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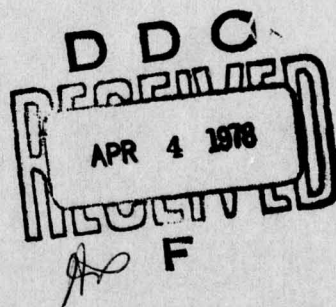
APPROXIMATE MODELS FOR OFF-SHORE
CONCRETE GRAVITY STRUCTURES

by

WILLIAM EMMERT DUVAL

Course 1

May 1976



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APPROXIMATE MODELS FOR OFF-SHORE
CONCRETE GRAVITY STRUCTURES.

by

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WILLIAM EMMERT DUVAL

B.S., U.S. Military Academy

(1969)

Master's thesis,

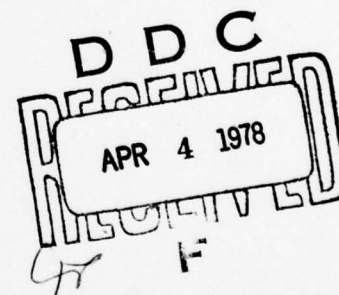
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ABSTRACTAPPROXIMATE MODELS FOR OFF-SHORE
CONCRETE GRAVITY STRUCTURES

by

WILLIAM EMMERT DUVALL

Submitted to the Department of Civil Engineering on 7 May, 1976
in partial fulfillment of the requirements for the degree of
Master of Science in Civil Engineering.

This thesis is concerned with the dynamic response of off-shore concrete gravity structures to the loading imposed by random ocean waves in deep water. The purpose and scope is to study previous, present, and future platforms for a general understanding of what has been developed and why. An attempt to model a hypothetical structure with specific dimensions and parameters representative of the present offshore construction industry is then made using a computer program. The model is a hollow, tapering concrete column fixed as a cantilever atop a bottom-sitting caisson and having an axial load imposed by a typical deck for a concrete oil drilling and production platform.

In this model, two degrees of freedom (translational and rotational) at each node in one plane only, beam theory with a cubic expansion for concrete column deflection, and linear wave theory with a drag coefficient equal to zero is used. Wave forces are derived from a spectrum of waves with a distribution of energies over all wave frequencies. This spectrum is then condensed to a small number of frequencies due to cost and storage limitations in the computer.

At present, thirteen concrete platforms for the North Sea are on order or under construction and the trend seems to be toward even deeper water and more severe environments. The cost of these multi-purpose platforms now exceeds \$150M each. In terms of investment, safety, and energy production, understanding these offshore structures is vital.

Thesis Supervisor: Jerome J. Connor

Title: Professor of Civil Engineering

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LIST OF SYMBOLS

$A(\xi)$	=	cross-sectional area at any point along column
C	=	damping coefficient (per cent of critical damping)
C_D	=	coefficient of drag
C_I	=	coefficient of inertia
E	=	Young's Modulus
F	=	force/unit length of column
H	=	wave height (trough to crest)
$I_y(\xi)$	=	moment of inertia at any point along column
K	=	stiffness of matrix or elements of stiffness matrix
K_G	=	geometric stiffness matrix or elements of geometric stiffness matrix
L	=	wave length
M	=	meters
M_2	=	deck mass
$N(\xi)$	=	axial load due to deck weight and column self-weight
P	=	vector of loads imposed by ocean waves
T	=	wave period
SWL	=	Still Water Level
$V(\xi)$	=	volume of concrete within the column
W	=	temporary constant equal to $W_2 + w_{\text{column total}}$

LIST OF SYMBOLS

(Continued)

W_2	=	deck weight
acc	=	horizontal water particle acceleration
a	=	change in column internal radius between bottom and top of column
b	=	change in column external radius between bottom and top of column
c_1	=	bottom internal radius of column
c_2	=	bottom external radius of column
d	=	thickness of deck
e	=	length of deck
f	=	width of deck
g	=	acceleration due to gravity (9.81 M/sec^2)
h	=	water depth (SWL to ocean bottom)
k	=	wave number ($\frac{2\pi}{L}$)
l	=	total column length or element length
m	=	mass matrix or elements of mass matrix
$m_1(\xi)$	=	mass at any point along column
$r_1(\xi)$	=	internal radius at any point along column
$r_2(\xi)$	=	external radius at any point along column
t	=	time
u	=	horizontal water particle velocity

LIST OF SYMBOLS

(Continued)

$w_1(\xi)$	=	weight at any point along column
$w_{\text{column total}}$	=	total column weight
x	=	translation along the x-axis
\dot{x}	=	velocity along the x-axis
\ddot{x}	=	acceleration along the x-axis
z	=	position along length of column measured from base
α	=	arbitrary constants in the cubic expansion of $x(z)$
ζ	=	portion of loading equation which is time-dependent
η	=	instantaneous water surface position above or below still water level (SWL)
ξ	=	non-dimensional length ($\frac{z}{l}$)
θ	=	rotation
ρ	=	density of water (1.0 ton/M^3)
ρ_1	=	concrete density (2.402 ton/M^3)
ρ_2	=	deck average density
ϕ	=	velocity potential
χ	=	portion of loading equation which is position-dependent
ψ	=	interpolation functions of x

LIST OF SYMBOLS
(Continued)

ω = radian frequency
 ∇ = Laplacian operator

SUPERSCRIPTS

' = derivative with respect to ξ or z
. = derivative with respect to time

SUBSCRIPTS

1 = value at lower end of column or element
2 = value at upper end of column or element
i = row position in a matrix or a vector
j = column position in a matrix

Chapter 1

INTRODUCTION

1.1 Problem and Scope

The construction of off-shore concrete gravity oil platforms is a field of high cost, high risk, environmental unknowns, little experience, and much speculation. For these reasons, a preliminary study of the history, development, construction techniques, and modeling for off-shore platforms is a necessity. A logical and inexpensive means of obtaining static and dynamic response of these structures would be helpful in planning, design and analysis. Each is a one-of-a-kind design specifically suited to its ocean weather location, seabed characteristics, and operational functions. Some store crude oil; some pump, separate, and feed pipelines; and some drill up to sixty wells from a single platform to efficiently pump a whole field. Floating as well as bottom-fixed rigs are used and each has its advantages and disadvantages. (32,67,74,77)

The most serious problem, it seems, is that the trend toward deeper waters and more hostile environments has pushed steel jacket platforms to their limits. So much design information is closely guarded, proprietary data that each builder may well have widely varying limits and safety factors for their structures. Concrete platforms

offer advantages that compensate for the areas in which steel jackets may presently be deficient, if not unsafe.(46) There is ample reason , then, to analyze concrete and concrete platforms for the deep off-shore areas of the world.

Studies by Taylor (82), Weide (97), Van Den Bunt (90), and Oortmerson and Boreel (64) have initiated the dialogue required for concrete structures. The preponderance of study so far, however, has been related to slender steel members used in jacket construction. Dynamic response of this category has been particularly addressed by Nath and Harleman (54), and Foster (27), as well as others. Concrete structures, however, have different geometries, have more axial load due to self weight from shape and thickness, and have far different material properties than steel structures.

This thesis will first provide a broad look at the history of concrete off-shore structures as well as a comprehensive look at proposed future structures.

The proposed future designs lead to some understanding of what the important design aspects are for concrete platforms and what further research is needed for larger, safer and cheaper concrete platforms.

The second goal of this thesis is the modeling of the dynamic response of a specific concrete platform subjected

to random ocean wave loadings. A chapter on wave and structure theory will discuss how to model an actual structure. The geometry and how to account for its variations, the axial load from the deck as well as the self-weight of the concrete, and an integration in the time domain for varying wave loads are all accounted for in the computer modeling program. The computer program listing and a set of program definitions is provided at the end to enable continued improvement of this program for further work.

1.2 General Background and History

The off-shore industry cannot claim too much longer a history than the years since World War Two. A few structures, however, from an earlier period are worth discussing for their historical value and to point out milestones achieved and problems overcome in the development of our present off-shore construction industry.

The first marine reinforced concrete structure in Great Britain was built at Southampton in 1899. It is a jetty with a 100' by 40' deck mounted on piles and is worth mentioning because it is still standing! Unlike a sister pier built in Southampton in 1902 which has since badly deteriorated due to rusting of reinforcement steel, this

pier remains in good condition to this day. Its remarkable longevity can be directly attributed to a very low water/cement ratio in the original concrete mix. The sister pier had a high water/cement ratio and the explanation is that the water/cement ratio controls capillary continuity within the concrete matrix. Seawater penetration, especially in the "splash zone", is inversely related to continuity of capillaries and, in turn, directly related to dense, dry, low water/cement ratio concrete.(8,48)

Concrete hulls were used in transport ships of both the First and Second World Wars due to steel shortages. These ships performed well throughout their lives and were a success in every sense of the word. In view of these successes it seems surprising that we do not have concrete hulls in much wider use today. The development of huge floating petrochemical factories, however, may cause a return to extensive use of concrete for floating craft.

One of the concrete-hulled ships of World War One was the "Atlantus" built in 1918. She was examined in 1928 after having run aground on a sand bar and it was found that some rusting of the reinforcing steel had begun, but in general, the concrete was quite impermeable to sea water. The examination further revealed, however, that due to poor construction techniques, coverage of reinforcing steel in most places was less than one-sixteenth of an inch! All in

all, it's no wonder that there was some rusting after ten years.

The tanker "Selma", built in Mobile in 1918, was examined in 1953 on a sand bar where she had been stranded since 1928. The 1953 concrete sample tests showed no rusting of the reinforcing steel with one inch of concrete coverage and also showed a compressive strength of 10,000 PSI. All in all, these concrete hulls have made a very impressive showing for strength and durability in a harsh marine environment. (48)

In the early 1930's some beach-type oil wells were built in the surf of the Santa Barbara Channel. These structures had four legs which were reinforced concrete caissons, a fifth central caisson through which wells were drilled, and a deck. The structure was placed upon the beach sand and could not be considered very stable at all. Consequently, a row of wood pilings was driven to the seaward side of the platforms and cable was woven in a figure-eight pattern around the wood piles to help dissipate the breaking wave forces on the structure. Both overturning and sliding were a serious threat. (20) Each caisson was filled with dredged sand for additional stability. In the center of each caisson was a small cellar or well for equipment storage and work areas. As drilling progressed to deeper water, a ring of concrete was tremied around the

bottom of each caisson. This ring provided further stability against sliding and overturning as well as being a scour inhibitor at the caisson base.

A large, single concrete-filled cofferdam similar to today's EKOFISK was patented by L.B. Collins of the Barnsdall Oil Co., in June, 1930. He suggested driving four large corner piles forming the corners of a square within a six meter diameter circle. The piles were then used as supports for a six meter circular template from which sheet piling was driven. Once closure of the sheet piling was achieved, tremie concrete was used to fill the cofferdam "cell" forcing the water out. A central hole left by a pipe allowed drilling for oil through the center of the "artificial island". The artificial island methods of off-shore work today stem from this specific idea and other early designs. (35,85)

Mr. Collins also designed a braced steel platform for greater than thirty-five meter water depths which he estimated to be significantly below the cost of concrete cofferdam construction. This partly accounts for the Gulf of Mexico development of steel jacket platforms. As early as 1930 the cost advantages were recognized for relatively shallow water.

World War Two, besides refloating the concrete boat hull program was also responsible for the prefabricated breakwater concept in which finished modules were towed to the work area for utilization. The need for this type of structure resulted from the requirement to off-load ships rapidly at the beaches and to move vast quantities of materials through the temporary ports. The hostile weather environment necessitated a shelter of some type for off-loading ships and battle conditions made this necessity a matter of life and death.

