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# Analysis for the Effectiveness of Sediment Dredging in the Approach Channel at the Nakdong River Estuary Barrage

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## Abstract

The upstream channel of the Nakdong River Estuary Barrage (NREB) has experienced sedimentation problems requiring annual dredging operation after the construction. The main purpose of sediment dredging is to prevent flooding during late summer. Numerical simulation and volume analysis using field surveying data for the Lower Nakdong River have been conducted to quantify the bed changes with and without dredging operation and to analyze the effectiveness of dredging at the NREB. As a result, it is presented that the bed change rate (sedimentation rate) after dredging is much faster than the bed condition without dredging. The water surface rising of the maximum 10 cm was generated in case the dredging was not considered in the modeling. Volumetric analysis of bed changes using field surveying data presented that 41 percent of total sediment erosion was eliminated by natural flushing and 59 percent was dredged in the field. Because it is noticeable that dredged section is redeposited rapidly after dredging during low flow through the 2D simulation, it is expected that most of total sediment erosion (at least more than 41% of total sediment erosion) is caused by natural flushing due to the floods. Therefore, it is highly recommended to use natural flushing or intentional sluicing techniques for sedimentation control methods at the NREB.

Keywords: *bed changes, nakdong river estuary barrage, numerical modeling, sediment dredging*

## 1. Introduction

The Nakdong River Estuary Barrage (NREB) was built in 1983-87 near the Eulsuk Island in Korea to prevent salt-water intrusion in the estuary. The 2.3-km-long barrage includes 510 m of 10 gates section and 1,720 m of a closed dam section with a navigation lock, fish ladder, and other related structures (Ji, 2006). The NREB provides the control of the upstream water level and the local road for auto-traffic, and prevents salt-water intrusion into the Lower Nakdong River.

Since the construction of the barrage, the Lower Nakdong River has experienced sedimentation problems requiring dredging. Most of the sedimentation occurs before and after floods and during low flows. The gates cause backwater effects upstream of the barrage, which results in sediment deposition. The main purpose of dredging sediments is to maintain the flood conveyance capacity of the upstream channel on the Lower Nakdong River during typhoons and floods, which are coupled with high water levels. Historical records (1990 to 2007) indicate an average of 524,170 $m^3$ per year of dredging with a high cost (Ji *et al.*, 2011). The dredging has been annually conducted since 1990 in the approach channel from the NREB to 3.5 km upstream and the material dredged is primarily non-cohesive fine sand. The quantitative analysis of dredging operation should be evaluated to reduce sedimentation and to substitute dredging for alternatives.

To preserve the reservoir capacity and maintain the navigation channel, dredging operations have been used widely in lakes, reservoirs, and barrages, even though it costs highly (Ji, 2006). The feasibility and method of dredging operation are determined depending on the size of sediment volume, the location to dredge, the particle size and geometry of deposits, and the water level. There are several methods to dredge sediment, which can be classified into hydraulic and mechanical dredging. Many small siphon dredges are used in Chinese reservoirs (Morris and Fan, 1997). However, this method has a few limitations about head differences and water level of a reservoir. Also, a cable-suspended dredge pump, which is one of the specialized hydraulic dredging systems, is used for precision dredging with a submerged video monitor. A cable-suspended pneumatic pump was used to dredge 550,000 cubic meters of silt from Gibraltar

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Reservoir at Santa Barbara (Morris and Fan, 1997). Mechanical dredging removes the sediment with a closed or unclosed bucket. Compared to hydraulic dredging, mechanical dredging carries the sediment with low water contents, and excavated amounts are relatively small. It may be suitable for gravel or large materials of a reservoir. To dredge sediments of about 524,170 $m^3$ per year at the upstream channel of the NREB, hydraulic suction dredging with a cutterhead and a large pump has been used over 18 years.

The purpose of this study are to perform the numerical simulation and to analyze field surveying results of bed changes for assessing the effectiveness of sediment dredging at the Lower Nakdong River. Therefore, outcomes in this study should be used to improve the present method to control sediment deposition and to propose a new approach to solve sedimentation problem upstream of the Nakdong River Estuary Barrage.

