CHAPTER 97

CHARACTERISTICS OF TIDAL INLETS ON THE PACIFIC COAST OF JAPAN

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ABSTRACT

Tidal inlets on the Pacific coast of Japan were studied with respect to three characteristic variables of the throat section:(1) Throat area,A;(2) Throat width,B; and (3) Direction of throat section,Θ_{ts}. For each of these three variables, multiple regression analysis was performed stepwise by introducing external variables such as tidal prism, mean flow rate of tidal flow, wind energy, wave energy and so on into a linear regression model. Exposure condition of throat section to open sea was also introduced into the analysis.

First step analysis derived quite reliable result on the direction of throat section;

$$\Theta_{ts}(\text{degree}) = -60.0 + 0.88\ \Theta_{pwv}(\text{degree}),\ r=0.964$$

where Θ_{pwv} is the direction of wave energy which penetrates into a backed bay through tidal inlet and r the correlation coefficient between Θ_{ts} and Θ_{pwv}. However, results on both throat area and throat width were not satisfactory enough even after the performance of more than eighth step analysis on them.

Similar analysis was further performed on both throat area and throat width of the classified data due to the magnitude of geometrical parameters r_{as} and r_{hxb} respectively, where r_{as} is the ratio of throat area to mean surface area of backed bay and r_{hxb} the ratio of the maximum depth at the throat section to throat width. As a result, the former regressions on both throat area and throat width were improved remarkably. Multiple correlation of the regressions were all greater than 0.930.

INTRODUCTION

Tidal inlet problems have been a big concern for coastal engineers who are engaged in maintaining or developing water basins such as bays, lagoons, and estuaries. Especially, characteristics of the minimum flow section or throat section of tidal inlet have been the most important subjects to be investigated since they govern the functional operation of various facilities built inside the basins above.

Many distinguished works have been done on the characteristics of throat section. In 1931, M.P.O'BRIEN(4) made a survey on the tidal inlets located on sandy beaches on the Pacific coast of the United States, and found the following well known relationship between the cross sectional area of throat section and the corresponding tidal prism;

$$A(\text{km}^2)=4.063\text{x}10^{-2}\ P(\text{km}^3)^{0.85} \quad \ldots\ldots\ldots\ldots\ldots(1)$$

where A is the cross sectional area of throat section measured below mean sea level and P the corresponding tidal prism for spring tidal range. In 1969,

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O'BRIEN(5) further found that the same relationship held for a large number of additional jettied inlets located on sandy beaches of the Pacific, Atlantic and Gulf coasts of the United States although a slightly different relationship did for a limited number of unjettied inlets;

$$A(km^2)=6.65\times10^{-2}\ P(km^3) \qquad \ldots\ldots(2)$$

In 1973, J.W.JOHNSON(3) made similar analysis on the tidal inlets located on sandy beaches on the Pacific coast of the United States and found the following relationship between their throat areas and corresponding tidal prisms;

$$P(km^3)/A(km^2)=1.729\times10^1\ P(km^3)^{0.1} \qquad \ldots\ldots(3)$$

He also showed that different relationship held for a limited number of unjettied inlets on the above coast;

$$P(km^3)/A(km^2)=1.676\times10^1 \qquad \ldots\ldots(4)$$

Here, it should be noted that JOHNSON used mean tidal range for the evaluation of tidal prism instead of spring tidal range. These are similar results obtained by O'RRIEN since Eq.(3) and (4) would be transformed into the following equations respectively;

$$A(km^2)=5.784\times10^{-2}\ P(km^3)^{0.9} \qquad \ldots\ldots(5)$$

$$\text{and} \quad A(km^2)=5.965\times10^{-2}\ P(km^3) \qquad \ldots\ldots(6)$$

On the other hand, P.BRUUN and F.GERRITSEN(1) analysed the throat areas of tidal inlets on sandy coasts of the United States, Holland, Denmark and Portugal by introducing the idea of so called "Stable shear stress". As a result, they pointed out that stable throat area could be better described by the maximum flow rate of tidal flow than by tidal prism.

Through the brief review of the previous works, the following facts can be noticed;

1). Tidal inlets on sandy beaches were mainly investigated.
2). Throat area was the major concern among the characteristics of tidal inlet.
3). Effects of a single external variable such as tidal prism or the maximum flow rate was introduced into the analysis of throat area although investigators pointed out the necessity of evaluationg the effects of (1) Other external variables;(2) Geometrical features of both inlets and backed bays; and (3) Geological features of tidal inlets and backed bays in the analysis of throat area.

Similar statistical analysis on tidal inlets are quite few in Japan. So, the author will perform a statistical analysis on the characteristics of tidal inlets located on the Pacific coast of Japan. Here, it should be noted that most tidal inlets on the Pacific coast of Japan are not on sandy beaches but on the rugged rocky coasts. In this study, characteristicts of throat section will be investigated as well. Figure 1 shows a model of throat section. Investigation will be made on the following three variables;

1). Throat area, A, measured below mean lower low water, in square kilometers.
2). Throat width, B, measured below MLLW, in kilometers.
3). Direction of throat section, θ_{ts}, measured in azimuth, in degree.