The concept developed to achieve rapid, sheltered off-loading of cargo ships consisted of a rectangular, hollow hull of concrete rounded on both ends. It was towed by tugs to a designated anchorage. The breakwaters were ballasted with water and sunk in place upon arrival at the port areas. As soon as possible, dredged sand was pumped into their hulls to provide stability from English Channel storm buffetting. Water ballasted stability had to suffice for the first few weeks of use.

The entire project was under British direction, as towing time precluded any construction and float-out from the United States. The construction problems were enormous when coupled with the war-time shortages found everywhere. At that time no conveyor systems were available and all concreting had to be done in a very labor intensive

manner. The "assembly-line" approach was not used. Instead, hundreds of small construction sites spread along the British coastline were used simultaneously. A twenty-four hour a day, seven day a week schedule was initiated resulting in one hundred and forty-seven of these behemoths being built in less than eight months. Each unit was, in essence, a five story reinforced concrete building capable of moving through the water without breaking transversely due to wave action. These units were called "Phoenixes" and a number of articles concerning their construction and use came out of World War Two. (40, 79)

"Phoenixes" were towed to the anchorage by sea-going tug boats. Each "Phoenix" had a crew of six and an anti-aircraft crew and gun to assist in the protection of vulnerable, off-loading cargo ships. (95)

Following World War Two, everything connected with off-shore construction work was essentially oil industry related or developed. This seems perfectly reasonable in that the oil industry had the motivation, finances, and requirement to move offshore for oil. The tremendous costs involved in marine construction work appear only sensible when the return on investment exceeds the cost. So far, for deep ocean work, only oil has provided that return. Ocean mining will, of course develop rapidly in the future and will use many oil industry developed techniques.

The first platforms for oil drilling were made from wooden piles driven in shallow water to which a wooden deck was added. These platforms were really on land, only it was the land under one, two, or three feet of swamp water in the Louisiana bayous. The natural progression was to move into deeper and deeper swamps, the Mississippi River Delta, the near-shore Gulf of Mexico area, and finally, the deep Gulf. The first wooden piles were driven from flat-bottomed barges, already almost scraping bottom in the swamps, which were ballasted with water until they settled on the muck in a fairly stable attitude. They could easily be taken up and moved to a new site when drilling was completed. As the water got deeper, short stubby columns were erected on the barge and a second deck atop the columns was added enabling the barge itself to be completely inundated.

Perhaps a digression is required here to discuss a few aspects of off-shore oil. This digression will explain terms, highlight problems and solutions, and give a broad brush of what work must be accomplished from off-shore platforms.

Essentially, oil industry work can be separated into exploration and production. Exploration is generally done from floating, moveable rigs which drill to determine presence, flow, and quality of oil. They move often and

cannot afford extensive and expensive site accoutrements. Production platforms, on the other hand, are generally bottom-fixed; remain twelve to twenty years; and pump, store, and transfer the crude oil from the field of oil wells to pipelines or tankers.

Exploration drilling from floating rigs is extremely sensitive to environmental influences. Waves and wind, especially in the more severe areas now requiring exploration, limit drilling time and increase the costs tremendously. When wind and waves safety limits are exceeded, drilling must stop. The drill string extends beneath the floating rig to the ocean floor. Water depths far beyond three hundred meters are now common and two to three thousand meters beneath the earth's surface is a normal drilling depth. Retrieving the drill string each time severe weather intrudes is a tedious and expensive operation. Imagine, also, "threading the needle" to put the drill string back into the hole when drilling is resumed. Television cameras and bottom-sitting sonar instruments help achieve accurate repositioning.

Floating rigs, with long, brittle drill string dangling, must remain accurately on position. As little as a five degree deviation from the vertical can snap the drill string. Dynamic positioning by small thrusters and directional propellers coordinated by on-board

computers and bottom-sitting sonar instruments have been developed to achieve these tolerances.

The drill string, of course, is brittle and very slender. American Petroleum Institute standard drill tubes are four and one-half inches outside diameter. As the floating drill ship heaves in the waves (i.e., vertical motion) alternating slack and axial load could be imposed on the drill string, easily breaking it. A series of sliding joints allow up to five meters of heave in the string itself and tensioning arms on a derrick on the ship can take up even more slack. Not only can the ship not be allowed to bear down on the string, but the string cannot even begin to support its own weight. As can be seen, drilling from a floating platform is a complicated, expensive task. Much specialized equipment and many proprietary techniques are used to cut costs and achieve results.

Production oil work is somewhat different than exploratory. The demands and cost are great here, too, but the movement problem is gone. In general, an oil well is expected to produce oil for twelve to twenty years with perhaps thirty per cent recovery. Various techniques have been developed to force a waning well to produce a greater flow of oil. Steam, gas, or water injection are often used if any of those elements are available in large quantities. Re-drilling and pressurized injections are

also used to cause greater flows. Each of these methods adds equipment and paraphernalia to an oil platform which may be pumping from sixty wells simultaneously. Drilling of these multiple wells also takes place from the deck of these platforms. Directional drilling techniques allow drill strings to move nearly horizontally one or two miles from the platform location. Two or three large platforms can easily cover and work an active oil field covering many square miles. Simultaneous wells also produce greater percentage recovery from a single oil field due to even draw-down of oil through the soil-rock matrix.

In addition to drilling, pumping, and injecting oil wells, the huge production platforms may store, separate, compress gas, flare gas off, load tankers, or feed pipelines to the shore. The variety of operations performed on a single production platform as well as the deeper water and more severe weather environments are the reasons for the increasing size and cost of off-shore platforms. Specifically, size and storage capacity have essentially led to the introduction of concrete as a construction material. The cost of the amount of material required to contain and surround one million barrels of oil essentially prohibits the use of steel today, while sheer mass required to provide gravitational stability against sliding and overturning as well as countering the buoyancy of oil tends also to favor concrete. (37,70)

This short digression has helped to explain some of the stability requirements; some storage, mass and environmental limitations; and some cost aspects of mobile and fixed drilling. Some of the barges used in the early days are still in use due to the sameness of platform requirements. If it still works, it is used. The earliest of these submersible barges is now owned by Kerr-McGee and has operated in four and one-half to six and one-half meters of open water in the Gulf of Mexico since 1948.

In the late 1940's, experience in the Gulf of Mexico and Lake Maraccaibo, Venezuela led to the development and proliferation of steel jacket platforms. These structures are open steel trusses pinned to the sea bed with piles driven from above the water surface. The cost until now has been low and fabrication techniques have been refined over many years. By 1953 there were seventy platforms in water depths to seventy feet and they cost about \$1.25 million each. Today, jackets go to four hundred seventy-five feet and cost \$50 million each. A concrete platform that stores crude can cost over \$450 million.

That brings us in a general manner to the present day. Steel jackets have gotten taller, heavier, and more expensive. Foundation requirements have become more important and yet it seems there is more uncertainty today about siting and foundation stability than ever before.

Concrete structures attempt to solve steel jacket problems in three ways. First, concrete gravity platforms require no piling, but instead sit on huge foundation mats directly on the sea bed. Levelling and grouting take place, but short installation time can be achieved. Second, construction in a sheltered area, outfitting near land with no heavy at-sea lifts, and ease of construction with slip-forming techniques all contribute to cost savings. Third, the ability to use the large concrete mass for storage purposes enhances the attractiveness of using concrete platforms for multi-purpose off-shore centers. Specific present and future designs will be discussed next. (6,45,80)

At this time only five of dozens of designs for gravity platforms have been selected for construction. Contracts have been awarded for thirteen platforms from these five designs (Table 1).

Chronologically, the first of these platforms is the Ekofisk C which is a storage container located in the North Sea's Ekofisk Field. Owned by Phillips Petroleum, Ekofisk C gathers crude oil through short undersea pipelines from several steel production platforms in the vicinity, consolidates and reservoirs the production of the entire Ekofisk Field, and serves as the pumping point for a 350 - kilometer, one meter diameter pipeline to Teeside, England.

<u>NAME</u>	<u>OWNER</u>	<u>BUILDER</u>	<u>YARD</u>	<u>INSTALLATION DATE</u>	<u>TYPE</u>
Beryl A	Mobil	Ellefsen/Aker/Selmer	Stavanger, Nor.	1975	Condeep
Brent B	Shell/Esso	Ellefsen/Aker/Selmer	Stavanger, Nor.	1975	Condeep
Brent C	Shell/Esso	McAlpine/Seatank	Ardyne Pt., Scot.	1976	Seatank
Brent D	Shell/Esso	Ellefsen/Aker/Selmer	Stavanger, Nor.	1976	Condeep
Cormorant A	Shell/Esso	McAlpine Seatank	Ardyne Pt., Scot.	1976	Seatank
Dunlin A	Shell/Esso	Andoc	Rotterdam, Neth.	1976	Andoc
Ekofisk C	Phillips	Ellefsen/Aker/Selmer	Stavanger, Nor.	1973	Jarlan
Frigg TPl	Elf-Norge	McAlpine/Seatank	Ardyne Pt., Scot.	1975	Seatank
Frigg TCP-2	Elf-Norge	Ellefsen/Aker/Selmer	Andalsne, Nor.	1976	Condeep
Frigg CDP1	Total	Howard/Doris	Andalsne, Nor.	1975	Jarlan
Frigg Booster 1	Total	Howard/Doris	Stromstad, Sweden	1977	Jarlan
Ninian 1	BP/Burmah	Howard/Doris	Loch Kishorn, Scot.	1977	Jarlan
Stratfjord	Mobil	Ellefsen/Aker/Selmer	Stavanger, Nor.	1976	Condeep

Table 1. Concrete Gravity Platforms

Ekofisk C was built by the Ellefsen/Aker/Selmer joint venture in Stavanger, Norway and was installed in 1973. Is is basically of the "Jarlan" type of off-shore structures, named after the developer of perforated breakwaters which dissipate wave forces by breaking them up through a concrete "sieve" arrangement. Ekofisk C stands in 70 meters of water and is a double right circular cylinder. The outer cylinder is perforated to dissipate wave forces, there is an open surge chamber between the two cylinders, and the inner cylinder is the storage tank. The storage tank holds one

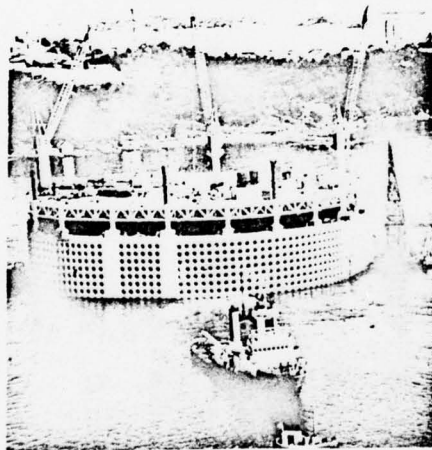


Figure 1.2.1

EKOFISK Oil Storage Tank

million barrels of crude oil while the two-story deck on top of the tank serves as an oil and gas processing center and a pumping point. (23, 26, 34, 71, 92)

The second design is called the Condeep Platform and has proved to be the most popular. Five construction contracts for Condeep have been awarded by Mobil, Shell/Esso, and Elf-Norge to Ellefsen/Aker/Selmer who are also the designers. The Condeep is essentially a caisson and tower system intended for 100 - 180 meter water. All five Condeeps are to be located in the North Sea and are intended for the Beryl (1), Brent (2), Cormorant (1), Frigg (1) and Stratfjord (1) fields. The Condeep has been designed to handle drilling, production, and storage making it an efficient and flexible unit weighing 200,000 dwt and costing about \$150 million.