## 2. Site Description of the Lower Nakdong River

The Lower Nakdong River has a drainage area of about 23,384 $km^2$ and spans 510 km from the north across South Korea (Park *et al.*, 2008). The average width of the Nakdong River is approximately 45 m and reaches 250 m in the Lower Nakdong River and 500 m at the NREB. Based on the Mulgeum station, the average water depth is 2-3 m on the Lower Nakdong River (from the NREB to Samrangjin). The Lower Nakdong River has a very mild bed slope of approximately 0.0001 to 0.0002 m/m and has one tributary, the Yangsan River. The mean annual precipitation of the Nakdong River basin is 1,186 mm and the mean annual temperature ranges from 12 to 16°C. The median grain size of bed material at the Gupo Bridge located in 15 km upstream from the NREB is 0.25 mm.

The Nakdong River Maintenance General Planning Report (KMOCT, 1991) presented the roughness factor of 0.023 for Manning's n which was determined for the Lower Nakdong River through the analysis using the field data of historic floods, bed materials, and bedforms. Also, a Darcy-Weisbach friction factor ($f$) of 0.03 was used to compute the backwater profile of the Lower Nakdong River in the NREB maintenance manual (ISWACO-NEDECO, 1987). If the averaged depth 3m of the Lower Nakdong River is applied to their relations between different friction factors, Manning's n of 0.023 produced the Darcy-Weisbach friction factor of 0.03. In this study, Manning's n of 0.023 was used for 1D and 2D flow simulation.

Because resistance to flow depends largely on bedform configurations, three methods (Simons and Richardson, 1963 and 1966), Bogardi (1974), and Van Rijn (1984)) to predict bedform configurations are selected to verify the feasibility of given roughness factors (Ji, 2006). The backwater profile was calculated based on the mean daily flow of the Lower Nakdong River, and then the bedform configurations were determined by three methods. The calculation results show that the bedform configurations of the Lower Nakdong River consist of ripples and dunes, which is in good agreement with the field observations in 2003 and 2007 using the sound navigation ranging as shown in Fig. 1.

