

CHAPTER 181

Structural Response of Dolos in Waves

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ABSTRACT

Several numerical models for estimating wave forces on dolosse are presented. These models are incorporated into a finite element method (FEM) analysis of a 42-ton unit. The results of the analysis permit identification of unit structural failure with respect to wave conditions.

INTRODUCTION

One means of protecting breakwaters and shorelines from wave-induced forces has been through the deployment of dolos concrete armor units. A typical dolos armor unit is shown in Figure 1. These randomly placed units form an interlocking yet porous armor layer providing a high degree of hydrodynamic stability. However, in the past, dolos armor units in severe wave environments, such as the breakwaters in Crescent City, California and Port Sines, Portugal, have experienced structural failures (Magoon, 1974, and Magoon and Baird, 1977). The unsatisfactory behavior of these units has prompted investigations into the wave loading on dolos armor units and an assessment of the subsequent dynamic structural response of the dolos unit.

This paper summarizes recent research conducted on the structural response of dolos armor units subject to wave forces. Several mathematical models (Tedesco and McDougal, 1985, and McDougal et al, 1988) developed for estimating wave forces on a single armor unit are presented. These wave force models were incorporated into a finite element method (FEM analysis of the dolos unit). Two types of analyses were conducted: 1) direct application of a critical wave to the armor unit restrained against rigid body motion, and 2) application of impact forces generated when wave-induced rigid body motion occurs causing dolos impacts.

SIMPLE WAVE-SLAMMING MODEL

In this model, the force on the dolos is estimated from the slamming of the wave with the structure. Only the horizontal component of

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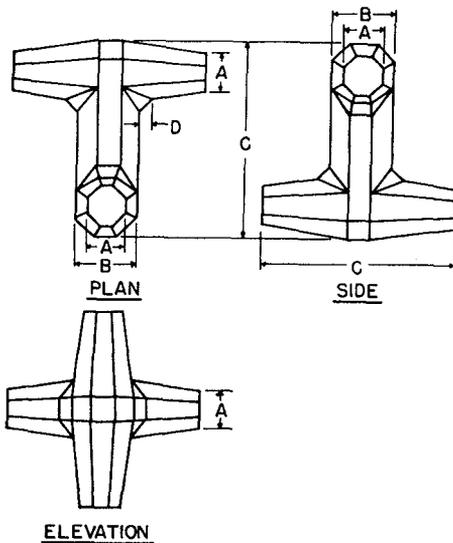


Fig. 1. Dolos Armor Unit.

this impact force is examined, which for the assumed geometry, is larger than the vertical component. Slamming is an important consideration in the design of ocean structures in the splash zone. As a result, a small body of information exists on wave-impact forces on horizontal cylinders. Kaplan (1979) and Kaplan and Silbert (1976) have developed models for both the horizontal and vertical forces due to impact. The models include the effects of buoyancy, pressure gradients, momentum flux (including added mass), and drag. Results are in reasonable agreement with measurements for the horizontal force but not for the vertical.

Experimental results suggest that the impact force, F , may be expressed in a simpler form

$$F = \frac{1}{2} C_s \rho d l U^2, \quad (1)$$

in which ρ is the fluid density; d is the diameter of the cylinder; l is the length of the cylinder; U is fluid velocity; and C_s is a slamming coefficient (Sarpkaya, 1978). The slamming coefficient is a function of the immersion depth of the cylinder and, therefore, a function of time. A time-dependent slamming coefficient has been empirically developed (Sarpkaya, 1978):