Among these variables, the last two are those added specially in this study since often usage of tidal inlets by super-tankers or big container

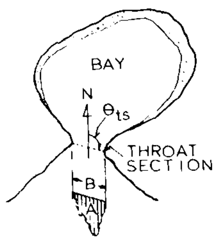

Fig.-1. Model of throat section.

ships has necessitated to obtain full information on both throat width and direction of throat section for both functional operation of ports and safety navigation.

On the other hand, the following ten external variables will be provided for the analysis of the characteristic variables;

1). Wind energy off the tidal inlet :E_{owd}
2). Direction of wind energy off the tidal inlet :Θ_{owd}
3). Wind energy penetrating into throat section :E_{pwd}
4). Direction of wind energy penetrating into throat section :Θ_{pwd}
5). Wave energy off the tidal inlet :E_{owv}
6). Direction of wave energy penetrating into throat section :Θ_{owv}
7). Wave energy penetrating into throat section :E_{pwv}
8). Direction of wave energy penetrating into throat section :Θ_{pwv}
9). Volume of tidal prism for mean tidal range :P
10). Mean rate of tidal flow at the throat section :V_n

Multiple regression analysis will be performed stepwise on each of the characteristic variables by introducing external variables one by one into a linear regression model preset. The details of the analysis will be presented in the following Chapters.

SURVEY OF THE BASIC DATA

Figure 2 shows the map of Japan. Along the Pacific coast of Japan, ninety five tidal inlets were chosen for analysis.

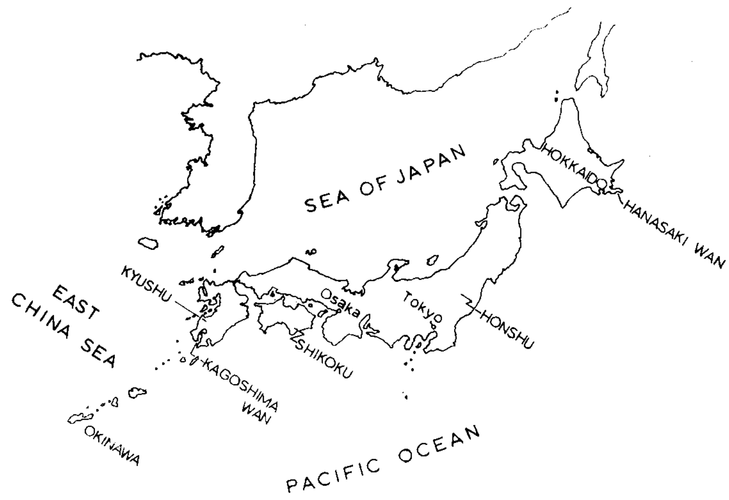

Fig. 2. Map of Japan and her adjacent areas.

Those inlets are distributed almost evenly along the Pacific coast of Japan from Hokkaido to Kagoshima. The inlets whose throat sections are stabilized either by jetties or other artificial works were not considered in the sampling stage. For each inlet selected, the following data were collected through

the various sources;
A). Geometrical features of inlets and their backed bays.
B). Geological features around inlets and their backed bays.
C). Wind data around the inlets.
D). Wave and tidal data around the inlets.
Details of the data survey will be described in the following sections.

A. Geometrical features of inlets and their backed bays.

Basing on the most recent nautical charts, published by the Japan Maritime Safety Agency, the following data were measured;
1). Surface area of bay measured below mean higher high water: S_h(km^2)
2). Surface area of bay measured below mean lower low water : S_l(km^2)
3). Shore length of the bay measured below MLLW : l_s(km)
4). Principal axial length of bay measured below MHHW : l_p(km)
5). Width of the throat section measured below MLLW : B(km)
6). Direction of the throat section : θ_{ts}(degree)
7). Opening angle of tidal inlet against open sea : θ_{op}(degree)
8). Throat area of tidal inlet measured below MLLW : A(km^2)
9). Maximum depth of the throat section measured below MLLW : h_x(m)
10). Mean tidal range at the bay : $2a_n$(m)

B. Geological features around the inlets and their backed bays.

Geological information along beaches were surveyed through the "Geological Maps of Japan"(6) published by the Economical Planning Agency of Japan. Information on bottom materials were checked through the "Bottom Sediment Chart of the Adjacent Seas of Japan"(10) published by the Japan Maritime Safety Agency. Those information were also referred to those shown in the corresponding nautical charts.

C. Wind data around the inlets.

Thirty four meteorological stations were chosen along the Pacific coast of Japan. These stations are all located near the selected inlets. At each station, the monthly maximum winds recorded during the period of 1967 to 1971 were picked up through the "Annual Report of the Japan Meteorological Agency". At the inlets where stations were not located nearby, wind data were estimated by the interpolation method basing on the monthly maximum winds obtained at the close stations.