A heavy concrete mat mounted by 19 cylindrical domed storage cells, each 50 meters high and 20 meters in diameter, form the lower portion while 3 or more towers continue upward over 100 meters, slipformed from selected individual cells. All of the Condeeps are being built in Stavanger, Norway and plans are to install them all by September, 1976. Only one is now in place. Storage capacity for one million barrels of crude oil is provided, production of approximately 300,000 barrels/day is anticipated, and water depths of 100-

27.

180 meters are acceptable. Each of the five Condeeps is slightly different due to specific site requirements, owner requirements, or both. (1, 26, 29, 42, 44, 72, 88)

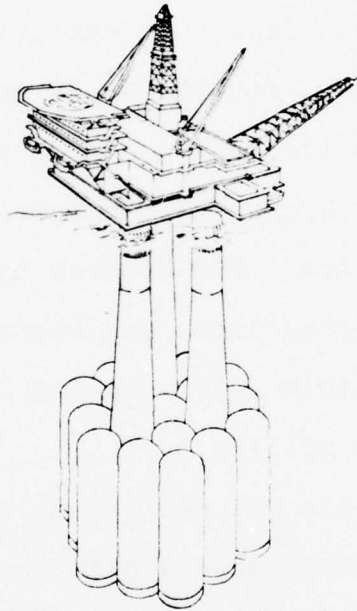


Figure 1.2.2

CONDEEP

The third type of platform under contract is actually the first of the completed designs. Called Seatank and developed by the French Sea Tank Company, this platform is a caisson and tower arrangement. Licensing agreements with Sir Robert McAlpine Co. in England and Ing. Thor Furuholmen in Norway ensures that these two firms will get all the construction contracts in the North Sea for this design. McAlpine has signed contracts for three Seatants with Shell/Esso (2) and Elf-Norge for the Brent, Cormorant, and Frigg fields. McAlpine is doing all construction at Ardyne Point, Scotland for the three Seatanks.

Seatank has thirty-six cylindrical cells arranged in a square (6 per side) with four towers extending upward from four of the cells. It is designed to store 650,000 - 1,000,000 barrels of crude oil, to stand in 140 meters of water, and will be refloatable and moveable. The Brent C platform is 105 meters square at the base, the cells are 60 meters high and approximately 14 meters in diameter, and the total height is 151 meters. Seatank too, is designed as a drilling, production, and storage platform.

The massive concrete mat upon which the storage cells sit in a tower and caisson arrangement has a steel skirt around and protruding about three meters down from it. As the platform is settled onto the reasonably level site

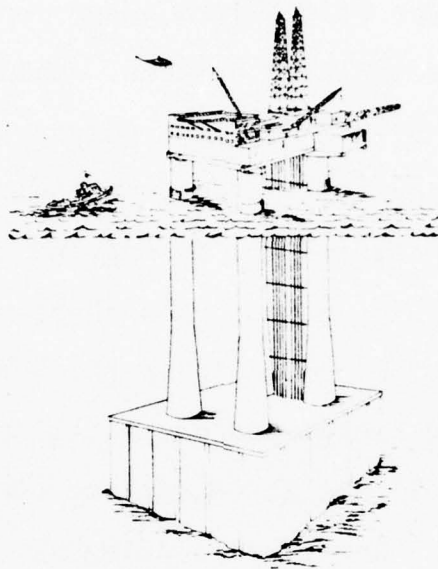


Figure 1.2.3

SEATANK

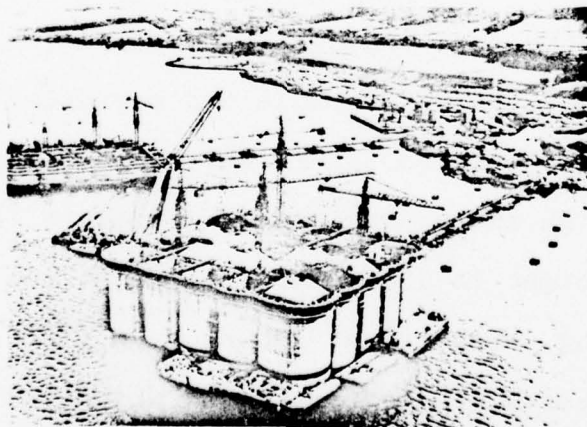


Figure 1.2.4

SEATANK Under Construction

selected for it, the skirt penetrates the seabed and somewhat anchors the platform. Gravity, however, is intended to be the sole means of ensuring stability. After the skirt has "sealed" the foundation, pumping ports are opened underneath the concrete base and grout is injected to even the seabed irregularities and to aid in resisting sliding and scour. (16, 22, 26, 72, 89)

The fourth platform under contract (and the third tower and caisson arrangement) is the Andoc Platform built by an Anglo-Dutch consortium for Shell/Esso's Dunlin Field. It is being built at Rotterdam, Netherlands while the steel deck is being fabricated in England. This platform has 81 cells arranged in a square base with four tapered towers protruding upward. The towers are largely concrete, but are topped by steel towers extending to, through, and above the water surface. Andoc is a drilling and production platform intended for 155 meter water depths. It stores nearly 1 million barrels of crude oil (72, 26)

The final platforms under construction are three Howard/Doris type of "Jarlan" platforms being built by Howard/Doris, a British-French combine, for Total Oil (2) and BP/Burman for their Frigg (2) and Ninian Fields. These platforms are similar to the tower and caisson concept, but are arranged with a 140 meter diameter circular mat as the

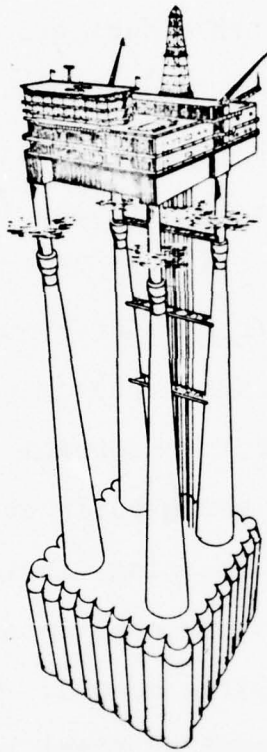


Figure 1.2.5

ANDOC

base. From this base, an outer vertical skirt 15 meters high extends upward. Made of concrete with perforations of the Jarlan type in it, the vertical skirt moderates ocean current and wave scour action at the base. Inside the skirt the storage cells, cylindrical and domed, are

formed as in a caisson and tower-type platform. At the very center of the cluster of cells is a nine meter diameter tower approximately 127 meters high which contains risers and drill string equipment. From the top of the storage cells an outer cylinder 45 meters in diameter extends to the surface with the nine meter tower inside. Internal concrete bracing links the large cylinder with the tower. In the area of wave action, 22 meters above the surface to 53 meters below the surface, the outer cylinder has "Jarlan"-type perforations to dissipate wave forces. The deck is a monolithic four meter thick pad set atop both the inner tower and the outer cylinder rigidly fixing them to each other. The Ninian platform is the largest and most massive of all concrete platforms under construction. (26, 60, 72, 86, 11)

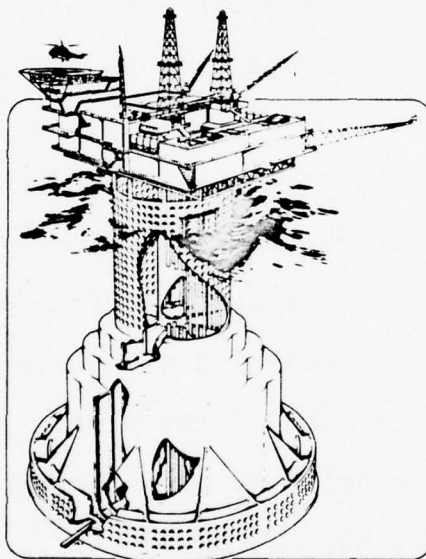


Figure 1.2.6
Ninian Field's Jarlan - Type Platform by C.G. Doris Co.

1.3 The Future of Offshore Structures

The array of ideas and proposals for future offshore structures is large and varied. A comprehensive survey is out of date before completion and overlap, duplication, and varied useage makes categorization difficult. Perhaps the broad divisions of "fixed", "floating", and "other" will be sufficient.

The fixed structures include concrete, steel, hybrid, compliant, and a host of other platforms. All rest on the sea floor or are in some way dependent upon transferring gravity loads and horizontal wave loads to the earth. A few proposed fixed structures in random order are:

a) Tilt-up/Jack-up ("Tu-Ju") - Proposed by Raymond International, this platform is a steel jacket and deck arrangement intended for 100 - 300 meter water depths, 200 km/hr maximum winds, and 32 meter maximum waves. The jacket floats to the site horizontally and is upended and set on the bottom by controlled flooding. It has four legs and a typical tubular steel bracing system. Two of the legs are oversized and are sealed. They act as the floats for the jacket in the towed, horizontal position. The other two legs are hollow and are used for drilling and pumping and have all necessary conductors, risers and drill

string equipment built into them. Around the base of all four legs are collars containing pre-positioned piles ready to be cut loose and driven immediately upon jacket positioning.

The deck section is built as a barge and floats to the jacket site complete and self-contained. It is configured with wells that match the legs of the jacket so that it can be floated into the exact position for mating with the legs. Hydraulic jacking devices then lift the deck out of the water as the deck "climbs up" the jacket legs. No storage capacity is available, but this system is intended to be disassembled and reused leaving only the cut off piles in the sea bed. (65, 83).

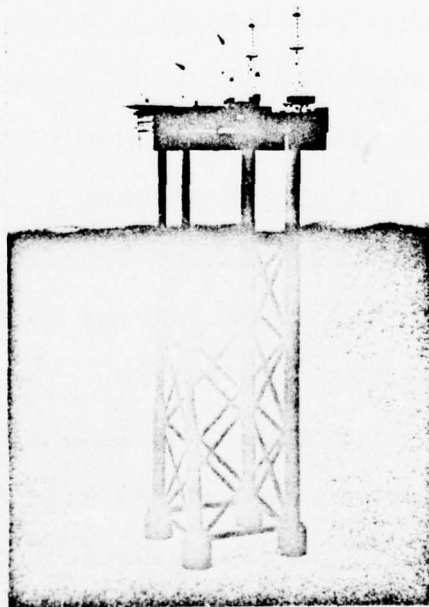


Figure 1.3.1 Raymond International's Tilt-Up/Jack-Up

b) Breakwater/Oil Storage System - Designed by Raymond International under contract to the Corps of Engineers for the U.S. East Coast, and especially the Delaware Bay area, this system provides a "building block" set of cubic concrete units fitted together at sea to make a sheltered harbor. Intended to solve the problem of shallow U.S. harbors and deep draft oil tankers, these large, hollow precast units are floated to the site, formed in a continuous breakwater line, and sunk in succession side-by-side. Inner compartments are then filled with dredged sand for ballasting leaving most of the hollow interior available for oil storage. The seaward side of each unit has a perforated face for wave force dissipation.