$$C_s = \frac{5.15}{1 + 19 \frac{Ut}{d}} + \frac{0.55 Ut}{d}. \quad (2)$$

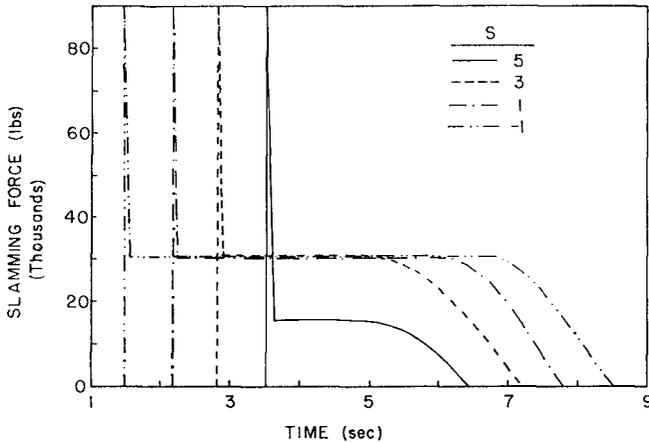
The maximum value for C_s at $t = 0$ is 5.15 and this value is appropriate if a static structural analysis is performed (Sarpkaya and Isaacson, 1981). For dynamic analyses, a value of 3.2 is suggested. Therefore, eq. (2) is accordingly scaled for use in the present dynamic analysis.

The foregoing formulation is, of course, only valid when some portion of the cylinder is immersed. However, when the cylinder is totally immersed, the formulation is inappropriate. Experimental results of Sarpkaya (1978) indicate that this formulation is only valid up to the point where the top of the cylinder is just below the free surface. Therefore, at this depth (when the slamming coefficient is at minimum)

the forces are assumed to no longer be impact dominated and a drag formulation is adopted.

$$F = \frac{1}{2} C_D \rho S d U^2, \tag{3}$$

in which S is the fraction of the cylinder which is immersed and C_D is a drag coefficient. It is noted in eq. (2) that the minimum value for the slamming coefficient is 0.5. This is of the same order as the drag coefficient for a smooth cylinder. Therefore, for purposes of calculation, this minimum value of C_S will be used for C_D . Several representative time histories of force are shown in Fig. 2. For a given wave and cylinder size, the duration of the force is a function of the position of the



cylinder relative to the stillwater level. The peak impact force is not a function of elevation because the horizontal velocity is assumed to be constant. The tailing off of the force depends upon the ratio of the cylinder diameter to the wave height.

Fig. 2. Time history of slaming force. (S is height above SWL in feet)

An FEM (ADINA, 1984) analysis was conducted on three different sizes of dolosse subject to the simple wave slaming model. An isometric view of the model is depicted in Fig. 3. The analyses were performed for concrete compressive strengths, f'_c , of 5000 psi and 4000 psi for each model. The dolosse were assumed to be unreinforced, and the tensile strength of the concrete was assumed to be equal to the split cylinder strength, f_{ct} , of the concrete (where $f_{ct} = 6.7\sqrt{f'_c}$).

The failure of the dolosse depends on the maximum slaming load. This load, in the present analysis, is only a function of the wave conditions for a specific dolos unit. This load is calculated as discussed above and regions of structural stability are identified as a function of the wave conditions. These results are shown in Fig. 4 for a 42-ton dolos in which T is the wave period, T_c is the resonant period, H is the wave height, and H_H is the maximum stable wave height for the unit. Stable and failure regions are identified for 4000 psi and 5000 psi concrete. It is noted that structural failure would occur for the 4000 psi concrete at wave conditions for which the unit is hydrodynamically

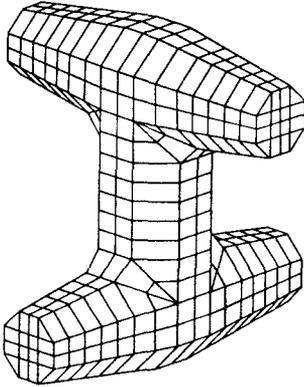


Fig. 3. Isometric view of FEM Model

stable. The higher strength concrete unit is very nearly at failure at these wave conditions.

