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# Acceleration and Impact of Structures Moved by Tsunamis or Flash Floods

by

Frederick E. Camfield

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Techniques are given for determining the velocity of a structure moved by a tsunami or flash flood and impact forces with another structure. Solutions can be obtained for velocity and impact force as a function of the initial distance between the structures and the velocity of the surging water.



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# PREFACE

The information in this technical aid was presented at the U.S. Army Engineer Division, South Pacific's Water Level Prediction short course in San Francisco, California, 30 March-1 April 1976, and at the Tsunami Symposium, sponsored by the Tsunami Committee of the International Union of Geodesy and Geophysics, held in Ensenada, Mexico, 23-26 March 1977. The work was carried out under the coastal structures program of the U.S. Army Coastal Engineering Research Center (CERC).

The report was prepared by Dr. Frederick E. Camfield, Hydraulic Engineer, Coastal Design Criteria Branch, under the general supervision of Robert A. Jachowski, Chief, Coastal Design Criteria Branch.

Comments on this publication are invited.

Approved for publication in accordance with Public Law 166, 79th Congress, approved 31 July 1945, as supplemented by Public Law 172, 88th Congress, approved 7 November 1963.

JOHN H. COUSINS
Colonel, Corps of Engineers
Commander and Director

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CONVERSION FACTORS, U.S. CUSTOMARY TO METRIC (SI) UNITS OF MEASUREMENT

U.S. customary units of measurement used in this report can be converted to metric (SI) units as follows:

| Multiply | by | To obtain |
|---|---|---|
| inches | 25.4 | millimeters |
| | 2.54 | centimeters |
| square inches | 6.452 | square centimeters |
| cubic inches | 16.39 | cubic centimeters |
| feet | 30.48 | centimeters |
| | 0.3048 | meters |
| square feet | 0.0929 | square meters |
| cubic feet | 0.0283 | cubic meters |
| yards | 0.9144 | meters |
| square yards | 0.836 | square meters |
| cubic yards | 0.7646 | cubic meters |
| miles | 1.6093 | kilometers |
| square miles | 259.0 | hectares |
| knots | 1.8532 | kilometers per hour |
| acres | 0.4047 | hectares |
| foot-pounds | 1.3558 | newton meters |
| millibars | $1.0197 \times 10^{-3}$ | kilograms per square centimeter |
| ounces | 28.35 | grams |
| pounds | 453.6 | grams |
| | 0.4536 | kilograms |
| ton, long | 1.0160 | metric tons |
| ton, short | 0.9072 | metric tons |
| degrees (angle) | 0.1745 | radians |
| Fahrenheit degrees | 5/9 | Celsius degrees or Kelvins[1] |

[1]To obtain Celsius (C) temperature readings from Fahrenheit (F) readings, use formula: $C = (5/9)(F - 32)$.

To obtain Kelvin (K) readings, use formula: $K = (5/9)(F - 32) + 273.15$.

## SYMBOLS AND DEFINITIONS

| | |
|---|---|
| A | cross-sectional area of submerged part of structure |
| a | length of rectangular building in direction of flow |
| b | width of rectangular building transverse to direction of flow |
| $C_D$ | coefficient of drag |
| $C_M$ | mass or inertia coefficient |
| d | projected dimension of a structure, or width of a flat surface |
| F | force accelerating the structure |
| L | height of a submerged cylinder or building, or length of a flat surface |
| t | time |
| u | velocity of surging water |
| $u_b$ | velocity of moving structure relative to ground |
| V | volume of water displaced by structure |
| x | distance in direction of structure motion |
| $\alpha$ | a coefficient |
| $\rho$ | density of the water |

# ACCELERATION AND IMPACT OF STRUCTURES MOVED BY TSUNAMIS OR FLASH FLOODS

*by*

*Frederick E. Camfield*

## I. INTRODUCTION

A high velocity flow of a wall of water surging over land, such as found in some tsunamis or flash floods, may carry forward structures which will impact with other structures. The resulting impact forces, combined with the force of the surging water, may result in serious damage of structures which would otherwise withstand the surging water. Therefore, a means of estimating the forces on a structure resulting from the impact of other structures is needed.

## II. ACCELERATION AND IMPACT OF STRUCTURES

Camfield (in preparation, 1978)[1] shows that the distance, $x$, a structure will move, as a function of time, $t$, is given as

$$x = ut - \frac{1}{\alpha} \ell n \; (\alpha ut + 1) \qquad (1)$$

where $u$ is the velocity of the water and $\alpha$ is a constant defined by

$$\alpha = \frac{C_D A}{2\,V(1 + C_M)} \qquad (2)$$

- $A$ = cross-sectional area of the submerged part of the structure transverse to the direction of motion
- $V$ = volume of water displaced by the structure
- $C_D$ = coefficient of drag given in the Table
- $C_M$ = mass coefficient given in Figure 1 for rectangular structures (from Riabouchinski, 1920)[2].