Raymond has also developed a travelling gantry arrangement and assembly procedures which screeds a gravel pad, positions adjacent units, and advances itself during breakwater assembly. (65, 68)

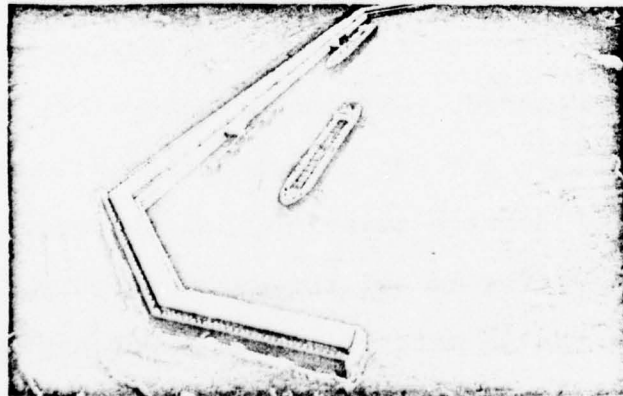


Figure 1.3.2 Breakwater/Oil Storage System

c) Prestressed Concrete Tower - Proposed by Dravo Ocean Structures of the United States, this platform is designed for low construction cost, for short construction time, and assembly-line fabrication techniques. The single large cylindrical leg or tower is cast in short sections like concrete pipe. The sections are then assembled on a barge which has saddles to position each section for alignment. A base plate is put on one end and a cap is put on the other end. Post-tensioning tendons are then fed through conduits aligned to run through each section from cap to base plate and tensioned. Upon completion of post-tensioning, the barge is ballasted down until the hollow tower is floating. Barges are reused for new assemblies as the completed towers are towed horizontally to the site, up-ended, and set in place by controlled flooding. Piles are required to pin the base plate firmly to the ocean floor and a complete deck assembly must be placed on the cap. Each platform is designed for a specific locale although modification and customizing in the assembly-line procedure can be accomplished. Obvious drawbacks are the relatively small base plate and cap necessitating pile anchorage, no allowance for storage capacity, and the requirements for heavy at-sea lifts to set the deck assembly. Another drawback is the 38 meter limit to water depth in the design so far. (17)

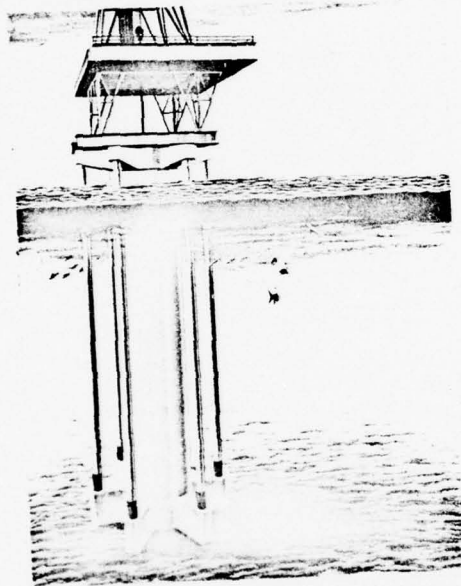


Figure 1.3.3
Prestressed Concrete Tower

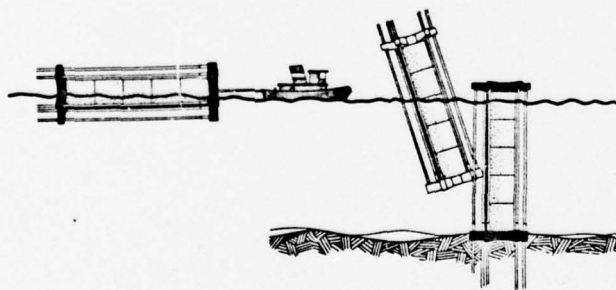
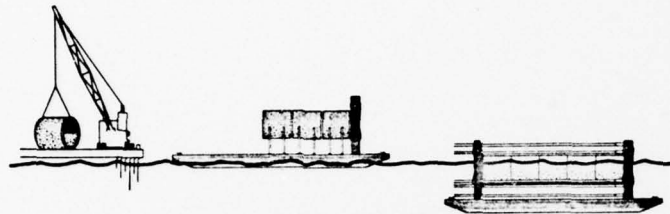


Figure 1.3.4
Dravo Ocean Structures Construction
Sequence for Prestressed, Post-Tensioned
Concrete Tower

40.

d) Subsea Production Systems - These systems, under development by Lockheed and TRW, provide the ability to cap, pump, separate, meter and otherwise control wells with a small, remote underwater unit. About the size of several railroad cars, they are in use now in the Gulf of Mexico and the North Sea on an experimental basis. These units must be linked to a pipeline and manifold, to a large storage facility, or to a Single Point Mooring Buoy for immediate pumping into tankers. The long-term hope is to build sophisticated systems that are environment-proof, operate remotely, require little installation effort and could even be manned and used as undersea drilling sites. (15, 30, 61)

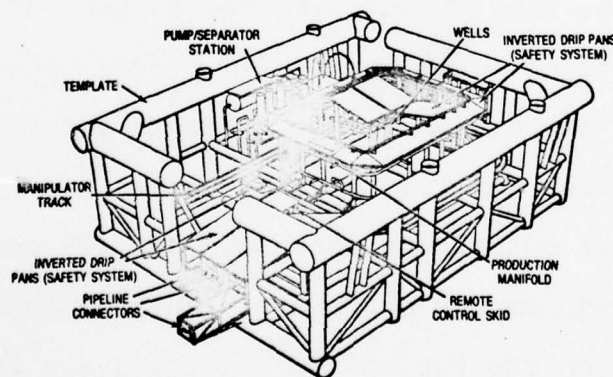


Figure 1.3.5 Exxon's Subsea Production System Module

e) Steel Gravity Platform - This idea has been developed by Gem-Hersent, a French combine in the steel fabricating/offshore industry. The platform consists of three decks stacked on top of each other which are floated to the offshore assembly site in this configuration. The assembly site is a sheltered, deep-water location where the bottoms of four steel legs are fitted to the lower deck and it is ballasted down until the intermediate deck can receive the tops of the legs in its lower wells. After connection the lower and intermediate decks are ballasted, four more legs are set in place, and the top deck is positioned on top of these legs. The platform can then be towed upright to its site and positioned on the bottom. The lower deck is a pad or mat that transmits wave and wind forces to the seabed and is filled with dredged sand at the site for weight and stability. The intermediate deck is located midway between the seabed and the water surface where it effectively serves as a brace for the four tubular steel legs. The top deck is well out of the water and has all the normal drilling and pumping equipment. This equipment has been positioned on the top of the stacked decks from the very earliest outfitting, eliminating heavy crane lifts at sea.

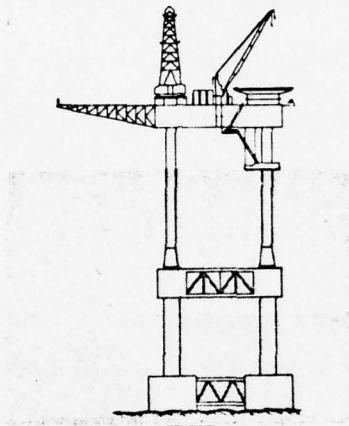


Figure 1.3.6 Gem-Hersent Steel Gravity Platform

f) Hybrid Gravity Platforms - Several hybrid platforms of the fixed type have been proposed. They are intended to utilize the best properties of different construction materials for different parts of the platform. The Chicago Bridge and Iron Company, builder of the Abu Dhabi "Teardrop" steel storage tanks, is proposing a reinforced concrete foundation raft with a steel jacket. This platform would be designed for 180 meters of water.

depth and would allow 60 wells to be drilled after emplacement. The large flat raft provides weight and is a stable anchorage for the steel jacket legs. It is not hollow and does not provide for crude oil storage, but the large, flat concrete raft does allow the jacket and foundation to be refloated with the aid of attachable pontoons for movement to a new drilling site. (10)

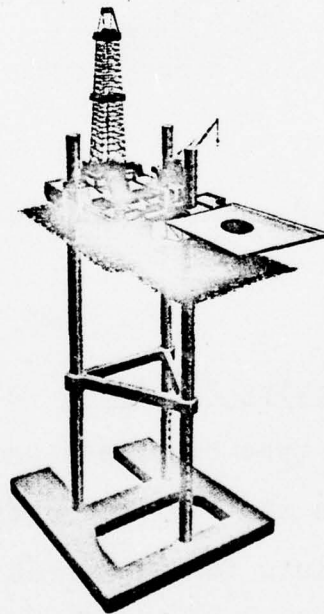


Figure 1.3.7 Bethlehem Steel's Hybrid Gravity Platform

Another hybrid platform which has been proposed uses three large concrete cellular pads or "spuds". These "spuds" have crude oil storage capacity and serve as baseplates. The three baseplates are connected by tubular steel members and have other inclined tubular steel membranes which meet at a collar forming a triangular pyramid. Through the collar and standing vertically is a steel tubular tower which extends to and through the water surface and which supports the deck section. The analysis of this structure appears to be greatly simplified, as all connections are very closely approximated as pinned. Another advantage is that the difficult welding of the usual tubular joint seen in most steel jackets is eliminated.

(58)

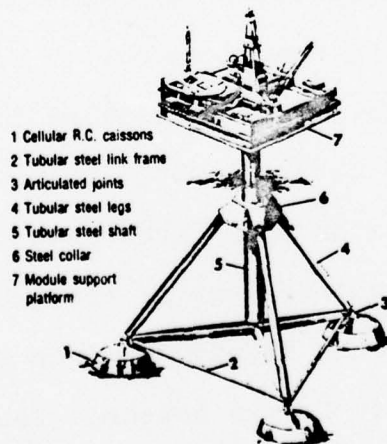


Figure 1.3.8 Pinned Hybrid With Concrete "Spuds"

On the one hand these platforms utilize steel in the legs and cross bracing where high strength at small cross sections and well known material properties are required. Concrete, on the other hand, is used for foundation, leg anchorage, and storage parts where large mass at low cost and easy fabrication are required.

C.G. Doris has also proposed a concrete and steel hybrid of four towers looking very much like the tower and caisson structures presently being constructed. This hybrid would be for drilling, production, or storage and has anti-scour protection provided by a "Jarlan" perforated skirt around the base. (28)

g) Guyed or Compliant Tower - Exxon Corporations design team has proposed a very slim steel truss platform cable guyed to the ocean bottom and compliant with ocean wave motions. This 24 well platform is designed for 180-620 meter water depths, is square in cross section, and rests on four "spud cans" at the bottom ends of the four corner legs of the truss tower. The proposed platform has twenty 3.5 inch suspension bridge cables anchoring it to the bottom. Fairleads carry the cable from the anchoring point on the deck straight down

the tower to a point fifty meters below the water surface where the approximate center of wave pressure is located. It is desirable to have the cables exert the horizontal restraints at this point. The cables then drape to the ocean floor where they are anchored by a 140-ton series of jointed, articulated weights. As the tower moves, the jointed sections of the weights are lifted one-by-one adding weight and restraint to each cable as each successive section is lifted off the seabed. As a final anchorage, lengths of cable connect the last jointed weight section to a pile-driven or explosively driven seabed anchorage.

