cgFLOAT©

designed for Microsoft Windows

USER'S Manual

RUNET®
software & expert systems

http://www.runet-software.com

Contents

1. About cgFLOAT

Although the structural modeling of a floating bridge or breakwater poses no particular difficulty, the implementation of the short crested waves in the nodal loads needs to be done carefully.
The response calculation can be done with existing computer programs (SAPIV, STRUDL, NASTRAN, ...) with additional help from other programs, to simulate the sea state and process the results. This procedure can prove to be time and money consuming, risking the opportunity of errors in the handling and transformation of the data.
The program cgFLOAT, combines fluid structure and stochastic process theories in one program. In this way the response computation of floating structures is reduced to a routine problem.

The following aspects have been implemented in the program:

1. Flexibility and ease of modeling with reduction of input data for floating bridges and breakwaters.
2. Continuous structures as well as structures with flexible connectors.
3. Frequency and time domain analysis.
4. Boat wake analysis.
5. Frequency dependent hydrodynamic coefficients.
6. Short-crested waves.
7. Wave Time series simulation from wave spectra.
8. Monte Carlo simulation of random sea state.
9. Programming optimisation for reduced cost and central memory requirements.
10. Graphical output of results in convenient format.

Following is a brief theoretical background of the program (more in this can be found in ref. 6)
Additional publications, references 25 to 34.
Verification of the accuracy of the program has been done with the response of the original Hood-Canal bridge for which there exist actual field measurements under various wave loadings, Ref. [9, 10, 18].

2. How to get started

Short introduction

You run **cgFLOAT**. Open a file in a folder you choose.
In cgFLOAT you complete all the data in the corresponding pages. (General, Load correlation, pontoons, connectors, Hydr. Coefficients, Wave data).
In the page Computations, by pressing **Run Float**, the FLOAT computational modulus is running and the output is created and text shows on the screen. You can preview the output file with Note-Pad or Word with the corresponding buttons.
In the page Graphics you can see the graphical output (mode shapes, frequency domain, and time domain analysis), by pressing the button Show Graphs.
It will be helpful to follow the examples in the \DOC\Examples\ pdf or word files.
With the menu [Tools/Unit Conversion], and [Tools/Cross Section Areas] extra tools to help you converting units or to compute cross-section areas are included.

Files

The program is installed in a folder \cgFLOAT. Inside this folder a subfolder \Examples is created, where some examples are included and a folder \Projects, where you may create your project files.

The files in the folder \cgFLOAT are :
FLOAT, [Dos application (32 bit)]. The main solution modulus of program FLOAT.
This program runs with Input a text file FL_IN.TXT and produces an output text file FL_OUT.TXT. Both these files are in the same directory with FLOAT.
The Input file structure is described in the program users manual. In this user manual, the word Card means a Line in the text input file. The data in this file must be input in strict format as it is described in the program users manual.

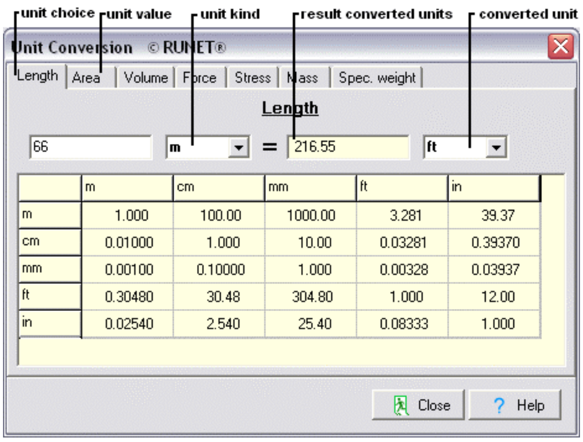
cgFLOAT, [Windows application (32 bit)].
By running this program you create the input text file. The Float program runs automatically from inside cgFLOAT and consequently you obtain the output text file. cgFLOAT creates its own data file in a folder the user specifies. The main file with the data has the form FileName.FDT.
cgFLOAT also creates in the same folder with the FileName.FDT, the files FileName_INP.TXT and FileName_OUT.TXT files that are the input and output file of the program FLOAT. So to work with the results you simply open with a text editor the file File_Name_OUT.TXT.

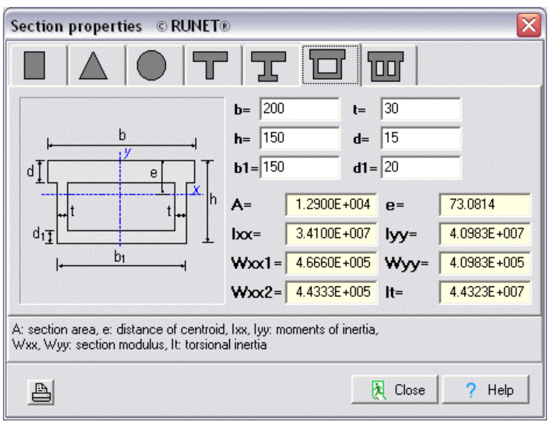
\Examples
Example01: floating breakwater with rigid connectors. Loading, standard spectrum.
Example02: floating breakwater with rigid connectors. Loading, standard spectrum.
Example03: floating breakwater with flexible. Loading, standard spectrum.
Example04: floating breakwater rigid connectors. Unequal pontoons
Example05: floating breakwater with flexible connectors. Unequal pontoons

In the folder \Doc for each example a doc or a pdf file is included with step-by-step directions of how to run the program with the particular example.

Tools

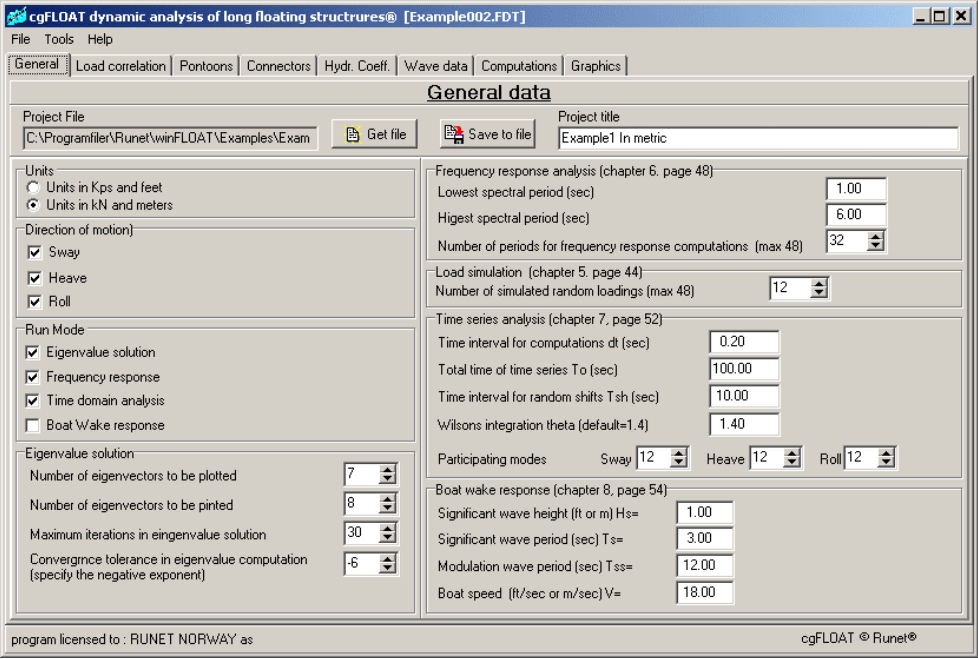
From the menu Tools:





3. Running an example

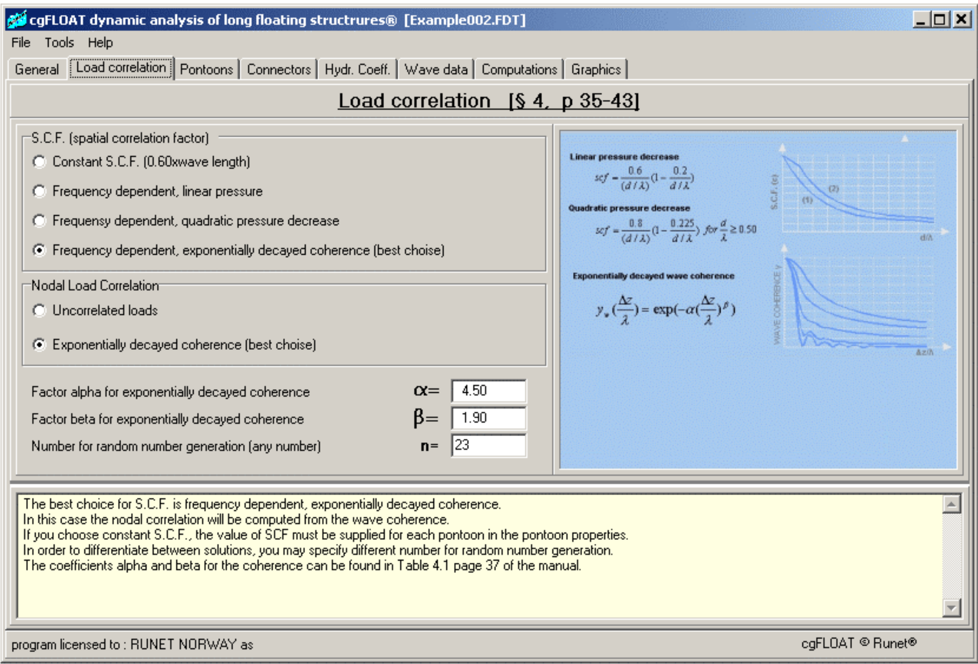
General data



After you open the file, the data are saved at various moments automatically.
Chapters Frequency Domain Analysis, Time Domain Analysis, Boat Wake Response explain the methods of analysis.