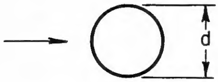
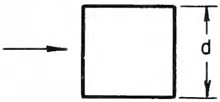
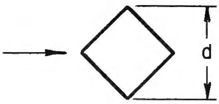
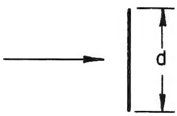
Example solutions of equation (1) are shown in Figure 2.

---

[1]CAMFIELD, F.E., "Tsunami Engineering," U.S. Army, Corps of Engineers, Coastal Engineering Research Center, Fort Belvoir, Va. (in preparation, 1978).

[2]RIABOUCHINSKI, D., "Sur la Resistance des Fluides," *International Congress of Mathematics*, Strasbourg, 1920, pp. 568-585.

Table. Drag coefficients.

| Object | L/d | Reynolds number | $C_D$ |
|---|---|---|---|
| Circular cylinder | 1 | $10^5$ | 0.63 |
| | 5 | $10^5$ | 0.74 |
|  | ∞ | $10^5$ | 1.20 |
| | ∞ | $>5 \times 10^5$ | 0.33 |
| Square cylinder  | ∞ | $3.5 \times 10^4$ | 2.0 |
|  | ∞ | $10^4$ to $10^5$ | 1.6 |
| Rectangular flat plate (totally submerged) | 1 | $>10^3$ | 1.1 |
| | 5 | $>10^3$ | 1.2 |
|  | 20 | $>10^3$ | 1.5 |
| | ∞ | $>10^3$ | 2.0 |

NOTE.--L = The height of a submerged cylinder, or the length of the flat plate.

d = The projected dimension shown, or the width of the flat plate.

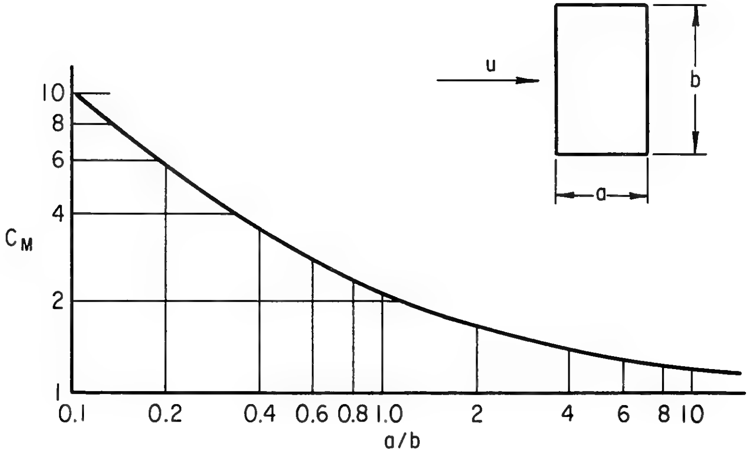



Figure 1. $C_M$ for two-dimensional flow past rectangular bodies, irrotational flow with no separation (from Riabouchinski, 1920)[2].

[2]RIABOUCHINSKI, op. cit., p. 7.

