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Tidal Dynamics and Tidal Current Power Generation in the Uldolmok Waterway

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Abstract. Uldolmok waterway is famous for its strong tidal current with maximum current of about 12knots, which is located between the Chindo island off the southwestern tip of Korean peninsula and mainland. A serious of field observations, along with numerical modeling, have been carried out over the last several years, in order to understand the tidal dynamics and to examine the related variables according to the tidal current power plant (TCPP) operation.

Introduction

The Uldolmok waterway is a channel connecting the entrance of the South Sea and the Yellow Sea (Fig. 1). Its width is order of 1-2 km, its length is about 15 km, and the water depth is about 15 m. As shown in Fig. 1, the waterway has a narrow section of about 250 m width. This site is well known for its strong tidal flow and a pre-feasibility study for power generation utilizing these tidal currents was made in 1985-1986 by Korea Ocean Research and Development Institute [1], in 1992 for basic research program in order to examine tidal feature around narrow strait and again through recent observations since 2002, when direct current measurement using ADCP, for the first time, was successfully carried out. Tidal dynamics is described in the Uldolmok waterway from the analysis of the tide and tidal current observations. Based upon the validation of the tidal numerical model, numerical modeling approach has been shown to be a useful tool for getting information such as tidal environment change and the related variables according to the TCPP operation, when TCPP development scheme of tidal current power plant is designed in the waterway.

Characteristics of principal and shallow water tidal components

To further investigate the characteristics of the shallow water constituents in the Uldolmok waterway, tide level recordings were carried out at 5 stations along the channel during the period of January to February, both in 1992 and 2002. For a month-long data analysis 8 related components well as 27 major components were included, with nearby station (Mokpo) being a reference permanent tidal station.

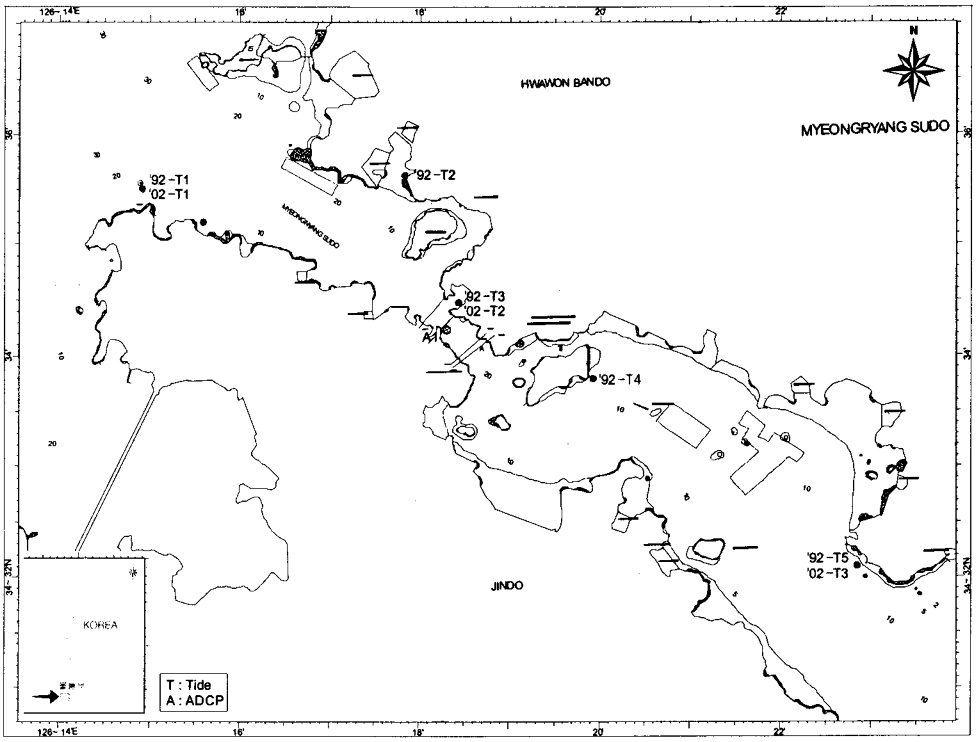

Fig. 1 Station map in the Uldolmok waterway between Chindo and the mainland of Korean peninsula (92T and 02T: tide, A1: ADCP)