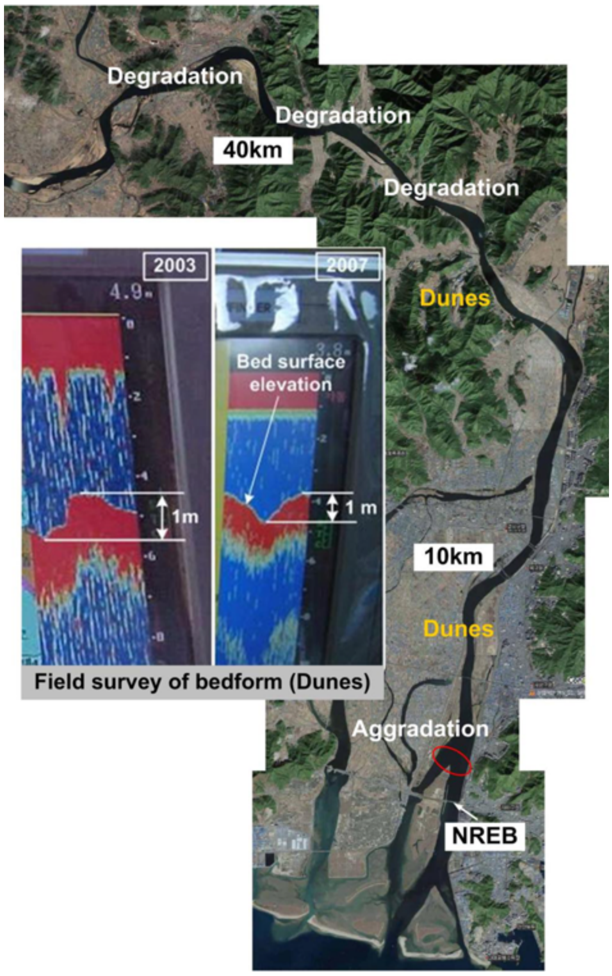

Fig. 1. Bedform Observation on the Lower Nakdong River

Korea Water Resources Corporation (KOWACO) collected sediment field data in 1995 at the Jindong Station, which is located in 80 km upstream of the NREB, and presented calculated total sediment load of Jindong Station. Measured sediment field data and the Modified Einstein Procedure (Colby and Hembree, 1955) were used to estimate the total sediment load at Jindong Station (KOWACO, 1995). Because presently used suspended sediment sampler such as point and depth integrated samplers cannot collect the sediments for the entire water column, the unmeasured load must be estimated and added to the measured load to estimate the total load using the Modified Einstein Procedure. Sediment field data include suspended sediment concentrations, and particle size distributions of suspended sediment and bed material. Calculated sediment discharge data of Jindong Station by KOWACO were compared with several total sediment load equations in Fig. 2. The total sediment load calculated by the Modified Einstein Procedure is referred to as field data in this study. The Engelund and Hansen (1967) method overestimated the total load at Jindong Station. Shen and Hung (1972), Ackers and White (1973), Yang (1979),

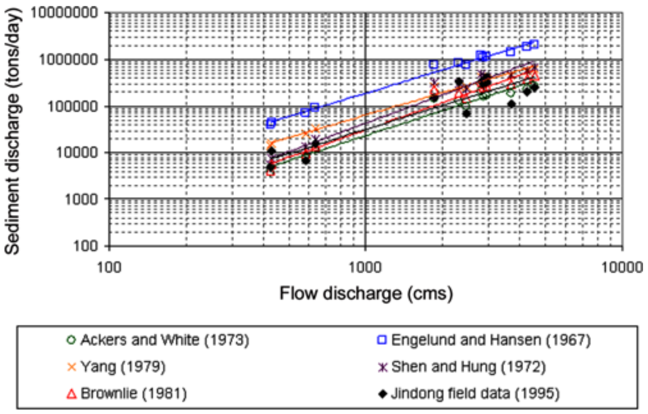


Fig. 2. Sediment Transport Equations Comparison of Jindong Station (Ji, 2006)

and Brownlie (1981) equations show relatively good agreement with the field data.

## 3. 1D Simulation of Bed Elevation Changes using the HEC-6 model

### 3.1 Modeling Conditions and Sediment Transport Equation for HEC-6 Modeling

Flow discharge and stage hydrographs for one month of September 2003 was applied for boundary conditions to simulate bed changes after Typhoon Maemi hit the Lower Nakdong River on September 12, 2003. Bed elevation changes in the 50-km-long channel section upstream of the NREB were simulated using the HEC-6 model for one month with Typhoon Maemi in 2003. Also, to analyze the long-term changes of bed elevation after construction of the NREB, bed changes from the NREB to Jindong Station (80 km upstream of the NREB) have been simulated for 14 years (1990 to 2003). The gauging data of flow discharge and water stage from 1990 to 2003 were used for boundary conditions of the long-term simulation.

According to the preliminary study for the sensitivity analysis of bed change simulation for different sediment transport formulas using the HEC-6 model performed by Jeong *et al.* (2010), Ackers and White (1973), Engelund and Hansen (1967), Yang (1979) and Toffaleti (1969) equations were recommended for the 1D simulation of bed changes in the Lower Nakdong River. The following Yang's equation for sediment transport equation, which was relatively consistent with field measurement of sediment discharge at Jindong Station, was adopted in the model:

$$\log C_{ts} = 5.165 - 0.153\log\frac{\omega d_s}{\nu} - 0.297\log\frac{u_*}{\omega} + \left(1.780 - 0.360\log\frac{\omega d}{\nu} - 0.480\log\frac{u_*}{\nu}\right)\log\frac{VS}{\omega} \quad (1)$$

where,

$C_{ts}$ = Total sand concentration (in ppm by weight)

$d_s$ = Median particle diameter.