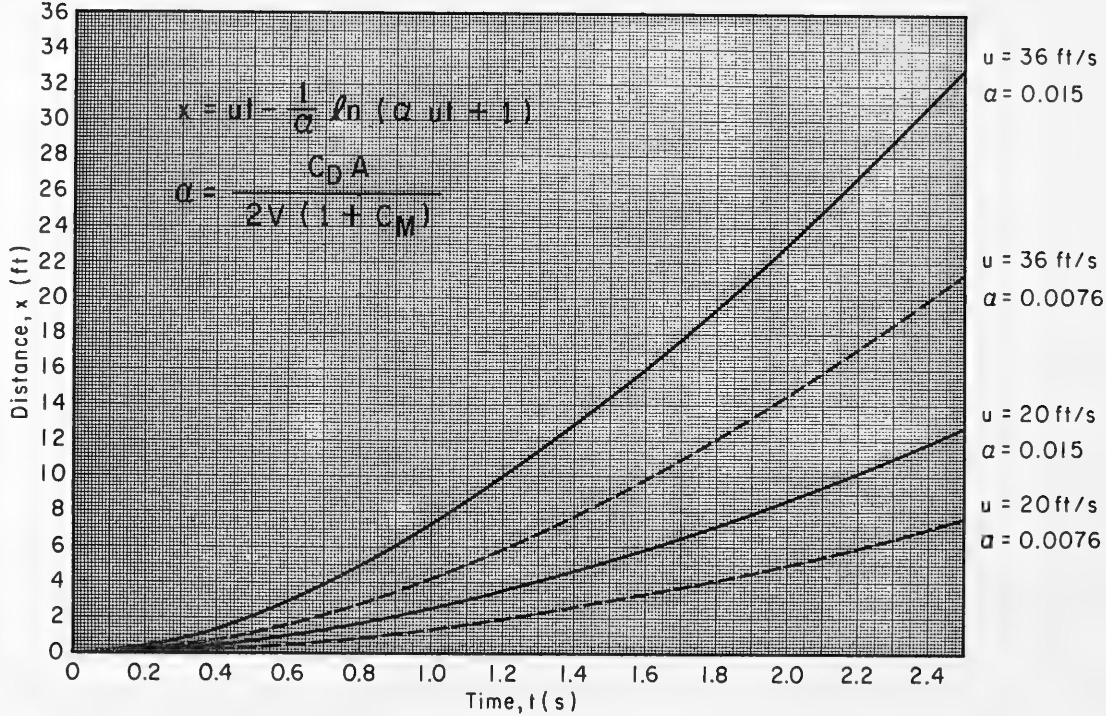



Figure 2. Example plots of x versus t for structures moved by surge.

For a structure completely immersed in water, i.e., flow passes around all sides of the structure (including both the top and the bottom), the forces act against the projected surface area of the structure normal to the direction of flow. Coefficients of drag, $C_D$, can be obtained from the Table for known structure dimensions. For a structure resting on the ground, where there is neither underflow nor overflow, the structure can be treated as an infinitely long (i.e., infinitely high) structure to determine the appropriate coefficient from the Table.

When a structure rests on the ground and overtopping water creates overflow where there is no underflow, or when a structure is supported or floating above the ground so that there is underflow but no overflow, the following procedure may be used to determine the coefficient of drag. The drag acts against the submerged part of the structure. Create a "mirror" of the submerged part at the surface where no flow occurs. This gives a completely immersed structure with a height equal to twice the submerged height of the actual structure. The coefficient of drag for the actual structure can then be obtained from the Table, using the width of the actual structure and a height equal to twice the submerged height of the actual structure. This is illustrated further in the example problem.

The velocity of the structure, $u_b$, as a function of time, is

$$u_b = u - \frac{u}{\alpha ut + 1} \tag{3}$$

and the force, F, accelerating the building at any instant in time is

$$F = \rho V \alpha \, (u - u_b)^2 \tag{4}$$

where $\rho$ is the mass density of water (seawater ≃ 2 slugs per cubic foot (1,026 kilograms per cubic meter) and freshwater 1.94 slugs per cubic foot).

* * * * * * * * * * * * * * EXAMPLE PROBLEM * * * * * * * * * * * * * * 

GIVEN: A tsunami is 12 feet (3.66 meters) high at the shoreline, and moves on to the shoreline as a steep-fronted surge. A building is swept forward, and impacts with another building after being carried through a distance of 20 feet (6.1 meters). The building is rectangular, 40 feet (12.2 meters) wide and 14.4 feet (4.4 meters) deep in the direction of flow, and is submerged to a depth of 10.5 feet (3.2 meters) as it is carried forward (Fig. 3). The velocity of the surge is approximated as $u = 36$ feet (11 meters) per second.

FIND:

(a) The time required for the building to impact with the other building;