D. Wave and tidal data around the inlets.

Wave data available were all collected through various sources(2,7,8,9,11,12). However, reliable data were obtained only at a few spots where waves were recorded continuously during the period of 1967 to 1971. Among these data, the monthly maximum waves were picked up for the analysis. At the inlets where reliable wave data were not obtained, waves were estimated by the method of SVERDRUP-MUNK-BRETSCHNEIDER basing on the data of monthly maximum winds at the corresponding inlets. The monthly maximum waves recorded continuously during the other period than the above were also referred to the waves estimated by S-M-B method, and the larger ones were adopted as the monthly maximum waves.

Data of tidal range at each inlet were collected through the corresponding nautical charts.

EVALUATION OF THE EXTERNAL VARIABLES

As shown in INTRODUCTION, ten external variables were provided. These are the variables related to wind energy, wave energy, tidal prism, and mean rate of tidal flow at the throat section of tidal inlet. In the following sections, derivation of the equations on these variables will be described briefly.

A. Equations of wind energy and the related terms.

Basing on the monthly maximum winds, wind diagram at the offshore of each selected inlet was produced. Figure 3 shows a wind which blows from the ith direction.

Suppose the velocity of this wind to be V(i) and its frequency of occurrence over five years to be f(i). Then, the horizontal component of wind energy off the inlet, $E_{owdh}(i)$, is evaluated by

$$E_{owdh}(i) = \frac{1}{2}\rho_a V(i)^2 (f(i)/60)\sin(22.5(i-1)) \quad \ldots(7)$$

where ρ_a is the air density. Similarly, the vertical component of this energy, $E_{owdv}(i)$, is evaluated by

$$E_{owdv}(i) = \frac{1}{2}\rho_a V(i)^2 (f(i)/60)\cos(22.5(i-1)) \quad \ldots(8)$$

then, the probable wind energy off the inlet, E_{owd} is evaluated by

$$E_{owd} = \sqrt{\left(\sum_{i=1}^{16} E_{owdh}(i)\right)^2 + \left(\sum_{i=1}^{16} E_{owdv}(i)\right)^2} \quad \ldots\ldots(9)$$

The direction of this energy, θ_{owd}, can be obtained by

$$\theta_{owd} = \sin^{-1}\left(\sum_{i=1}^{16} E_{owdh}(i)/E_{owd}\right) \quad \ldots\ldots\ldots\ldots(10)$$

Figure 4 shows a wind which penetrates into the throat section from the ith direction. The penetrating energy, E_{pwd}, and its direction, θ_{pwd}, are then obtained through Eqs.(9) and (10) respectively by summarizing the corresponding terms over the opening angle of the tidal inlet instead of full range.

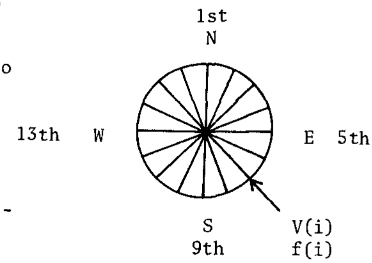

Fig.-3. Wind data which blow from ith direction.

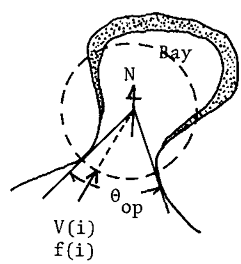

Fig.-4. Wind data which penetrates into throat section from ith direction.

B. Equations of wave energy and the related terms.

Basing on the monthly maximum waves, wave diagram was produced at the offshore of each inlet. Now, suppose the height of wave coming from the ith direction to be H(i), wave length to be L(i), wave period to be T(i), and the frequency of occurrence over five years to be f(i). Then, the horizontal component of wave energy off the tidal inlet, $E_{owvh}(i)$, is given by

$$E_{owvh}(i) = \frac{1}{2}\rho_w g H(i)^2 L(i)(f(i)/60)\sin(22.5(i-1)) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots(11)$$

Similarly, the vertical component of this energy, $E_{owvv}(i)$, is given by

$$E_{owvv}(i) = \frac{1}{8}\rho_w g H(i)^2 L(i)(f(i)/60)\cos(22.5(i-1)) \quad \ldots\ldots(12)$$

where ρ_w is the density of sea water. The probable wave energy off the inlet is then given by

$$E_{owv} = \sqrt{\left(\sum_{i=1}^{16} E_{owvh}(i)\right)^2 + \left(\sum_{i=1}^{16} E_{owvv}(i)\right)^2} \quad \ldots\ldots(13)$$

The direction of this wave energy, Θ_{owv}, is given by

$$\Theta_{owv} = \sin^{-1}\left(\sum_{i=1}^{16} E_{owvh}(i)/E_{owv}\right) \quad \ldots\ldots(14)$$

Penetrating wave energy, E_{pwv}, and its direction, Θ_{pwv}, can be obtained through Eq.(13) and (14) respectively by summarizing the corresponding terms over the opening angle of the tidal inlet instead of full range.

