CHAPTER 129

CONCEPTS IN DESIGN OF COASTAL STRUCTURES

Casimir J. Kray*

Timber Structures

Certain design of the existing and proposed coastal structures for lateral loading in the United States is presently based upon the use of timber which is structurally inefficient in the elastic range. Figure 1, for example, indicates the plan of timber pile structure. This is a low- capacity dolphin composed of 19 piles, where piles in line of load carry two times axial load and three times larger shear than next piles in line of load.

A relatively small load will be conducive to yield in the tension or compression members. Repetitive loading will gradually cause collapse of such structure.

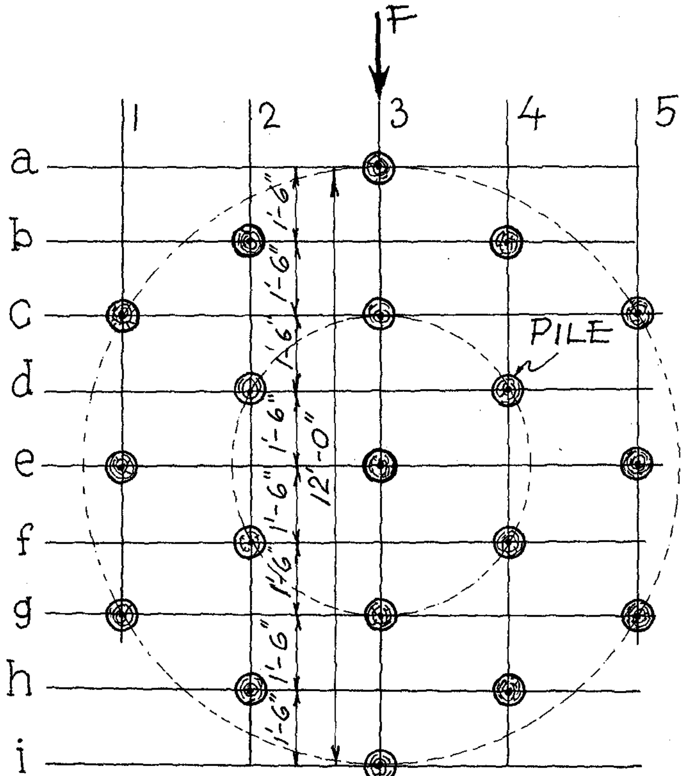
Being inefficient in the elastic range, timber structures may nevertheless, be adequate to provide safety for condition of shallow water, moderate wind pressures, moderate tides, and for moderate cross and reversing currents. However, such factors as: traffic safety, the possibility of marine borer attack, the location of structures in greater water depths, where they are exposed to waves, currents, tides, winds, and floating objects, indicate a need for larger capacity, more reliable and functional coastal structures consistent with the growing requirements.

Alternate Materials and Structural Considerations

The other type of coastal, rigid type structures, using reinforced concrete or structural steel with extensive bracing or with batter piles, are expensive and unyielding. This stiffness may be a reason for inflicted damages to the vessels and to structures themselves upon contact. These rigid structures are also prone to catastrophic failures during earthquakes.

*Consultant, Waterfront Structures, Naval Facilities Engineering Command, Alexandria, VA

By reason of the foregoing shortcomings of timber structures in general and rigidity of reinforced concrete, there is a trend in the Navy to high strength steel tubular sections, to be used singularly, or in groups for resilient type structures, see fig. 2.



PILES a-3 & i-3 CARRY TWICE LARGER LOAD & THREE TIMES LARGER SHEARS THAN PILES C-3 & g-3, REF 1.