The compliant tower is designed for a maximum 31 meter wave height and is intended to move horizontally about 2% of its height as it complies with the wave forces. Real economy is seen in the use of much less steel than a rigid structure requires to resist wave forces. A one-fifth scale platform 113 meters tall has been built and installed in 92 meters of water in the Gulf of Mexico. (72)

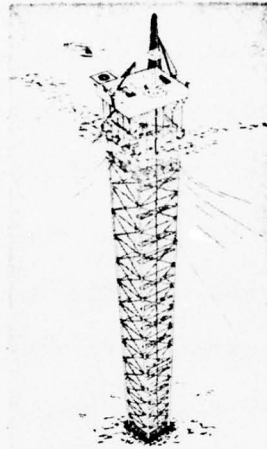


Figure 1.3.9 Exxon's Guyed, Compliant Steel Tower

h) Concrete Gravity - A large number of concrete gravity platforms very similar to the five types of platforms now under construction have been proposed. Almost all are caisson and tower arrangements and are designed by firms wishing to compete for the present business in the North Sea. They are:

1) Seadeck - A joint venture of Cementation, Marples Ridgeway and Netherlands Offshore Concrete calling themselves Sea Platform Constructors (Scotland)

is developing a site in Loch Fyne, Scotland. They hope to sell their three-tower concrete caisson and tower platform to Union Oil, Total Oil, or Shell/Esso. (72)

2) Taywood Setrust - Taylor Woodrow and Selection Trust have obtained a site on Cromarty Firth, Scotland to build their three-tower concrete caisson and tower platform. Taylor Woodrow with John Mowlem, Ltd., also have the United Kingdom license for Condeep. (72)

3) Campeon Bernard/Lind/Kier - This combine has designed a three-towered, all concrete, prestressed platform. They have no site and no contract. (72)

4) Selmer Tripod and Tripod 300 - Proposed by Ing F. Selmer of Norway, these platforms are designed for 300 meter water depths. The Tripod has three storage tanks each tapering to a tower in a "bottle shape" configuration with a deck on top of the three towers. A variation proposes slipforming at an angle for the three tower legs until they meet at an intermediate collar. Tests indicate that the angled slip forming technique will work well. (72,78)

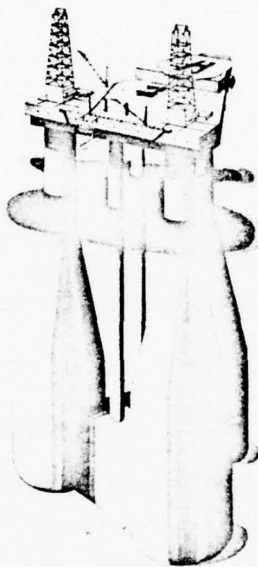


Figure 1.3.10 Selmer Tripod Concrete Gravity Platform

5) Subtank - This proposal is also of the hybrid type referred to earlier. Designed by K/S Subtank of Norway, the separately cast concrete caisson storage units are joined at sea to form the base. The steel towers are then added with the deck being placed last in a heavy, at-sea lift. (72)

6) Caledonian (Forth 150) - The Caledonian Group proposes a standard square base, four-tower platform to be built in Scotland. The Forth 150 Platform is a variation of the basic Caledonian tower and caisson for 150 meter North Sea water depths. One million barrel crude oil storage capacity, 48-well drilling capacity, and 30.5 meter maximum waves are a few of the design parameters for Caledonian. (18,72)

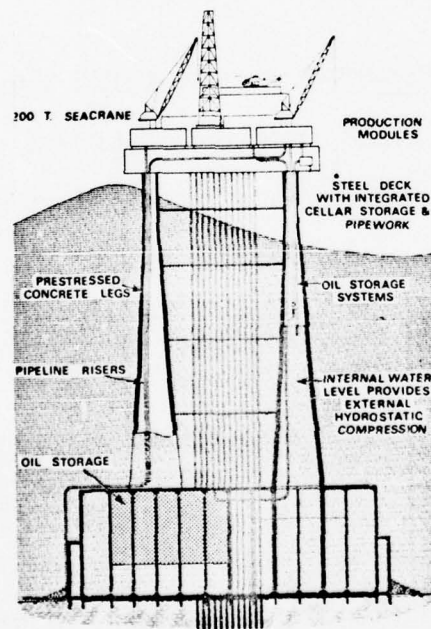


Figure 13.11 Caledonian Groups Forth 150 Concrete Gravity Platform

7) Costain-Halcrow - The proposal is a tower and caisson structure almost identical to the Condeep.

(72)

8) Wimpey - This joint venture of George Wimpey - Brown & Root is a latecomer to the concrete platform race, but should be a formidable competitor due to their vast offshore experience with steel jackets. They propose a three-tower, tiered caisson, concrete platform for greater than 160 meter water depths. (72)

9) Laing-GTM-ETPM - This joint venture proposes a three-tower, circular caisson platform. The main advantage will be float-out of the structure with as little as seventeen meters of draft. It differs little from the others in appearance and design. (72)

10) Bouygues - This French concern has acquired a site at Bantry Bay, Ireland where they propose building a clustered caisson arrangement with as many as twelve tapered towers supporting the deck. Storage capacity would be about 1.5 million barrels of crude oil. (72)

1) Technomare - The Technomare Platform proposed by the Italian company of the same name is a steel gravity platform designed to cope with very special problems in a specific field. The Technomare will be used in the Loango Field where water depth is about 90 meters and the oil is located very close to the earth's surface. In this instance, regular directional drilling cannot be used and the wells must be started at a slant. Normally, a batter-pile supported structure could be built in this depth with slant drilling advantages, but difficult sub-surface conditions preclude this. To solve the problem, the drill string conductors are splayed and the overall shape is that of a pyramid. The structural system uses three large supporting baseplates with a floatation cylinder attached to each. These base plates are connected by a triangular framed system which in turn supports a central axially symmetric hexagonal tower. From the deck on top of the hexagonal tower protrude two vertical and twelve slanted conductors for drilling. The array of twelve conductors slanting downward and outward give the platform its pyramidal, splayed appearance.

On order are one drilling and three production platforms and plans are available for different variations and configurations for up to 180 meter water depths where

53.

these directional problems might again occur. The settlements expected are one centimeter initially and fifteen centimeters over the long term. (59,72)

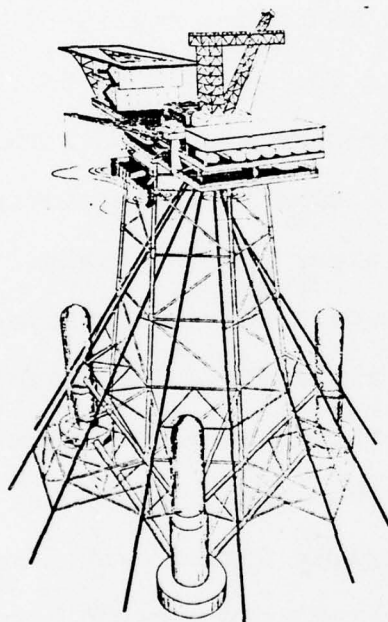


Figure 1.3.12

Italian Technomare Platform for Slant Well Drilling

The proposed floating structures include concrete, steel, and hybrid designs in some very exotic forms. The exotic forms point to future offshore needs and proposed methods of satisfying those needs. It is interesting to compare the differences and similarities between permanently floating concrete platforms and the bottom-fixed gravity platforms which must be floated to their fixed sites and refloated when moved to new sites.

All of the floating platforms are, of course, supported by the buoyance of seawater. However, a link to the ocean floor for the positioning, drilling, pumping, storing, tensioning, or some other function is usually maintained. Because of this link, although vertical loads (i.e. foundation considerations) are no longer a problem, horizontal loads may still have to be transferred to the seabed. A few proposed floating structures are:

a) TLP - The Tension Leg Platform proposed by Deep Oil Technology, a subsidiary of the Fluor Corporation, is a triangular steel floating platform with three bottle shaped floatation legs. As with any semi-submersible, the further beneath the area of wave action one can place the buoyant displacement structures, the smaller will be the motion due to wave action, hence the bottle shaped legs.

The TLP is also tied by cables to anchors on the ocean floor and winched down to a deep-riding, floating position. The anchors are placed directly under each leg and are not spread in a splayed array. The anchors are hollow steel cylinders 5.5 meters in diameter, 3.4 meters long and are weighted by an iron-ore slurry which is pumped down after they are lowered to the bottom.

There are several advantages with the TLP. First, the platform displays no wave-induced motion because the cables are always in tension. Stresses in the cables are mitigated by positioning the largest displacement portion of the floatation legs well below the area of wave action. Second, less steel is used in constructing a floating platform than in a bottom-fixed platform and costs will be less for deep water sites. Third, the platform and anchors are moveable and reuseable at different locations and in different environments. Construction does not have to be delayed for soil testing and siting decisions.

A one-third prototype has been built and was tested during March - June 1975 in 60 meters of water off Catalina Island, California. Results are not available yet, but press releases indicate that the test was a success. (37,72)

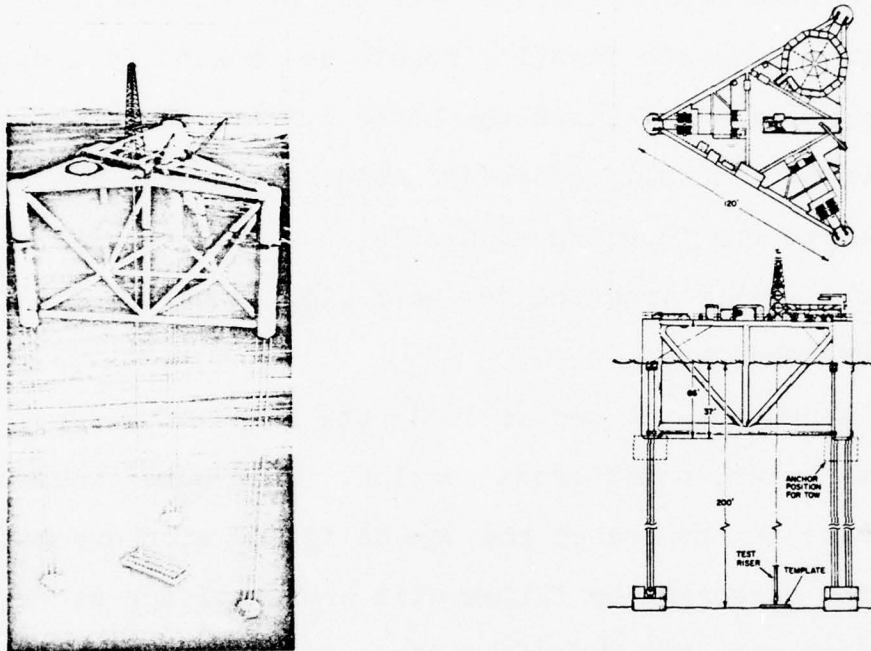


Figure 1.3.13
Deep Oil Technology's Tension Leg Platform

b) CaSub - The Cable-Stayed Submerged Buoyant Production Platform is a tethered, floating platform similar to the TLP. The platform consists of two separate modules, one floating and the other resting on the bottom. The floating portion is a concrete right circular cylinder which floats very low in the water and has buoyancy and

storage tanks located below the area of wave action. A production and pumping deck similar to that found on the Ekofisk platform is located well out of the water. Oil is pumped from the floating module to tankers by a dry loading spar which keeps the hoses out of the water; a more environmentally desirable loading system. The tanker ties up to the floating module as at a SPAR or SPMB and is loaded directly from the one-half million barrel floating storage capacity. (9,72)

The underwater module is in the shape of a torus with a rectangular, domed cross section. This huge concrete ring sits on the seabed and can be filled with dredged sand for anchorage or filled with crude oil for storage depending upon the owner's desires. Up to two million barrel storage capacity with refloat and move capability can be designed for the bottom section. Joining the two sections is a fan, almost cone-shaped array of 24 - 72 cables tethering the floating module. The cable system is highly redundant, allowing several adjacent cables to be cut with no effect at all on platform response to wave loadings. The system is not intended to be as rigid as the TLP and would use synthetic fiber parallel-lay cables. The synthetic cables would stretch allowing vertical movements of one meter and horizontal movements of one-

half to two-thirds of a meter in a sixteen meter wave. Steel cables would be used for deep water up to 300 meters. A 1:110 scale model was tested successfully on this proposed all-concrete design and further studies are being pursued. (9,72)