C. Equations of tidal prism and mean rate of tidal flow.

Tidal prism, P, was evaluated by the following equation;

$$P(km^3) = S_n(km^2) \times 2a_n(m)/1000 \quad \ldots\ldots(15)$$

where S_n is the mean surface area of the backed bay which was obtained by averaging the surface area measured at MHHW and that measured below MLLW, and $2a_n$ the mean tidal range in the backed bay.

The mean rate of tidal flow at the throat section, V_n, was evaluated by the following equation;

$$V_n(m/sec) = \frac{P(km^3)}{A(km^2) \times T/2(sec)} \times 1000 \quad \ldots\ldots(16)$$

where T is the duration of tidal cycle.

STEPWISE MULTIPLE REGRESSION ANALYSIS ON THE CHARACTERISTIC VARIABLES

The following equation shows a linear regression model assumed between each of the characteristic variables and external variables;

$$Y = C_0 + \sum_{i=1}^{m} A_i X_i \quad \ldots\ldots(17)$$

where Y indicates one of the characteristic variables, C_0 the regression constant, X_i the ith external variable introduced into the regression model, A_i the partial regression coefficient of X_i, and m the number of the external variables introduced into the analysis. Thus, Eq.(17) actually shows the linear regression model assumed for the mth step analysis on Y.

Analysis is performed stepwise by introducing external variables one by one at each step of analysis into the regression model above. A variable is introduced into the regression model at each step of analysis in such an order that the maximum multiple correlation may be obtained by its introduction. F test is performed at each step of analysis by setting the significance level of 5 %, and the analysis will be proceeded until the introduction of new variable becomes insignificant.

The actual analysis was initiated by checking the correlation coefficients between the characteristic variables and external ones. Correlation coefficients between each of the characteristic variables and external ones were investigated on the following cases;

1). When the values of both characteristic variables and external ones are

original ones.
2). When the values of characteristic variables are original although the values external variables are converted into logarithmic values.
3). When the values of both characteristic variables and external ones are all converted into the logarithmic values.
Exposure condition of throat section was also introduced into the analysis. Table 1 summarizes the results of correlation analysis. In this table, exposed inlets mean the inlets whose throat sections are exposed to open sea, and protected inlets indicate the ones whose throat sections are protected against the intrusion of winds and waves by either islands or peninslas.

Table 1. Correlation coefficients between each of three characteristic variables and ten external variables.

External variable	Exposed inlets(N=66)						Protected inlets(N=29)					
	A (orig. values)	B	θ_{ts}	A (log values)	B	θ_{ts}	A (orig. values)	B	θ_{ts}	A (log values)	B	θ_{ts}
P	.643	.718	-.133	.844	.873	.062	.928	.777	.187	.824	.772	.276
V_n	.268	.413	-.124	.286	.443	-.075	.560	.439	-.058	.051	.162	-.182
E_{owd}	.095	.077	.002	.030	.112	-.024	.132	.030	.048	.239	.132	.100
θ_{owd}	.170	.154	.043	.148	.219	.085	.244	.175	.480	.357	.147	.471
E_{pwd}	-.136	-.093	-.127	-.199	-.144	-.130	--	--	--	--	--	--
θ_{pwd}	.081	.098	-.149	-.031	.067	-.003	--	--	--	--	--	--
E_{owv}	-.137	-.086	-.082	-.263	-.161	-.085	-.162	-.021	.123	-.090	.010	.113
θ_{owv}	.132	.158	.044	.018	.097	.273	.120	.055	-.252	-.160	-.138	-.196
E_{pwv}	-.022	-.035	-.055	-.154	-.148	-.139	--	--	--	--	--	--
θ_{pwv}	-.036	-.052	.964	-.007	-.032	.849	--	--	--	--	--	--

From this table, the following facts can be seen;
1). In case of throat area and throat width, log converted variables generally show higher correlation coefficients than do the original values of them.
2). In case of the direction of throat section, original values of the variables generally show higher correlation coefficients than do the log converted variables.
3). Influence of exposure condition to correlation coefficients is not clear in case of both throat area and throat width although it is significant in case of the direction of throat section.

Basing on these findings, it was decided to use log converted variables for the analysis of both throat area and throat width, and original variables for the analysis of the direction of throat section. Details of the analytical results will be shown in the next Chapter.

RESULTS ON THE STEPWISE MULTIPLE REGRESSION ANALYSIS

Multiple regression analysis was performed stepwise on each of the characteristic variables of (1) Whole inlets;(2) Exposed inlets; and (3) Protected inlets. Table 2 shows the regressions obtained by the first step analysis together with those obtained by the final step analysis. In this table, R indicates the multiple correlation of the regression on each characteristic variables, and numerals in each colomun show the partial regression coefficients of the corresponding external variables.