FIG 1 - PLAN OF TIMBER PILE STRUCTURE

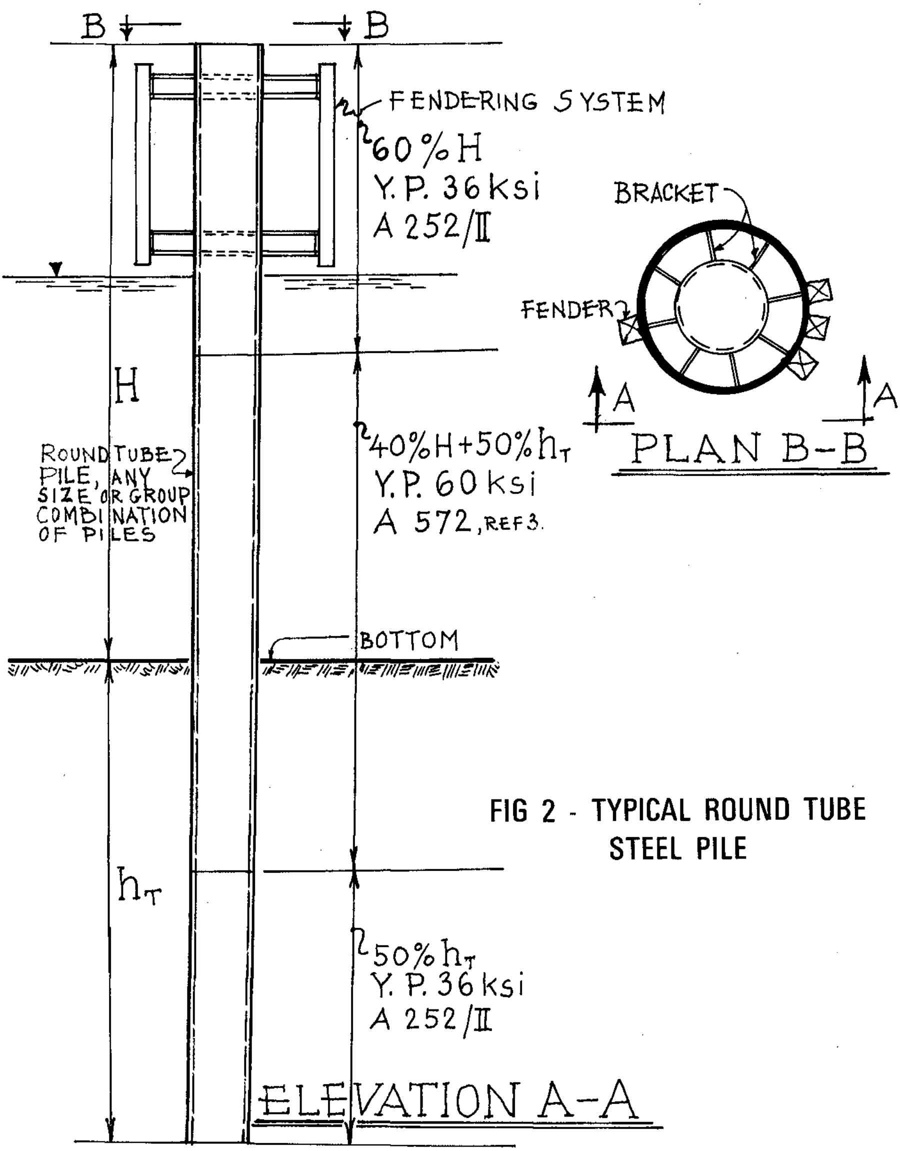


FIG 2 - TYPICAL ROUND TUBE STEEL PILE

COHESIONLESS FOUNDATION SOIL			
PILE SIZE Φ-IN t-IN	EMBEDMENT DEPTH ft	FORCE F KIPS	ENERGY E FT-KIPS
36 × 3/4	40	27	30
48 × 3/4	48	48	45
60 × 3/4	72	74	65
60 × 1	76	100	97
60 × 1 1/4	79	125	131
60 × 1 1/2	82	153	167
72 × 3/4	80	106	84
72 × 1	84	143	130
72 × 1 1/4	88	180	175
72 × 1 1/2	91	212	222

NOTE:

1. $f_y = 60$ KSI $\cdot \gamma_s = .05$ K/FT^3 $\cdot f = 7$ K/FT^3 $\cdot K_p = 3$
2. FORCE APPLICATION $H = 50$ FT ABOVE THE COHESIONLESS BOTTOM

FOUNDATION SOIL	CHARACTERISTIC LENGTH	DEPTH OF EMBEDMENT FOR LONG PILE BEHAVIOR
COHESIONLESS	$T = \sqrt[5]{EI/f}$	MIN. $h_T = 3T$
COHESIVE	$T = \sqrt[4]{4EI/K}$	MIN. $h_T = 2T$

EI – FLEXURAL RIGIDITY OF PILE (MODULUS OF ELASTICITY K/FT^2 × ×MOMENT OF INERTIA OF PILE SECTION FT^4)

f – COEFFICIENT OF HORIZONTAL FOUNDATION MODULUS K/FT^3

K – –"– –"– –"– –"– –"– K/FT^2

FIG 3 - CAPACITIES OF VARIOUS SIZE ROUND TUBE STEEL PILES

Such steel piles will provide:

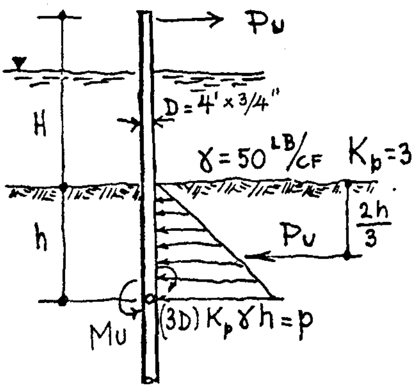
a. Improved pile to soil transfer of forces.

b. More efficient sharing of centric and eccentric forces by all piles; also better resistance to torsional forces, and better mobilization of torsional strains, to enable high energy storage.

c. Possibilities of larger deflections, for high energy absorption in bending, because the flexural elastic strain energy for steel is very high. Grade of steel can be varied in each pile, during the fabrication process.

d. Far greater efficiency in torsion, remarkably more than that in bending.

This is because the torsional shear stress is the same around the circumference of the pile and along its length. That advantage should be distinguished from bending stresses, which vary from zero at neutral axis, to a maximum at extreme fibers of the cross section; and from zero at the top of the pile to the maximum at the bottom.



$$P_u = \int_0^h p\,dh = \frac{(3D)K_p\gamma h^2}{2} \quad (1)$$

$$h = \sqrt{\frac{2P_u}{(3D)K_p\gamma}} \quad (2)$$

$$M_u = P_u\left(H + \frac{2h}{3}\right) \quad (3)$$

Ex: For $P_u = 100^K$ $h = 10.54'$ (Eq 2)
$H = 50$ ft

FIG 4 - ULTIMATE LOAD CONDITIONS FOR A PILE

Some assumptions made for design of resilient structures with tubular, round steel piles are:

a. Slope changes at upper ends of group of two piles (or more) should not be constrained, which is particularly important in weak soils.