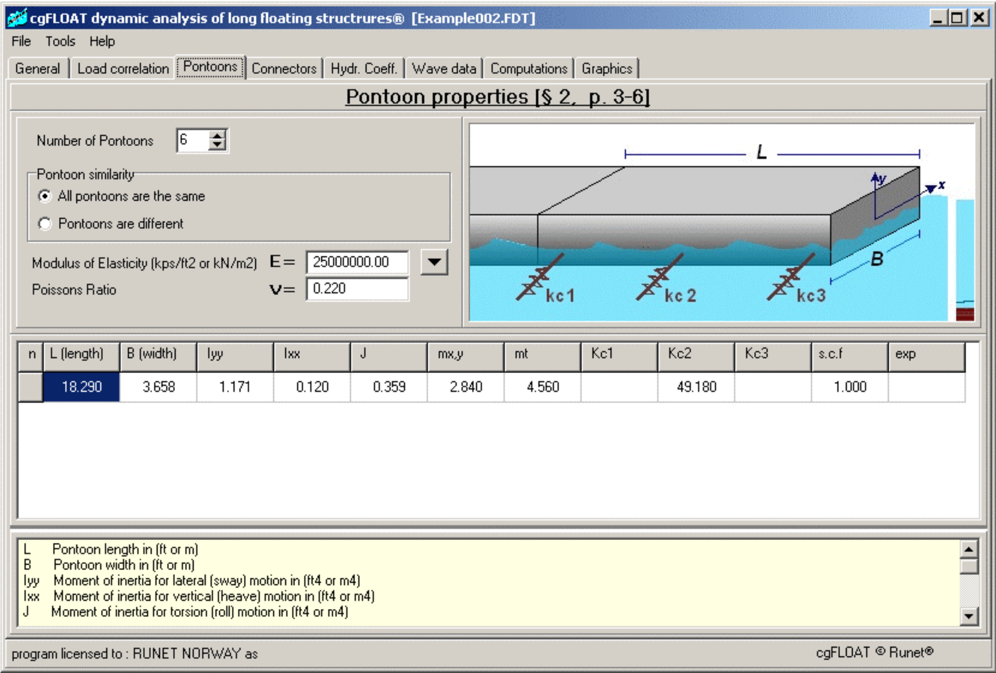
Load Correlation

The Load Correlation is explained in Spatial Correlation of Nodal Loads

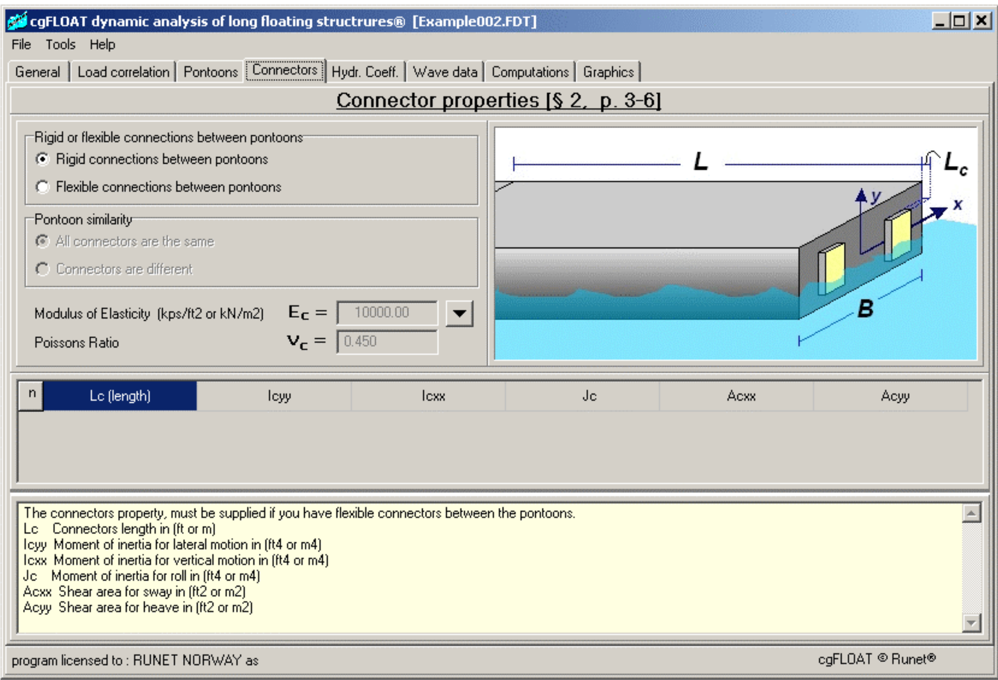


Pontoon Properties

The structural model is explained in Structural Model
Pontoons Properties



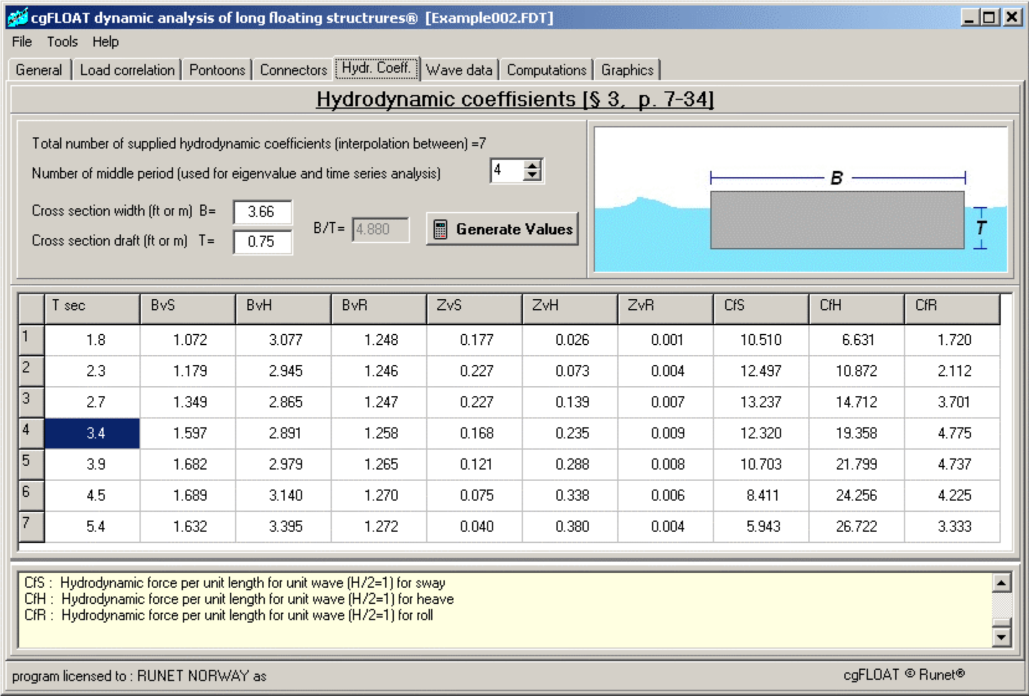
Connectors properties



Hydrodynamic coefficients

The values for the hydrodynamic coefficients are created automatically by pressing the button Generate Values. Chapter 3 of the users manual has the corresponding tables of hydrodynamic coefficients. The values for the added mass are (1+β) where b the values of the tables, (structural mass + added mass)/structural mass.

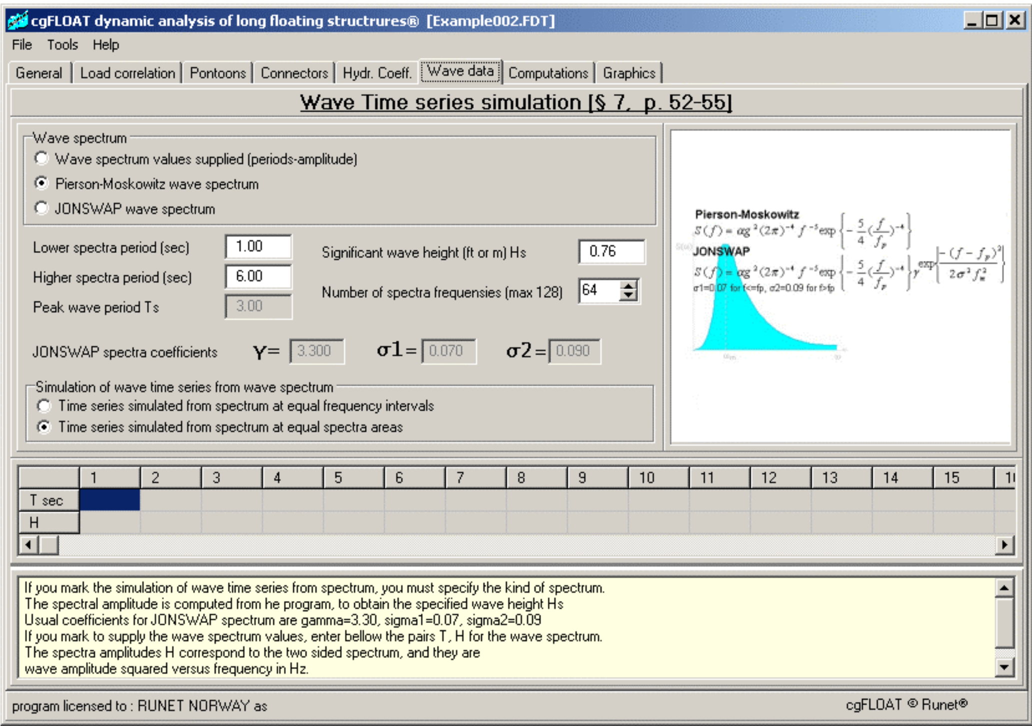
More about hydrodynamic coefficients



Wave data

Boat Wake Response

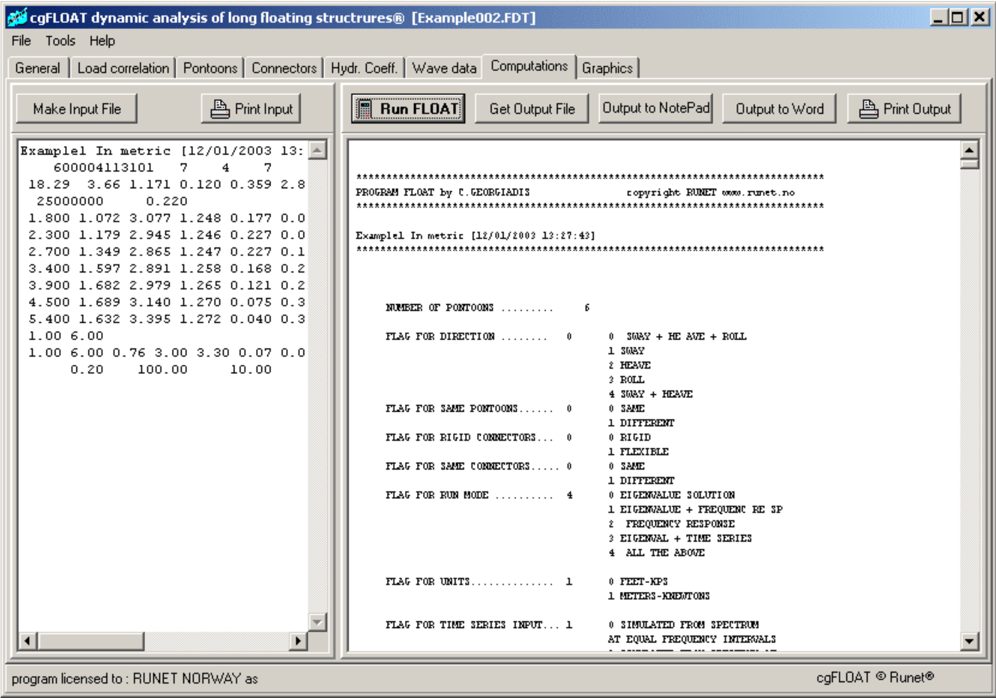
Wave Coherence



cgWindwaves A program for Forecasting of wind generated waves

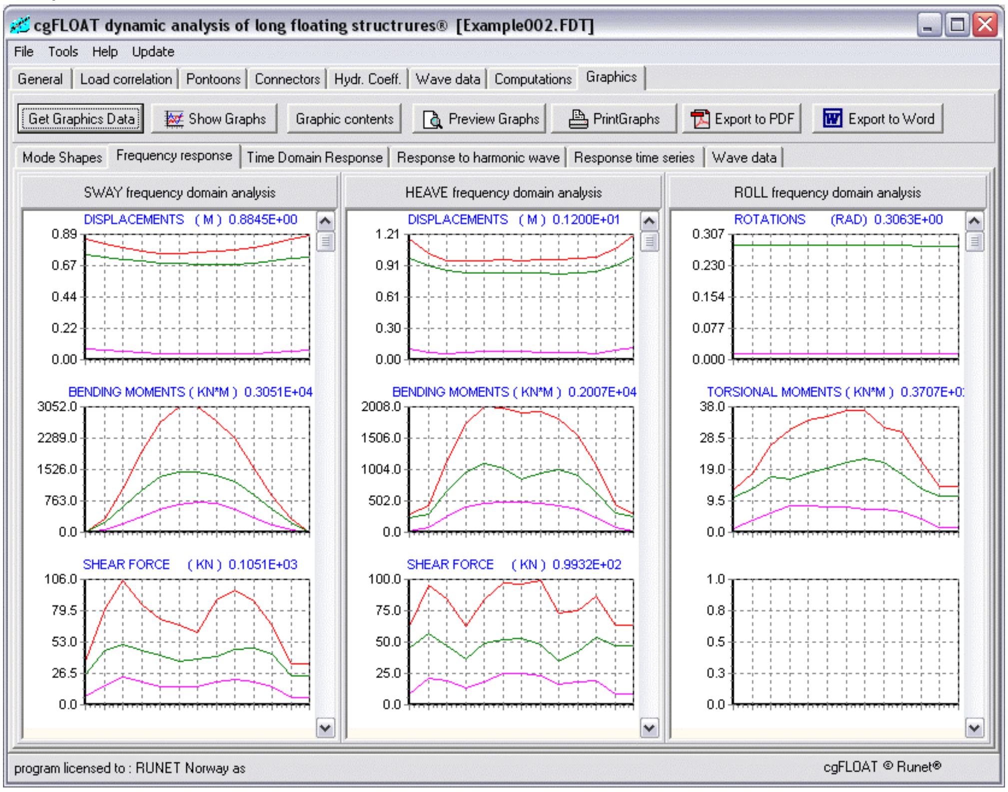
Computations

Press **Run FLOAT** to run the main computation modulus.
The output file is created in the directory of the data file and has the ending FileName_OUT.TXT.
With the buttons [Output to NotPad] and [Output to Word] you can preview the output file from the NotPad or the Word.



Graphic results

These graphic results can be preview or printed:
Mode shapes - Frequency response - Time domain Response - Response to harmonic wave
Responce time series - Wave data



4. Structural Model

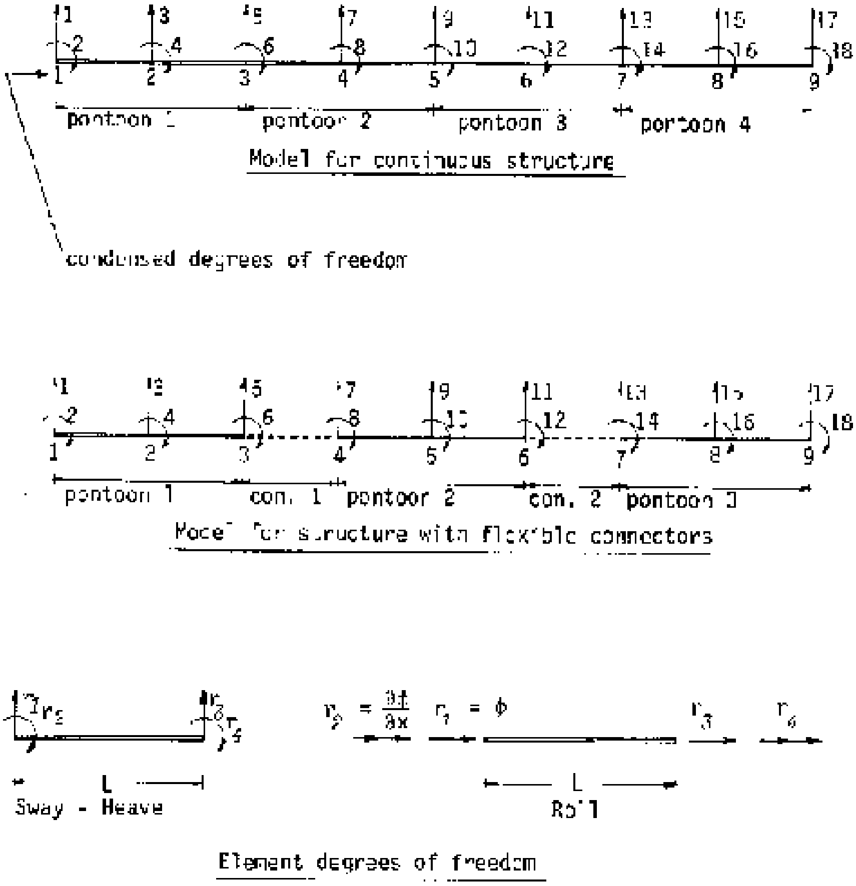
The program computes the response of straight floating bridges and breakwaters. In such cases neglecting the small coupling between sway and roll due to hydrodynamic mass and damping, the response can be considered uncoupled for the three directions of motion; sway, heave, roll. A future extension of the program will be for the case of curved bridges, where the response is three-dimensional.

