Chap 7. Hydraulic Model Tests with Irregular Waves

7.1 Similarity Laws and Model Scales

- Geometric similitude (length)
- kinematic similitude (velocity and acceleration)
- dynamic similitude (all forces)

inertia, gravity, viscous force, surface tension

↘ ↙

important for sea waves → Froude similitude

For Froude law (see Table 7.1),

horizontal and vertical length scale = $l_r = l_m / l_p$

horizontal and vertical velocity scale = $V_r = V_m / V_p$

time scale = $t_r = l_r / V_r$

Froude law requires

$$\frac{V_m}{\sqrt{g l_m}} = \frac{V_p}{\sqrt{g l_p}} \rightarrow V_r = \sqrt{l_r} \quad \text{and} \quad t_r = \sqrt{l_r}$$

Wave pressure (force per unit area): $p_r = \rho_r V_r^2 = \rho_r g_r l_r = l_r$ for $\rho_r = 1$, $g_r = 1$

Force per unit length: $p_r \times l_r = l_r^2$

Weight per unit length: $w_r = S_r \rho_r g_r l_r^3 / l_r = l_r^2$ if $S_r = 1$

Weight of armor unit: $W_r = S_r \rho_r g_r l_r^3 = l_r^3$ if $S_r = 1$

⋮

Typically, $l_r = \frac{1}{50} \sim \frac{1}{150}$ for harbor model tests

$l_r = \frac{1}{10} \sim \frac{1}{50}$ for coastal structure model tests

Require wave period > 0.5 s in laboratory to minimize scale effects, $T_s \geq 1.0$ s, $H_s \geq 10$ cm or so (at least several cm).

7.2 Generation of Irregular Waves and Data Analysis

7.2.1 Irregular Wave Generator (Read text)

7.2.2 Preparation of Input Signal to the Generator (see Fig. 7.2)

- Specification of incident wave spectrum (target): $S_w(f)$
- Specify transfer function: $F(f,h)$
- Compute spectrum of wave paddle motion: $S_G(f) = S_w(f)/F^2(f,h)$
- Input signal (time series) of paddle motion
- Generate waves in a tank and measure incident waves
- Compare measured and target spectra until specified design waves are reproduced.

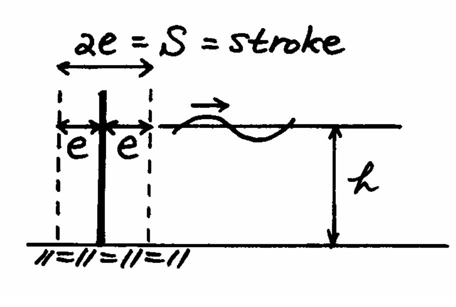
For a linear system response,

Input				Output
$x(t)$ $S_x(f)$	→	Transfer function $F(f)$	→	$y(t)$ - time series $S_y(f)$ - spectrum
paddle motion		$S_y(f) = \lvert F(f)\rvert^2 S_x(f)$		incident wave

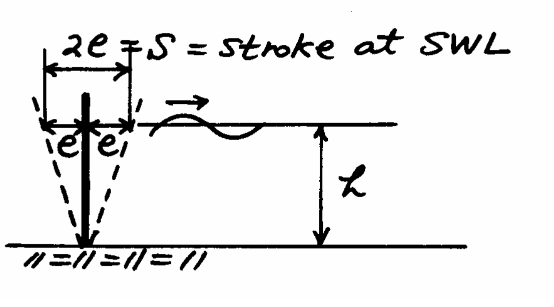
$$F(f) = \frac{\text{height of sinusoidal motion of } y(t) \text{ for given } f}{\text{height of sinusoidal motion of } x(t) \text{ for given } f}$$

on the basis of linear monochromatic wavemaker theory

<u>Piston</u>



<u>Flap</u>



For piston type ($j=1$),

$$F_1(f)=\frac{H}{2e}=\frac{4\sinh^2(kh)}{2kh+\sinh(2kh)}$$

For flap type ($j=2$),

$$F_2(f)=\frac{H}{2e}=\frac{4\sinh(kh)}{kh}\frac{1-\cosh(kh)+kh\sinh(kh)}{2kh+\sinh(2kh)}$$

where $kh\tanh(kh)=\frac{h}{g}(2\pi f)^2$; kh can be found for given f and h.