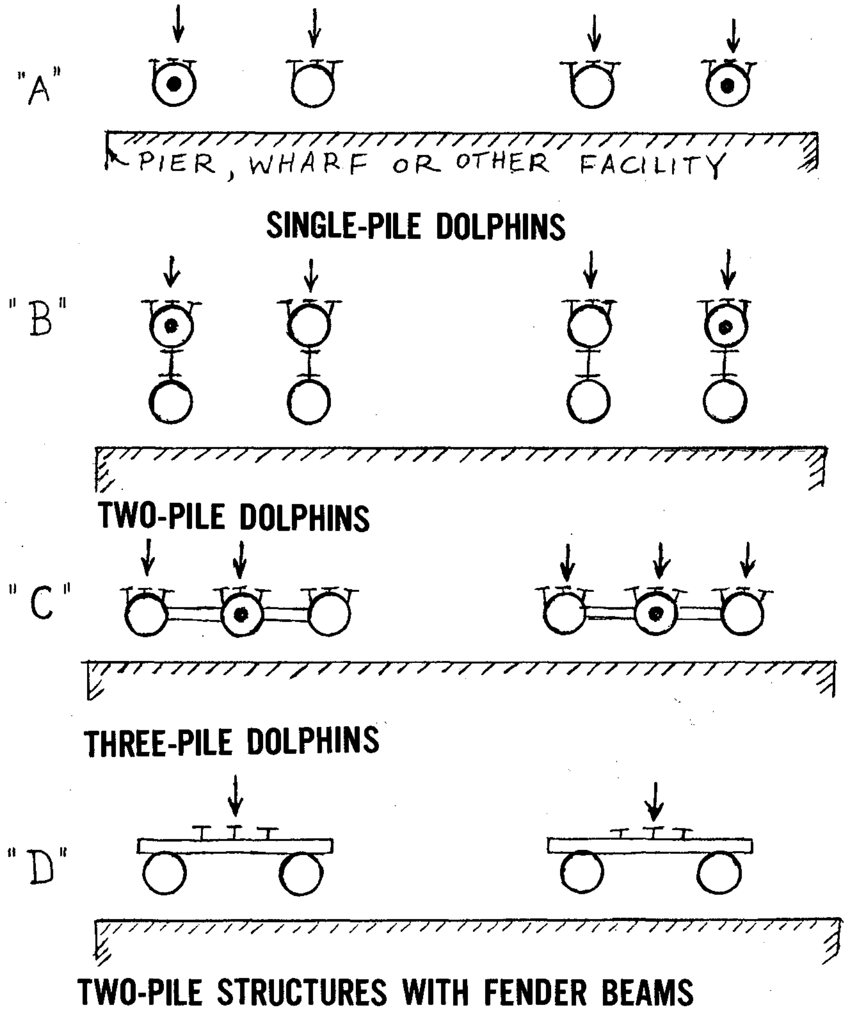


FIG 5 - VARYING CAPACITY PROTECTIVE STRUCTURES
ALTERNATIVE CONFIGURATIONS

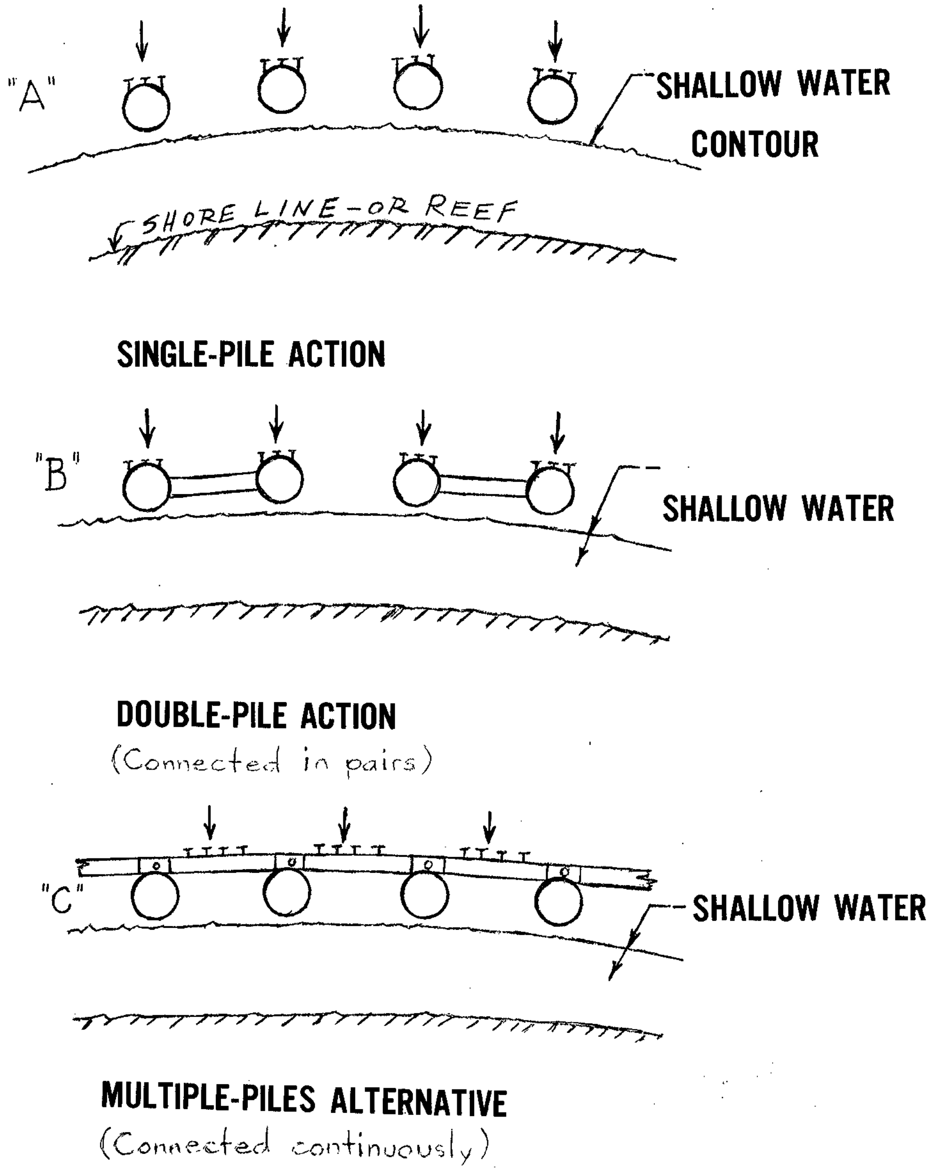


FIG 6 - VARYING RESPONSE SAFETY STRUCTURES

b. 50% of yield point in piles is used for mooring and for berthing forces.

c. 75% of yield point is used for energy absorption.

d. 1/8" wall thickness is provided additionally, for effects of corrosion.