Finite beam elements of half pontoon length, and linear elastic springs for the lateral anchoring are used in the structural modeling. A consistent mass and bouyancy matrix is used, based on a third degree polynomial element displacement field Ref. [5], [24]. The structural idealization as well as the stiffness and mass matrices are shown in Figures 2.1 a, b.
In the same figures are shown the stiffness matrices for flexible connectors (if any exist between the pontoons), based on a constant curvature displacement field due to their smaller length.

Elastic springs for the lateral anchoring can be specified at the ends and middle of each pontoon. The nodal point spacing can be chosen closer than half pontoon length by specifying pontoons shorter than the actual ones. In the later case and in case of a structure with connectors, very stiff connectors should be specified to simulate the rigid connections between the shorter pontoons (see Fig 2.2).

Assembling the structure stiffness and mass matrices and condensing the rotational degrees of freedom, the equations of motion are:

$$[m]\{\ddot{r}(t)\} + [c]\{\dot{r}(t)\} + [k]\{r(t)\} = \{R(t)\} \qquad (2.1)$$



$$[K_B^p] = \frac{E_p I_p}{L^3}\begin{bmatrix} 12 & -6L & -12 & -6L \\ -6L & 4L^2 & 6L & 2L^2 \\ -12 & 6L & 12 & 6L \\ -6L & 2L^2 & 6L & 4L^2 \end{bmatrix}$$

Bending stiffness
for pontoons

$$[K_T^p] = \frac{G_p J_p}{30L}\begin{bmatrix} 36 & -3L & -36 & -3L \\ -3L & 4L^2 & 3L & -L^2 \\ -36 & 3L & 36 & 3L \\ -3L & -L^2 & 3L & 4L^2 \end{bmatrix}$$

Torsional stiffness
for pontoons

$$[K_W^p] = \frac{sL}{420}\begin{bmatrix} 156 & -22L & 54 & 13L \\ -22L & 4L^2 & -13L & -3L^2 \\ 13L & -3L^2 & 22L & 4L^2 \end{bmatrix}$$

Buoyancy stiffness

$s = wb$ Heave

$s = wb^3/12$ Roll

w : water specific weight

b : cross - section width

$$[M^p] = \beta\frac{mL}{420}\begin{bmatrix} 156 & -22L & 54 & 13L \\ -22L & 4L^2 & -13L & -3L^2 \\ 54 & -13L & 156 & 22L \\ 13L & -3L^2 & 22L & 4L^2 \end{bmatrix}$$

Mass matrix

$$\beta = \left(\frac{hydr. + struct.mass}{struck.mass}\right)$$

$$m = \iint_{A_c} \rho \, g \, dA \text{ (Heave, Sway)}; \; m = \iint_{A_c} \rho \, g r^2 \, dA \text{ (Roll)}$$

$$[K_T^c] = \begin{bmatrix} \frac{G_c J_c}{L_c} & 0 & \frac{-G_c J_c}{L_c} & 0 \\ \frac{-G_c J_c}{L_c} & 0 & \frac{G_c J_c}{L_c} & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix}$$

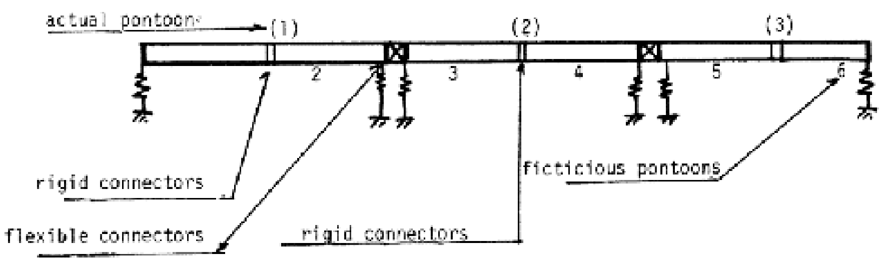
Torsional stiffness connectors

$$[K_B^c] = \begin{bmatrix} \frac{G_c A_c}{L_c} & 0 & \frac{-G_c A_c}{L_c} & 0 \\ 0 & \frac{E_c I_c}{L_c} & 0 & \frac{-E_c I_c}{L_c} \\ \frac{-G_c A_c}{L_c} & 0 & \frac{G_c A_c}{L_c} & 0 \\ 0 & \frac{-E_c I_c}{L_c} & 0 & \frac{E_c I_c}{L_c} \end{bmatrix}$$

Bending stiffness connectors

Stiffness and Mass Matrices

where : [m], [c] virtual mass and damping matrices (structure + Hydrodynamic).
[k] structure stiffness + buoyancy matrix
{R(t)} exciting wave forces
{r(t)} nodal displacements
The above equation is solved in frequency and time domain as discussed in paragraphs 6 and 7 below.



5. Hydrodynamic Coefficients

The hydrodynamic forces in the oscillating structure are: added mass (proportional to the structure acceleration), added damping (proportional to the structure velocity), and exciting force (proportional to the incident wave). The way these forces are computed is described in Ref. 6, and Ref.33. Here are presented in summary some results in tables and graphs for practical use obtained using program HYDRO. Detailed description of the theory behind this program and its use can be found in the above references.

In the graphs and tables following are presented the coefficients:

$\beta_1, \beta_2, \beta_3$ for the **Hydrodynamic mass**.
ξ_1, ξ_2, ξ_3 for the **Hydrodynamic damping**
$\delta_1, \delta_2, \delta_3$ for the **Hydrodynamic exciting forces**.

(where subscripts 1, 2, 3 are used for the three directions of motion: sway, heave, roll).
Using the above coefficients we can get (per unit length of structure):

Added Mass:

sway $M_S = \beta_1(\rho_w A)$ (3.1.a)

heave $M_H = \beta_2(\rho_w A)$ (3.1.b)

roll $M_R = \beta_3 \{\rho_w (B/2)^4 + c^2 \beta_1(\rho_w A)\}$ (3.1.c)

Added Damping:

The above coefficient represent percent of critical damping in respect to the virtual mass.

Exciting Forces:

sway $F_{sway} = \delta_1 (\rho_w g)(B/2)(n(\tau)) = C_F^S n(t)$ (3.2.a)

heave $F_{heave} = \delta_2 (\rho_w g)(B/2)(n(\tau)) = C_F^H n(t)$ (3.2.b)

roll $F_{roll} = \delta_3 (\rho_w g)(B/2)^2 (n(\tau)) + c * F_{sway} = C_F^R n(t) + c * F_{sway}$ (3.2.c)

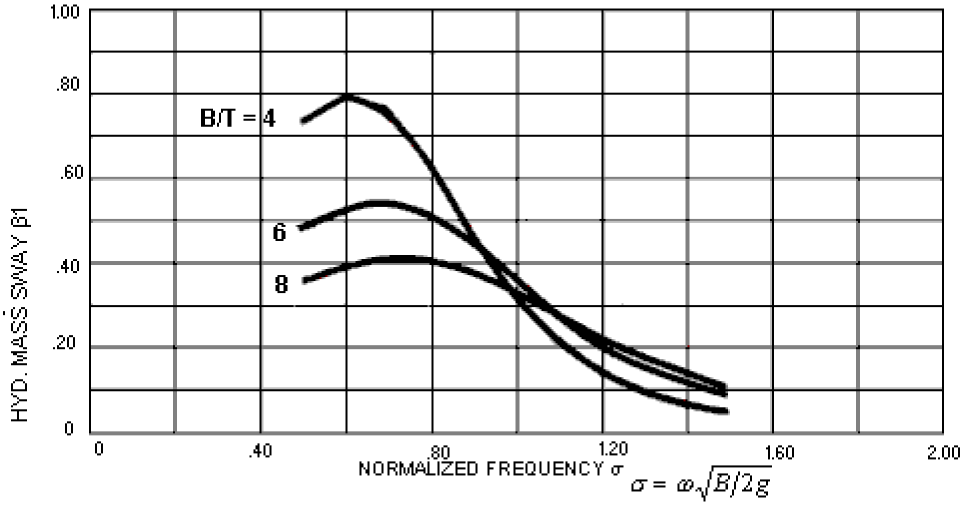
To take into account the directional wave spectrum the coefficients (delta) have been modified, (Table 3.2)

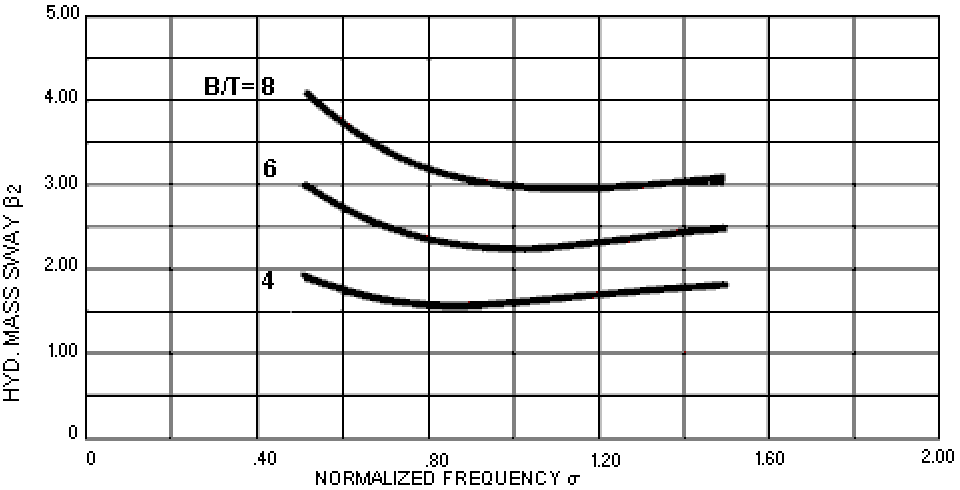
All, the above coefficients are frequency dependent and in the graphs the normalized frequency has been used

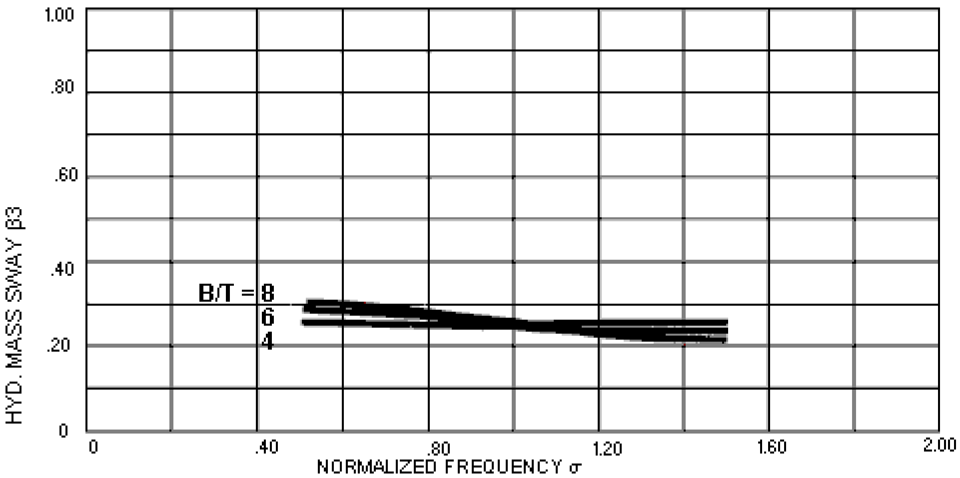
σ Normalized frequency $\sigma = \omega\sqrt{B/2g}$

Hydrodynamic Mass (rectangular section B/T = 4, 6, 8)
Hydrodynamic Damp (rectangular cross section B/T = 4, 6, 8)
Hydrodynamic Force for Wave Direction (rectangular cross section B/T = 4, 6, 8)
Hydrodynamic Exiting Force for Different Wave directions (rectangular cross section B/T = 4)
Hydrodynamic Exiting Force for Different Wave directions (rectangular cross section B/T = 6)
Hydrodynamic Exiting Force for Different Wave directions (rectangular cross section B/T = 8)
Table 3.1 Hydrodynamic Coefficients, Tabulated Results of Figures 3.1, 3.2, 3.3

