142743 → Dr. Roz

Evaluation of pier fendering systems

In ports and harbours, vessel docking facilities must be adequately protected in order to avoid damage to both the vessel and the pier. As a result many types of fendering systems exist for this purpose. It is becoming increasingly difficult to evaluate these fender systems and a simplified procedure is needed to determine what fender systems are adequate for the given parameters. The purpose of this article, by Dr K N Derucher, Associate Professor and Head of Department of Civil Engineering, Stevens Institute of Technology Hoboken, New Jersey, is to provide such a procedure.

In the design of a fendering system two methods are utilised by the designers; namely, the Forced Acceleration Method and the Kinetic Energy Method. In the Force Acceleration Method the induced or applied force to the system, caused by the vessel's impact, is:

$$F_a = M\ (v^2_i - v^2_f/2\triangle_s \qquad (1)$$

where:

- M = mass of the vessel
- v_i, v_f = initial and final velocity
- $\triangle_s$ = deformation of the system at point of impact

the resisting force of the system is:

$$F_r = (3\triangle_s EI/L^3) + \Sigma K\triangle_s \qquad (2)$$

where:

- E = modulus of elasticity of the support (pile if such)
- I = moment of inertia of the support
- L = length of the support
- K = spring constant of the fender

In applying this method the designer would assume an allowable $\triangle_s$ and initial stiffness I. If the resisting force F_r is greater than the applied force F_a, then the actual $\triangle_s$ would be smaller than assumed. The induced stress of the system would be compared to the allowable or ultimate stress of the material.

In the Kinetic Energy Method the induced energy caused by the vessel is given by:

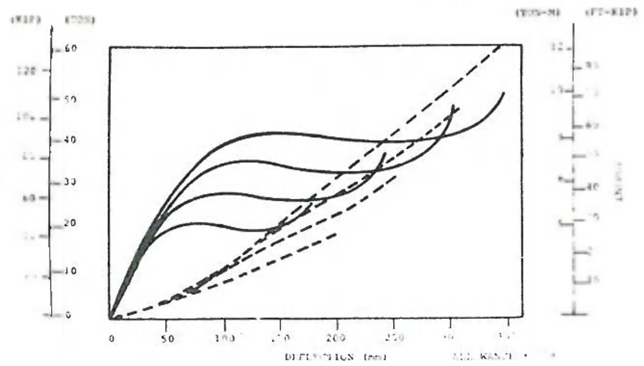
$$E_{in} = \tfrac{1}{2} Mv_i^2\ (C_H)\ (C_S\ (C_C)\ (C_E) \qquad (3)$$

where:

- C_H = hydrodynamic coefficient = $1 + 2D/B$
- D = draught of the vessel
- B = beam of the vessel
- C_E = eccentricity coefficient
- C_S = softness coefficient
- C_C = configuration coefficient

The C coefficients (C_H, C_E, C_S and C_C) can be set equal to 1.0 for the worst case. Other variations can be obtained for specific vessel variables.

Fig 1 Typical characteristic curve



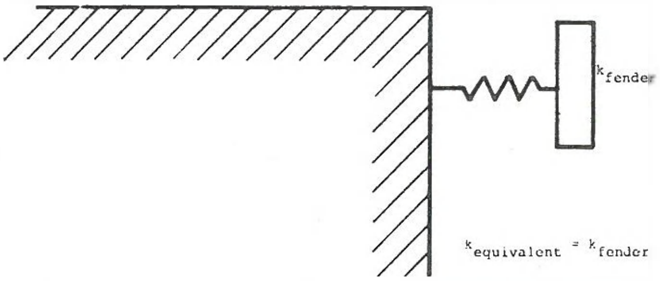


Fig 2 Closed dock structure with fender

The output energy or that energy that can be absorbed by the system is:

$$E_o = F \cdot \triangle_s + \Sigma \tfrac{1}{2} K\ \triangle^2_f \qquad (4)$$

where:

- F = force applied or induced
- $\triangle_s$ = deformation of the support
- $\triangle_f$ = deformation of the fendering system

but;

$$\triangle_s = FL^3/3EI \text{ (if a piling system)} \qquad (5)$$

therefore:

$$E_o = (F^2L^3/3EI) + \Sigma \tfrac{1}{2}\ K\ \triangle^2 \qquad (6)$$

Using equations 3 and 6 of the Kinetic Energy Method and assuming $\triangle = FL^3/3EI$ or zero, the induced force F is determined. The resulting $\triangle$ can then be evaluated and used to re-evaluate E_o if $\triangle = 0$ was originally assumed. The resulting stress can then be calculated and compared with the allowable or ultimate stress of the material.