MULTI-COMPONENT WAVE FORCE MODEL

The precise specification of the wave loads in the breaker zone is extremely difficult. However, there are many structures built in this zone and several approximate analysis methods have been developed. Kaplan (1979) and Kaplan and Silbert (1976) developed Morison type equations (Morison et al, 1950) for a horizontal cylinder in the "splash zone" where the structure is not in continuous contact with the wave. This model includes the slamming of the fluid on the structure as the structure penetrates the free surface. A primary assumption is that the wave

length is large with respect to the structure diameter. Kaplan and Silbert (1976) showed that the vertical force per unit length on a horizontal cylinder for a normally incident wave can be expressed as the sum of the buoyant, inertial, kinetic and drag forces as follows:

$$F_{VH} = \rho g A_i + (m_3 + A_i) \ddot{\eta} + K_{HV} \frac{\partial m_3}{\partial z} \dot{\eta}^2 + \frac{\rho}{2} \dot{\eta} |\dot{\eta}| d \left(\frac{z}{r}\right) C_{DV} \left(\frac{z}{r}\right), \tag{4}$$

where the first subscript on F denotes the force direction and the second indicates the cylinder orientation. The force component notation is shown in Fig. 5. Also, K_{VH} is an empirical force coefficient, ρ is the mass density of the fluid, g is the acceleration of gravity, A_i is the immersed area, $\ddot{\eta}$ and $\dot{\eta}$ are the vertical wave velocity and acceleration, respectively, $d(z/r)$ and $C_{DV}(z/r)$ are the depth dependent diameter and drag coefficient, respectively, and m_3 is the vertical added mass.

The horizontal force on a horizontal cylinder can similarly be stated as the sum of inertial, kinetic and drag forces:

$$F_{HH} = (m_2 + \rho A_i) \dot{u} + K_{HH} \frac{\partial m_2}{\partial z} \dot{u}^2 + \frac{\rho}{2} u |u| h \left(\frac{z}{r}\right) C_{DH} \left(\frac{z}{r}\right), \tag{5}$$

where K_{HH} is an empirical force coefficient, u and \dot{u} are the horizontal water particle velocity and acceleration, respectively, and m_2 is the horizontal added mass. For the case of a vertical cylinder, the previous equation for horizontal force can be directly applied to yield

$$F_{HV} = (M_4 + \rho A_i) \dot{u} + K_{HV} \frac{\partial m_4}{\partial z} \dot{u}^2 + \frac{\rho}{2} u |u| DC_{DH} \tag{6}$$

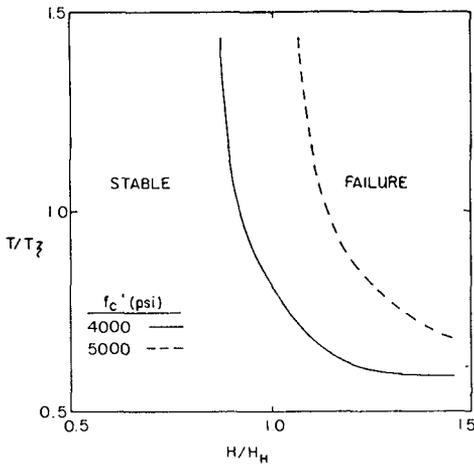


Fig. 4. Failure envelope for 42-ton dolos unit.

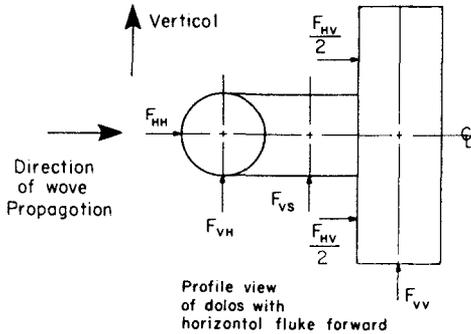


Fig. 5. Dolos orientation and wave force component notation.

in which K_{HY} is an empirical force coefficient. The vertical force on a vertical cylinder can be expressed as the sum of form drag and buoyancy acting on the lower end of the cylinder to yield

$$F_{VV} = \rho g \pi r^2 + \frac{\rho}{2} v |v| \pi r^2 C_D, \quad (7)$$

where v is the vertical water particle velocity at the cylinder base. Finally, the vertical force on a horizontal cylinder parallel to the direction of wave propagation is assumed to be buoyancy dominated and thus given by

$$F_{VS} = \rho g A_i. \quad (8)$$

These force equations are similar in form to the Morison equation. However, potential theory is employed to determine the kinetic term and the coefficients, m_2 , m_3 , m_4 and C_D , which are in terms of the geometric properties as well as flow and cylinder roughness characteristics.