$u_*$ = Shear velocity

$VS$ = Unit stream power

$\nu$ = Kinematic viscosity, and

$\omega$ = Fall velocity of sediment,

### 3.2 Modeling Results and Analysis

As results of thalweg line changes by Typhoon Maemi, maximum degradation of 1.59 m was simulated near 45 km upstream of the NREB and bed elevation near 40 km upstream was degraded about 0.65 m as shown in Fig. 3(a). Sediment deposition of 0.80 m compared to the initial bed elevation was calculated in the downstream section (2 km upstream of the NREB) because of the expanded channel width causing the velocity decrease. Field measurement for bed changes in the Lower Nakdong River has been annually conducted only for the approach channel of 3.5 km section from the NREB. Therefore, field data for thalweg lines upstream from 3.5 km to 80 km were not available to compare with 1D modeling results. However, it was confirmed that the simulation results of HEC-6 was qualitatively similar to the field observations of bedform in 2003 and 2007 using the sound navigation ranging as shown in Fig. 1.

Bed changes from the NREB to Jindong Station also have been simulated for 14 years (1990 to 2003) after construction of the NREB and the simulation result has been plotted in Fig. 3(b). As a result, the thalweg line from Samrangjin (40 km upstream of the NREB) to Jindong was degraded after the placement of the NREB. On the contrary, it was represented in the simulation

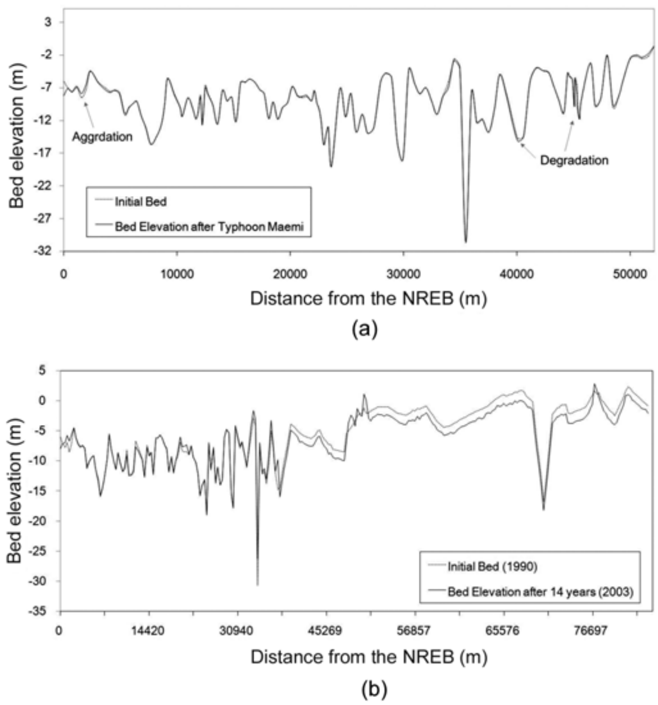


Fig. 3. HEC-6 Results of Bed Elevation Changes: (a) Thalweg Line Change After Typhoon Maemi (2003), (b) Thalweg Line Change After 14 Years (1990-2003)

that bed elevations near the NREB, 20 km, and 35 km were increased due to sedimentation. The results of the HEC-6 modeling to analyze the characteristics of bed changes in the Lower Nakdong River showed typical features of sediment deposition near the estuary barrage or dam due to the decreased velocity.