Considering the phase lags of the constituents (Table 1) it is clear that the tidal waves propagate from 92T5 to 92T1. It is noticeable that, in spite of the short distance between the stations (about 9km), a big difference in phase lag occurs over the narrow part of the waterway. It seems that the tidal waves along the narrow channel should propagate quite slowly probably due to the bottom friction. It is also worth noting that the phase lag differences of semi-diurnal constituents are about two times as large as those of diurnal constituents. With relatively large amplitude of semi-diurnal constituents this large phase lag will result in the stronger current speeds of semi-diurnal constituents over those of the diurnal constituents. Probably in case of semi-diurnal constituents it is likely that more potential energy is converted into kinetic energy through the narrow section, therefore inducing the smaller amplitude of semi-diurnal constituents.

Table 1 Tidal harmonic constants for major components from observed data (Jan. to Feb., 2002) along the Udolmok waterway, Korea. Ph(phase) is referred to135°E. For the locations of stations, see Fig. 1.

Stations	M2		S2		K1		O1	
	Amp(m)	Ph(deg)	Amp(m)	Ph(deg)	Amp(m)	Ph(deg)	Amp(m)	Ph(deg)
T1(92T1)	1.279	21.9	0.421	69.1	0.316	243.9	0.227	211.9
T2(92T3)	1.177	15.8	0.391	61.3	0.302	243.1	0.214	213.7
T3(92T5)	1.201	333.6	0.453	11.1	0.308	219.9	0.209	188.8

Shallow water tides are found in basins or rivers of shallow depth and they are generated as a nonlinear interaction to external tidal oscillations. The results of analyses at 5 stations for the shallow water tides are listed in Table 2.

Table 2 Tidal harmonic constants for major shallow water components from observed data (15 Jan. to 14 Feb., 1992) along the Udolmok Waterway, Korea. See caption of table 1 for phase lags.

Stations	M4		MS4		MN4		MSF		MM	
	Amp(m)	Ph(deg)	Amp(m)	Ph(deg)	Amp(m)	Ph(deg)	Amp(m)	Ph(deg)	Amp(m)	Ph(deg)
T1	0.111	198.1	0.098	262.4	0.046	152.3	0.012	68.2	0.032	150.7
T2	0.096	186.4	0.085	262.2	0.040	147.0	0.048	350.8	0.088	26.5
T3	0.029	205.3	0.037	294.9	0.006	157.3	0.131	190.6	0.109	233.0
T4	0.088	159.7	0.073	238.1	0.036	135.4	0.020	42.6	0.054	137.6
T5	0.079	154.0	0.069	224.8	0.033	120.9	0.004	186.0	0.041	147.6

In case of overtide (M4) the magnitude of amplitude along the waterway are order of 10 cm except for T3 located near the narrowest section of the channel, and it is quite interesting that the variation of amplitude along the waterway is not smooth. Further the amplitude distributions of compound tides MS4, MN4 also show the same trend as that of M4. In case of lower harmonics MSf and MM the amplitudes at T3 are larger than those of other stations in contrast to higher harmonics. Such a significant amplitude variation of the shallow water constituents may be related to a non-linear phenomenon around the narrow part of the waterway.

The remarkable characteristic of quarter-diurnal tides or higher harmonics (M4, MS4 and MN4) takes place in the phase lag distribution of the above components. The phase lag patterns of quarter-diurnal components show that the quarter-diurnal tidal waves propagate from 92T5 to 92T1 direction, but discontinuous behavior or abrupt jump in phase lag is found at T3, again strongly suggesting that some nonlinear process take places around the narrowest part of the waterway. One point is to keep it in mind that an external M4 tidal wave propagating from 92T5 to 92T1 may exist, since its existence is expected to be possible by the propagation of corresponding tidal wave around southwestern Korean Peninsula. The results of the depth-averaged two dimensional model for the M4 tide in the Yellow and East China Seas in reference [1] support the interpretation that the external M4 tide with 10 cm amplitude exists around the southwestern tip of Korean peninsula, as shown in Fig. 6a of reference[1].