Design engineers use some form of the force acceleration method or the kinetic energy method. In using the force acceleration method each engineer determines the necessary force required then approaches the respective marine fendering catalogue and determines the type of fendering system from the force (load)-deflection curves. In using the kinetic energy method each engineer determines the necessary energy required then again approaches the respective marine fendering catalogues and determines the type of fendering system from the energy-deflection curves. Fig 1 shows a typical load-deflection/energy-deflection curve.

However, the problem port and harbour engineers face is that there are so many marine fenders to chose from it is difficult to determine which is the best system for his needs. Thus, a simplified method is needed for fender evaluation.

Analysis of fender systems

In the design of a fender system it is possible to assume that the system is equivalent to a mass supported by a spring. In such a system, it is assumed that the spring constant k is equivalent to the response of the system and the spring mass M represents the vessel. Examination of such a spring mass system results in the following general equations:

$$Y_{max} = V_o/\lambda \qquad (7)$$

$$a_{max} = V_o\ \lambda \qquad (8)$$

$$P_{max} = k\ y_{max} \qquad (9)$$

$$t_{max} = \pi/2\lambda \qquad (10)$$

where:

- λ = $(k/M)^{1/2}$
- k = spring constant
- M = spring mass which represents the vessel
- y_{max} = maximum displacement
- a = acceleration
- P = force
- t = time
- V_o = original velocity

In which the parameters for such a system are as follows:

- W = weight of vessel (tons)
- V_o = initial velocity of vessel (knots)

In which the conversions are as follows:

- W_s (kips) = $W \times 2$
- $M = W_s/g = W_s/(32.2 \times 12)$ k sec^2/in
- $V_o = V_{knots}$ (1.689 × 12) in/sec

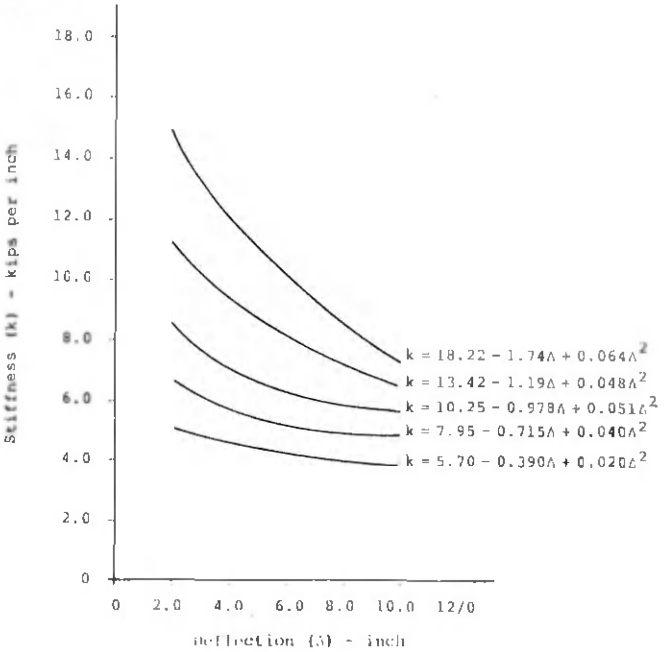


Fig 3 Stiffness versus deflection

The spring parameter k, which is equivalent to the deformation due to a unit load is computed as:

$$k = 1/\triangle_s \qquad (11)$$

where:

$\triangle_s$ = deformation of the system

In utilising this approach the question arises as to the value of k. If one is dealing with a pier or dock structure as shown in Fig 2 then the k value will be equal to the k of the fender. In order to determine the k of the fender it is necessary to develop k-$\triangle$ curves. The k-$\triangle$ curves are developed from the load deformation curves (similar to that shown in Fig 1). In other words, the given loads are divided by their corresponding deformations and are now referred to as a stiffness value, k. These stiffness values are then plotted versus the deformations, $\triangle$; thus, k-$\triangle$ curves are formed as shown in Fig 3.