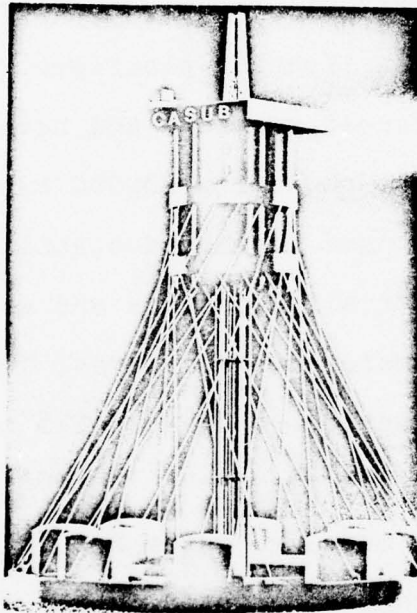


Figure 1.3.14
Cable-Stayed Submerged Buoyant Production Platform

c) CONDRILL and CONPROD - These proposed platforms are two very similar floating adaptations of the Condeep concrete platforms. Intended for exploratory drilling, production, or easily moveable storage of crude oil, the type of deck-mounted equipment is the only modification necessary to perform any of these tasks. Up to one-half million barrels of storage capacity is available in these circular, low floating platforms. They are made entirely of reinforced concrete and have an elliptically-shaped bottom slab, requiring 20,000 cubic meters of concrete, for ballast and increased stability during rough seas. Designed for all locations and weather situations and up to thirty meter maximum waves, this Ellefsen platform has fourteen cylindrical storage cells and up to eight short legs supporting the deck. During drilling operations, a ten-leg tension mooring system has been proposed, but dynamic positioning can be used during this and all other operations. (19,72)

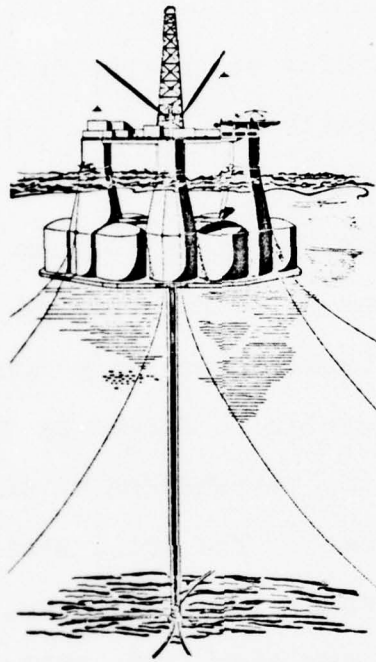


Figure 1.3.15
CONPROD Production Platform

d) Tuned Sphere Drill-Ball - One of the most exotic of all offshore platform proposals is the Tuned Sphere. This platform consists of a large sphere 46 meters in diameter and a smaller sphere approximately fifteen to twenty meters in diameter. The large sphere floats in the ocean drawing about thirty meters of water and has four legs attached to it and rising at an inclined

angle to form a tetrahedron. The small sphere is mounted near the peak of the tetrahedron, far above the water surface, and is "tuned" to control the rolling period of the structure by adding or subtracting water ballast. This platform is dynamically positioned, self-propelled, has a uniquely low structural weight for its volumetric capacity, and can be built for less than fifteen million dollars. A square drilling deck is mounted on the four tetrahedron legs about midway between the large sphere and the small sphere. The oil derrick is formed by the tetrahedron legs with the point of the tetrahedron as the top of the block and tackle arrangement. The drill string hangs vertically, piercing both the spheres and the deck, and is rotated by the drill table on the deck. The ballasting mass of water for the small top sphere is expected to be less than 500 tons. (87)

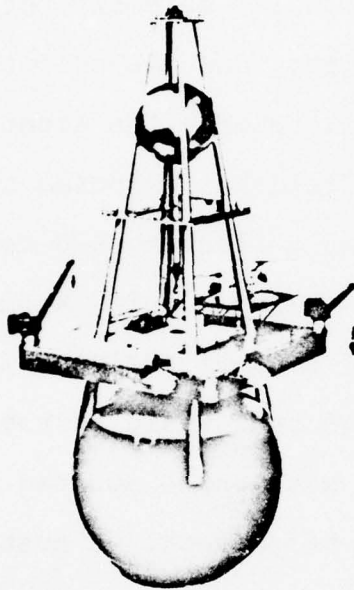


Figure 1.3.16
The Tuned Sphere Drilling Ball

e) Concrete Hulls - Several proposals have been advanced for floating chemical, petrochemical, fertilizer, and LPG plants. They would be built on floating concrete barge-type hulls and would be fully sea-going, self-propelled ships. The petrochemical plant would be used to develop the production of an offshore gas field

not serviced by a pipeline. It would use the available gas to manufacture ammonia and urea fertilizer ingredients and would cost about 150 million dollars. The short construction time, the modular assembly techniques in dry dock areas, the portability, and the ability to bring the market to the gas field all enhance the economies of this proposal.

Atlantic Richfield has proposed a prestressed concrete barge-type vessel as a floating LPG terminal in Indonesia. Costing 32 million dollars, this 141 meter by 42 meter by 17 meter hull would contain twelve cylindrical steel LPG storage tanks. Each tank would be twelve meters in diameter and 51 meters long with three mounted fore and three mounted aft both above and below deck. A host of other possibilities for floating plants and ocean-going processing systems will come of age as the economies of concrete floating systems is tested and proved. (10,39)

f) Big Buoy 6000 - The final proposed floating platform is the Big Buoy 6000 developed by Norway's Trosvik Group. The cylindrical floating rig would be a hybrid of concrete and steel construction with drilling, production, and up to 300,000 barrel storage capability. As a floating unit its displacement would be about that of a 100,000 dwt tanker and would have a deck capacity of 6,000

tons. The massive, low-floating concrete displacement section of the platform would be as far below the area of wave action as possible and it is estimated that the roll, heave, and pitch characteristics of the Big Buoy 6000 would be about one-half that of a conventional steel semi-submersible. (57)

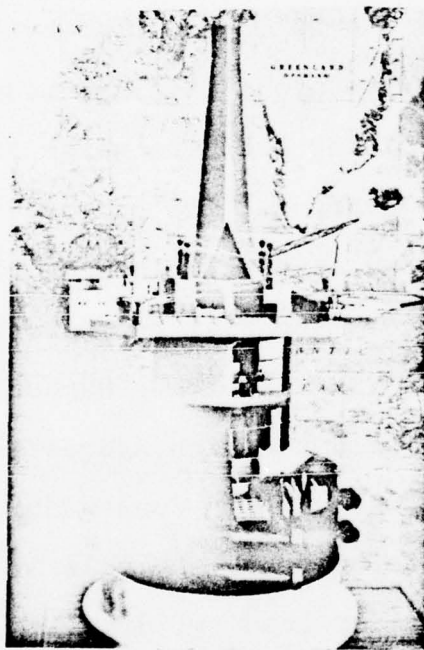


Figure 1.3.17
Trosvik Group's Big Buoy 6000

The category of "other", mentioned at the beginning of this section, includes some special applications, some ideas already in use which could and should be expanded, and some ideas which are so unique that they deserve a separate category. The "other" ideas include:

a) Sand Bag - A truly unique ocean structure has been suggested by Golder and Associates of Ottawa, Canada. The Sand Bag is constructed by filling an impermeable membrane with hydraulically dredged sand while simultaneously draining the pore water from the sand once it is inside the membrane. The hydrostatic pressure of the water stabilizes the sand at or near vertical slopes while the membrane protects the fill from erosion by scour, ocean currents, and wave action. Support in depths up to 200 meters is now possible with hydrostatic sand structures and research is continuing on construction techniques, stability at greater depths, and possible applications. Artificial islands for loading, drilling, power production and other near shore processes seem possible. (63)

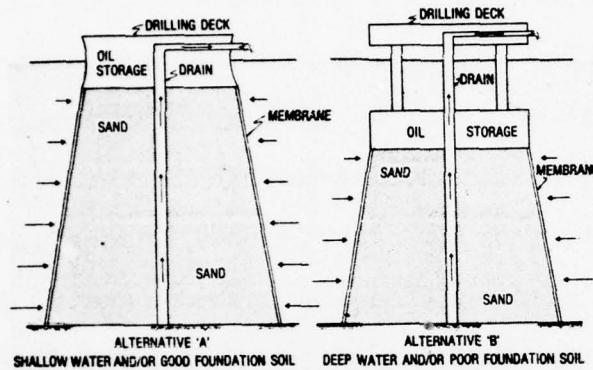


Figure 1.3.13
Golder and Associates' "Sand Bag"

b) Articulated Platforms - This platform idea is several years old and has had several trials. CFEM, a French concern, developed the design and built a test platform in the bay of Biscay. It has also built and installed a 150 meter articulated column for Mobil's Con-deep Platform, Beryl A, in the North Sea. An articulated platform consists of a heavy steel baseplate filled with concrete, a universal swivel joint, and a column with buoyancy tanks to float the upper end. The floating upper end is compliant with wave actions and allows the column to drift within 20° of the vertical from its lower end attached to the universal joint and baseplate.

The Mobil articulated platform recently had trouble when it collapsed during the installation stages. Designed with a 1400 ton baseplate and for 23 meter waves, this platform buckled while being positioned, apparently from buoyancy problems. It has a triangular cross-section and is an open steel lattice structure in the lower half. The upper half has buoyant tanks, crawl spaces, and a deck with pumping gear and loading spars. Again, the advantages of tying the tanker to this compliant platform and loading in the dry is environmentally superior to hoses in the water. A one meter diameter submerged pipeline connects the articulated platform to Beryl A.

Articulated platforms offer lower construction cost, fewer siting problems, and an environmentally cleaner method for loading. Deep-water fixed meteorological sites, mooring platforms, and offshore mining are also possible future uses for articulated columns. Dravo Ocean Structures has the CFEM Western Hemisphere license. (3,7,22,29)

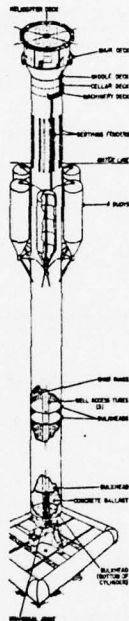


Figure 1.3.19
Typical Articulated Platform

c) SPAR - An application akin to articulated platforms is the SPAR loading and mooring structures. The one presently in use was built by IHC Holland for Shell/Esso's Brent Field and is intended to be a temporary structure. Its purpose is to maintain initial production from exploratory wells in a field where pipelines can not or

will not be built or will be delayed. It is a vertical cylinder floating 30 meters off the seabed with 300,000 barrel crude oil storage capacity. It is 30 meters in diameter and 137 meters in length. The SPAR is anchored by six anchor lines and is designed to float at a constant draft due to the differences in specific gravity of oil, water, and air. When full of oil, water is pumped into a separate buoyancy chamber to keep the structure low in the water. When empty, water replaces the oil and air is pumped into the buoyancy chamber to keep the SPAR from sinking too deep.

The mobility and flexibility of this structure are advantages, but limited storage capacity, short term rather than long term intended useage, and limited operating conditions are its shortcomings. For instance, 2.5 to 4 km/hr wind conditions and five meter waves are maximums for loading operations.

The SPAR has a future in offshore mining developments, prepositioned supply and refuelling locations, and for other tethered, floating applications. (2)

d) UNI-PILES - Over four hundred Uni-Piles have been installed in Lake Maricaibo, Venezuela by Raymond International, the developer, constructor, and installer

70.

of this unit. A Uni-Pile is a single pipe pile structure 1.7 meters in diameter which is used to reduce costs of drilling and production in less than thirty meters of water. The prestressed concrete pile is driven over a well and a precast concrete "mini-platform" with pumping equipment is placed on top. This shallow water application saves greatly on the cost of submerged pipelines and presently expensive subsea production equipment.