## 4. 2D Simulation with and without Dredging

### 4.1 CCHE2D Model and Boundary Condition

Bed changes with and without dredging operation at the NREB are simulated using the CCHE2D model which is a two-dimensional depth-averaged, unsteady, flow and sediment transport model. The CCHE2D model was developed by the National Center for Computational Hydroscience and Engineering (NCCHE), at The University of Mississippi. The flow model is based on depth-averaged Navier-Stokes equations. The sediment transport module is used to simulate non-uniform sediment (both non-cohesive and cohesive) using non-equilibrium transport models. Three different non-equilibrium transport approaches are proposed to handle the cases where the sediment transport occurs mainly as bed load, mainly as suspended load, or total load. The equations for this module include transport equations for bed load and suspended load, the bed change equation, and the bed sorting equation (Jia and Wang, 2001). The strength of the CCHE2D model among other 2D bed change models is various options for selecting sediment transport equations and modes. Many developers and researchers have validated the CCHE2D model using field data (Jia and Wang, 2001). The calibration of the CCHE2D model for the approach channel of the NREB was also performed with field data by Han (2010). The applicable sediment transport equation and sediment transport mode for the NREB were the following Ackers and White (1973) equation and bed load type validated through his study.

$$C_w = c_{AW2} G \frac{d_s}{h} \left(\frac{V}{u_*}\right)^{c_{AW1}} \left(\frac{c_{AW5}}{c_{AW3}} - 1\right)^{c_{AW4}} \qquad (2)$$

where,

$C_w$ = Total sediment concentration by weight,
$c_{AW1}$, $c_{AW2}$, $c_{AW3}$, $c_{AW4}$, and $c_{AW5}$ = Variables depending on the dimensionless particle diameter
$G$ = Specific gravity of sediment, and
$h$ = Flow depth
$V$ = Flow velocity

The approach channel for numerical modeling stretches for 3 km as shown in Fig. 4. The flow discharge in Samrangjin Station (40 km upstream of the NREB) was used for the upstream boundary condition and the water level at the NREB was applied for the downstream boundary condition as plotted in Fig. 5. Total simulation time was 104 days from July 24th to November 4th in 2002. The annual dredging has been operated in the modeling section to eliminate the deposited sediment and to prevent the water level increase by flood events. The deposited sediment above the reference height of each cross section is eliminated by dredging. Therefore, the annual field surveying has been conducted before dredging and after flood season.


Fig. 4. 2D Modeling Section and Dredging Area in 2002 of the NREB

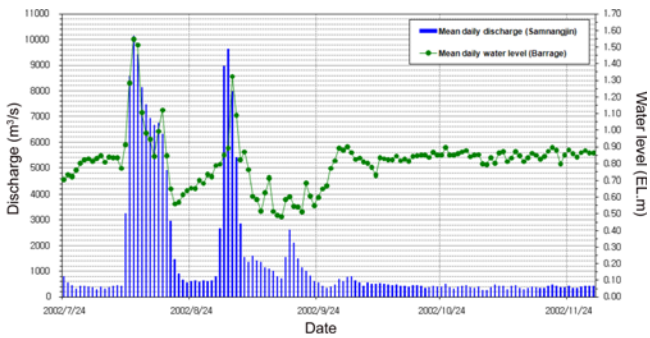


Fig. 5. Discharge and Water Level Data at the Lower Nakdong River (Han, 2010)

### 4.2 Modeling Results and Analysis

The numerical simulation was conducted using the CCHE2D model to calculate and to quantify the bed changes with and without dredging operation at the NREB. Computed results with and without dredging are compared in Figs. 6 to 9.

Fig. 6 shows the final bed elevation after 104 days from July 24th to November 4th in 2002. The bed elevation with dredging (Fig. 6(b)) after the flood season is lower than the case without dredging (Fig. 6(a)) except the inlet area. The simulation results for bed changes with and without dredging are compared in Fig. 7. Because bed changes were evaluated based on the initial bed elevation, it is more useful to compare cross-sectional geometries of initial bed (Jul. 24th, 2002), final beds after simulations with and without dredging, and final bed survey data (Nov. 4th, 2002). Based on the comparison, it is noticeable that the simulation results with dredging have better agreement with the field survey data (Nov. 4th, 2002) because the dredging in the field was operated actually in 2002.