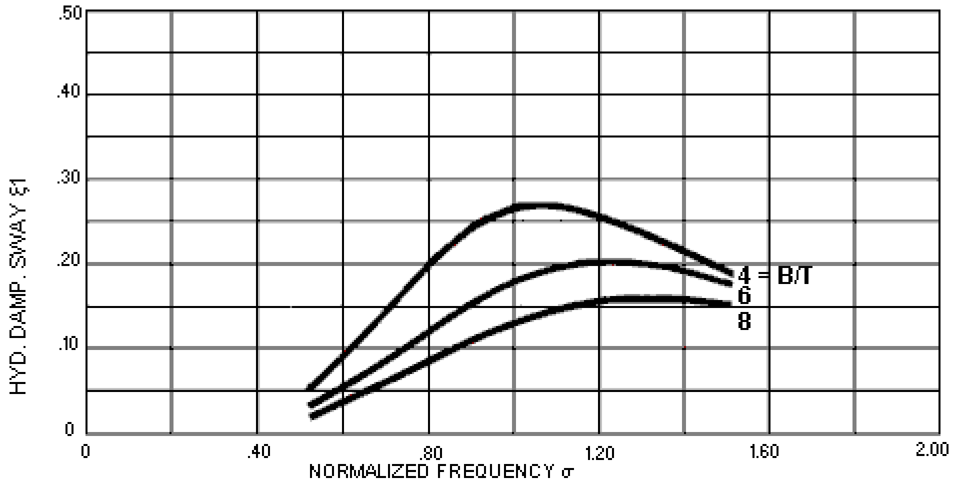
Hydrodynamic Mass

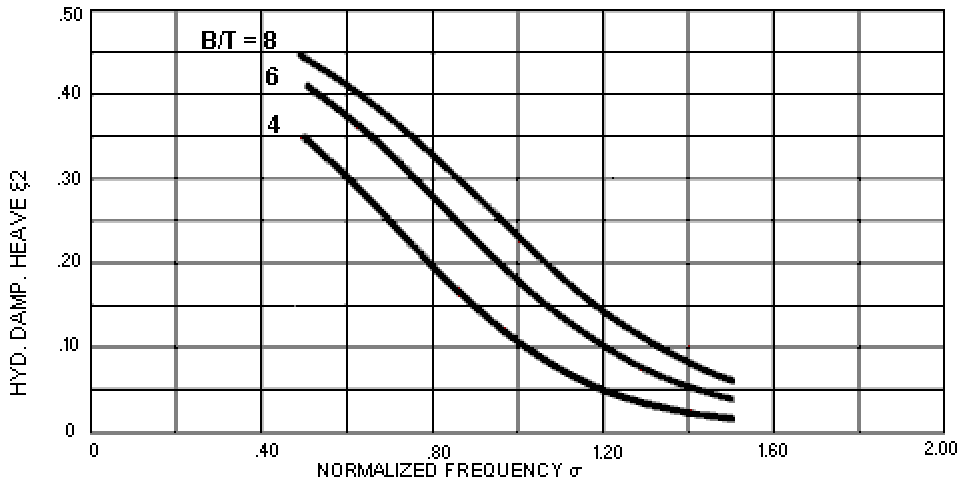


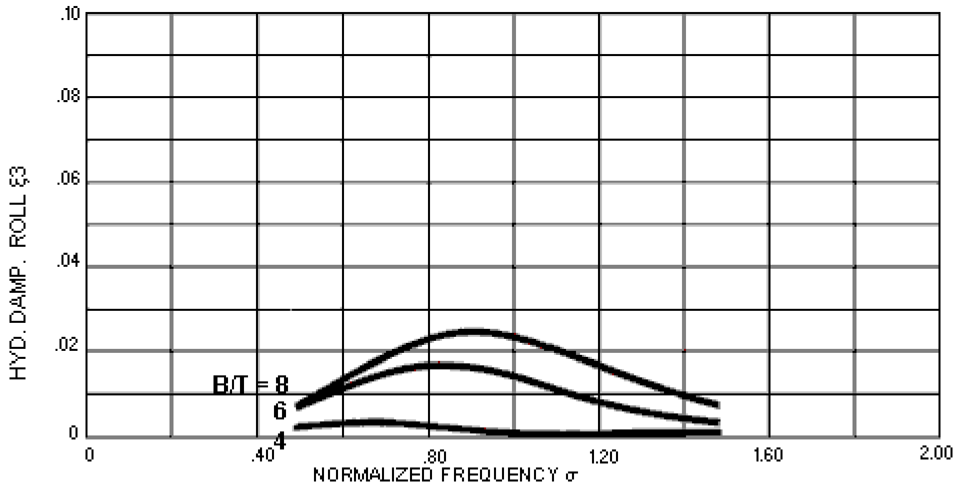




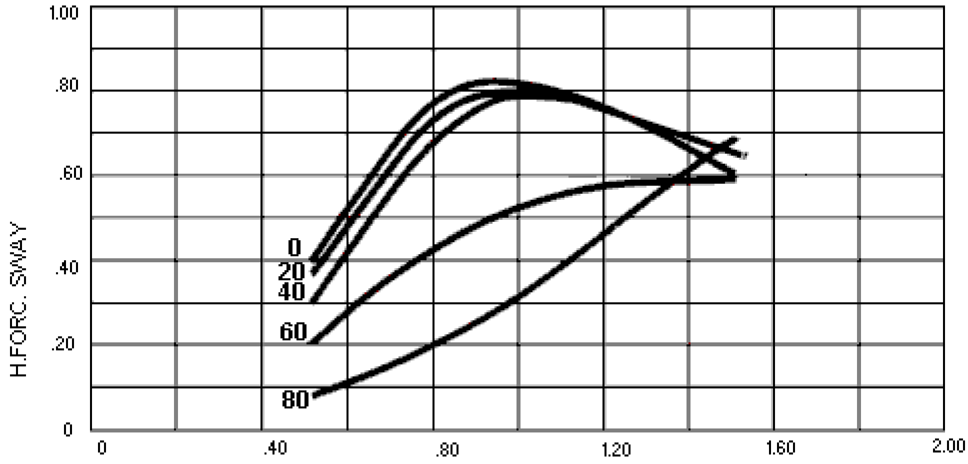
Hydrodynamic Damping

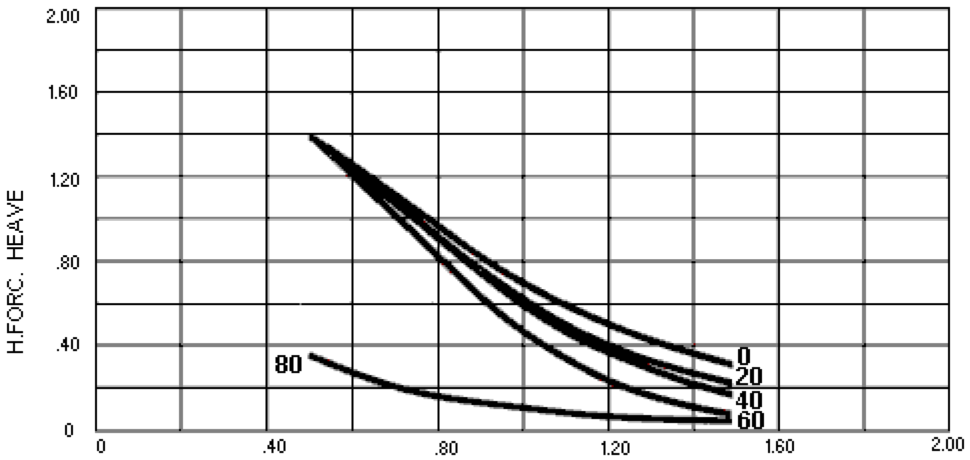


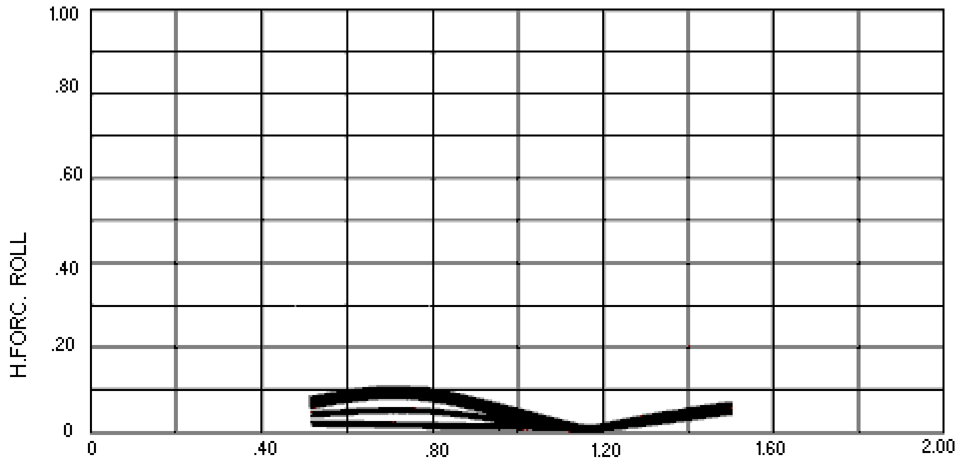




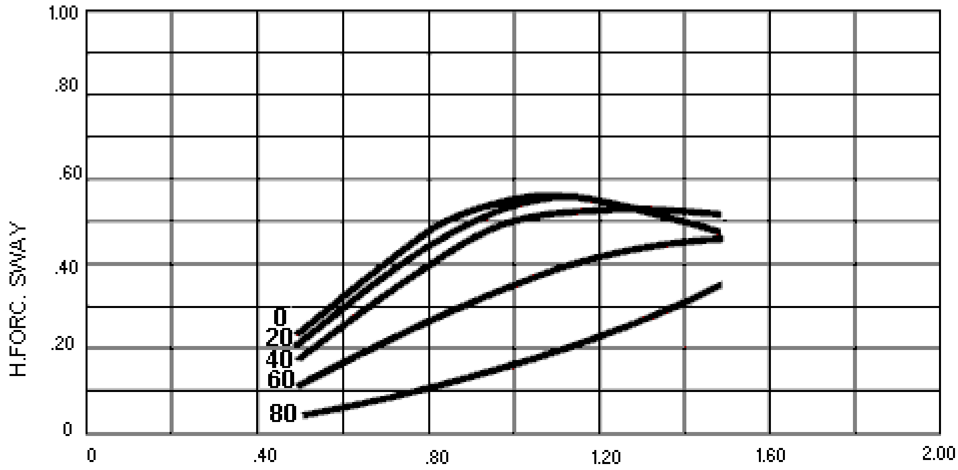
Hydrodynamic Exiting Force 4

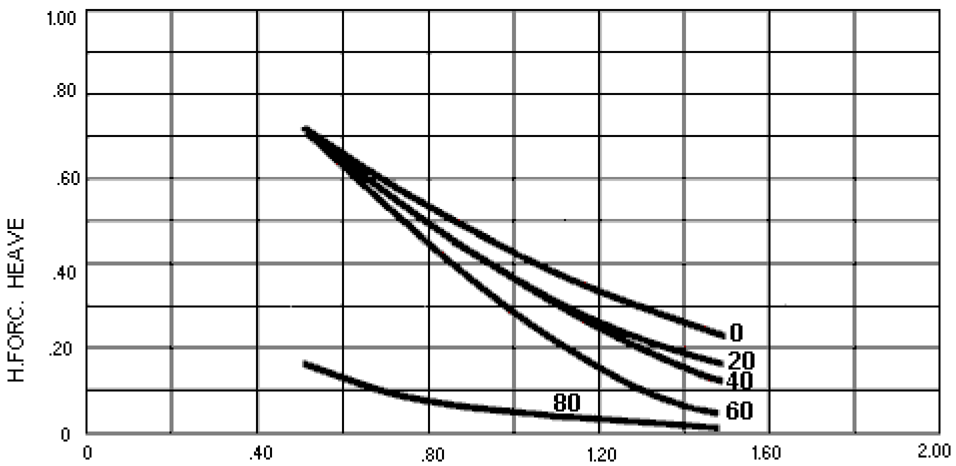


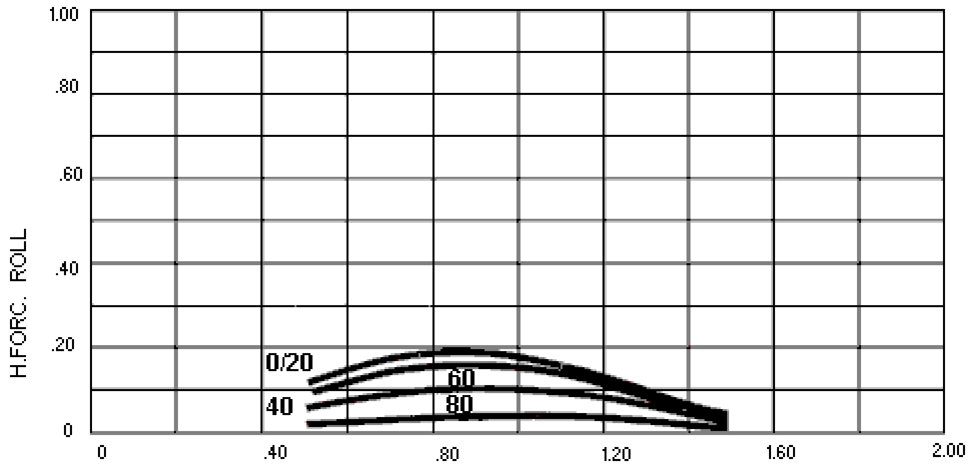




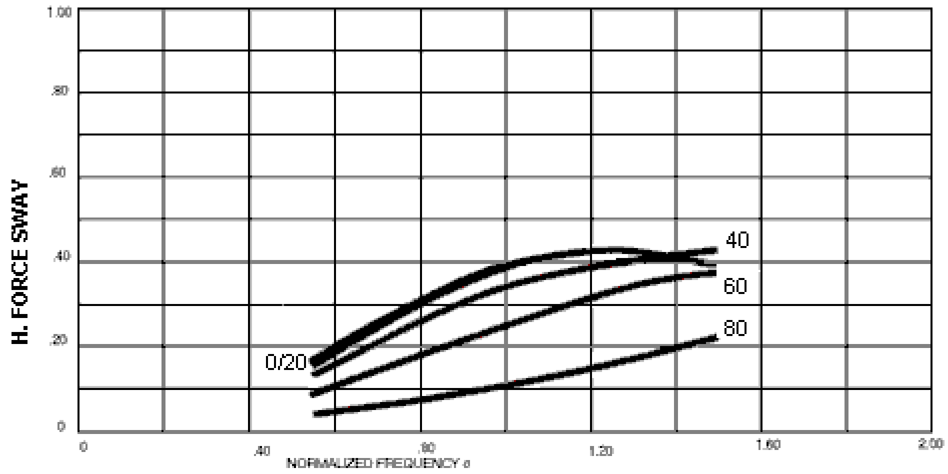
Hydrodynamic Exiting Force 6

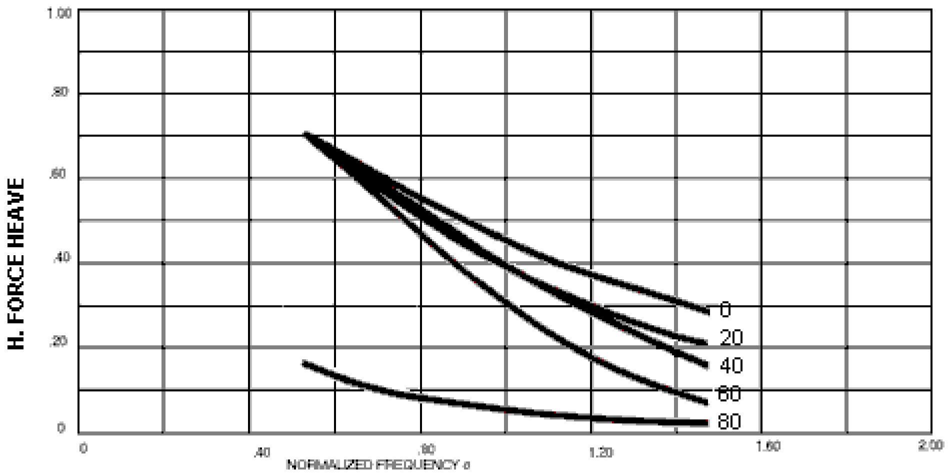


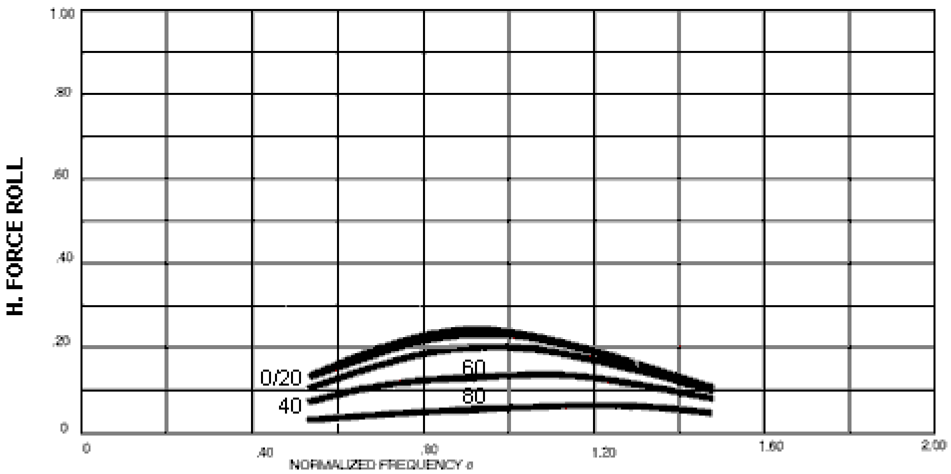




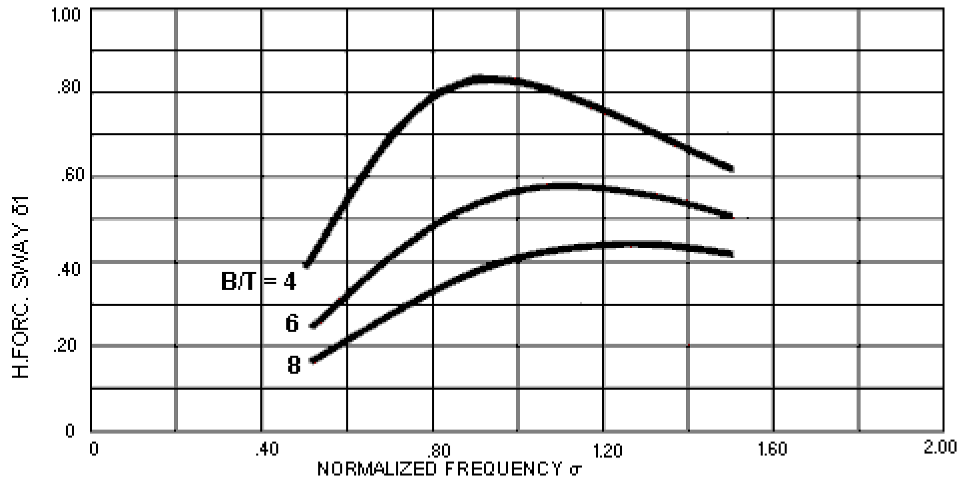
Hydrodynamic Exiting Force 8

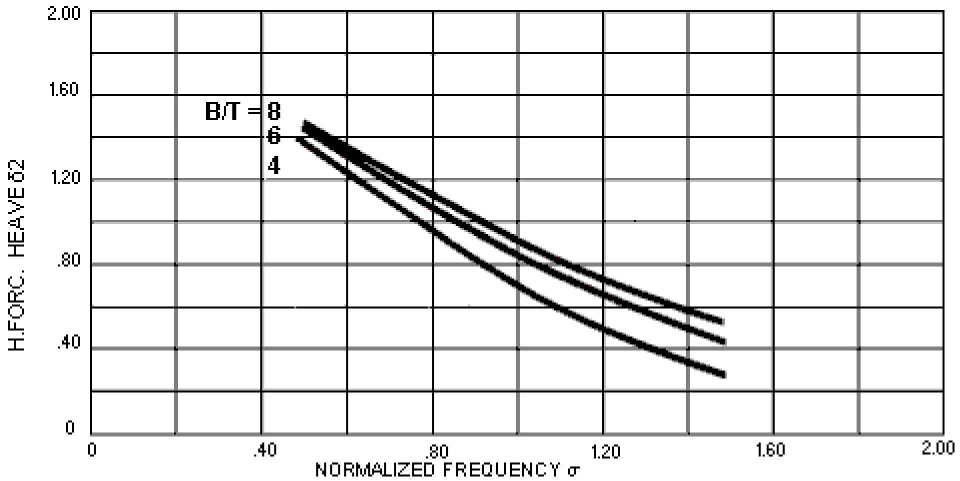






Hydrodynamic Force





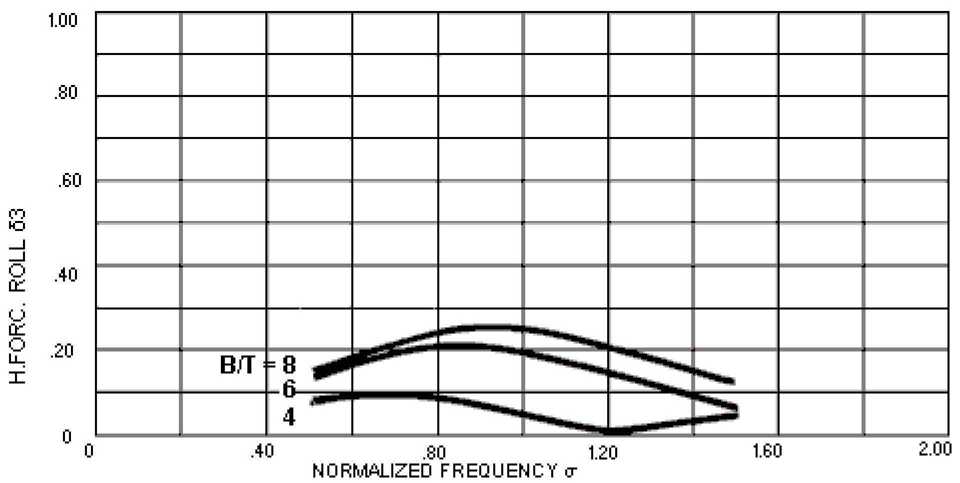


Table 3.1

$\sigma = \omega\sqrt{B/2g}$		MASS			DAMPING			FORCE		
		SWAY	HEAVE	ROLL	SWAY	HEAVE	ROLL	SWAY	HEAVE	ROLL
B/T=4	.50	.742	1.923	.261	.049	.353	.002	.391	1.410	.076
	.60	.806	1.722	.258	.092	.307	.003	.554	1.270	.092
	.70	.778	1.604	.255	.148	.254	.003	.701	1.130	.096
	.80	.650	1.551	.252	.204	.199	.003	.796	.990	.087
	.90	.482	1.546	.251	.245	.149	.001	.832	.854	.068
	1.00	.334	1.575	.251	.264	.107	.001	.824	.727	.045
	1.10	.225	1.621	.253	.264	.074	.000	.794	.614	.022
	1.20	.152	1.672	.254	.251	.051	.000	.754	.516	.002