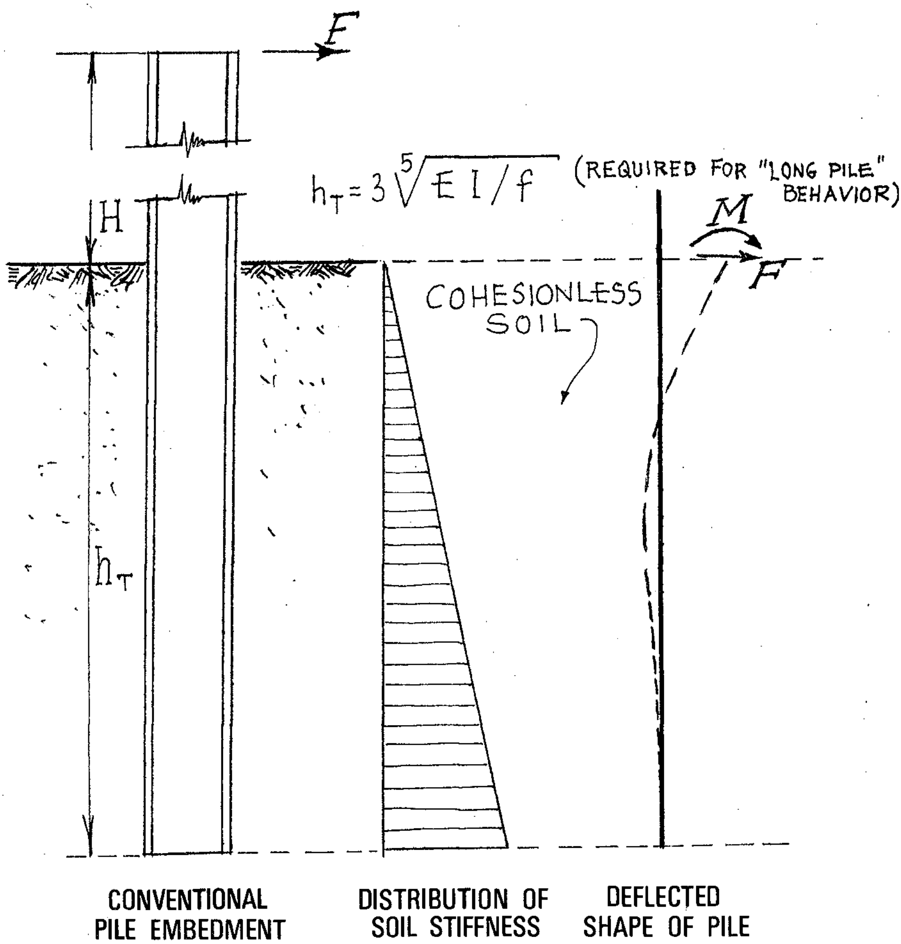


FIG 7 - PILE-SOIL INTERACTION

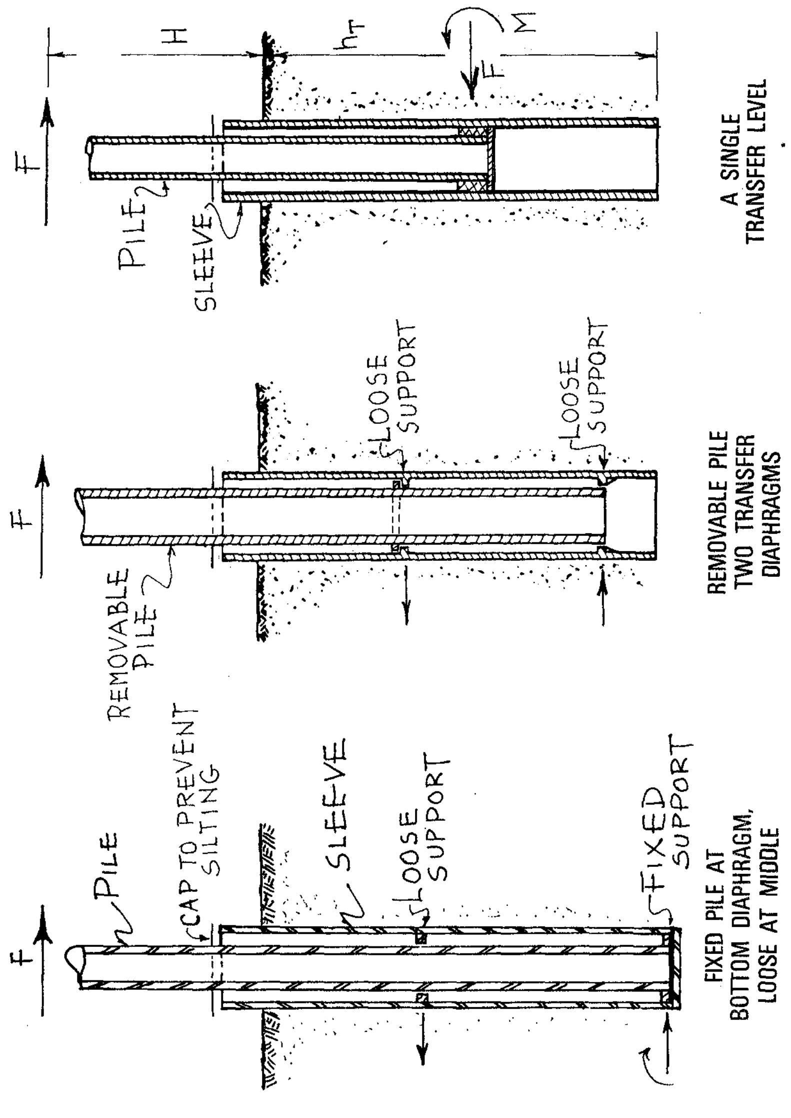


FIG 8 - ALTERNATE USE OF SLEEVE - VERTICAL SECTION
PILE TO SLEEVE FORCE TRANSFER, REF 2.