From each k-$\triangle$ curve one can determine the k of the fender by simply writing the equation of the curve in quadradic form. Thus, k of the fender would equal $A\triangle^2 + B\triangle + C$. Already knowing the A, B and C parameters of the curve and assuming a value for $\triangle$ (usually zero) one can determine the numerical value for k of the fender.

If this were a piling system with a fender attached, the general response of such, when subjected to a vessel, is computed by removing the pile and examining its effect as a cantilever beam, as shown in Fig 4. In this system a k-equivalent must be developed which is equal to the product of the k of the pile and the k of the fender divided by the sum of the k of the pile and the k of the fender. In this case the k of the fender is developed as described for a pier or dock structure. The k of the pile is equal to:

$$k_{\text{of the pile}} = 3EI/L^3 \qquad (12)$$

Thus, these $k_{\text{equivalent}}$ values may now be used in the general equation in place of the spring constant. Once the k values are determined and the various analysis parameters are known then an evaluation can be made as to which fender system is adequate. The final two steps in the analysis process is to determine the percent deflection remaining and percent reserve energy. These equations are as follows.

% deflection remaining =

$$\triangle_{max} - \triangle_{act}/\triangle_{max} \times 100\% \qquad (13)$$

in which:

$\triangle_{max}$ = maximum deflection which the fender system will undergo

$\triangle_{act}$ = actual deflection which is produced from the calculations

and,

$$\% \text{ reserve energy} = E_{max} - E_{act}/E_{max} \times 100\% \qquad (14)$$

where:

E_{max} = maximum energy which the fender system can absorb

E_{act} = actual energy computed from the calculations

If the percent deflection remaining is zero or the $\triangle_{max}$ has been exceeded then the system is inadequate for use under the given conditions. Thus, the same is true as far as the percent reserve energy is concerned. If the percent reserve energy is zero or the E_{max} has been exceeded then the proposed system is inadquate for the given conditions. In either case if the system is found to be inadequate, and it is used, failure will result upon vessel impact and damage will be done to the dock, piling, and/or vessel.

Application

For the general purpose of discussion, an arbitrary example will be presented such that the reader may follow through with the calculations for their own problems.

Let us assume that we have a 65 000 dwt vessel approaching a closed dock structure (with a fender attached to the dock). The vessel will have an approach velocity of 0.24 knots. The proposed fendering system characteristic curves are shown in Figs 5, 6 and 7. The k-$\triangle$ curve is represented in Fig 5 and the value is $k = 0.057\triangle^2 - 2.46\triangle + 34.37$. Figs 6 and 7 show the load-deflection and energy-deflection curves respectively. We can now proceed with our problem in a step by step fashion.