	1.30	.104	1.720	.255	.230	.034	.000	.708	.433	.017
	1.40	.075	1.758	.255	.207	.024	.000	.661	.360	.031
	1.50	.057	1.784	.255	.184	.017	.001	.615	.291	.042
B/T=6	.50	.491	2.996	.287	.029	.414	.006	.226	1.459	.125
	.60	.541	2.672	.285	.053	.377	.010	.319	1.337	.164
	.70	.559	2.457	.278	.086	.332	.014	.411	1.216	.193
	.80	.529	2.323	.265	.123	.281	.016	.487	1.097	.207
	.90	.458	2.253	.252	.156	.229	.016	.538	.979	.204
	1.00	.369	2.234	.243	.180	.180	.014	.563	.866	.189
	1.10	.284	2.252	.237	.193	.137	.011	.569	.761	.166
	1.20	.213	2.293	.235	.196	.101	.008	.562	.667	.138
	1.30	.159	2.346	.235	.191	.073	.005	.546	.585	.110
	1.40	.119	2.400	.237	.181	.053	.003	.523	.511	.083
	1.50	.090	2.450	.239	.169	.038	.002	.497	.437	.061
B/T=8	.50	.369	4.083	.303	.020	.447	.007	.157	1.484	.138
	.60	.408	3.642	.304	.037	.417	.013	.220	1.370	.182
	.70	.429	3.338	.298	.060	.377	.018	.284	1.260	.219
	.80	.424	3.134	.284	.086	.331	.023	.341	1.152	.244
	.90	.392	3.005	.267	.111	.281	.025	.385	1.046	.252
	1.00	.342	2.937	.251	.132	.232	.024	.414	.942	.247
	1.10	.285	2.917	.239	.147	.186	.021	.431	.845	.230
	1.20	.230	2.933	.232	.155	.145	.017	.437	.756	.206
	1.30	.183	2.972	.228	.157	.111	.013	.436	.677	.177
	1.40	.145	3.025	.227	.154	.083	.010	.428	.605	.148
	1.50	.114	3.081	.228	.148	.062	.007	.413	.533	.122