Tidal current and related dynamics

Tidal current from ADCP mooring in the central point was observed during Jan. to Feb., 2002 and Sep. to Oct. 2003. Depth averaged along- and cross-channel component of current is shown in Fig. 2.

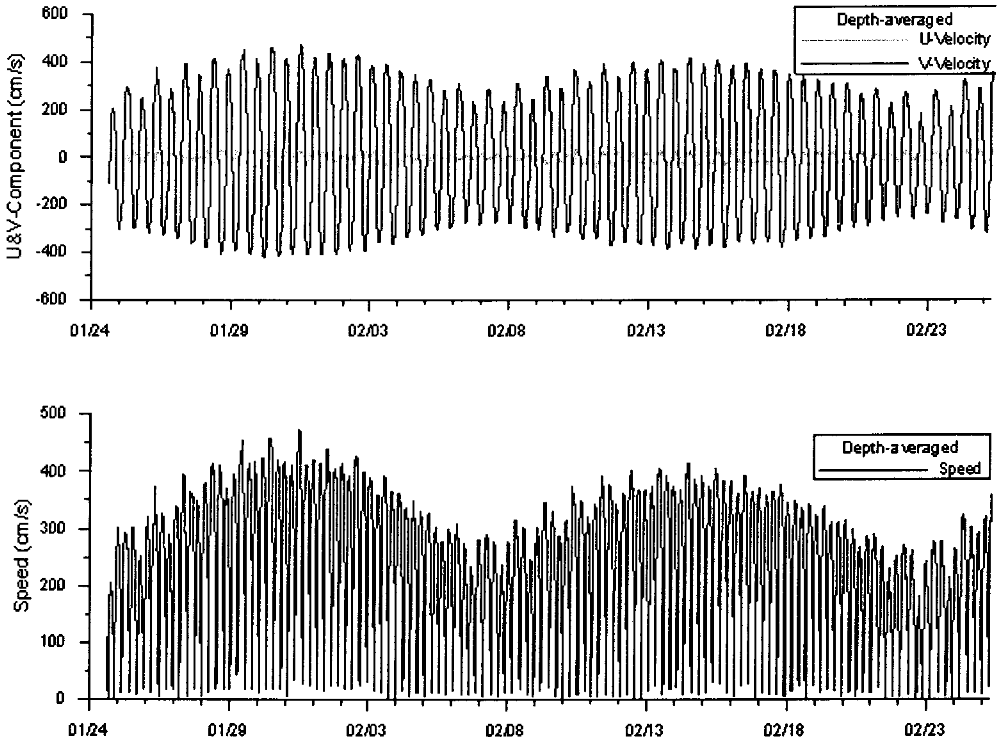

Fig. 2 Depth-averaged along-channel(v) and cross-channel(u) current components and speed

The depth averaged-speed and current speed at 4 representative water depths were calculated. Max speed at 25m from bottom (total water depth is over 27m) is 598 cm/s, while instantaneous maximum current speed is about 630 cm/s at 23m from the bottom. Depth averaged speed is 244.1cm/s and instantaneous maximum current speed is 475 cm/s. This strong tidal current along with strong generation of the nonlinear components indicates that there exists complicate nonlinear process as well as high frictional dissipation.

Figure 3 presents that the time variation of sea level slope (02T3-02T1) and depth mean current at narrowest section. The M2 amplitude of sea level slope is 1.0m with maximum amplitude of about 1.5m. The M2 phase lag of sea slope leads the phase lag of M2 current nearly by 16°, implying that sea level difference is rather balanced nearly by linear bottom friction. Considering that perfect balance between sea level difference and linear bottom friction can be achieved with 0° difference, the deviation of balance about 20% may be explained by local accelerative balance. The barotropic energy flux vector from numerical modeling of the M2 tidal component flows toward the central narrowest section, as seen in Fig. 6, which implies that much energy is dissipated there and some the energy flowing into the narrowest section may be used for higher and lower harmonic component generation, as well as distortion of mean (or residual) sea level depression to be shown from numerical modeling.