For this case,

$S_x(f)=S_G(f)$ = paddle spectrum

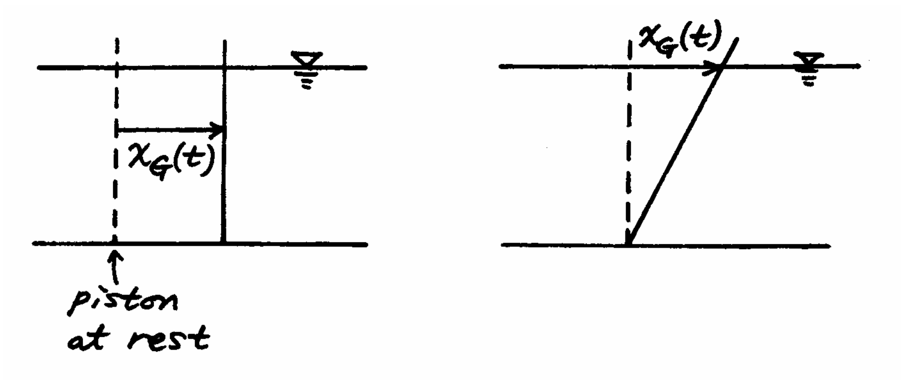
$S_y(f)=S_w(f)$ = incident wave spectrum

$$S_w(f)=F_j^2(f)S_G(f),\quad j=1,2$$

$$\downarrow$$

$$S_G(f)=\frac{S_w(f)}{F_j^2(f)}$$

For estimated $S_G(f)$, need to generate the corresponding time series of the paddle displacement $x_G(t)$.



Three digital simulation methods are available. But the inverse FFT method is the most common and easiest.

$$x_G(t) = \sum_{n=1}^{N} a_n \cos(2\pi f_n t + \varepsilon_n) \quad \text{with} \quad f_n = n\Delta f$$

$\uparrow$ $\qquad\qquad$ $\uparrow$

$a_n = \left[2S_G(f_n)\Delta f\right]^{1/2}$ $\qquad$ random phase distributed uniformly over $[0,2\pi]$

$\uparrow$

use random number generator

Use an inverse FFT rather than summation. After time series $x_G(t)$ of paddle motion is calculated, compute time series of voltage signal to move paddle, using a calibration curve between paddle displacement and voltage.

Measure incident waves in the tank after steady state is established ($\because$ low frequency waves travel faster) or use the remedy suggested in Goda (p.232), i.e., phase-delayed generation of waves (high-frequency first)

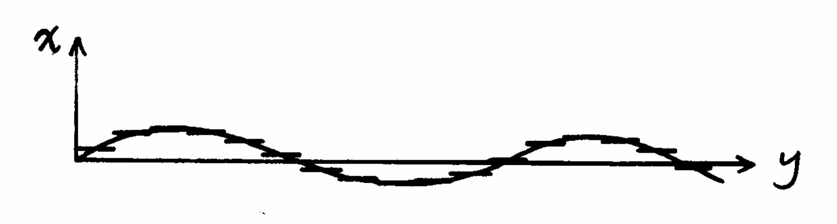
Compare target spectrum $S_w(f)$ and measured spectrum $S_m(f)$. Also check representative wave heights and periods expected from $S_w(f)$ against measured values. Generally $S_w(f) \neq S_m(f)$.

Adjust the transfer function

$$F_{new}(f) = F_{old}(f)\left(\frac{\sqrt{S_m(f)}}{\sqrt{S_w(f)}}\right)^{-1}$$

Repeat the above procedure until $S_w(f) \cong S_m(f)$.

7.2.3 Input Signals to a Multidirectional Wave Generator



$$\eta(x,y,t)=\sum_{m=1}^{M}\sum_{n=1}^{N}A_{mn}\cos(k_m x\cos\theta_n + k_m y\sin\theta_n - 2\pi f_m t+\varepsilon_{mn})$$

At $x=0$,

$$\eta(0,y,t)=\sum_{m=1}^{M}\sum_{n=1}^{N}A_{mn}\cos(k_m y\sin\theta_n - 2\pi f_m t+\varepsilon_{mn})$$

$$x_G(y,t)=\sum_{m=1}^{M}\sum_{n=1}^{N}a_{mn}\cos(k_m y\sin\theta_n - 2\pi f_m t+\varepsilon_{mn})$$

$$\uparrow$$

$$a_{mn}=\left[2S_G(f_m,\theta_n)\Delta f\Delta\theta\right]^{1/2}$$

$$S_G(f_m,\theta_n)=\frac{S_w(f_m,\theta_n)}{F_j^2(f_m)}$$

7.2.4 Data Recording and Analysis

Analog data $\rightarrow$ AD converter $\rightarrow$ digital data $\rightarrow$ PC

Exception: impulsive breaking wave pressure needs sampling rate of several thousands Hz. Need high-speed AD converter.

Details of data analysis in Chapter 10.

7.3 Experimental Techniques for Irregular Wave Tests

7.3.1 Model Tests on Harbor Tranquility

• Irregular wave tests (better reproduction of field situation) give smoother spatial variation of wave heights than regular wave tests (see Fig. 7.4 and 7.5).

• To account for directional spreading, use Eq. (6.1)

$$K_{eff} = \left[\frac{\sum K_j^2 D_j}{\sum D_j} \right]^{1/2} \quad \leftarrow \text{weighted average for different directions}$$

where $K_j = \dfrac{H}{H_I}$ for j-th direction

D_j = relative wave energy in j-th direction (see Table 3.2, p.50)

• Numerical simulations can be used in parallel with hydraulic model tests to save time and total cost.

• If only a regular wavemaker is available, make tests for several different wave periods and directions, and then take the weighted average (cf. Table 3.1 to 3.3).