According to the comparison of cross-sectional geometries with and without dredging (Fig. 8), the final bed elevation with

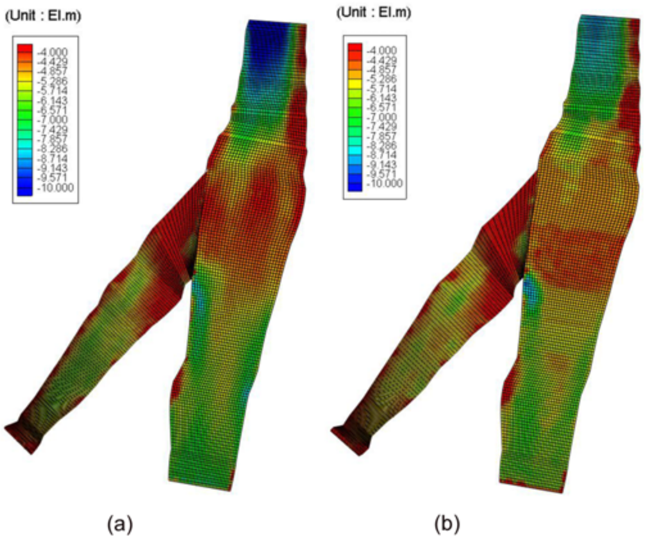


Fig. 6. Simulation Results of Final Bed Elevation with and without Dredging: (a) Bed Elevation without Dredging, (b) Bed Elevation with Dredging

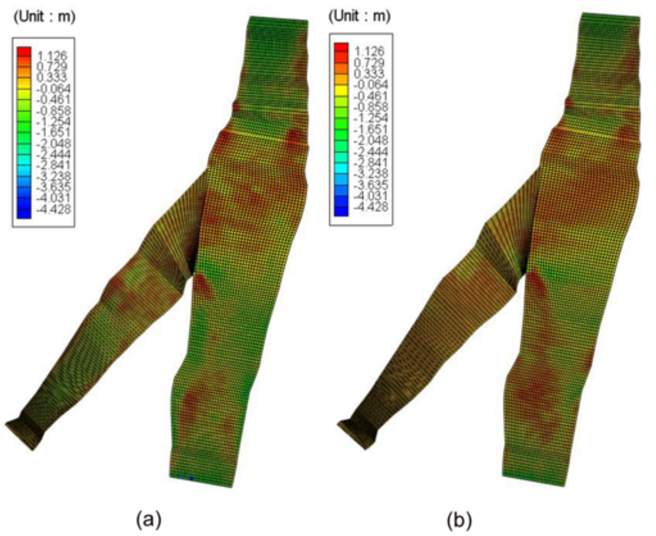


Fig. 7. Simulation Results of Bed Changes with and without Dredging: (a) Bed Changes without Dredging (b) Bed Changes with Dredging