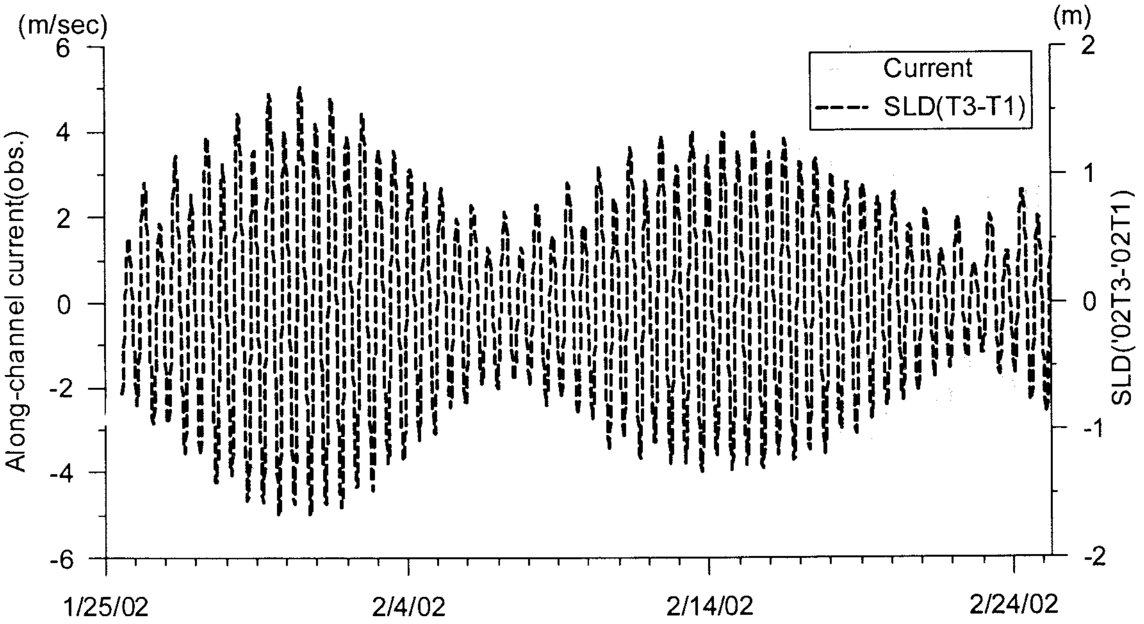

Fig. 3 Sea level difference (SLD) and along-channel current

Volume flux, energy flux vector, and a maximum power

In order to further investigate the characteristics of the tide and tidal current depth-averaged numerical modeling has been carried out in the Uldolmok waterway, with fine (20～50m) grid resolution. The governing equation and numerical method are described in reference [2]. The validation of the model result against the observations is shown in Fig. 4. Based upon this reasonable result of the model validation, the energy flux vector and volume flux through the narrowest section are computed in Figs. 5 and 6, respectively. The peak volume flux for M2 component is about 2.07 x $10^4 m^3/s$, with the M2 amplitude of the head difference (Fig. 3) being 1.0m. Following the Eq. 7 of Garrett [3] the maximum M2 tidal mean power is about 42,000 KW.