Table 3.2

σ		H.FORC. THETA=0			H.FORC. THETA= 20			H.FORC. THETA= 40			H. FORC. THETA =60			H.FORC THETA=80		
		SWAY	HEAVE	ROLL	SWAY	HEAVE	ROLL	SWAY	HEAVE	ROLL	SWAY	HEAVE	ROLL	SWAY	HEAVE	ROLL
B/T=4	.50	.375	1.394	.076	.352	1.383	.071	.293	1.375	.059	.191	1.393	.038	.067	.346	.013
	.60	.527	1.244	.092	.495	1.222	.086	.424	1.210	.072	.273	1.203	.046	.100	.256	.017
	.70	.668	1.096	.097	.629	1.059	.091	.563	1.049	.078	.355	1.006	.049	.140	.196	.018
	.80	.767	.954	.089	.726	.897	.083	.684	.896	.074	.425	.813	.045	.188	.152	.018
	.90	.814	.821	.071	.777	.742	.066	.761	.751	.058	.477	.633	.034	.246	.120	.015
	1.00	.817	.701	.048	.791	.601	.044	.786	.614	.036	.513	.473	.021	.311	.095	.008
	1.10	.792	.600	.024	.779	.482	.021	.771	.488	.014	.540	.339	.006	.383	.075	.002
	1.20	.749	.516	.002	.748	.389	.001	.736	.379	.008	.560	.233	.011	.460	.060	.016
	1.30	.697	.445	.017	.703	.319	.020	.697	.289	.025	.572	.155	.026	.538	.047	.032
	1.40	.640	.379	.032	.645	.264	.034	.663	.216	.040	.577	.100	.040	.610	.036	.049
	1.50	.586	.312	.041	.577	.215	.044	.636	.160	.052	.573	.064	.051	.671	.027	.066
B/T=6	.50	.220	1.445	.124	.207	1.433	.117	.171	1.421	.096	.112	1.443	.063	.039	.334	.022
	.60	.309	1.312	.162	.291	1.289	.152	.244	1.268	.126	.159	1.266	.082	.057	.246	.029
	.70	.397	1.183	.190	.374	1.144	.179	.322	1.121	.152	.210	1.082	.098	.077	.187	.036
	.80	.471	1.060	.205	.447	.999	.194	.398	.982	.168	.259	.900	.108	.101	.144	.041
	.90	.524	.944	.205	.502	.858	.194	.460	.851	.172	.305	.728	.111	.128	.113	.045
	1.00	.553	.839	.190	.537	.726	.182	.503	.729	.163	.346	.570	.108	.158	.089	.046
	1.10	.562	.746	.166	.554	.609	.160	.525	.613	.144	.382	.431	.099	.190	.070	.046
	1.20	.553	.668	.137	.554	.514	.133	.531	.505	.120	.412	.315	.086	.227	.055	.043
	1.30	.533	.600	.106	.539	.439	.103	.528	.406	.094	.436	.221	.070	.266	.044	.037
	1.40	.504	.535	.077	.509	.380	.074	.523	.320	.069	.452	.150	.053	.309	.034	.030
	1.50	.472	.463	.055	.467	.325	.048	.517	.247	.046	.459	.100	.036	.352	.027	.021
B/T=8	.50	.154	1.470	.137	.145	1.458	.129	.119	1.444	.106	.078	1.466	.069	.027	.328	.024
	.60	.215	1.347	.181	.230	1.323	.170	.169	1.297	.141	.111	1.297	.092	.039	.240	.032
	.70	.277	1.228	.217	.262	1.188	.205	.222	1.156	.172	.146	1.118	.112	.053	.181	.040
	.80	.333	1.115	.242	0316	1.052	.229	.274	1.022	.194	.182	.942	.128	.068	.139	.047
	.90	.377	1.010	.251	.362	.920	.239	.319	.899	.206	.218	.774	.138	.084	.109	.052
	1.00	.407	.915	.246	.396	.795	.236	.356	.784	.206	.252	.619	.141	.101	.086	.056
	1.10	.424	.831	.228	.419	.683	.222	.381	.677	.195	.286	.482	.139	.120	.068	.056
	1.20	.428	.759	.202	.430	.590	.199	.399	.574	.176	.316	.363	.132	.141	.053	.056
	1.30	.422	.696	.170	.428	.516	.169	.410	.478	.153	.343	.0264	.120	.163	.042	.053
	1.40	.409	.633	.138	.414	.456	.135	.420	.389	.129	.364	.186	.105	.188	.032	.050
	1.50	.390	.563	.112	.388	.401	.103	.428	.310	.105	.377	.128	.087	.214	.025	.045

6. Spatial Correlation of Nodal Loads

To deal with the short-crested waves, two methods have been implemented in the program to take into account the spatial correlation of the wave loading.
The first is the S.C.F. method which consists of weighting the nodal loads by a factor to take into account the fact that the wave pressure is not fully correlated between nodal points. The nodes are assumed to be far enough so that the nodal loads are uncorrelated. (Measurements in Hood Canal and Evergreen floating bridges show that after a distance 0.6λ the wave forces can be considered uncorrelated, Ref. 9, 18, 20.)
The S.C.F. factor was developed empirically from measurements on the Hood Canal floating bridge and more about it can be found in Ref. 13.
In fig. 4.1 is shown the variation of S.C.F. with the ratio of nodal distance to wave length. The two curves shown on this figure correspond to linear, curve 1, or quadratic, curve 2, decrease of in-phase loadings from 0 to 0.6λ(lamda).

$$c = \frac{0.6}{d/\lambda}\left(1 - \frac{0.2}{d/\lambda}\right) \qquad (4.1)$$

$$c = \frac{0.8}{d/\lambda}\left(1 - \frac{0.225}{d/\lambda}\right) \qquad (4.2)$$

$$\text{for} \quad \frac{d}{\lambda} \geq 0.5$$

Figure 4.1
Spatial Correlation Factor vs. ratio of nodal distance to wave length

The second method is described in Ref. 6 and consists in a theoretically developed wave correlation. Briefly it is as follows:
The wave coherence along the bridge is assumed to vary exponentially and for two points at distance Δz assumed to be of the form:

$$\gamma_w(\Delta z/\lambda) = \exp\left(-a(\Delta z/\lambda)^{\beta}\right) \qquad (4.3)$$

The values of α and β (beta) depend on the wave directional spectrum. In Fig. 4.2 are shown curves of the form y=exp(-axβ), and in Fig. 4.3 are shown curves for the wave coherence between two points at distance z on the bridge obtained for a directional spectrum of the form:

$$S(f,\theta) = S(f)\cos^{n}(\theta - \theta_0) \qquad (4.4)$$

Using least square fitting the values of α and β can be obtained by fitting curves of fig. 4.2 to those of fig. 4.3. (All these have been done using a small program COHER). Results for α and β values are shown in Table 4.1.
The nodal load cross-spectral densities can be written in the form:

$$S_{RiRj}(\omega) = \bar{\delta}(\omega)\rho_{ij}(\omega)S_w(\omega) \qquad (4.5)$$

where ρij (ω) depends on α, β and the nodal distances and can be easily computed using numerical integration (eight point Gauss quadrature method proved to be adequate).

Then the nodal loads are constructed from N series of uncorrelated loads,
Xi (t), i = 1,....N, as:

$$R_i(t) = \sum_{j=1}^{N} a_{ij} X_j(t) \qquad (4.6)$$

In order for the nodal loads to satisfy (4.5) the computation of aij is reduced to an eigenvalue problem and aij are obtained as:

$$[a_{ij}] = [Q]\cdot[\Lambda]^{1/2}[Q]^T \qquad (4.7)$$

where [Λ] is the eigenvalue matrix of [pij] in respect to a unit matrix and [Q] are the corresponding eigenvectors.

	θ_o	0°	10°	20°	30°	40°	60°	80°
n=2	α	4.47	1.70	1.42	1.14	.90	.53	.32
	β	1.91	1.27	1.23	1.20	1.13	1.21	1.39
n=4	α	4.44	2.36	1.49	1.15	.87	.44	.20
	β	2.14	1.74	1.44	1.37	1.35	1.38	1.50
n=6	α	3.09	2.33	1.68	1.08	.82	.38	.14
	β	2.12	1.95	1.78	1.53	1.51	1.48	1.58
n=8	α	2.33	2.09	1.61	1.10	.75	.34	.11
	β	2.09	2.04	1.92	1.74	1.62	1.58	1.65
n=10	α	1.87	1.77	1.44	1.05	.70	.31	.08
	β	2.07	2.05	1.98	1.85	1.70	1.65	1.69
n=12	α	1.57	1.52	1.28	.97	.64	.28	.07
	β	2.06	2.06	2.00	1.92	1.74	1.70	1.73

Table 4.1 results of Program COHER for α and β Coefficients Fitting Eq. 4.3 to Curves of Figure 4.3

7. Monte Carlo Simulation of Random Sea States

In a wave spectrum there are an infinite number of sea states, each one resulting in different loading in the structure.

To estimate the expected response values a Monte Carlo simulation is followed in this program.

For this the structure response is calculated for N sets of different nodal loads resulting from the same wave spectrum.

The mean and standard deviation between these sample response values are calculated and they approximate the expected response value and its standard deviation provided the sample number N is large enough.

To figure out an appropriate value for N, runs should be made with different N values and from the variation of the results the value of N can be judged. From experience a value for N between 8 and 16 seems adequate. As an example Fig. 5.1, 5.2, and 5.3 show results for N = 8, 16, 24. The small difference between the results for N = 16 and 24, shows that a value for N = 16 is adequate.

Ref.5 and Ref.29

8. Frequency Domain Analysis

First the response to short-crested harmonic waves of single frequency ω (omega) is calculated assuming the structure oscillates in a steady state with frequencyω. Again two methods are implemented corresponding to the two approaches of [4], above. To take into account the wave spatial correlation (para. 4), the nodal loads are computed as follows (Fig. 6.1.):

a)

$$R_i(t) = \left(\frac{c_{i-1} \cdot (\omega, L_{i-1}) \cdot L_{i-1} + c_i \cdot (\omega, L_i) \cdot L_i}{2} \right) \bar{\delta}(\omega) \cdot \eta(\omega) \cdot \sin(\omega t + \Phi_i) \qquad (6.1)$$

$c_i(\omega, L_i)$ is a spatial correlation factor, S.C.F..
$\bar{\delta}(\omega)$ is the hydrodynamic force coefficient, (Table 3.2.)
$\eta(\omega)$ is the wave amplitude.
ϕ_i is a random phase angle.

This angle can be chosen with a uniform probability between 0 and Φ (phi). A value of Φ(phi) equal to π/2 produces less correlated loads than equal to 2π (pi) [6].

b)

$$R_i(t) = \bar{\delta}(\omega)\,\eta(\omega) \sum_{j=1}^{N} a_{ij} \sin(\omega t + \Phi_j) \qquad (6.2)$$

Here the nodal loads are constructed from N uncorrelated time series, as described in para. 4 and aij are obtained from Eq. (4.7) for the wave coherence function assumed to be of the form of Eq. (4.3).

The structure loaded as shown in Figure 6.2, and oscillating in a steady state will have displacements:

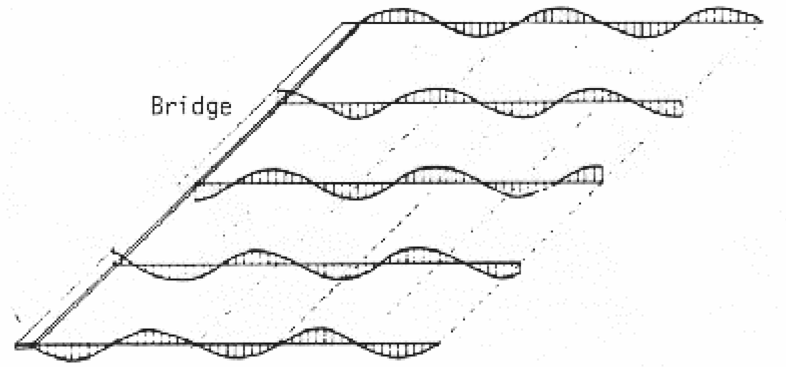


Figure 6.2 Nodal Harmonic Loads

$$r_i(t) = r_i \cdot \sin(\omega t + \psi_i) = r_i \cdot \sin\omega t \cdot \cos\psi_i + r_i \cdot \cos\omega t \cdot \sin\psi_i = \\ = a_i \cdot \sin\omega t + b_i \cdot \cos\omega t \quad (6.3.a)$$

and

$$\dot{r}_i(t) = a_i \cdot \omega \cdot \cos\omega t - b_i \cdot \omega \cdot \sin\omega t \quad (6.3.b)$$

$$\ddot{r}_i(t) = -a_i \cdot \omega^2 \cdot \sin\omega t - b_i \cdot \omega^2 \cdot \cos\omega t \quad (6.3.c)$$

$$\{r(t)\} = \{a\} \cdot \sin\omega t + \{b\} \cdot \cos\omega t \quad (6.4)$$

$$\{R(t)\} = \{A\} \cdot \sin\omega t + \{B\} \cdot \cos\omega t \quad (6.5)$$

where $\{a\} = \{a_i\}$, $\{b\} = \{b_i\}$, $\{A\} = \{A_i\}$, $\{B\} = \{B_i\}$
and,

$$A_i = \frac{1}{2}\{C_{i-1} \cdot (\omega, L_{i-1}) \cdot L_{i-1} + C_i \cdot (\omega, L_i) \cdot L_i\} \cdot \bar{\delta}(\omega) \cdot \eta(\omega) \cdot \cos\phi_i \quad (6.6.a)$$
$$B_i = \frac{1}{2}\{C_{i-1} \cdot (\omega, L_{i-1}) \cdot L_{i-1} + C_i \cdot (\omega, L_i) \cdot L_i\} \cdot \bar{\delta}(\omega) \cdot \eta(\omega) \cdot \sin\phi_i \quad (6.6.b)$$

or

$$A_i = \bar{\delta}(\omega) \cdot \eta(\omega) \cdot \sum_{j=1}^{N} a_{ij} \cdot \cos\phi_j \quad (6.7.a)$$

$$B_i = \bar{\delta}(\omega) \cdot \eta(\omega) \cdot \sum_{j=1}^{N} a_{ij} \cdot \sin\phi_j \quad (6.7.b)$$

in case of (6.2).