For illustration, figure 3 lists static force and energy absorbing capacities of various size tubular steel piles in cohesionless subgrade soil for forces applied at 50 ft from the bottom of the sea.

In consideration of the above-described items, there might be circumstances in which it would be desirable to transfer lateral forces acting on coastal structures into the soil through piles in bending, without the severe constraints to such bending which are imposed by soil behavior.

Regarding soil pile interaction, see figure 4 for the ultimate load capacity of a pile in cohesionless soil. It is assumed in figure 4, that the pile reaches its ultimate load condition, when a yield hinge develops at a certain depth. This is a commonly used approximation for interaction with cohesionless subgrade soil. In such a case, passive soil pressure counteracts the horizontal force action. Yield moment in the pile resists bending moment, caused by the horizontal forces.

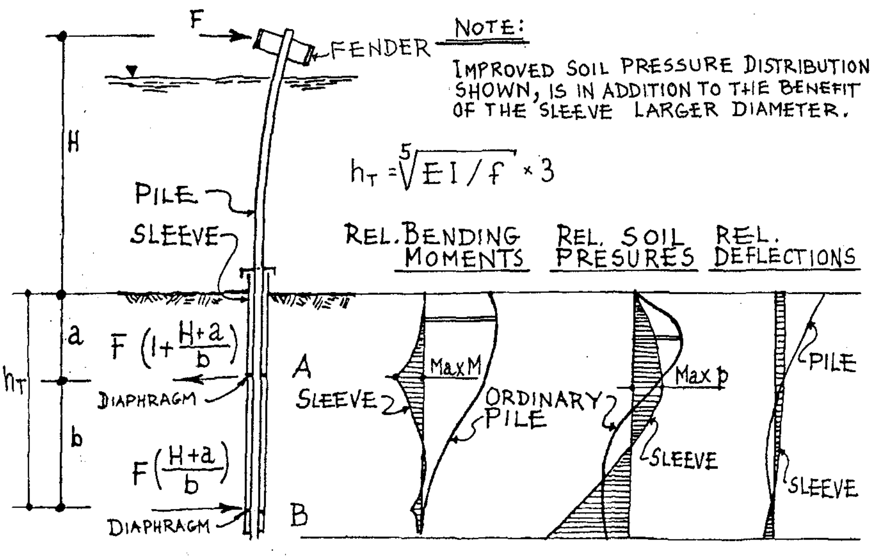


FIG 9 - RELATIVE-BENDING MOMENTS & SOIL PRESSURES

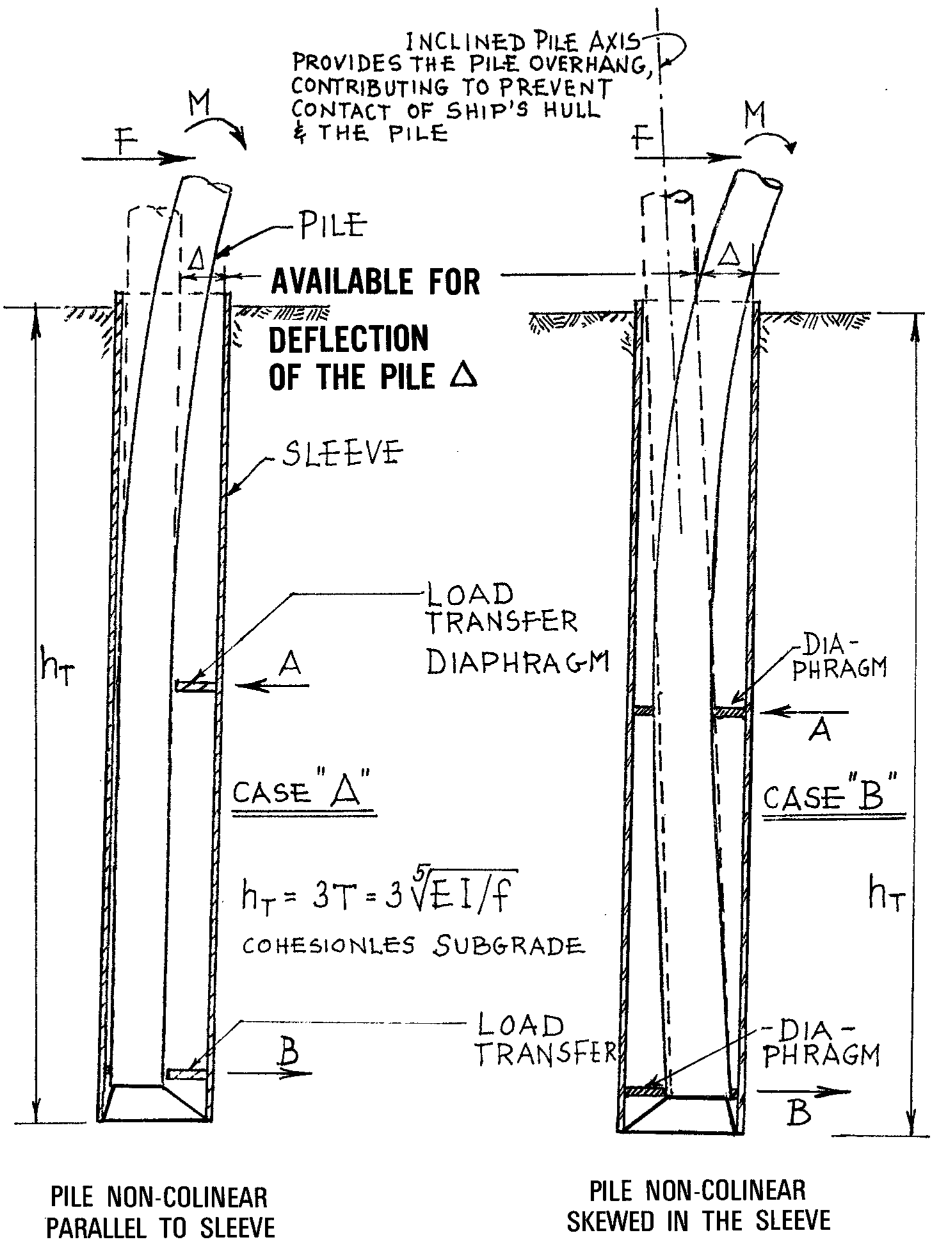


FIG 11 - VERTICAL SECTION - PILE IN THE SLEEVE
FOR MAXIMUM DEFLECTION

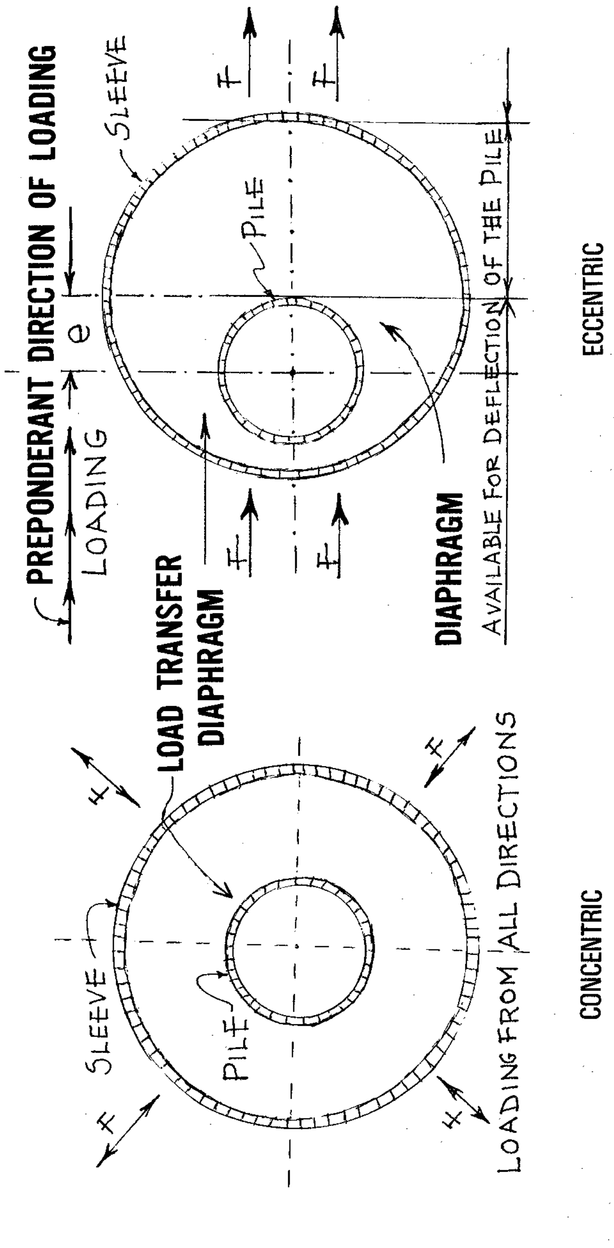


FIG 10 - LOCATIONS OF PILE IN THE SLEEVE - PLAN