• If regular wave tests are used for spectral average, do not intend to draw a contour map of wave height (like Fig. 7.4), but focus on important locations.

7.3.2 Model Tests for Breakwater Stability

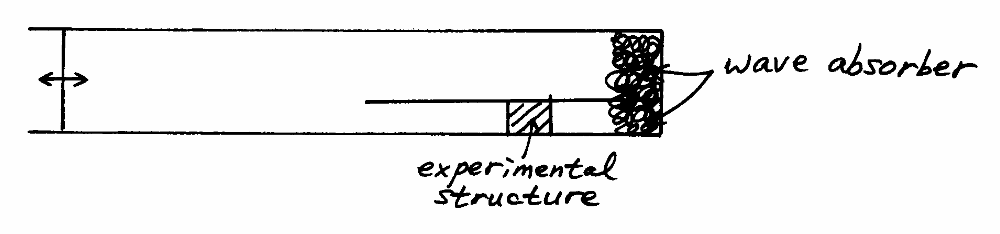
Stability of upright section of a vertical breakwater can be investigated by two different ways:

(1) Pressure measurement
- provides temporal and spatial variation of wave pressure
- high pressure may not cause sliding if duration is short
- more research-oriented

(2) sliding test
- more practical
- increase wave height or decrease weight of upright section until sliding occurs (see Fig. 7.6)
- threshold condition of sliding can be determined

Irregular wave tests with vertical breakwater may cause accumulation of energy in wave tank due to multi-reflection between wavemaker and model structure. Remedies are:

(1) very long flume → frictional damping of reflected waves, but larger waves should be generated in order to get the incident wave height we want in front of the structure
(2) partition of wave flume



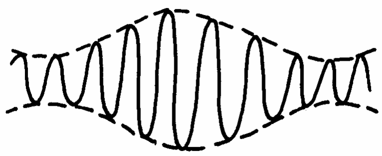
(3) Use reflected-wave absorbing wavemaker ← appears to cause 10~20% reflection instead of 100%

A sliding test with a regular wave of $H_{\max}$ may be possible (∵ Sliding of a caisson is governed by a single highest wave)

Stability of armor units of rubble foundation
- examined by visual observation
- the stability limit should be examined by gradually increasing wave height

Stability of sloping mound breakwaters
- low reflection → multi-reflection is not serious → irregular waves should be used
- visual observation of armor blocks
- wave heights beyond stability limit should be used → relation between damage and wave height
- irregular wave tests are sensitive to wave groupiness → take average of several runs

same $\overline{H}$ or $H_{1/3}$



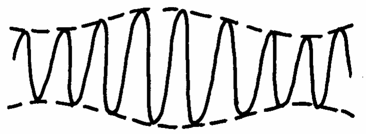
larger fluctuation of wave heights

↓

larger wave groupiness

↓

larger damage



smaller fluctuation

- wave groupiness may be important for reliability-based design method for breakwaters

7.3.3 Model Tests for Wave Overtopping and Reflection of Seawalls and Other Structures

• Run-up, overtopping, reflection → very complicated → not easy to solve analytically → mainly based on hydraulic model tests

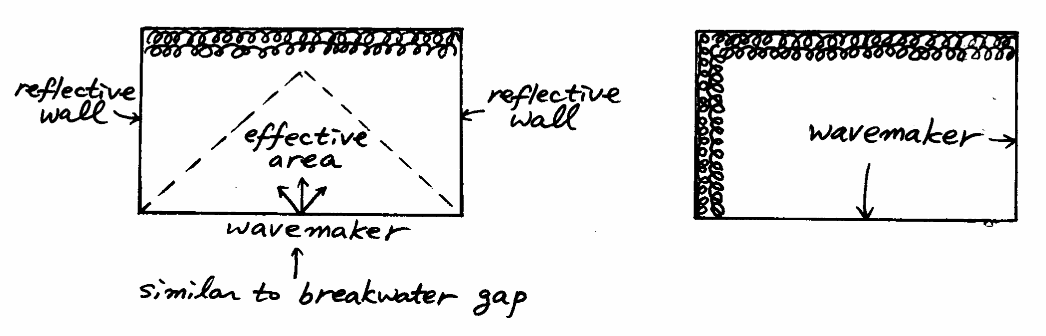
• Model tests with regular waves:
  overtopping, run-up → various wave heights
  reflection from perforated walls → various wave periods

• Reflection from vertical breakwater with energy-dissipating blocks → generate harmonic waves ($T_R = (1/2 \sim 1/3)T_I$)

7.4 Model Tests Using Multidirectional Wave Generator

Limitations:

(1) Narrow effective areas



(2) Absorption of reflected waves from model structures is difficult because the reflected waves come back to the wave paddles at oblique angles, which are difficult to detect.

Problems for which multidirectional wavemaker is desirable: diffraction dominated problems

- harbor tranquility
- 3D stability of breakwater head
- spatial variation of run-up and overtopping of finite-length seawalls