Writing the damping in the form :

$$[c]=2\,\xi(\omega)\,\omega[m] \quad (6.8)$$

relation (2.1) becomes:

$$\begin{bmatrix} [k] - \omega^2[m] & -2 \cdot \xi \cdot \omega^2 \cdot [m] \\ 2 \cdot \xi \cdot \omega^2[m] & [K] - \omega^2 \cdot [m] \end{bmatrix} \begin{Bmatrix} \{a\} \\ \{b\} \end{Bmatrix} = \begin{Bmatrix} \{A\} \\ \{B\} \end{Bmatrix} \quad (6.9)$$

Solving (6.9) the sin and cos terms, {a} and {b} for the displacements are obtained and consequently the bending moments and shearing forces. The corresponding maximum values are computed as:

$$\max r_i = \sqrt{a_i^2 + b_i^2} \qquad (6.10)$$

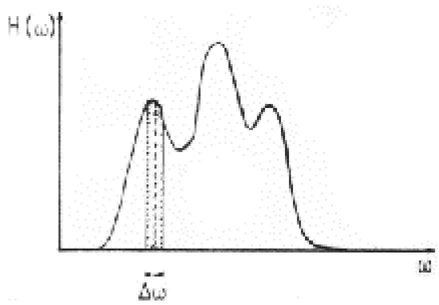


Figure 6.3.a Response to unit amplitude waves

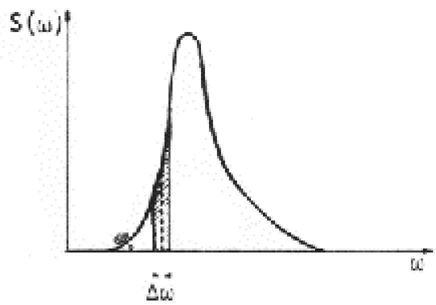


Figure 6.3.b. Wave Spectrum

The frequency response H(ω) (H/omega) to unit wave amplitude [η(ω) = 1] is evaluated for different wave periods and different sets of random phase angles. Maximum average values and standard deviations between the sets of random shifts are computed and the maximum values along the bridge are plotted for each wave period.

For the response due to a wave spectrum (Fig. 6.3.b), the wave field is constructed by the superposition of certain number of harmonics with amplitude the square root of the corresponding spectral area, and the structural response amplitude is computed as:

$$r = \int_0^\infty H(\omega) \cdot \eta(\omega) \cdot d\omega \qquad (6.11)$$

Again the response to a wave spectrum is computed for different sets of random phase angles for the wave harmonics, and maximum, average and standard deviations values are computed and plotted along the bridge length. The above procedure is as if we superimpose Figure (6.2) for different wave periods and amplitudes η(ω), with a result shown in Figure (6.4) in which the structure is loaded with different time series having the same energy spectrum and being either the uncorrelated case (6.1) or the appropriate correlated case (6.2).

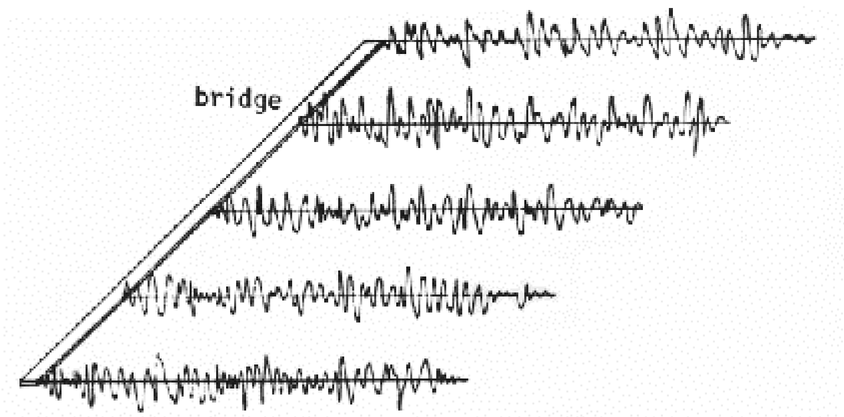


Figure 6.4 Nodal wave loading

9. Time Domain Analysis

The mode superposition method has been adopted for the time domain analysis, being a more economic solution as the higher mode shapes do not participate in the response. Constant hydrodynamic coefficients S.C.F. and load correlation matrix, are assumed as computed for the peak spectrum frequency. The generalized Jacobi's method [1] is used in the eigenvalue solution. The above method seems more appropriate due to the small number of eigenvalues and to the fact that the condensed stiffness and mass matrices, although not banded, are strongly diagonal which helps in the fast convergence of Jacobi's method.

The wave time series are inputted or constructed from the wave spectrum as described in [4], by superposition of harmonics:

$$w(t) = \sum_{i=1}^{M} n_i(\omega_i) \cdot \sin(\omega_i \cdot t + \psi_i) \qquad (7.1)$$

where : ψi are random angles from 0 to 2π and ωi , i = 1, 2 . . . . M are frequencies in which the wave energy spectrum is split, chosen either at equal spacing or at equal spectra areas between them

$$\eta(\omega) = \sqrt{S(\omega)\Delta\omega} \quad \text{(Fig 6.3.b)}$$

To construct different samples of time series the above time series ω(t) are shifted at random intervals. If the time series are constructed from the wave spectrum, for each set of random shifts the time series are reconstructed from (7.1) with different phase angles, ψ. For the corresponding cases of (6.1) and (6.2) the nodal loading is constructed as:

$$a) \quad R_i(t) = \{c_{i-1} \cdot (\omega_0, L_{i-1}) \cdot L_{i-1} + c_i \cdot (\omega_0, L_i) \cdot L_i\} \cdot \bar{\delta}(\omega_0) \cdot w(t + T_i) \qquad (7.2)$$

$$b) \quad R_i(t) = \bar{\delta}(\omega_0) \cdot \sum_{j=1}^{N} a_{ij} \cdot w(t + t_j) \qquad (7.3)$$

$$c) \quad R_i(t) = \bar{\delta}(\omega_0) \cdot \sum_{j=1}^{N} a_{ij} \cdot w_j(t) \qquad (7.4)$$

where Tj is the shifting interval range between 0 and TSH, where TSH should be inputted and should be about two to four times the peak wave period.(delta) and Ci are described in para. 6 and correspond to the peak wave frequency. In the third case the time series wj(t) are constructed using linear filtering methods as is discussed in para. 4.

The decoupled equations of motion are integrated using Wilson's theta method [1], which is unconditionally stable for theta >=1.4.

To be able to manipulate the large amount of data in a small central memory, the time integration and all further manipulations are done by writing the time series in blocked form, the optimum size of which is computed by the program to minimize execution time and meet memory limits. Again maximum, average and standard deviations are computed between the sets of randomly shifted time series and plotted along the bridge length. Also, representative time series of the response from each set of randomly shifted series can be plotted for three bridge locations, left bridge end, left quarter span and middle of the bridge.

10. Boat Wake Response

For the response to boat wakes [Ref 32] the wave forces have been modeled as shown in Figure 8.1.

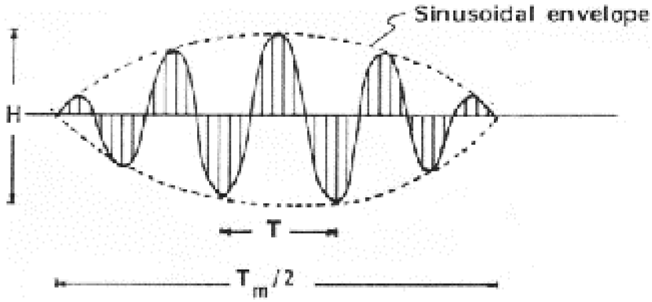


Figure 8.1 Boat wake (Tm/T =9)

$$n(t) = \frac{H}{2} \cdot \sin\left(2\pi \frac{t}{T_m}\right) \cdot \sin\left(2\pi \frac{t}{T}\right) \qquad (8.1)$$

From observed data it seems that a ratio Tm/T of 3 to 15 is appropriate.
The loading of the bridge at a time t (t = 0 when the wake is at the left end) is shown in Figure 8.2 and can be represented by the following relations:

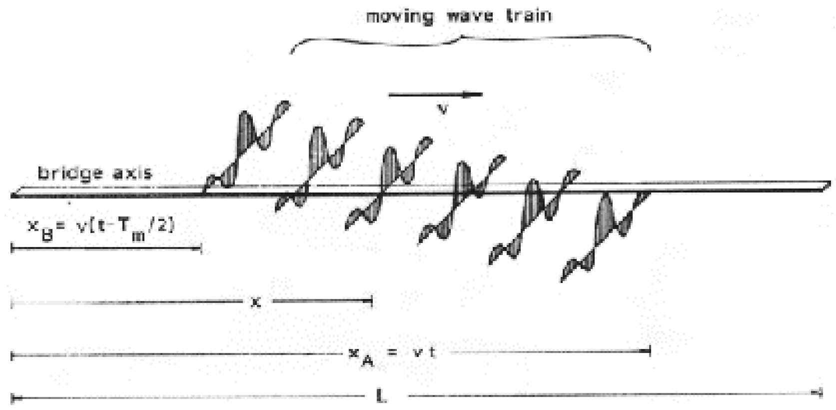


Figure 8.2. Boat wake loading

$$f(x) = \delta(\omega,\beta) \cdot \left(\frac{H}{2}\right) \cdot \sin\left(\frac{2\pi}{T_m} \cdot \frac{x_A - x}{V}\right) \cdot \sin\left(\frac{2\pi}{T} \cdot \frac{x_A - x}{V}\right) \qquad \text{for } x_B \le x \le x_A \qquad (8.2)$$

$$f(x) = 0, \qquad \text{for } x < x_B \text{ or } x > x_A \text{ and } x_A = Vt,\ x_B = V\left(t - \frac{T_m}{2}\right)$$

V is the boat speed parallel to the bridge. Assuming linear displacement field for the bridge (Fig. 8.3) we have for node i:

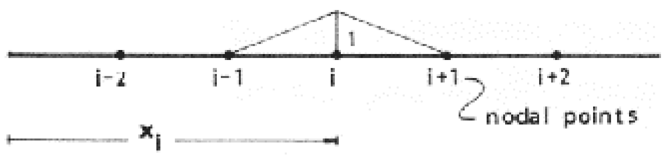


Figure 8.3. Linear displacement field for - node i .

$$\mathcal{N}_i(x) = \frac{x - x_{i-1}}{x_i - x_{i-1}} \quad x_{i-1} \le x \le x_i$$
$$\mathcal{N}_i(x) = \frac{x_{i+1} - x}{x_{i+1} - x_i} \quad x_i < x < x_{i+1} \qquad (8.3)$$
$$\mathcal{N}_i(x) = 0 \quad x < x_{i-1},\ x > x_{i+1}$$

Applying virtual work, the nodal loads are computed as:

$$R_i(x) = \int_0^L N_i(x) \cdot f(x) \qquad (L = \text{bridge length}) \qquad (8.4)$$

Relation (8.4) can be integrated explicitly for the nodal loads. Another way of computing the boat wake response is by loading the nodal points with a time delay (Δt) (deltat) between them, where:

$$\Delta t = \frac{\Delta \ell}{V} \qquad (\Delta \ell : \text{nodal distance}) \qquad (8.5)$$

The forces would be determined by multiplying (8.1) by $\delta(\omega,\theta)$ and by an appropriate "contribution length", which may or may not be the same as the nodal spacing.

The latter case of computing the nodal loads, can give erroneous results if the nodes are not closely spaced and the "contribution length" properly chosen. Results of boat wake response are shown in Figure 8.4 for a breakwater with flexible connectors.

11. Wave Coherence

The wave coherence along the bridge is assumed to vary exponentially and for two points at distance Δz assumed to be of the form:

$$\gamma_w(\Delta z/\lambda) = \exp\left(-a(\Delta z/\lambda)^{\beta}\right) \qquad (4.3)$$

The values of α and β depend on the wave directional spectrum. In Fig. 4.2 are shown curves of the form y=exp(-axβ), and in Fig. 4.3 are shown curves for the wave coherence between two points at distance z on the bridge obtained for a directional spectrum of the form:

$$S(f,\theta) = S(f)\cos^n(\theta - \theta_0) \qquad (4.4)$$

Using least square fitting the values of Table 4.1 for of a and β are obtained.

	θ_o	0°	10°	20°	30°	40°	60°	80°
n=2	α	4.47	1.70	1.42	1.14	.90	.53	.32
	β	1.91	1.27	1.23	1.20	1.13	1.21	1.39
n=4	α	4.44	2.36	1.49	1.15	.87	.44	.20
	β	2.14	1.74	1.44	1.37	1.35	1.38	1.50
n=6	α	3.09	2.33	1.68	1.08	.82	.38	.14
	β	2.12	1.95	1.78	1.53	1.51	1.48	1.58
n=8	α	2.33	2.09	1.61	1.10	.75	.34	.11
	β	2.09	2.04	1.92	1.74	1.62	1.58	1.65
n=10	α	1.87	1.77	1.44	1.05	.70	.31	.08
	β	2.07	2.05	1.98	1.85	1.70	1.65	1.69
n=12	α	1.57	1.52	1.28	.97	.64	.28	.07
	β	2.06	2.06	2.00	1.92	1.74	1.70	1.73

Table 4.1 results of Program COHER for α and β Coefficients Fitting Eq. 4.3 to Curves of Figure 4.3

12. Examples

Example 1 of Breakwater

The response of a breakwater of length (8x 75' = 600') with rigid or flexible connectors will be modeled as an example.