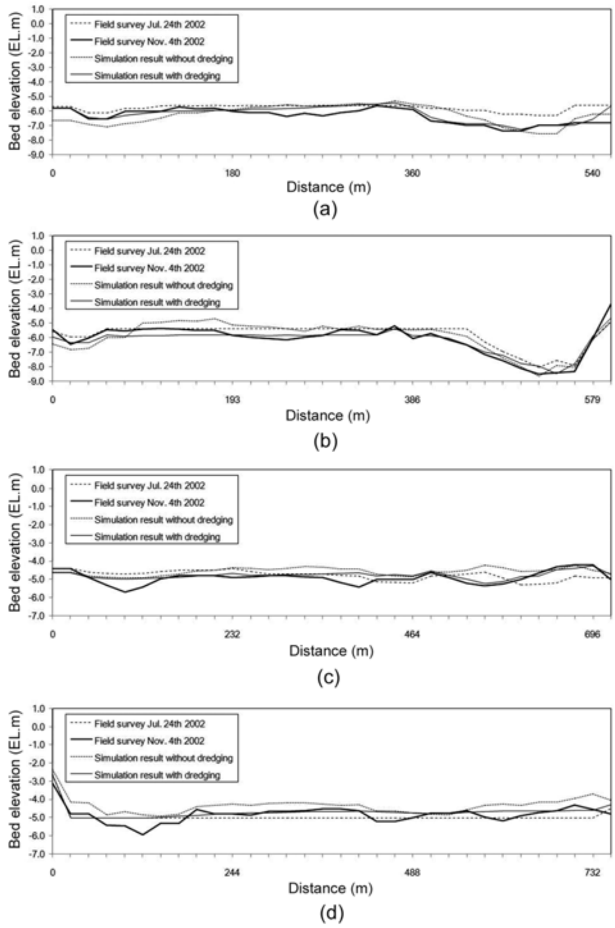


Fig. 8. Comparison of Cross-sectional Changes Measured in the Field and Simulated by the CCHE2D Model with and without Dredging: (a) 1.2 km Upstream of NREB, (b) 1.4 km Upstream of NREB, (c) 2.0 km Upstream of NREB, (d) 2.2 km Upstream of NREB

dredging is lower than that without dredging. Especially, the dredging section between 2 km to 2.5 km upstream of the NREB had a larger difference of bed elevations between the existence and nonexistence of dredging compared to the dredging section from 1 km to 1.5 km. More sediment deposited in the section of 2 km to 2.5 km caused a lager difference in bed elevations with and without dredging after the flood season. From a geometrical point of view, the section of 2 km to 2.5 km from the NREB has an abrupt increase in channel-width. The large amount of sedimentation in this area was the result of decreased flow velocity due to the increased channel width. Therefore, it is established that the countermeasures to control flow velocity and direction are necessary to reduce sediment deposition in this area.

According to the analysis of Fig. 7 and 8, the channel bed changes with dredging were greater than the bed changes without dredging especially in the dredging sections. It is represented that the bed change rate (sedimentation rate) after dredging is much faster than the bed condition without dredging. Therefore, it is indicated that the dredging can be effective to reduce the water level increase by floods, but it is not the best way to solve the sedimentation problem at the NREB. Also, the sedimentation reduction methods through the control of flow velocity and direction in the section between 2 km to 2.5 km upstream of the NREB can be more effective than the dredging operation for the long run.

The water surface elevations with and without dredging for peak flow ($Q_{peak} = 9{,}560\ m^3/s$) were compared to analyze the water level increase in case of no dredging. The water level was increased locally and restrictively in the area between 2 km to 2.5 km. The water surface rising of the maximum 10 cm was generated in case the dredging was not considered in the modeling.

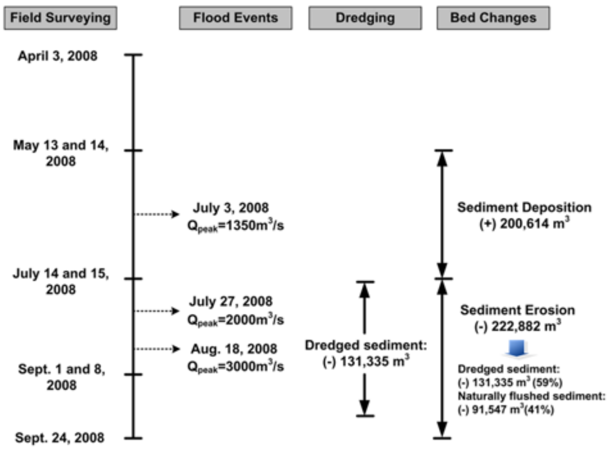


Fig. 9. Volumetric Analysis of Bed Changes using Field Surveying Data (2008)

## 5. Volumetric Analysis for Bed Changes using Field Data

Volumetric analysis of bed changes was performed using field surveying data in 2008 at the NREB. Additional field surveying for volumetric analysis of bed changes was executed three times as well as two regular annual surveying in April and September 2008 (Fig. 9). Sediment dredging was operated from July 16th to September 19th 2008 and dredged sediments were corresponding to the amount of 131,335 m$^3$. Sedimentation volume deposited from May 13 to July 15 including the first flood event is (+) 200,614 m$^3$ as shown in Fig. 9 and the sign of (+) represents sediment deposition. Also, the volumetric bed change from July 15 to September 24th is (–) 222,882 m$^3$ and the sign of (–) represents sediment erosion. During this period, the sediment volume of (–) 91,547 m$^3$, which is 41% of total sediment erosion, was flushed by natural flow and sediments of (–) 131,335 m$^3$ (59%) were dredged in the field.

