caisson
Alternative plan III- easy construction - economic cost - no exposing and disturbing the supporting piles under the foundation (strong stability) - easy to repair the local damage and loss		<ul> <li>possibility of particle erosion in floods, riprap slumping and sliding</li> <li>obstruction for the navigation</li> </ul>	sloping structure with riprap

Table 5-1. Strength and weakness of three alternatives

The advantages and disadvantages of three alternative designs are listed in Table 5-1. The Alternative plan II was eliminated from the application for the Gupo Bridge piers because of the stability problem. Although the Alternative plan III was considered as the stable and economic design, it still has navigation problems. In next chapter, the selected Alternative plan III for the Gupo Bridge piers will be more discussed with respect to engineering design and preliminary design. The detail calculation and design of the Alternative plan II and III are attached in Appendix I and II

## 5.2 Alternative plan III

Pier scour depth and Scour hole width

Considering the error to drive sheet piles around a pier, sheet piles would be driven 2.5m away form the edge of a pier in the square shape for the Subway Bridge piers and the rectangular shape for the Gupo Bridge piers. Before detail explanations and figures about the sheet piles, the pier scour depth and scour hole width of retrofitting piers enclosed by sheet piles are calculated in Table 5-2 and 5-3.

	P11	P12	P15	P16
Scour Depth (m)	Square (Sheet pile)	Square (Sheet pile)	Square (Sheet pile)	Square (Sheet pile)
Pier Width, b (m)	15.2	13.2	13	13
FHWA HEC-18 (Richardson et al. 2001:Modified CSU)	10.4	9.3	9.2	9.2
Melville (1997)	22.1	19.8	19.6	19.6
Ansari and Qadar (1994)	19.9	18.2	18	18
Breusers and Raudkivi (1991)	8.7	8.2	8.2	8.2
CSU (Richardson et al. 1975)	14.5	12.6	12.4	12.4
Neill (1973)	17.9	15.3	15.1	15.1
Application	10.4	9.3	9.2	9.2

Table 5-2.	The results	of pier	scour	depth
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Table 5-3. The results of pier scour hole width

Pier	Sheet pile	Width (m)	Scour depth (m)	Width of scour holes, W (m)
P11	square	15.2	10.40	20.8
P12	square	13.2	9.30	18.6
P15	rectangular	13.0	9.20	18.4
P16	rectangular	13.0	9.20	18.4

The calculated pier scour depths using different scour equatiosn are similar to the trend of the comparisons of many researchers in the references. The Melville (1997), Ansari and Qadar (1994), and Neill (1973) equations expected relatively deeper scour

depth than the FHWA HEC-18 and Breusers and Raudkivi (1991) equations. Richardson el al. (2001) indicate that existing equations, including the CSU equation, overestimate scour depth by flume and field studies on scour depth at wide piers in shallow flows and the Gupo Bridge case is under the criteria of the shallow flows which is the ratio of flow depth (y) to pier width (b) is less than 0.8; the ratio of pier width to the median diameter of the bed material ( $d_{50}$ ) is greater than 50; and the Froude number of the flow is subcritical. The FHWA HEC-18 equation contains the correction factor of  $K_w$  to consider the shallow flow condition. Therefore, for the application of the predicted scour depth, the result of the FHWA HEC-18 equation is selected for the Gupo and Subway Bridge piers. Using the determined scour depth, the width of the pier scour hole was estimated. Richardson et al (2001) suggest 2.0  $y_s$  for practical application, which is also used for the Gupo and Subway Bridge cases. The width of the scour hole ranges from 18 to 21 *m*.

#### **Riprap protection**

The calculated sizes of the riprap placed around piers (sheet pile pier) are shown in Table 5-4. The applied riprap size  $(50 \, cm)$  for the Gupo Bridge is slightly bigger than the averaged value of the results calculated by the Parola (1993, 1995), Richardson and Davis (1995) and Lauchlan (1999) equations.

Recommended gradations of the riprap from the U.S. Army Corps of Engineers are used for the Alternative design I and the results are shown in Table 5-5 and Figure 5-2.

According to the riprap thickness criteria in Chapter 4.1, the riprap thickness should not be (1) less than 12 inches (30 cm), (2) less than the diameter the upper limit of  $d_{100}$ , or (3) less than the 1.5 times the diameter of the upper limit  $d_{50}$ .

(1) > 12 inches (30 cm)

$$(2) > d_{100} = 2 \times d_{50} = 2 \times 50cm = 100cm = 1m$$

$$(3) > 1.5d_{50} = 1.5 \times 50cm = 75cm = 0.75m$$

For the safety, the 1.5 m would be selected as a riprap thickness in this case.