Future Uni-Pile useage could be expanded to shallow water meteorological and oceanographic recording stations and other lake useage. (10,65)

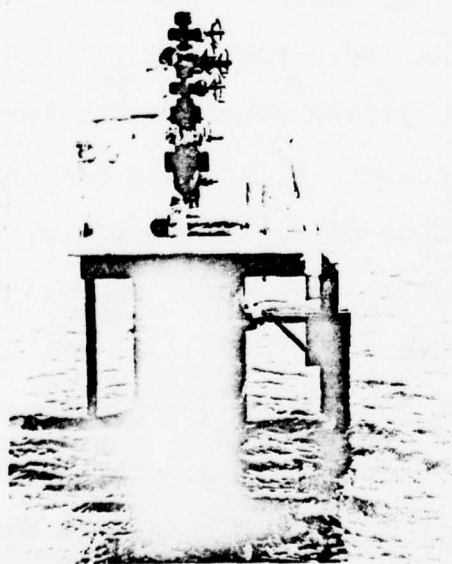


Figure 1.3.20
Raymond International's Uni-Pile in Lake Maracaibo, Venezuela

e) Floating Nuclear Power Plants - A subsidiary of Westinghouse has been formed for the purpose of building, on an assembly-line basis, floating nuclear power plants. The plants are towed to the site in a finished, tested form and are enclosed by a huge gravity breakwater system. Off-shore Power Systems, Inc., Jacksonville, has a construction site and has sold four units to New Jersey utilities. Due to recent problems with the U.S. economy, delivery has been delayed five years and the project is in limbo. If this idea becomes popular, forty percent of the U.S. electric demand can be served from offshore areas having 15 - 25 meter water depths and a stable geology.

Except for the nuclear steam supply system, little standardization has been achieved to date with nuclear plants. Clearly, siting requirements are a large factor in construction costs. A floating platform could help to standardize the site (i.e. the platform) and would lower cost and construction time while improving quality control in an assembly yard.

The platform is seen as a honeycombed concrete structure 120 meters by 120 meters by 13 meters with water-tight bulkheads. It would draw 10 meters of water and displace 150,000 tons. The breakwater would be built to a height of 10 to 25 meters above high tide and would sustain no

damage from a one hundred year storm or a ship collision. The entire plant and breakwater would require only ninety acres of sea floor, would be within the three mile limit for legal purposes, and would be located in water depths between 15 and 25 meters. For depths greater than 25 meters, construction costs for the breakwater become excessive, and less than 15 meters of water conflict with the draft of the floating plant.

Due to nuclear safety considerations, additional requirements must be met. A 290 km/hr wind as well as a tornado with tangential wind speed of 480 km/hr and advance speed of 96 km/hr are two. Additionally, the breakwater must protect the plant for a safe shutdown condition during a one in ten thousand year storm. (62)

f) Suction Platforms - A platform using the suction method of providing greater bottom fixity is usually a concrete gravity platform with a large, flat base and a skirt ten to fifteen meters high extending vertically downward from the edges of the platform pad. As the platform settles, the skirt embeds itself in the soil and a seal is formed. Ports are opened in the base as for grouting, but this time water is pumped out, evacuating the hollow space beneath the platform base.

The suction pulls the platform further into the soil and seats the platform even more firmly on its foundation. In heavy seas and storms, high waves create an even greater pressure difference and hold the platform more firmly, but the dynamic action of constant changes in pore pressure difference could have undesirable effects on the soil stability. Further testing is required for this technique, but in tests to date, twenty meter waves have been encountered with no serious soil problems. No platforms currently utilize this method of improved fixity.

g) Ocean Thermal Plant - Another project TWR, Inc. is working on is a floating power plant which uses the temperature differences between water depths to generate power. Ammonia or a similar substance is utilized because it will vaporize and condense at ocean water temperatures and can be used to drive "steam" turbines. The floating plant would consist of concrete displacement hulls, concrete intake tubes and standard electricity generating equipment. Unfortunately, efficiency is estimated to be 2 - 3 % and another difficulty is a proposed 610 meter concrete pipe 12 meters in diameter as an intake to reach depths of maximum temperature difference. The idea will get definite consideration because it seems pollution-free and has a low operating cost.

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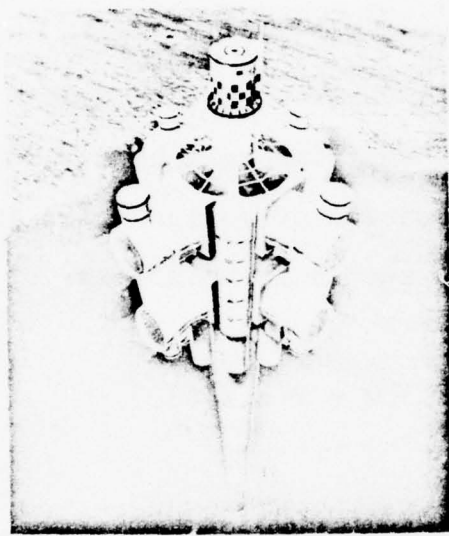


Figure 1.3.21
Lockheed's Conception of Ocean Thermal Plant

Chapter 2
WAVE AND STRUCTURE THEORY

2.1 Introduction

The modeling of a system similar to the ones described in the previous chapter is, of course, complex and expensive. A computer program written to accomplish this modeling, its goals and assumptions will be discussed in the next chapter. The equation of motion which can be used to accurately model such a structure is:

$$m\ddot{x} + (K + K_G) x = P(z, x, t)$$

where: m = mass

\ddot{x} = acceleration

K = stiffness

K_G = geometric stiffness due to axial load

x = displacement

P = imposed loading parallel to x-axis

z = length along axis perpendicular
to x-axis

t = time

This equation assumes no damping. The insertion of another term on the left-hand side of the equation equal to $C\dot{x}$ accounts for damping where C = damping coefficient and \dot{x} = velocity.(5) It will be excluded here, as this thesis will cover undamped response. Future modelers will be able to easily modify the basic program to include damping; structural or viscous. (5)

The means of evaluating the terms in the equation of motion may be derived from simple beam theory and linear wave theory. A complex structure such as an offshore concrete tower will undoubtedly have many degrees of freedom. The theory here will concern continuous, distributed mass systems. The left-hand side of the equation concerns the structure itself. Its terms may be evaluated from simple beam theory for a cantilever. Section 2.3 will describe the right-hand side of the equation in which linear wave theory will be used to evaluate $P(z,x,t)$; the loading vector.

The overall considerations which our theory must include, describe and account for are the following:

- a) a tapering, hollow column of concrete,
- b) a column which is a cantilever rigidly fixed at its base against rotation and translation
- c) a two-dimensional analysis; i.e. x-z plane only,
- d) a continuous, distributed mass system implying an infinite number of degrees of freedom,

- e) an axial loading imposed upon the cantilevered beam due to deck weight and column self-weight,
- f) translation in the x-direction approximated by a cubic expansion of x in ξ , a non-dimensional axial position co-ordinate equal to $\frac{z}{l}$.

2.2 Simple Beam Theory

The problem to be solved in this section is to evaluate the mass, stiffness, and geometric stiffness matrices for a simple beam of varying geometry with two degrees of freedom (rotation and translation) at each end (node). The fixity of the lowest end of the lowest element in the tapering column will be accounted for in the computer program. An infinite number of small elements is modeled by assuming continuous mass and loading distribution.

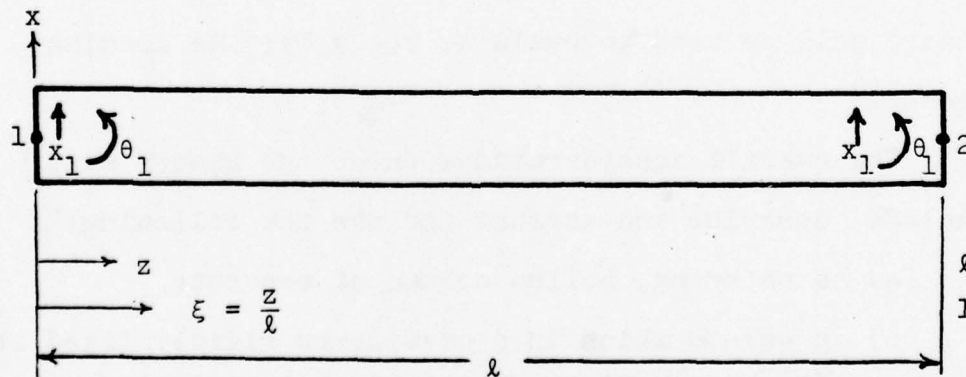


Figure 2.2.1 Simple Beam Parameters

A mathematical description is first required of the movement or deflection transversely with respect to axial position of a small beam element allowed to rotate and translate at each end.

$$\text{If:} \quad \xi = \frac{z}{l}, \quad d\xi = \left(\frac{1}{l}\right)dz, \quad \frac{d\xi}{dz} = \frac{1}{l}$$

$$\text{and:} \quad \theta = \frac{dx}{dz} = \frac{dx}{d\xi} \left(\frac{d\xi}{dz}\right) = \left(\frac{1}{l}\right) \frac{dx}{d\xi}, \quad \frac{dx}{d\xi} = l\theta = x'$$

Then a mathematical description of deflection can be written by assuming:

$$x = \alpha_0 + \alpha_1 \xi + \alpha_2 \xi^2 + \alpha_3 \xi^3$$

$$\text{and:} \quad x' = \alpha_1 + 2\alpha_2 \xi + 3\alpha_3 \xi^2$$

Evaluating these expressions at first one end ($\xi = 0$) and then the other end ($\xi = 1$), four equations in four unknowns can be derived:

$$x_1(0) = \alpha_0$$

$$x_2(1) = \alpha_0 + \alpha_1 + \alpha_2 + \alpha_3$$

$$x'_1(0) = \alpha_1 = l\theta_1$$

$$x'_2(1) = \alpha_1 + 2\alpha_2 + 3\alpha_3 = l\theta_2$$

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Substituting:

$$2\alpha_2 = \ell\theta_2 - 3\alpha_3 - \ell\theta_1$$

$$\alpha_2 = x_2(1) - x_1(0) - \ell\theta_1 - \alpha_3$$

Further substitution yields:

$$2x_2(1) - 2x_1(0) - 2\ell\theta_1 - 2\alpha_3 = \ell\theta_2 - 3\alpha_3 - \ell\theta_1$$

and

$$\underline{\alpha_3 = 2x_1(0) - 2x_2(1) + \ell\theta_1 + \ell\theta_2}$$

$$\alpha_2 = x_2(1) - x_1(0) - \ell\theta_1 - 2x_1(0) + 2x_2(1) - \ell\theta_1 - \ell\theta_2$$

and

$$\underline{\alpha_2 = -3x_1(0) + 3x_2(1) - 2\ell\theta_1 - \ell\theta_2}$$

Having evaluated $\alpha_0, \alpha_1, \alpha_2$, and α_3 we can back-substitute to write an expression for x as a function of ξ .

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$$\begin{aligned}
 x &= x_1(0) + \ell\theta_1\xi + (-3x_1(0) + 3x_2(1) - 2\ell\theta_1 - \ell\theta_2)\xi^2 + \\
 &\quad + (2x_1(0) - 2x_2(1) + \ell\theta_1 + \ell\theta_2)\xi^3 \\
 &= (1 - 3\xi^2 + 2\xi^3) x_1(0) + (3\xi^2 - 2\xi^3) x_2(1) + \\
 &\quad + (\xi - 2\xi^2 + \xi^3) \ell\theta_1 + (-\xi^2 + \xi^3) \ell\theta_2
 \end{aligned}$$

or

$$x = \psi_{x_1} x_1(0) + \psi_{x_2} x_2(1) + \psi_{\theta_1} \theta_1 + \psi_{\theta_2} \theta_2$$

where

$$\begin{aligned}
 \psi_{x_1} &= (1 - 3\xi^2 + 2\xi^3) \\
 \psi_{x_2} &= (3\xi^2 - 2\xi^3) \\
 \psi_{\theta_1} &= (\xi - 2\xi^2 + \xi^3) \ell \\
 \psi_{\theta_2} &= (-\xi^2 + \xi^3) \ell
 \end{aligned}$$

Differentiating with respect to ξ :

$$\begin{aligned}
 \psi'_{x_1} &= -6\xi + 6\xi^2 \\
 \psi'_{x_2} &= 6\xi - 6\xi^2 \\
 \psi'_{\theta_1} &= (1 - 4\xi + 3\xi^2) \ell \\
 \psi'_{\theta_2} &= (-2\xi + 3\xi^2) \ell
 \end{aligned}$$

and:

$$\psi''_{x_1} = -6 + 12\xi$$

$$\psi''_{x_2} = 6 - 12\xi$$

$$\psi''_{\theta_1} = (-4 + 6\xi)l$$

$$\psi''_{\theta_2} = (-2 + 6\xi)l$$

The above values of ψ are called the interpolation functions for a cubic expansion and can be used to find the structural properties of each element(73). The mass, stiffness, and geometric stiffness matrices are next evaluated after Clough and Penzien's method(14).