After deciding on the kind of piles most suitable for field conditions, next it will be the intent of the designer to optimize the structure-to-ground interface, for improved structural response to lateral loading.

Design Concepts in Development

Such structures which resist lateral load by pile bending, rather than by axial forces in piles, batter piles, or in the bracing; can absorb large amounts of energy, a major consideration in case of contact with floating objects propelled by wind, current, tides, and wave action. In the exploitation of this advantageous characteristic of piles in bending for coastal structures, it would be desirable to use structural steel- round tubular piles, preferably of high-yield strength.

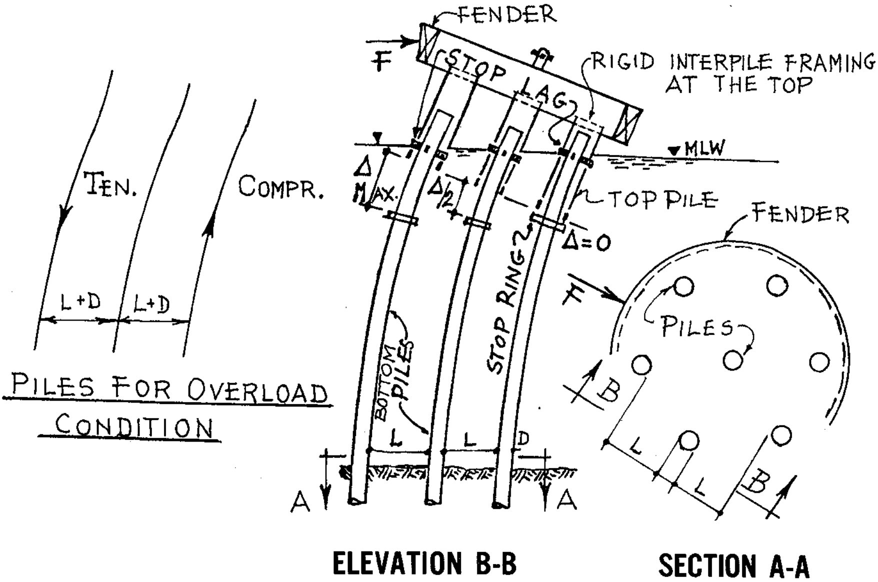


FIG 12 - SLIP JOINTED PILES' CLUSTER ELEVATION

Figure 5 shows structures composed of single, two pile and three pile dolphins, for protection of other vulnerable coastal installations or vessels from damage upon contact. Also, often they supplement lateral resistance of piers, wharves or quay walls, themselves not capable of supporting larger lateral loads. Figure 6 is an arrangement in plan of piles for various response, used for the single, double, and multiple pile action.