Table 2. Results of multiple regression analysis on the characteristic variables of throat section.

$$Y = C_0 + \sum_{i=1}^{m} A_i X_i$$

Step	C_0	P	E_{owd}	Θ_{owd}	E_{pwd}	Θ_{pwd}	E_{owv}	Θ_{owv}	E_{pwv}	Θ_{pwv}	V_n	R	Groups
Regressions on throat area;All variables-logarithmic values													
1 st	-.063	.600										.835	Whole
8 th	-.165	.586	-.085	.368	.069	-.261	-.028	.021	-.012			.862	
1 st	-.071	.579										.845	Exposed
8 th	-.189	.564	-.091	.239	.061	-.127	-.187	.008	.058			.865	
1 st	-.001	.655										.824	Protected
Regressions on throat width;All variables-logarithmic values													
1 st	1.188	.405										.843	
2 nd	-.689	.581									-.438	.917	Whole
9 th	-.890	.571	.005	.077	.014	-.004	.021	.029	.001		-.417	.924	
1 st	1.202	.400										.873	
2 nd	-.557	.573									-.411	.933	Exposed
9 th	-1.292	.573	-.063	.173	.073	.092	.048	.060	-.036		-.407	.945	
1 st	1.154	.411										.772	Protected
2 nd	-.842	.569									-.459	.864	
Regression on the direction of throat section;Original values													
1 st	-60.0									.880		.964	Exposed

From this table, the following facts can be found;

A. On the regressions of throat area.

1). Tidal prism has been introduced into every regression obtained by the first step analysis. This indicates that tidal prism is the most predominant external variable for throat area.

2). The first step regressions are barely improved by introducing additional external variables into the analysis. In case of exposed inlets, R of the first step regression is 0.845. However, R of the eight step regression is only o.865.

B. On the regressions of throat width.

1). Tidal prism is the most predominant external variable for throat width. In case of exposed inlets, R of the first step regression is 0.873.

2). Mean rate of tidal flow is the next predominant variable for throat width. The first step regressions are all improved considerably by the introduction of mean rate of tidal flow into the analysis. In case of exposed inlets, R of the second step regression is improved to 0.933 from 0.873.

3). Second step regressions, however, are barely improved by the performance of further step analysis. In case of exposed inlets, R of the nineth step regression is improved only to 0.945 from 0.933.

C. On the regression on the direction of throat section.

1). Direction of the penetrating wave energy is the most predominant external variable for the direction of throat section.

2). The first step analysis gave quite satisfactory regression on the direction of throat section as shown below.

$$\Theta_{ts}(\text{degree}) = -60.0 + 0.88\,\Theta_{pwv}(\text{degree})$$

where R of this regression is 0.964.

Figure 5 shows the relationship between the measured values of throat area of whole inlets and those estimated by the eighth step regression shown in table 2. In this figure, abscissa indicates the scale for the measured values of throat area, and ordinate the scale for the estimated values of throat area. As it can be seen from this figure, measured values of throat area scatter considerably around the estimated values of them. This fact shows that multiple regression analysis could not derive the satisfactory regression even after the introduction of eight external variables into the analysis.

In figure 6, measured values of throat width are plotted against the corresponding values of throat width estimated by the nineth step regression shown in table 2. In this figure, abscissa shows the scale for measured width and ordinate the scale for estimated width. Measured values of throat width still scatter around the estimated values of throat width. This fact also indicates that nineth step regression on throat width was not satisfactory enough.

Figure 7 shows the result of the first step analysis on the direction of throat section. In this figure, abscissa indicates the scale for the direction of penetrating wave energy and ordinate the scale for the direction of throat section. As it can be seen from this figure, data of θ_{ts} fall fairly close around the first step regression. Standard deviation of θ_{ts} from the regression was 28.4°. This fact indicates that the first step regression on θ_{ts} is quite satisfactory one. Here, some explanation should be added on the magnitude of Θ_{pwv}. Figure 8 shows the mutual relationship between θ_{ts} and Θ_{pwv} for the various magnitude of Θ_{ts}. As it can be seen from this figure, Θ_{pwv} becomes greater than 360° when Θ_{ts} becomes ~~greater~~ than 260°. In this case, Θ_{pwv} + 360 was used for the analysis of Θ_{ts} instead of Θ_{pwv}.

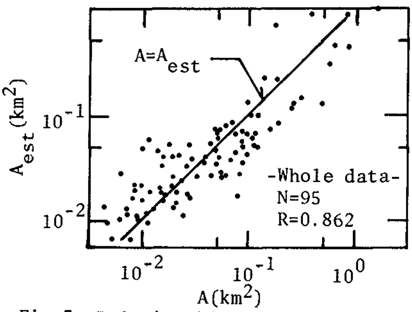

Fig-5. Relationship between A and A_{est}.