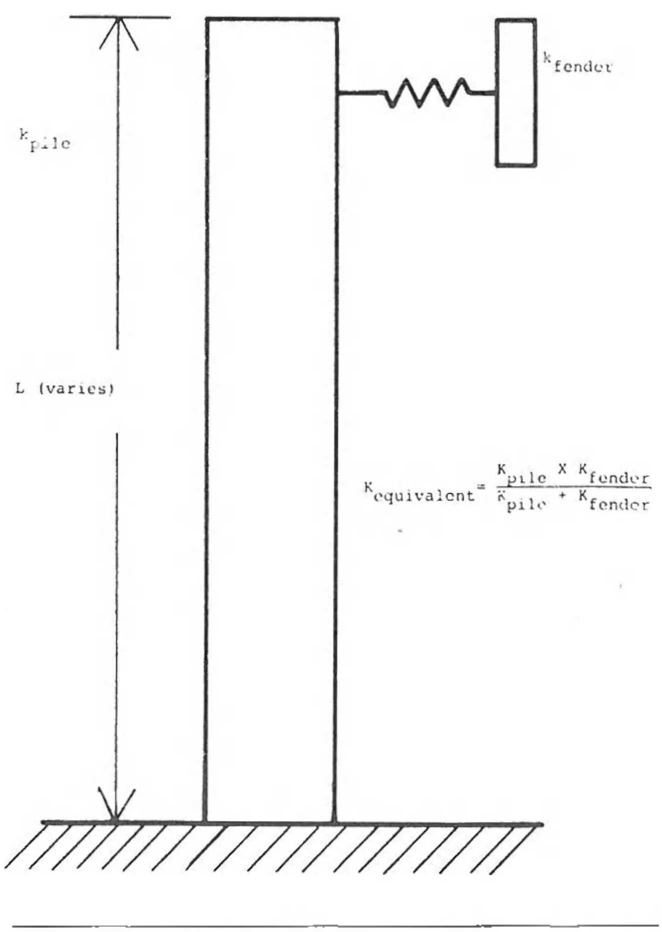
The first step in any analysis of a vessel impact with a fixed object is to determine the amount of energy to be absorbed.

Therefore:

$$E_{in} = \tfrac{1}{2} Mv^2_i (C_H)(C_S)(C_C)(C_E)$$

If one assumes the worst possible condition then the pro-

Fig 4 Piling system with fender



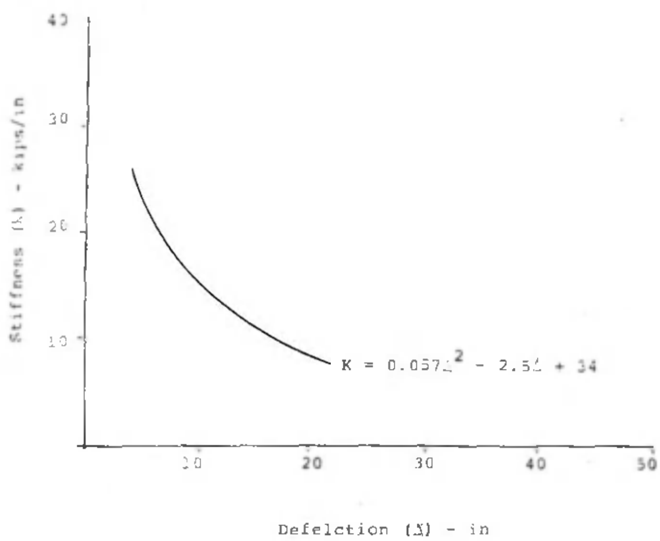


Fig 5 k– △ curve for proposed fender

duct (C_H) (C_S) (C_C) (C_E) is generally taken to be equal to one (1).

Thus:

$E_{in} = \frac{1}{2}$ (65 000 dwt × 2 000 lbs/ton × 1 Kip/1 000 lbs) (0.24 knots × 1.689 ft/sec/knot)² (1.0)

E_{in} = 322.98 Kip-feet

This is the energy absorbed by the dock structure and the vessel. It is generally assumed that the vessel absorbs 50% of the energy and in this case the dock structure absorbs the remaining 50%. Therefore, the total energy to be used in the evaluation of the fendering system is one-half of E_{in} of 161.49 Kip-feet.

Proceeding to the next step it becomes appropriate to determine the Y_{max} or the maximum deflection (actual deflection) of the proposed fender system.

Therefore:

$$Y_{max} = V_o/\lambda$$

where:

- Y_{max} = actual deflection in inches
- V_o = velocity upon impact, 0.24 knots (0.4 ft/sec or 4.8 inches/sec)
- λ = $(k/M)^{1/2}$
- k = Rigidity of the fender; $k = 0.057\triangle^2 - 2.46\triangle + 34.37$ and assuming $\triangle = 0$, k = 34.37
- M = mass of the vessel; W_s/g = 336.44 Kip-sec²/in