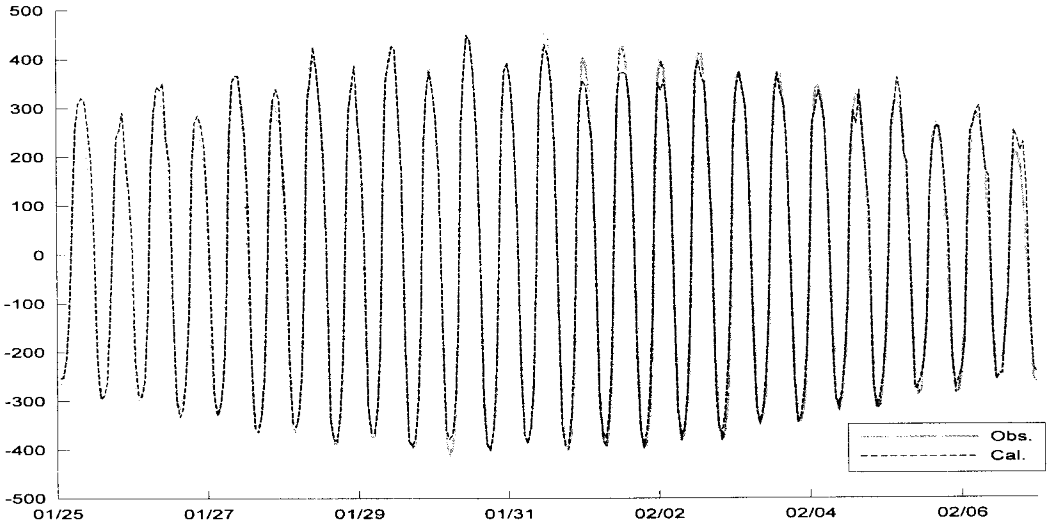

Fig. 4 Model validation of the depth averaged along-channel current (Obs) from ADCP data observed in 2002 and model result (Cal). Unit of vertical axis is cm/s