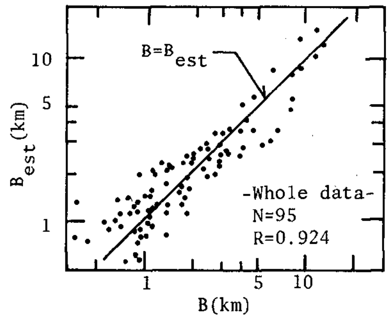

Fig.-6. Relationship between B and B_{est}.

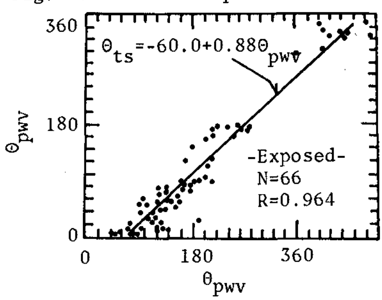

Fig.-7. Relationship between θ_{ts} and θ_{pwv}.

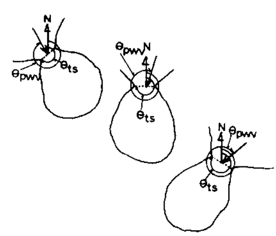

Fig.-8. Measurement of Θ_{pwv} against θ_{ts}.

DISCUSSION

In the previous Chapter, the author showed that the first step analysis or the simple regression analysis derived quite satisfactory regression on the direction of throat section. He also showed that satisfactory regressions were not obtained on both throat area and throat width by the performance of multiple regression analysis into which more than eight external variables were introduced.

This may be caused by the effects of the following factors which were not taken into account in the previous analysis;
1). Geometrical features of inlets and their backed bays.
2). Geological features around the inlets and their backed bays.
In these two factors above, geometrical features may control the contribution rate of the external variables to throat section. Thus, tidal inlets with different geometrical features will probably behave differently even if external variables of the same magnitude were induced on them. If this is true, more reliable regressions may possibly be obtained on both throat area and throat width by performing multiple regression analysis on the data of tidal inlets classified by certain parameters representing geometrical features of tidal inlets and their backed bays.

Then, the author provided the following twelve parameters which are all dimensionless;
1). r_{as}:Throat area/Mean surface area of backed bay
2). r_{bp}:Throat width/Principal axial length of backed bay
3). r_{bs}:Throat width/Shore length of backed bay
4). r_{es}:l_{es}/Shore length of backed bay
5). r_{hna}:Mean depth at throat section/Mean tidal range
6). r_{hnb}:Mean depth at throat section/Throat width
7). r_{hnp}:Mean depth at throat section/Principal axial length of backed bay
8). r_{hxa}:Maximum depth at throat section/Mean tidal range
9). r_{hxb}:Maximum depth at throat section/Throat width
10). r_{hxp}:Maximum depth at throat section/Principal axial length of bay
11). r_{op}:Opening angle of tidal inlet/360°
12). r_{ps}:Principal axial length/Shore length of backed bay
In these parameters above, l_{es} means the circumference of a virtual circle whose area is equal to mean surface area of backed bay.

On the other hand, the following two variables were provided to measure the reliability or the fitness of the final step regressions on both throat area and throat width which were obtained in the previous Chapter;

$$A_{fit}=A_{est}/A \times 100(\%)$$

and

$$B_{fit}=B_{est}/B \times 100(\%)$$

where A_{est} and B_{est} are the values of throat area and throat width estimated by their final step regressins shown in table 2.

In order to see the influence of the geometrical parameters upon A_{fit} and B_{fit}, correlation analysis was performed among them. Table 3 summarizes the results of analysis. From this table, the following facts can be noticed;
1). A_{fit} of both exposed inlets and protected ones has relatively high correlation with r_{as} or the ratio of throat area to mean surface area of backed bay.
2). B_{fit} of both exposed and protected inlets has considerably high correlation with r_{hxb} or the ratio of the maximum depth at throat section to throat width.

Table 3. Correlation coefficients between each of A_{fit} and B_{fit} and twelve parameters representing geometrical features of inlets and bays.