However, piles of such structures develop large shear and bending moment at the seabed elevation and imply lateral soil pressures which may well be above the elastic capability of many soils.

The loading, moments and forces are concentrated at the upper end of embedments where the soil is least resistant, see figure 7.

Therefore, certain improvisations are possible in order to provide for greater efficiency and safety in the applications of structural steel piles in coastal structures. For examples, the following could be done:

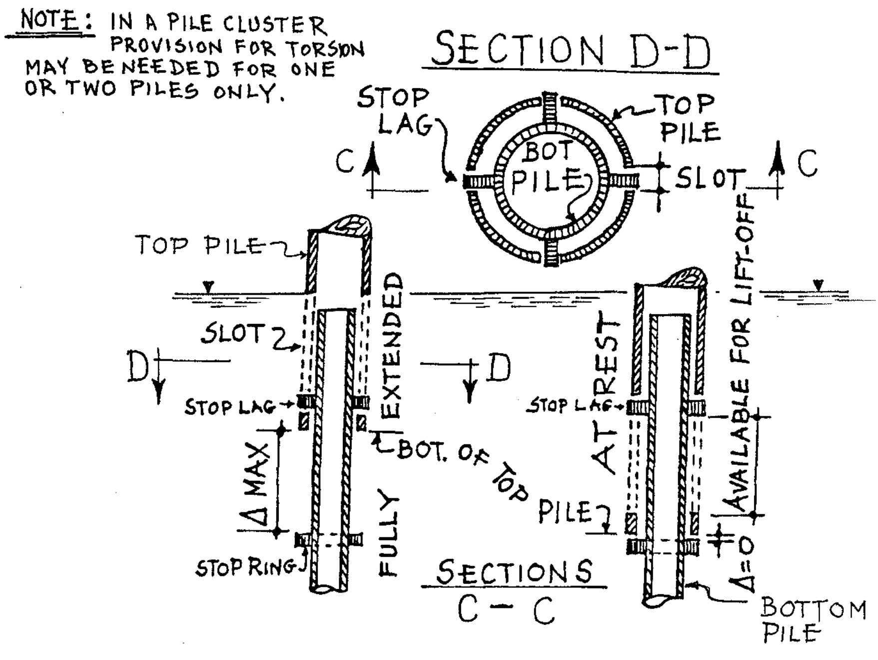


FIG 13 - DETAIL OF SLIP JOINT IN PILES

EXAMPLE : 7 PILES 36" PP X 0.75"; $f_y = 50$ ksi

ASSUME RATED CAPACITY AT $f_s = 28$ ksi

-"- SLIP-JOINT CLOSURE AT $f_s = 36$ ksi

	At Rated Capacity	At Joint Closure
DOLPHIN FORCE, F	191,000 LBS	245,000 LBS *
FORCE DISPL., Δ	16.8 INCHES	21.6 INCHES
ABSORBED ENERGY	133,700 LB-FT	220,000 LB-FT
MAX PILE SHEAR, AT SEABED	29,500 LBS	39,400 LBS
" " MOM., " "	167,000 LB-FT	200,000 LB-FT
" " VERT. LOAD	$\approx$ SHARE OF SELF-WT.	$\approx$ SHARE OF SELF-WT.
SLIP-JOINT TRAVEL	7.5 INCHES	9.7 INCHES

*After joint closure there is substantial additional force capacity (& modest additional energy capacity) as the pile pull-out capacity is mobilized.

FIG 14 - PERFORMANCE OF PILES' CLUSTER

The Sleeve Concept

In case of large shear and bending moment together with poor soil condition, the desired flexibility can be achieved by isolating the upper portion of the embedded section of pile from the soil contact by driving it through a pipe sleeve of larger diameter, see figure 8, which sketches three arrangements for transfer of forces from pile to sleeves. Mud-line force F and moment M react through load transfer diaphragms in the sleeve, as concentrated forces, at depths where soil resistance is greater. The sleeve of larger diameter than the pile delivers in turn the load to the soil.

Figure 9 depicts the comparison of moments, soil pressures and deflections for pile without sleeve, and for the sleeve action. Obvious smaller moments and better distribution of soil pressures as well as deflections result. Figure 10 illustrates two alternate relations between the pile and the sleeve as to location: concentric or eccentric. Figure 11 indicates two possible eccentric locations of the pile in the sleeve in vertical sections: with parallel axes of the pile and sleeve or skewed pile axis with respect to vertical sleeve. One case A is with constant eccentricity throughout the depth of embedment, the second case B with varying eccentricty, respectively.