In this study, linear wave theory was used to determine the values of wave variables to the maximum stable wave height for a 42-ton dolos on a 1V:2.5H slope as determined from Hudson's formula. The wave period was selected by choosing an Iribarren number of 2.5. The Iribarren number is the ratio of

for the design wave given in Table 1. The wave

Table 1. Wave and dolos specifications			
Wave		Dolos	
Height	33.4 ft	Elevation	12.0 ft
Period	12.77 sec	Fluke dia.	3.98 ft
Depth	42.8 ft	Fluke length	15.29 ft
		Shank dia.	4.89 ft
		Shank length	7.33 ft

the structure slope to the square root of the wave steepness. A value of 2.5 corresponds to a critical condition in which the wave breaks when rundown is at its lowest point (Bruun and Gunbak, 1977). The depth corresponds to the depth limited breaking for this wave height.

The dolos configuration is as shown in Fig. 5 with the horizontal fluke forward. The methodology developed for estimating wave forces is also applicable to the case with the vertical fluke forward. In both cases the shank is fixed in the horizontal plane and in line with the direction of wave propagation.

The multi-component wave force model was incorporated into an FEM analysis of a 42-ton dolos. In the analysis, the dolos unit was positioned among other units so that it is restrained only at the bottom of the vertical fluke which is perpendicular to the wave crest. The horizontal fluke is forward (seaward) and parallel to the wave crest.

For the specified wave loading and structure restraint conditions, the critical section in the dolos unit was located in the bottom portion of the vertical fluke, at the fluke-shank juncture, just below the fillet. The maximum tensile stress at the critical section was calculated to be 760 psi. This value exceeds the ultimate tensile strength of 743 psi (the modulus of rupture), thereby causing a structural failure.

IMPACT ANALYSIS

Damage to dolosse is primarily due to the impact forces resulting from the collision of units due to wave-induced rolling and rocking motions (Burchart, 1984). Knowledge of the rigid body motions is required for an appropriate design. Once the wave loads have been specified and the dolos orientation is known, the equations of motion can be solved numerically. The equations of motion for a dolos constrained as described in the previous section reduce to a single rotational degree of freedom. The equation of motion is (McDougal et al, 1988)

$$I\ddot{\theta}(t) + C\dot{\theta}(t) + K\theta(t) = M(t) \quad (9)$$

where θ , $\dot{\theta}$, and $\ddot{\theta}$ are the angular displacement, velocity, and acceleration, respectively, I is the mass moment of inertia, C is damping, K is stiffness, and M is the applied moment. In the analysis, $C = 0$ and the applied moment is given by the product of the time varying moment arms and the respective Kaplan forces. This equation was integrated using a fourth order Runge-Kutta algorithm.

In the present study, the case investigated is depicted in Fig. 6. The horizontal fluke is seaward and parallel to the wave crest. Under wave action, the dolos is permitted to pivot about the vertical fluke which is perpendicular to the wave crest. Damage to the unit occurs when the dolos falls back to its initial position and impacts another unit.

The FEM representation of the scenario is depicted in Fig. 7. The unit is assumed to impact a rigid contact surface at a contact velocity

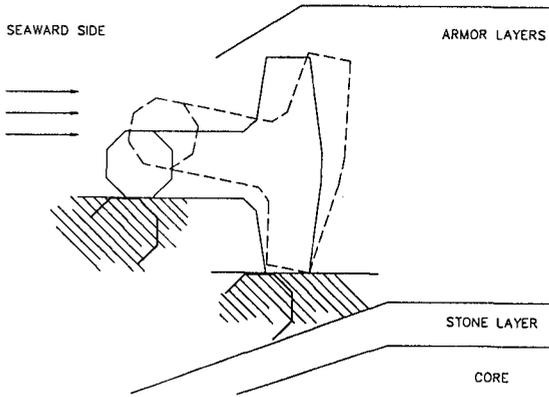


Fig. 6. Dolos orientation for impact analysis.