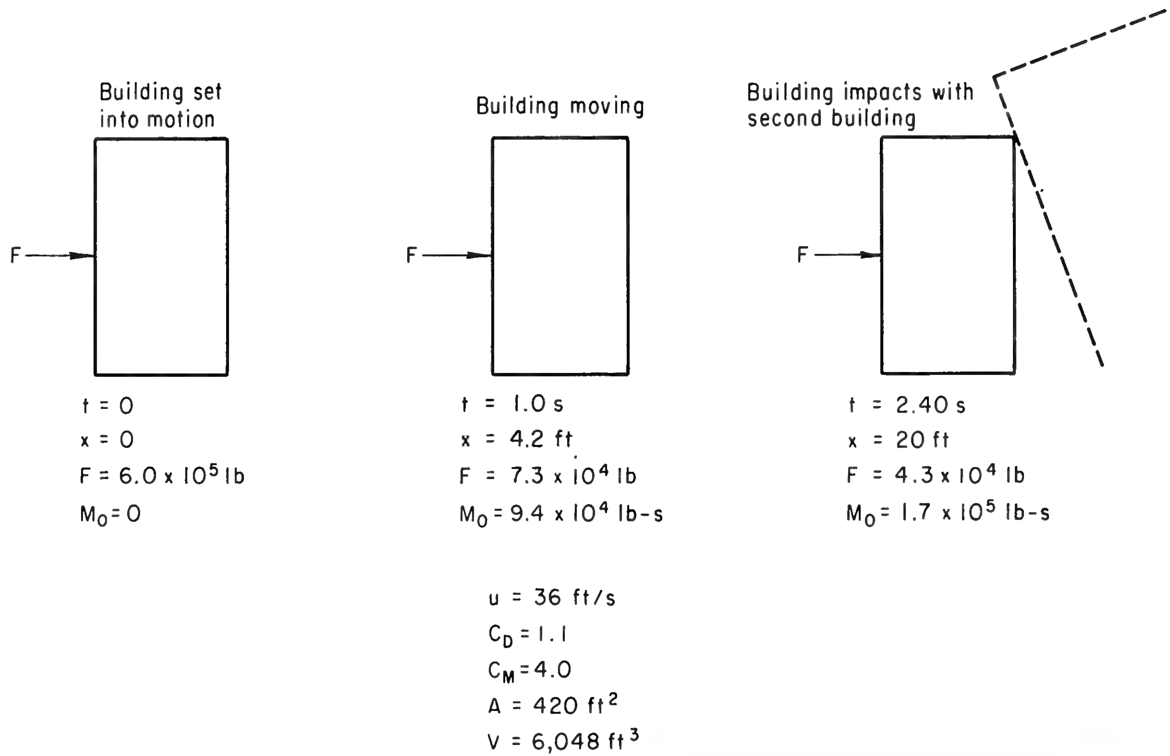



Figure 3. Building moved by tsunami surge.

(b) the force accelerating the building at the moment of impact; and

(c) the momentum of the building at the moment of impact.

SOLUTION:

(a) The submerged cross-sectional area of the building, transverse to the direction of the surge, is given as

A = width × submerged depth = 40 × 10.5 = 420 square feet (39 square meters) and the submerged volume (the displaced water) is

V = width × length × depth = 40 × 14.4 × 10.5 = 6,048 cubic feet (171 cubic meters).

The coefficient of drag can be approximated by assuming the side of the building is a flat plate. To determine an equivalent flat plate, using the Table, assume that the submerged depth for underflow and overflow (a totally submerged plate) is twice the depth of the building, or

$$\frac{L}{d} = \frac{40}{2 \times 10.5} = 1.9$$

and from the Table

$$C_D \simeq 1.1 \ .$$

From Figure 1, where

$$\frac{a}{b} = \frac{14.4}{40} = 0.36 \ ,$$

then

$$C_M = 4.0 \ ,$$

and equation (2) gives

$$\alpha = \frac{C_D A}{2V\ (1 + C_M)} = \frac{1.1 \times 420}{2 \times 6{,}048\ (1 + 4.0)} = 0.0076 \ .$$

The relationship between distance and time is shown in Figure 2, which for a distance of 20 feet gives

$$t = 2.40 \text{ seconds} \ .$$

(b) From equation (3)

$$u_b = u - \frac{u}{\alpha ut + 1} = 36 - \frac{36}{(0.0076 \times 36 \times 2.4) + 1}$$

$$u_b = 14.3 \text{ feet (4.35 meters) per second .}$$

From equation (4)

$$F = \rho V \alpha \ (u - u_b)^2$$

$$F = 2 \times 6{,}048 \times 0.0076 \ (36 - 14.3)^2$$

$$F = 4.3 \times 10^4 \text{ pounds } (1.9 \times 10^5 \text{ newtons})$$

(c) Momentum, $M_o$, at impact is

$$M_o = u_b \times \text{mass}$$

taking the mass of the building equal to the mass of the displaced water for a partially submerged building which is floating (the mass includes water within the building),

$$\text{mass} = \rho V = 2 \times 6{,}048 = 12{,}096 \text{ pounds-second squared per foot}$$

and the momentum is

$$M_o = u_b \times \text{mass} = 14.3 \times 12{,}096$$

$$M_o = 1.7 \times 10^5 \text{ pounds-seconds } (7.7 \times 10^5 \text{ newton-seconds})$$

* * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * *

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