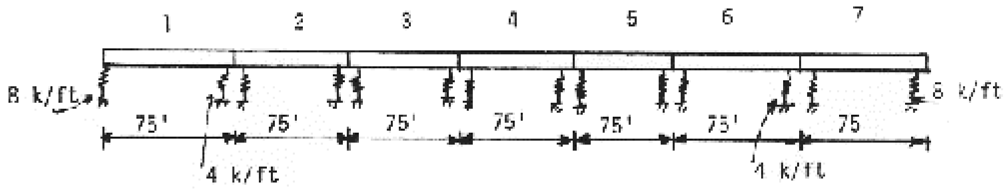


Figure 9.1

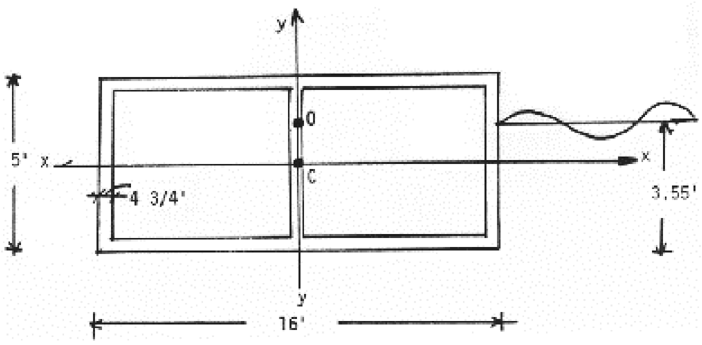


Figure 9.2

PONTOON PROPERTIES

Cross section area :

$$A_c = 16\times 5 - (16 - 3\times 0.396)\times(5 - 2\times 0.396) = \\ = 17.67\ \text{ft}^2$$

Moments of inertia:

$$I_{xx} = \frac{16\times 5^3}{12} - \frac{(16 - 3\times 0.396)\times(5 - 2\times 0.396)^3}{12} = \\ = 74.69\ \text{ft}^4$$

$$I_{yy} = \frac{5\times 16^3}{12} - \frac{(5 - 2\times 0.396)\times(16 - 2\times 0.396)^3}{12} + \frac{(5 - 2\times 0.396)\times 0.396^3}{12} = \\ = 473.27\ \text{ft}^4$$

$$I_0 = I_{xx} + I_{yy} = 74.69 + 473.27 = 547.96\ \text{ft}^4$$

$$J = \frac{4\times(5 - 0.396)^2(16 - 0.396)^2}{\dfrac{2\times(16 - 0.396) + 2\times(5 - 0.396)}{0.396}} = 202.28\ \text{ft}^4$$

Modulus of Elasticity $E = 417000\ \text{k/ft}^2$
Poisson Ratio $v = 0.22$

Mass:

$$m_x = m_y = \frac{3.55\times 16\times 0.064}{32.2} = 0.113\ \text{k slug/ft}$$

$$m_t = \frac{547.96}{17.67} \times 0.113 = 3.50 \text{ k slug ft}^2/\text{ft}$$

(mt is the mass inertia per unit length)

Hydrodynamic Coefficients for Example Breakwater

B/t = Width/draft = 16/3.55 =4.5

σ = normalized frequency $= \omega\sqrt{B/2g} = {}^{2\pi}\!/_{t}\sqrt{16/2(32.2)} = 3.13/T$

$\rho gB/2$ = hydrodynamic force factor in translation $= 0.064(16/2) = 0.512$

$\rho g(B/2)^2$ = hydrodynamic force factor in roll $= 0.064(16/2)^2 = 4.096$

From Table 3.1 the mass and damping coefficients are found to be:

T		Mass			Damping		
(sec)	σ	sway	heave	roll	sway	heave	roll
2	1.56	1.052	2.87	1.25	0.167	0.017	0.001
3	1.04	1.30	2.76	1.25	0.24	0.111	0.004
4	0.78	1.64	2.76	1.26	0.17	0.23	0.006
5	0.63	1.74	2.92	1.26	0.10	0.31	0.005
6	0.52	1.69	3.15	1.27	0.05	0.36	0.003

The Hydrodynamic Force Coefficients are:

T (sec)		Force δ(ω,0) non-dimensional			Force Coefficient, C_F for FLOAT program		
	σ	sway	heave	roll	sway	heave	roll
2	1.56	0.56	0.28	0.05	0.29	0.14	0.20
3	1.04	0.75	0.72	0.07	0.38	0.37	0.29
4	0.78	0.70	1.04	0.12	0.36	0.53	0.49
5	0.63	0.54	1.25	0.11	0.28	0.64	0.45
6	0.52	0.38	1.40	0.09	0.19	0.72	0.37

If the directional and short crested effects are to be included in the Hydrodynamic Force Coefficients and an exponentially decayed load correlation instead of in an SCF equation the following values from Table 4.5 would be used*

T (sec)		Force δ(ω,0) non-dimensional			Force Coefficient, C_F for FLOAT program		
	σ	sway	heave	roll	sway	heave	Roll
2	1.56	0.53	0.15	0.03	0.27	0.08	0.12
3	1.04	0.69	0.59	0.06	0.35	0.30	0.25
4	0.78	0.60	0.94	0.10	0.31	0.48	0.41
5	0.63	0.44	1.18	0.10	0.23	0.60	0.41
6	0.52	0.31	1.31	0.08	0.16	0.67	0.33

* this case was not run here but makes a good comparison run.

Flexible Connectors Modeling

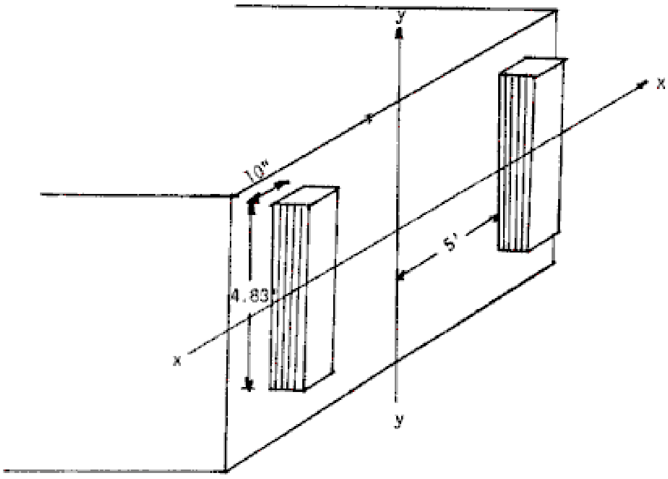


Figure 9.3

Shearing areas:

$$A_x = A_y = 2 \times \left(\frac{5}{6}\right) \times \left(\frac{10}{12}\right) \times 4.83 = 6.7\ ft^2$$

Moments of inertia:

$$I_{xx} = 2 \times \left(\frac{10}{12}\right) \times \frac{4.83^3}{12} = 15.6\ ft^4$$

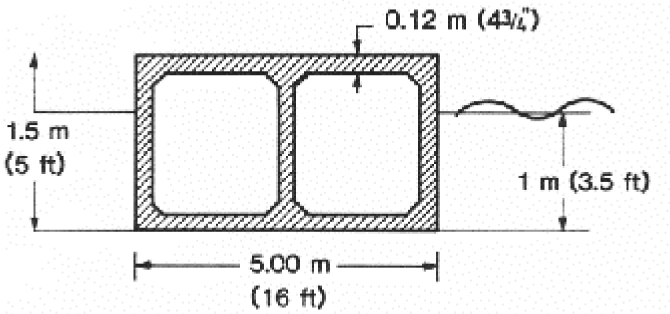
$$I_{yy} = 2 \times \left(\frac{10}{12}\right) \times 4.83 \times \left(5 + \frac{5}{12}\right)^2 = 936.2\ ft^4$$

$$J = 2 \times \left(\frac{10}{12}\right) \times 4.83 \times \left(5 + \frac{5}{12}\right)^2 = 936.2\ ft^4$$

Modulus of elasticity $E = 1000\ k/ft^2$
Poisson's ratio $\nu = 0.48$
Shearing modulus $G = 510\ k/ft^2$

Example 2 of Breakwater

Consider breakwater of Fig.



Width/draft ratio B/T = 4.00/1.00 =4
Normalize frequency factor

Converting wave period T in sec : $\sigma = \omega\sqrt{B/2g} = \frac{2\pi}{T}\sqrt{\frac{4.00}{2\times 9.81}} = \frac{2.83}{T}$

to σ normalized frequency
Cross section under water area : A=4.00 x1.00 = 4.00 m²
Distance of cross section centroid
rom free surface : C=-0.25m
Water specific mass : ρw=1000kg/m³
Acceleration of gravity : g = 9.81 m/sec²

From Fig. 6, 7, 8 or Table 2 we get for added mass and damping coefficients and existing force, in nondimensional form:

T		Mass β(σ)			Damping ξ(σ)			Force δ(σ,0)		
(sec)	σ	Sway	Heave	Roll	Sway	Heave	Roll	Sway	Heave	Roll
2	1.41	0.075	1.758	0.255	0.207	0.024	0.001	0.661	0.360	0.031
3	0. 5	0.408	1.560	0.251	0.254	0.128	0.001	0.828	0.790	0.056
4	0.71	0.766	1.600	0.255	0.154	0.248	0.003	0.710	1.116	0.095
5	0.57	0.787	1.782	0.259	0.079	0.321	0.003	0.505	1.31	0.087
6	0.47	0.740	1.923	0.261	0.049	0.353	0.002	0.391	1.41	0.076

And in dimensional form:

ADDED MASS : see Eq. (6.1, b, c)

			Added mass		
T sec	ω cyll/sec	σ	Sway kg/m	Heave kg/m	Roll kg m/m
2	3.14	1.41	300.	7032.	4099.
3	2.09	0.95	1632.	6240.	4118.
4	1.57	0.71	3064.	6400.	4272.
5	1.26	0.57	3148.	7128.	4340.
6	1.05	0.42	2960.	7692.	4361.

ADDED DAMPING FORCES : see Eq. (7.1, b, c)

Added damping force

T sec	ω cyll/sec	σ	Sway kg/m	Heave kg/m	Roll kg m/m
2	3.19	1.41	5590.	1663.	476.
3	2.09	0.95	5980.	5479.	433.
4	1.57	0.71	3416.	8098.	402.
5	1.26	0.57	1423.	9002.	241.
6	1.05	0.47	716.	8667.	129.

HYDRODYNAMIC EXCITING FORCES : Eq. (8.1, b, c)
Wave direction θ=0°

Hydrodynamic force for unit wave amplitude

T sec	ω cyll/sec	σ	Sway N/m	Heave N/m	Roll N.m/m
2	3.19	1.41	12969.	7063.	-2026.
3	2.09	0.95	16245.	15500.	-1864.
4	1.37	0.71	13930.	21896.	245.
5	4.26	0.37	9908.	25702.	937.
6	1.03	0.47	7671.	27664.	1064.

For the case of directional waves depending on the choice of spreading function the coefficients are evaluated from Tables 4, 5 and 6.

13. List of Figures

14. List of Symbols

The following is a list of symbols which are most commonly used in the text. Other symbols used are defined in the text when they first appear.

A Underwater cross-section area, Ac cross-section area

ao Normalized cross-section area ($a_o = A/(B/2)^2$) (underwater)

B Cross-section width

C Centroid of cross-section

C Centroid of cross-section

C_F^S, C_F^H, C_F^R Hydrodynamic Force Coefficients defined by Eqs. 3.2 a, b, c.

C Distance of centroid to free surface (positive upwards)

D Depth of fluid region

d Normalized depth (d = D/(B/2))

E, Ep, Ec Moduli of elasticity, subscripts for pontoons or connectors

EI Flexural rigidity

e Normalized modulus of elasticity

$$e = {2E}/{\rho_w} \cdot gB$$

F Cut-off frequency, force f Frequency in Hz, force per unit length

H Wave height, H(t) = 2η(t)

H Significant wave height (H1/3)

Ixx, Iyy Cross section moment of inertia

ixx, iyy Normalized momerrt of inertia

Io Cross-section polar moments of inertia

$$I_o = \iint_{dc} r^2 dA$$

g Acceleration of gravity

k Wave number (k = 2π/λ = ω2/g)

kj lateral stiffness normalized

$$k_j = 4k_j / \rho_w g B^2$$

γ Coherence

δ, δ(ω) Hydrodynamic force coefficient - nondimensional

$\bar{\delta}(\omega)$ Non-dimensional hydrodynamic force coefficient including directional effects

n Wave surface height from mean (η = η(t))

θ Wave direction relative to bridge axis

λ Wave length

$\xi, \xi_H^S, \xi_H^R, \xi_V^S, \xi_V^H, \xi_V^R$ Percent of critical damping, subscript for hydrodynamic or virtual mass, superscript for sway, heave and roll

ρω Water specific mass

σ Normalized frequency

$$\sigma = \omega\sqrt{B/2g}$$

Φ Wave potential

φ Nondimensional wave potential

ω Cyclic frequency

L Bridge length
Li nodal distance from node i to i+1
Lij nodal distance from node i to j
l normalized distance (l = L/(B/2))
M Moment
m mass per unit length, moment per unit length
N1(z), N2(z), Ni(z) Displacement functions
O Origin of axis on freewater surface
Ri Nodal loads
$R_{R_iR_j}(\tau)$ Correlation between Ri and Rj
$R_f(z_1, z_2, \tau)$ Correlation between forces at distances Z1 and Z2
ri Nodal distance
S(ω), S(f) SPectrum
$S\omega(\omega)$, $S\omega(f)$ Wave Spectrum
$S_{\omega(AB)}(\omega)$, $S_{\omega(z_iz_j)}(\omega)$ Wave cross-spectra between points A and B or Z1 and Z2
$S_{f(z_iz_j)}(\omega)$ Force cross-spectra between points Z1 and Z2
T Cross-section draft, wave period
t Time variable
X, Y, Z Coordinates
x, y, z Normalized coordinates (i.e., x = X/(B/2))
A Underwater cross-section area, Ac cross-se
ao Normalized cross-section area (a_o = A/(B/2 (underwater)
B Cross-section width
superscript for sway, heave and roll

15. List of Tables

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17. Documents

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