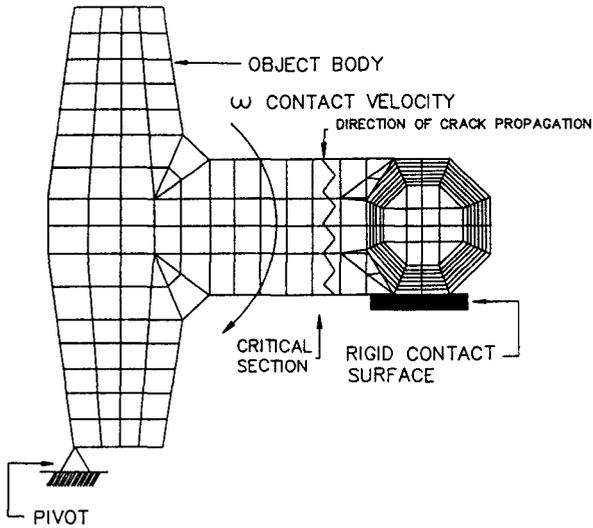


Fig. 7. FEM representation of impact analysis.

ω . The critical section in the unit is located on a vertical plane through the shank (Fig. 7). The dynamic stress history at the critical

section is presented in Fig. 8.

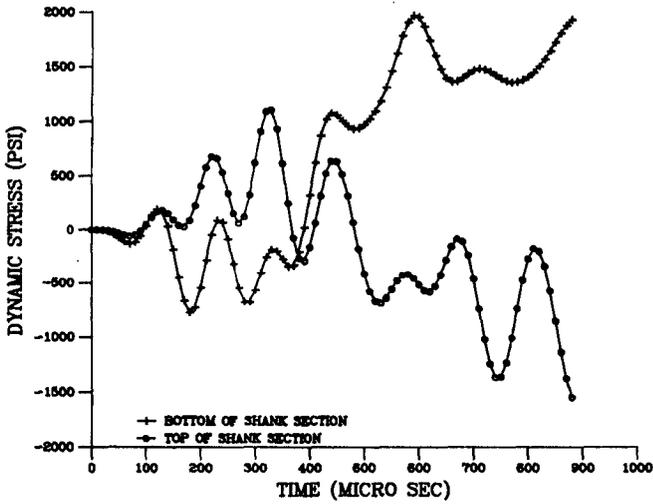


Fig. 8. Dynamic stress history for impact analysis.

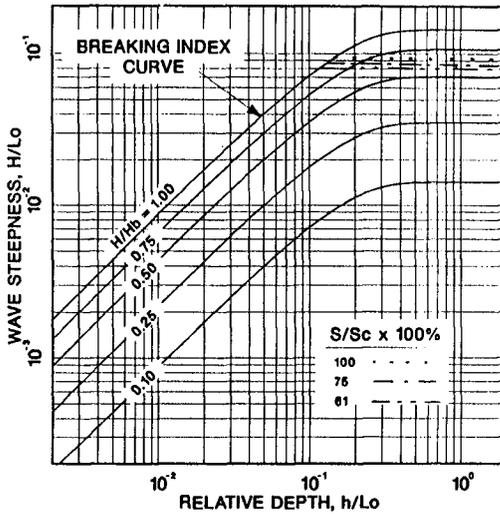


Fig. 9. Structural stability curves for a 42-ton dolos. (10 sec. wave period)

It is quite useful to be able to determine the wave conditions which induce a structural failure in the armor unit. Structural failure of a 42-ton dolos unit is depicted in Fig. 9 for a wide range of wave conditions at a constant period. Wave conditions producing 75% and 60% failure stresses are also presented in Fig. 9.

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