	(Exposed inlets,N=66) (Both orig)		(Both log)		(Pars log)		(Protected inlets,N=29) (Both orig)		(Both log)		(Pars log)	
Parameters	A_{fit}	B_{fit}	A_{fit}	B_{fit}	A_{fit}	B_{fit}	A_{fit}	B_{fit}	A_{fit}	B_{fit}	A_{fit}	B_{fit}
r_{as}	-.463	.216	*.608	.026	-.604	.029	-.574	.127	*.702	.154	-.604	.119
r_{bp}	-.326	-.520	-.427	-.554	-.437	-.519	-.385	-.611	-.498	-.737	-.433	-.729
r_{bs}	-.320	-.560	-.458	-.583	-.420	-.557	-.471	-.437	-.668	-.553	-.622	-.558
r_{es}	.191	.257	.221	.368	.129	.334	.641	.297	.609	.285	.579	.289
r_{hna}	-.403	.217	.526	.324	-.463	.285	-.290	.119	-.596	.387	-.568	.361
r_{hnb}	-.032	*.754	-.054	*.704	-.076	.685	-.027	*.939	-.083	*.954	-.043	*.927
r_{hnp}	-.348	.312	-.398	.137	-.426	.150	-.497	.349	-.609	.395	-.494	.364
r_{hxa}	-.297	.254	.428	.345	-.330	.314	-.298	.143	-.572	.390	-.518	.371
r_{hxb}	.018	.716	.038	*.745	.048	*.734	-.013	*.894	-.036	*.936	.022	*.910
r_{hxp}	-.286	.319	-.344	.174	-.345	.186	-.437	.362	.548	.372	-.412	.350
r_{op}	-.056	-.249	-.036	-.193	-.061	-.196	.025	-.187	.047	-.223	.064	-.219
r_{ps}	.057	.030	-.015	-.000	.073	-.019	-.457	.173	-.470	.211	-.495	.187

Note: (1). Both-orig; Values of A_{fit}, B_{fit} and parameters are original
(2). Both-log; Values of A_{fit}, B_{fit} and parameters are logarithmic
(3). Pars-log; Values of parameters are logarithmic although values of A_{fit} and B_{fit} are original

Figure 9 shows the distribution of A_{fit} of both exposed and protected inlets plotted against their corresponding values of r_{as}. From this figure, it can be seen that tidal inlets may be classified into the following three groups due to the magnitude of r_{as}.

1). Group in which throat area is alwaps overestimated by the final step regression.
2). Group in which throat area is always underestimated by the final step regression.
3). Group between the two above.

On the other hand, figure 10 shows the distribution of B_{fit} of both exposed and protected inlets plotted against their corresponding values of r_{hxb}. From this figure, it can be noticed that tidal inlets may also be classified into similar groups due to the magnitude of r_{hxb}.

1). Group in which throat width is always overestimated by the final step regression.
2). Group in which throat width is always underestimated by the final step regression.
3). Group between the two above.

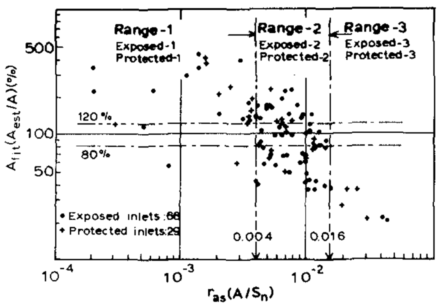

Fig.-9. Relationship between A_{fit} and r_{as}.

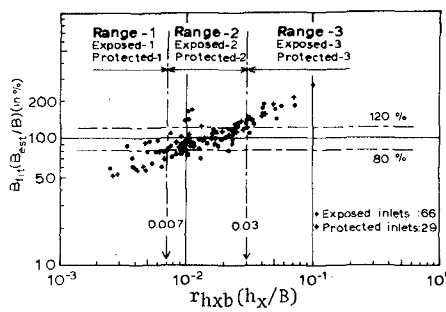

Fig-10. Relationship between B_{fit} and r_{hxb}.

Basing on these findings, tidal inlets were classified into the following groups shown in table 4 for the analysis of throat area.

Table 4. Classification of tidal inlets due to both exposure condition and magnitude of geometrical parameter, r_{as}.

Range of r_{as}	Groups classified	Sample number
$r_{as} < 0.004$	Exposed-1 Protected-1	14 10
$0.004 \leqslant r_{as} < 0.016$	Exposed-2 Protected-2	50 15
$r_{as} \geqslant 0.016$	Exposed-3 Protected-3	2 4

For the tidal inlets involved in Groups 1 and 2, stepwise multiple regression analysis was performed on their throat areas. Table 5 summarizes the final step regressions on them.

Table 5. Final step regressions on throat area of the classified inlets due to both exposure condition and geometrical parameter, r_{as}.

$$Y = C_0 + \sum_{i=1}^{m} A_i X_i$$

Step	C_0	P	E_{owd}	Θ_{owd}	E_{pwd}	Θ_{pwd}	E_{owv}	Θ_{owv}	E_{pwv}	Θ_{pwv}	R	Groups
8 th	-1.652	.681	-.103	.902	.375	-1.049	-.012	.707	-.176		.970	Exposed-1
8 th	.181	.831	-.134	.299	.135	.016	-.153	-.022	.039		.945	Exposed-2
1 st	.153	.856									.933	Protected-1
1 st	.430	.819									.976	Protected-2

As it can be seen through the values of R in table 5, the former regressions on throat area were improved significantly by introducing geometrical parameter, r_{as}, into the analysis.