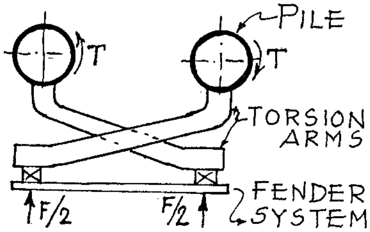
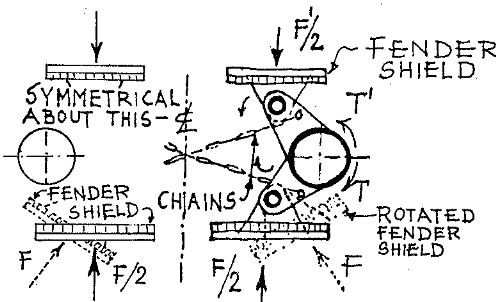


FIG 15 - TORSION ACTION PLAN



TO BE MORE EFFECTIVE, RATIO OF BRACKET ARM LENGTH TO WATER DEPTH MUST BE SUBSTANTIAL

FIG 16 - TORSION BRACKETS - PLAN

This concept has also utilization potential in columns for alleviating earthquake distress or permit thermal expansion of horizontal overhead members carried by such columns.

The Elongation of Tension Piles

To introduce in the outer piles of structure slip joints which would preclude pile axial tension forces until the prepositioned joint stops are engaged; see figure 12. This figure shows seven parallel piles supporting rigid deck platform with slip joints in piles, permitting their elongation without inducing moments at the connection with platform, until stop lag is engaged by the bottom of top pile.

Such slip joints in piles are relatively simple, and capable to transmit pile torsion, as well as, pile bending moment. See also figure 13 for slip joints in cluster of piles. At the bottom in section C-C and on the top section D-D, detail of slip joints are shown. At the right is a pile at rest and at the left in fully extended position. Outer piles are permitted to lengthen under loading without inducing moments in piles until stops in piles are engaged. Then axial forces are induced and moment, thus augmenting load carrying capacity of the structure. Figure 14 represents an example of such a structure performance.

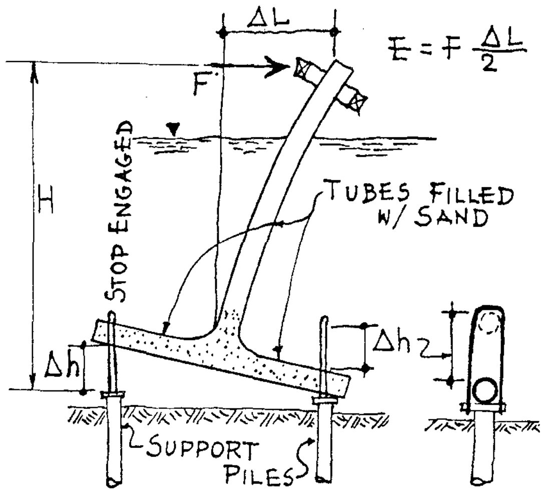


FIG 17 - TETRAPOD - GRAVITY BALANCED ELEVATION

Torsion - Mode Piles

This concept utilizes vertical tubular piles fitted with torque arms on which the outside forces act, causing torsional and bending stresses in the piles. This increases their deflection and energy absorbtion, see figure 15, which indicates plan of torsion action induced in piles by loading the projecting arms rigidly connected to piles.

(SAND-FILLED LOWER TUBES) EXAMPLE

(1) ALL TUBES PP 36"X 1.25" (f_y = 50 ksi; Max f_s = 30 ksi)

L (FT.)	LEG (FT.)	WEIGHT (LBS.)	F (LBS.)	ENERGY (LB-FT) 5' HOR. DISPL.	10' HOR. DISPL.
60	33	103,000	28,500	142,000	268,000
70	32	105,000	24,300	121,000	218,000

(2) ALL TUBES PP 48 X 2.50 (f_y = 50 ksi; Max f_s = 30 ksi)

L (FT.)	LEG (FT.)	WEIGHT (LBS.)	F (LBS.)	ENERGY (LB-FT) 5' HOR. DISPL.	10' HOR. DISPL.
60	41	277,000	95,000	475,000	890,000
70	40	280,000	78,000	390,000	700,000

Note: Max vert. force on one support point is equal to the above tabulated weight.

Max hor. force on one support is twice the dolphin capacity, F, tabulated above.

FIG 18 - PERFORMANCE OF A GRAVITY BALANCED TETRAPOD

Figure 16 depicts the other arrangement of torsion brackets for loads acting on either side of structure, as the case may be. Fender shields rotate on vertical pins thus being able to accept loads coming at an angle to the structure.

Tetrapod Concept

The idea utilizes a gravity-balanced tetrapod principle for a structure, consisting of a single-vertical pile, rigidly connected to three horizontal round steel tubular members in the seabed area.

Figure 17 is an example of tetrapod action in exaggeration. Lift of one of the legs on the side of the load is indicated.

The collision energy from floating objects is absorbed by bending of tubular elements. At large loads there is a lift-off at one of the three support points, rarely of two, and energy is absorbed by overcoming weight of steel members and sandfill in tubes - until stop is engaged for extra large load, see figure 17.

Figure 18 gives an example of tetrapod structures with tubular legs filled with sand in 60 ft and 70 ft of water depth for 36" and 48" diameter piles.

Acknowledgement

The above-discussed concepts suggest a number of design innovations which promise greater efficiency and performance for coastal structures. These ideas are in the experimental or development stage, currently being studied and investigated, by the Naval Facilities Engineering Command, with assistance from Hansen, Holley and Biggs Structural Engineers.

Reference

1. Bureau of Yards and Docks, Department of the Navy "Analysis and Design of Dolphins", Contract No. NBy37595, 1963

2. M.J. Holley, Jr. and C.J. Kray, "Sleeved Piles for Offshore Structures under Lateral Loading" Proc. Offshore Technology Conference, Houston, Texas, Paper No. OTC 1897, 1973

3. Naval Facilities Engineering Command, Department of the Navy "Design Standards for Structural Steel Dolphins in Cohesionless Soil", Contract No. N00025-71-C-023, 1973