In the 2D modeling section of this study, it was indicated that simulation with dredging had faster sedimentation than the one without dredging. Note that bed configuration after dredging was applied for the initial bed condition in 2D simulation with dredging. However, actual dredging was operated throughout three months from July 16th to September 19th 2008 in the field. Therefore, it is represented that sediments can be redeposited in the dredged section during the dredging period due to the fast sedimentation based on the 2D simulation results. Consequently, redeposited sediments could be eliminated by natural flushing due to the floods in July 27th and August 18th 2008. If the dredged section is redeposited rapidly after dredging during low flow, it is expected that most of total sediment erosion is caused by natural flushing due to the floods even though the dredging is operated.

## 6. Conclusions

Numerical simulation and field surveying for the Lower Nakdong River have been conducted to analyze the effectiveness of sediment dredging in the upstream channel of the NREB. The conclusions which can be drawn from this study are the following observations:

1. The HEC-6 modeling for bed changes in the Lower Nakdong River represented that the bed elevation was degraded after the construction of the NREB in the section from Samrangjin (40 km upstream of the NREB) to Jindong (80 km upstream of the NREB), however increased near the sections of the NREB, 20 km, and 35 km upstream due to sediment deposition. It was concluded that the bed change of the Lower Nakdong River presented typical features of sediment deposition near an estuary barrage due to the decreased velocity.
2. The numerical simulation using the 2D model has been conducted to calculate and quantify the bed changes with and without dredging operation at the NREB. The dredging section between 2 km to 2.5 km upstream of the NREB where the channel width abruptly widen had a larger difference of bed elevations between the existence and nonexistence of dredging operation compared to the dredging section between 1 km to 1.5 km. Therefore, it is concluded that the countermeasures to mitigate flow velocity decrease are necessary to reduce sediment deposition in the section between 2 km to 2.5 km upstream of the NREB.
3. According to the 2D simulation, the water level was increased maximum 10 cm locally and restrictively between 2 km to 2.5 km by floods when dredging was not applied. Based on simulation results of bed changes with and without dredging, the sedimentation rate after dredging (redeposition rate) is much faster than the bed condition without dredging. Therefore, it is indicated that the dredging can be a little effective to reduce water level increase by floods, but it is questionable that dredging is the best way to solve the sedimentation problem at the NREB for the long run.
4. Volumetric analysis of bed changes using field surveying data in 2008 presented that the sedimentation volume of 200,614 m$^3$ was deposited from May 13 to July 15 and the sediment erosion of 222,882 m$^3$ was produced from July 16th to September 19th. If the sediment volume dredged in this period (131,335 m$^3$) is considered for volumetric analysis, it is indicated that the sediment volume of 91,547 m$^3$ (41% of total sediment erosion) was naturally flushed by floods. Because it is noticeable that dredged section is redeposited rapidly after dredging during low flow through the 2D simulation, it is expected that most of total sediment erosion (at least more than 41% of total sediment erosion) is caused by natural flushing due to the floods. Therefore, it is highly recommended to use the natural flushing and intentional sluicing techniques for sedimentation control methods at the NREB.

In the Lower Nakdong River, geomorphologic field measurement has been conducted annually only for the approach channel of 3.5 km section from the NREB. The geomorphologic data upstream from 3.5 km to 80 km were not available to calibrate or to compare the bed changes with the 1D numerical modeling results. Therefore, note that this study limited 1D numerical analysis to qualitative interpretation rather than quantitative evaluation. The continuous acquisition of more geomorphologic field data in the Lower Nakdong River could improve the quality of studies about sedimentation analysis and implementations of various sediment control methods at the NREB.

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