Pier and flow conditions						Riprap size (m)							
Pier	Case	Sheet pile width (m)	Scour depth (m)	Flow depth (m)	Velocity (m/s)	Froude #	Specific gravity	Richardson and Davis (1995)	Parola (1993, 1995)	Lauchlan (1999)	Average (m)	Application (m)	Weight (kg)
P11	square	15.2	10.4	6.62	2.26	0.28	2.65	0.53	0.39	0.52	0.48	0.50	173.35
P12	square	13.2	9.3	6.62	2.26	0.28	2.65	0.53	0.39	0.52	0.48	0.50	173.35
P15	square	13.0	9.2	6.62	2.26	0.28	2.65	0.53	0.39	0.52	0.48	0.50	173.35
P16	square	13.0	9.2	6.62	2.26	0.28	2.65	0.53	0.39	0.52	0.48	0.50	173.35

Table 5-4. The results of riprap size calculation

 Table 5-5.
 The results of riprap grading

% finer by weight	Sieve diameter (xd50)	Riprap size (cm)
0	0.25	12.5
10	0.35	17.5
20	0.5	25
30	0.65	32.5
40	0.8	40
50	1	50
60	1.2	60
70	1.6	80
90	1.8	90
100	2	100



Figure 5-2. Riprap size gradation

### Filter calculation

To determine whether the filter is required or not, the calculation of the criteria for the filter (below) is necessary.

$$\frac{d_{50}(riprap)}{d_{50}(bed)} = \frac{500}{0.25} = 2000 > 40$$
$$\frac{d_{15}(riprap)}{d_{15}(base)} = \frac{212.5}{0.109} = 1950 > 40$$
$$\frac{d_{15}(riprap)}{d_{85}(base)} = \frac{212.5}{0.81} = 262 > 5$$

As shown in the calculation, filters are required since the riprap does not contain sufficient fines to act as the filter. The properties of the filter to be placed adjacent to the bed have followed ranges:

$$\frac{d_{50}(filter)}{d_{50}(bed)} < 40 \text{ so } d_{50}(filter) < 40 \times 0.25 = 10mm$$
  
$$\frac{d_{15}(filter)}{d_{15}(bed)} > 5 \text{ so } d_{15}(filter) > 5 \times 0.109 = 0.545mm$$
  
$$\frac{d_{15}(filter)}{d_{15}(bed)} < 40 \text{ so } d_{15}(filter) < 40 \times 0.109 = 4.36mm$$
  
$$\frac{d_{15}(filter)}{d_{85}(bed)} < 5 \text{ so } d_{15}(filter) < 5 \times 0.81 = 4.05mm$$

The properties of the filter to be placed adjacent to the riprap have followed ranges:

$$\frac{d_{50}(riprap)}{d_{50}(filter)} < 40 \text{ so } d_{50}(filter) > 500/40 = 12.5mm$$
$$\frac{d_{15}(riprap)}{d_{15}(filter)} > 5 \text{ so } d_{15}(filter) < 212.5/5 = 42.5mm$$



Figure 5-3. Filter design for the Alternative plan I

$$\frac{d_{15}(riprap)}{d_{15}(filter)} < 40 \text{ so } d_{15}(filter) > 212.5/40 = 5.3mm$$
$$\frac{d_{15}(riprap)}{d_{85}(filter)} < 5 \text{ so } d_{85}(filter) > 212.5/5 = 42.5m$$

These riprap filter requirement are shown in Figure 5-3. The filter should be the double layer of stone filters (filters for bed and riprap). Additional synthetic filter is also necessary to prevent pumping of soil particles. The layout of double stone filter layers and synthetic filter are shown in Figure 5-4.



Figure 5-4. Double stone filter layer and synthetic filter for the Alternative plan I

Melville (2000) recommends lateral extent of riprap layer of 3b to 4b. Therefore, the extent length from the edge of the pier is recommended at least 15 m in this case. However, the interval between the adjacent filter layers for the Gupo and Subway Bridge piers is left only 10 m and this area without the riprap would be easy to scour. Therefore, it is strongly recommended to cover the whole area between the piers for the riprap and filters (Figure 5-5). Also, the Pier 12 and 15 are pretty close to the new riverbank and the same size and gradation for the riprap and filter are suggested to protect the riverbank.



Figure 5-5. Plan view and front view of the Alternative plan I

#### Sheet pile

Considering the error to drive sheet piles around piers, sheet piles would be driven 2.5m away form the edge of piers in the square shape for the Subway Bridge (Figure 5-6) piers and the rectangular shape for the Gupo Bridge piers (Figure 5-7).

Recommended considerations to drive and construct sheet piles are summarized as the followings.

- Driven depth of sheet piles: 25 m

- Grouting (concrete mortar) the space between the cap concrete foundation and sheet pile with 3 *m* depth

- Partial grouting the inner space of sheet piles with 50 cm of a thickness and 20 m of a depth



Figure 5-6. Sheet pile layout for the Pier 11 and 12



Figure 5-7. Sheet pile layout for the Pier 15 and 16

## **CHAPTER 6. SUMMARY AND CONCLUSIONS**

### REFERENCES

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# **APPENDIX I: Alternative Plan II**

# **APPENDIX II: Alternative Plan III**