Figure 11 shows the distribution of throat areas of tidal inlets(Exposed-2) estimated by the corresponding final step regression plotted against their corresponding values of measured throat areas. From this figure, it can be noticed clearly that the regressions shown in table 5 are quite reliable ones.

Similar analysis was performed on throat width. Namely, tidal inlets were classified into the following groups due to both exposure condition and magnitude of geometrical papameter, r_{hxb}.

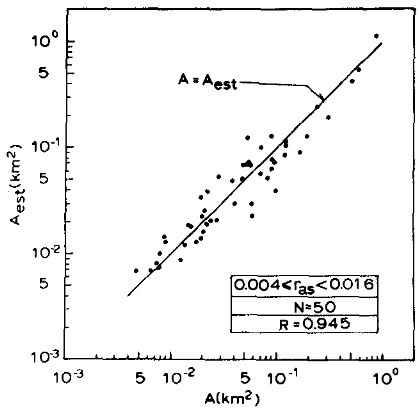

Fig.-11. Relationship between A and A_{est}.

Table 6. Classification of tidal inlets due to both exposure condition and magnitude of geometrical parameter, r_{hxb}.

Range of r_{hxb}	Groups classified	Sample number
$r_{hxb} < 0.007$	Exposed-1 Protected-1	11 9
$0.007 \leqslant r_{hxb} < 0.030$	Exposed-2 Protected-2	41 14
$r_{hxb} \geqslant 0.030$	Exposed-3 Protected-3	14 6

For the inlets of each group, multiple regression analysis was performed stepwise on their throat width. Table 7 summarizes the final step regressions on them.

Table 7. Final step regressions on throat width of the classified inlets due to both exposure condition and geometrical parameter, r_{hxb}.

$$Y = C_0 + \sum_{i=1}^{m} A_i X_i$$

Step	C_0	P	E_{owd}	Θ_{owd}	E_{pwd}	Θ_{pwd}	E_{owv}	Θ_{owv}	E_{pwv}	Θ_{pwv}	V_n	R	Groups
9 th	-.833	.387	-.225	.540	-.061	-.168	.116	.447	.041		-.077	.999	Exposed-1
9 th	-1.058	.478	-.027	.106	.060	.140	.018	.051	-.023		-.341	.971	Exposed-2
6 th	.341	.583	.241	--	.200	--	-.293	--	.093		-.184	.822	Exposed-3
2 nd	-1.770	.594									-.693	.993	Protected-1
2 nd	-.630	.529									-.395	.983	Protected-2
2 nd	-2.996	.937									-.150	.990	Protected-3

In this analysis, quite high value of multiple correlation was also obtained for each group of tidal inlets except the case of Exposed-3. This fact indicates that former regressions on throat width were improved significantly by introducing geometrical parameter, r_{hxb} into the analysis.

Figure 12 shows the distribution of throat width (Exposed-2) estimated by the corresponding final step regression in table 7 plotted against their corresponding values of measured throat width. From this figure, it can be noticed clearly that the regressions shown in table 7 are quite reliable ones except the regression for Exposed-3.

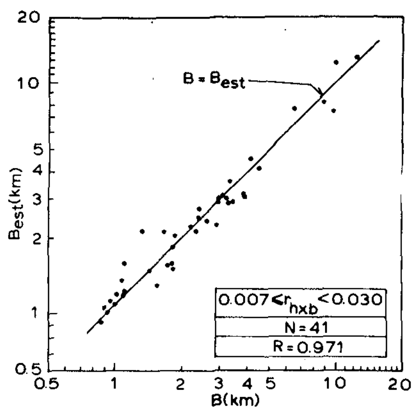

Fig.-12. Relationship between B and B_{est}.

CONCLUSION

Tidal inlets on the Pacific coast of Japan were studied with respect to three characteristic variables of their throat sections:(1) Throat area;(2) Throat width; and (3) Direction of throat section. For each of these three variables, multiple regression analysis was performed stepwise by introducing external variables such as tidal prism, mean rate of tidal flow, wind energy, wave energy and so on one by one into a linear regression model. Exposure condition of throat section to open sea and geometrical parameters of inlets and bays were also introduced into the analysis. As a result, the following facts were found;

1). Quite reliable regressions are found between throat area and external variables if the tidal inlets are classified due to the magnitude of geometrical parameter, r_{as} which is the ratio of throat area to mean surface area of the backed bay. These regressions are shown in Table 5.

2). Quite satisfactory regressions are found between throat width and external variables if the tidal inlets are classified due to the magnitude of geometrical parameter, r_{hxb} which is the ratio of the maximum depth at the throat section to throat width. These regressions are shown in Table 7.

3). Direction of the penetrating wave energy is the most predominant external variable for the direction of throat section, and quite reliable regression shown below is obtained for the exposed inlets.

$$\Theta_{ts}(\text{degree}) = -60.0 + 0.88\ \Theta_{pwv}(\text{degree})$$

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