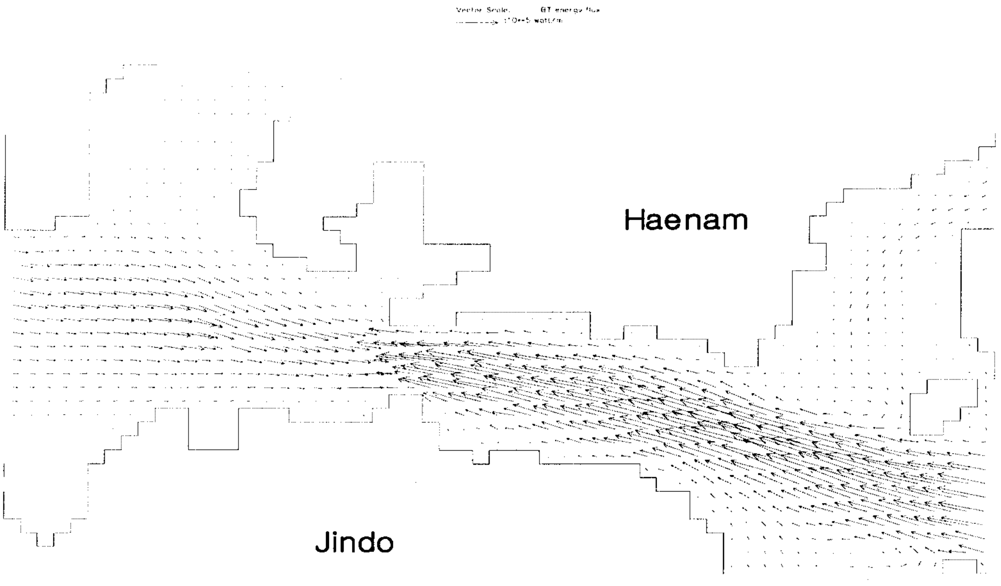

Fig. 5 Barotropic energy flux vector

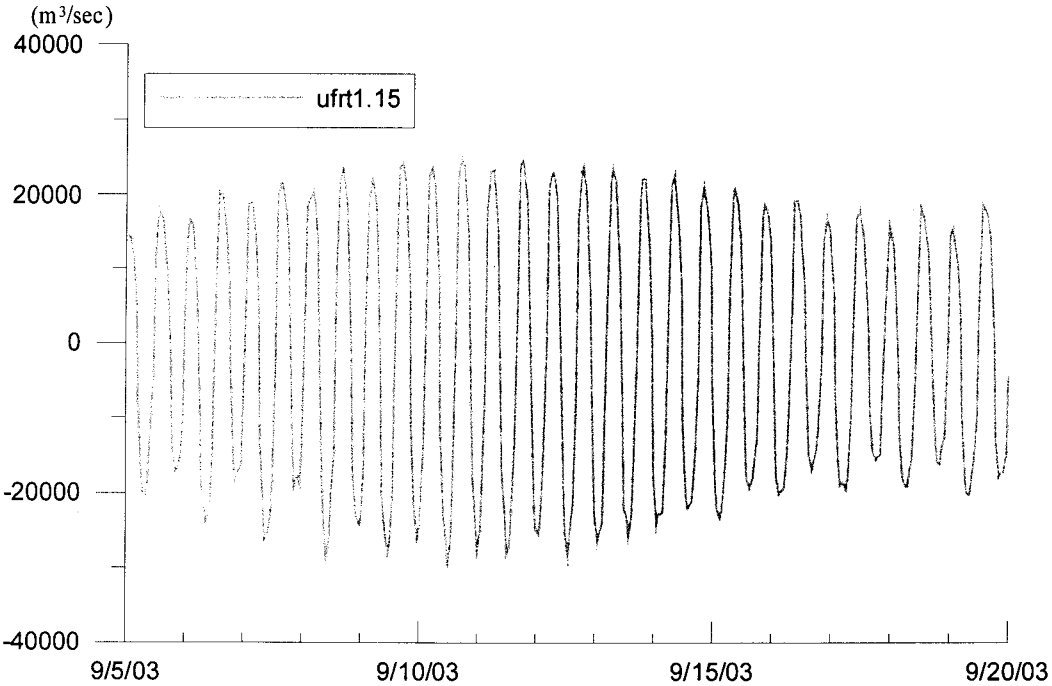

Fig. 6 Temporal variation of volume flux through the narrowest section of the Uldolmok waterway, maximum flood of -30,000 m^3/s and maximum ebb flux of 25,000 m^3/s

Numerical model experiment for TCPP application according to the scheme of tidal turbine arrays

The numerical model experiment was carried out in order to further investigate the power generation according to the scheme of the tidal array. One of the proposed schemes for TCPP arrays in the Uldolmok waterway is shown in Fig. 7 and the corresponding array assignment inside the numerical model for the turbine array can be schematized.

The energy dissipation rate by increasing bottom friction coefficient was estimated around the TCPP section and the corresponding current change was calculated. The power generation as well as volume decrease is calculated, with increasing friction or power increasing of Uldolmok TCPP.

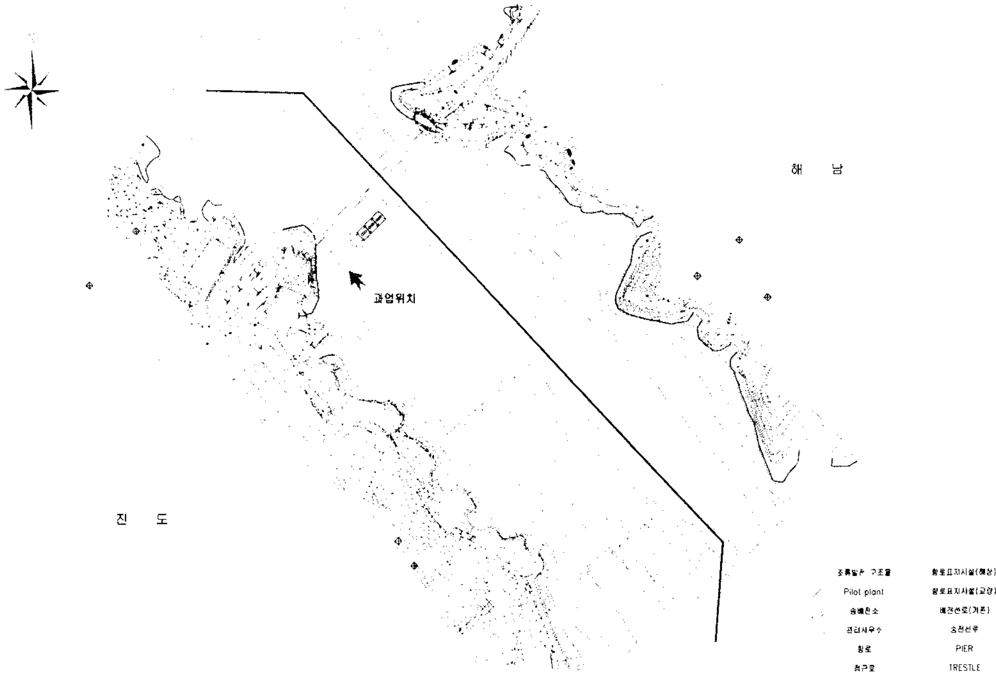

Fig. 7 Schematic view of three turbine arrays

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