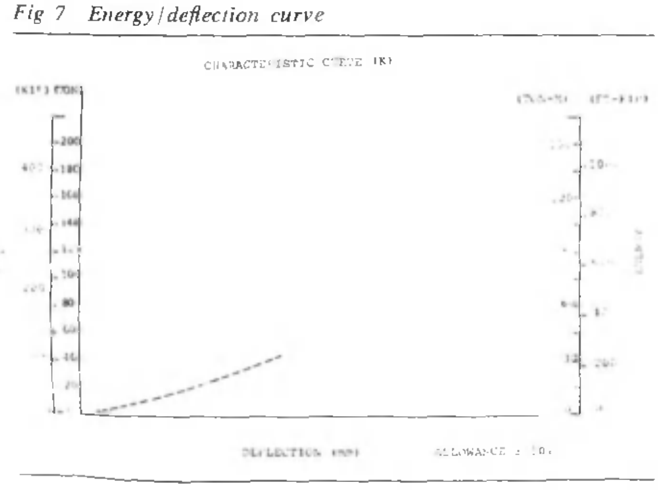
Thus:

$\lambda = (k/M)^{1/2} = (34.37/336.44)^{1/2} = 0.32\ sec^{-1}$

$Y_{max} = V_o/\lambda = 4.8/0.32 = 15.00$ inches

As a further consideration one may wish to determine the maximum load on the fender-dock structure, the maximum acceleration, and the stopping time.

Fig 7 Energy/deflection curve



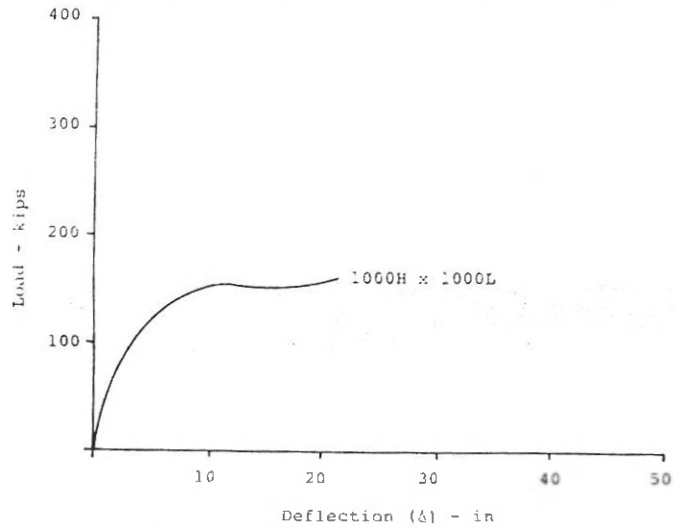


Fig 6 Load-deflection curve for proposed fender

Therefore:

$P_{max} = k\,Y_{max} = (34.37)(15.00) = 515.55$ Kips

$a_{max} = V_o\lambda = 4.8$ inches/sec × 0.32 sec⁻¹ — 1.54 ft/sec²

$t_{max} = \pi/2\lambda = 3.14/2 \times 0.32\ sec^{-1} = 4.91$ seconds

The final step will be to determine the percent deflection remaining and the percent reserve energy.

Threfore:

% deflection remaining $= \triangle_{max} - \triangle_{act}/\triangle_{max} \times 100\%$

The $\triangle_{max}$ value is obtained from Fig 6 and is given as stated before a value of 21.65 in and $\triangle_{act}$ was calculated as in step two and is equal to 15.00 in.

Thus:

% deflection remaining $= 21.65 - 15.00/21.65 \times 100\%$

% deflection remaining = 30.72

Now we must determine the percent reserve energy. From Fig 7 the energy deflection the maximum energy which this proposed fender can take is 257 Kips-ft. The actual energy is as we calculated in step one or 161.49 Kips-ft.

Thus:

% reserved energy $= E_{max} - E_{act}/E_{max} \times 100\%$

% reserved energy $= 257 - 161.49/257 \times 100\%$

% reserved energy = 37.1

Therefore, for this particular proposed fender system it would appear to be adequate and probably could handle a larger vessel and/or greater velocity of approach.

Conclusions

It would do little here to present data for several fenders and work through the equations. However, a method has been proposed which will aid the design or harbour engineer with the ability to properly select the most beneficial fendering system for his needs. Thus, the port engineer no longer has to study each individual fender system in detail.

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