STIFFNESS MATRIX

Definition:

$$K_{ij} = \int_0^l EI(z) \psi_i''(z) \psi_j''(z) dz$$

where

$$K = \begin{bmatrix} K_{x_1 x_1} & K_{x_1 x_2} & K_{x_1 \theta_1} & K_{x_1 \theta_2} \\ & K_{x_2 x_2} & K_{x_2 \theta_1} & K_{x_2 \theta_2} \\ & & K_{\theta_1 \theta_1} & K_{\theta_1 \theta_2} \\ & & & K_{\theta_2 \theta_2} \end{bmatrix}$$

Convert from "z" to "ξ" co-ordinates

Using:

$$\xi = \frac{z}{l}, \quad d\xi = \left(\frac{1}{l}\right) dz, \quad \frac{dz}{d\xi} = l$$

$$\frac{d\psi}{d\xi} = \left(\frac{d\psi}{dz}\right) \frac{dz}{d\xi} = l \frac{d\psi}{dz}$$

$$\frac{d^2\psi}{d\xi^2} = l \frac{d}{d\xi} \left(\frac{d\psi}{dz}\right) = l \left(\frac{d^2\psi}{dz^2}\right) \frac{dz}{d\xi} = l^2 \frac{d^2\psi}{dz^2}$$

or

$$\frac{d^2\psi}{dz^2} = \left(\frac{1}{l^2}\right) \frac{d^2\psi}{d\xi^2}, \quad \text{and} \quad \left(\frac{1}{l^2}\right) \psi''(\xi) = \psi''(z)$$

Therefore:

$$\begin{aligned} K_{ij} &= \int_0^l EI(\xi) \left[\left(\frac{1}{l^2}\right) \psi_i''(\xi) \right] \left[\left(\frac{1}{l^2}\right) \psi_j''(\xi) \right] (l d\xi) \\ &= \frac{EI}{l^3} \int_0^l I(\xi) \psi_i''(\xi) \psi_j''(\xi) d\xi \end{aligned}$$

As a check, assume E and I Constant:

$$\begin{aligned} K_{x_1 x_1} &= \frac{EI}{l^3} \int_0^l (\psi_{x_1}'')^2 d\xi = \frac{EI}{l^3} \int_0^l (-6 + 12\xi)^2 d\xi = \frac{EI}{l^3} \int_0^l (36 - 144\xi + 144\xi^2) d\xi \\ &= \frac{EI}{l^3} \left[36\xi - 72\xi^2 + 48\xi^3 \right]_0^l = \underline{\underline{\frac{2EI}{l^3} (6)}} \end{aligned}$$

83.

$$K_{x_1 x_2} = \frac{EI}{l^3} \int_0^1 (-6 + 12\xi) (6 - 12\xi) d\xi = \underline{\underline{\frac{2EI}{l^3} (-6)}}$$

$$K_{x_1 \theta_1} = \frac{EI}{l^3} \int_0^1 (-6 + 12\xi) (-4 + 6\xi) l d\xi = \underline{\underline{\frac{2EI}{l^3} (3l)}}$$

$$K_{x_1 \theta_2} = \frac{EI}{l^3} \int_0^1 (-6 + 12\xi) (-2 + 6\xi) l d\xi = \underline{\underline{\frac{2EI}{l^3} (3l)}}$$

$$K_{x_2 x_2} = \frac{EI}{l^3} \int_0^1 (6 - 12\xi)^2 d\xi = \underline{\underline{\frac{2EI}{l^3} (6)}}$$

$$K_{x_2 \theta_1} = \frac{EI}{l^3} \int_0^1 (6 - 12\xi) (-4 + 6\xi) l d\xi = \underline{\underline{\frac{2EI}{l^3} (-3l)}}$$

$$K_{x_2 \theta_2} = \frac{EI}{l^3} \int_2^1 (6 - 12\xi) (-2 + 6\xi) l d\xi = \underline{\underline{\frac{2EI}{l^3} (-3l)}}$$

$$K_{\theta_1 \theta_1} = \frac{EI}{l^3} \int_0^1 (-4 + 6\xi)^2 l^2 d\xi = \underline{\underline{\frac{2EI}{l^3} (2l^2)}}$$

$$K_{\theta_1 \theta_2} = \frac{EI}{l^3} \int_0^1 (-4 + 6\xi) (-2 + 6\xi) l^2 d\xi = \underline{\underline{\frac{2EI}{l^3} (l^2)}}$$

$$K_{\theta_2 \theta_2} = \frac{EI}{l^3} \int_0^1 (-2 + 6\xi)^2 l^2 d\xi = \underline{\underline{\frac{2EI}{l^3} (2l^2)}}$$

Stiffness Matrix (Constant E & I):

$$K = \frac{2EI}{l^3} \begin{bmatrix} 6 & -6 & 3l & 3l \\ -6 & 6 & -3l & -3l \\ 3l & -3l & 2l^2 & l^2 \\ 3l & -3l & l^2 & 2l^2 \end{bmatrix}$$

One of the considerations for modeling a typical offshore concrete platform included a varying geometry requiring a varying moment of inertia, I. Figure 2.2.2 on the next page illustrates the structure itself and the parameters required to describe the system using beam theory for the column. To describe the structure, the following parameters must be given:

- a = difference in internal column radius between top and bottom of column
- b = difference in external column radius between top and bottom of column
- c₁ = internal column radius at bottom of column
- c₂ = external column radius at bottom of column
- d = deck thickness
- e = deck length
- f = deck width
- ρ₁ = density of concrete

85.

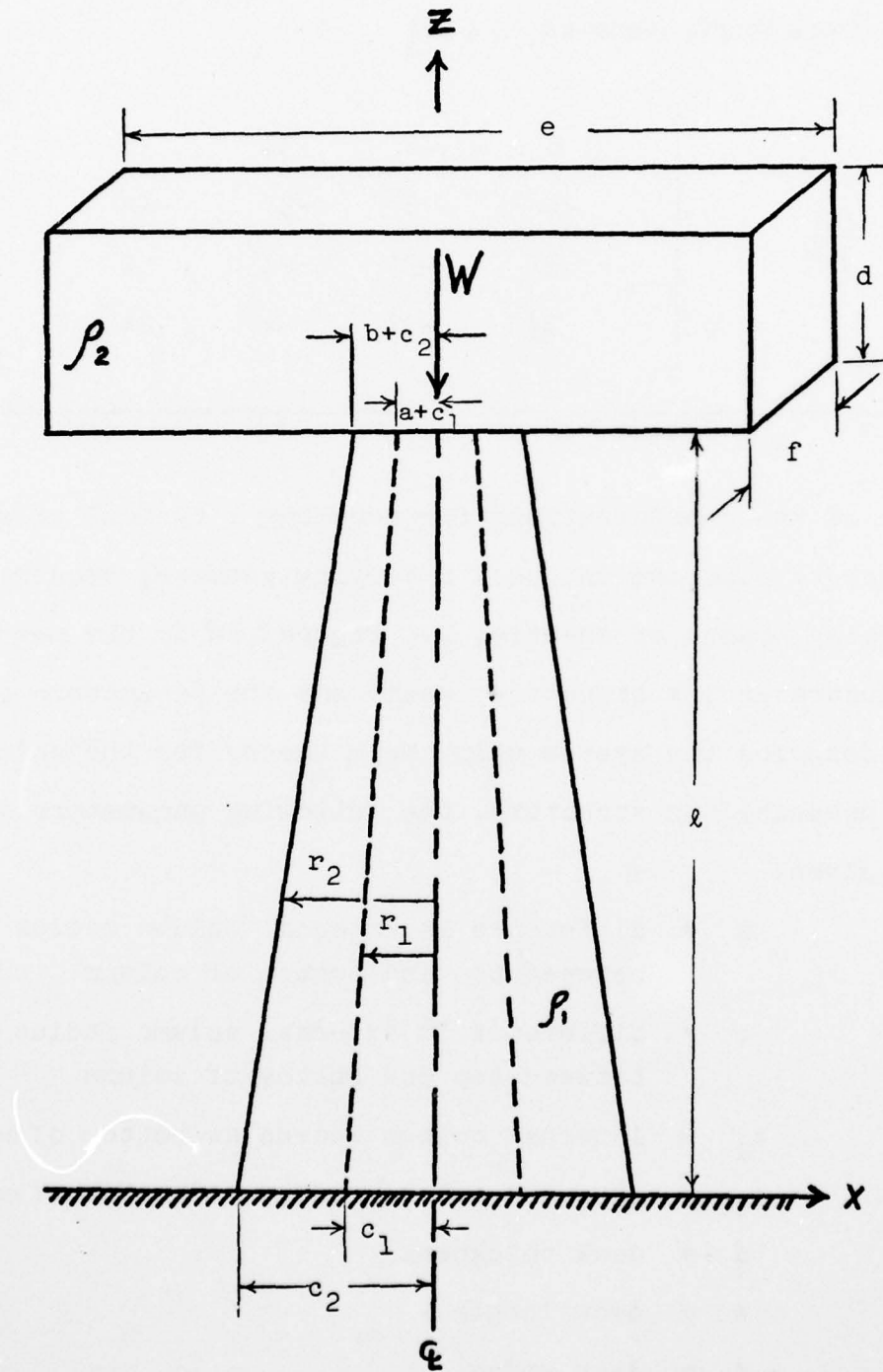


Figure 2.2.2
Tapering Column Parameters Used For Beam Theory

ρ_2 = average deck density

ρ = density of sea water

l = total column length

Throughout this paper the MKS system will be used exclusively.

Using the above parameters, the following may be calculated:

$$\xi = \frac{z}{l}$$

$$r_1 = a\left(\frac{z}{l}\right) + c_1 = a\xi + c_1$$

$$r_2 = b\left(\frac{z}{l}\right) + c_2 = b\xi + c_2$$

$$M_2 = \rho_2 def$$

$$W_2 = \rho_2 defg$$

$$\begin{aligned} A(\xi) &= \pi r_2^2 - \pi r_1^2 = \pi(r_2 + r_1)(r_2 - r_1) = \pi(b\xi + c_2 + a\xi + c_1)(b\xi + c_2 - a\xi - c_1) \\ &= \pi[(b^2 - a^2)\xi^2 + 2(c_2b - c_1a)\xi + (c_2^2 - c_1^2)] \end{aligned}$$

$$\begin{aligned} I_y(\xi) &= \frac{1}{4}\pi r_2^4 - \frac{1}{4}\pi r_1^4 = \frac{\pi}{4}(r_2^2 + r_1^2)(r_2^2 - r_1^2) \\ &= \frac{\pi}{4}(r_2^2 + r_1^2)(r_2 + r_1)(r_2 - r_1) \\ &= \frac{\pi}{4}[(b\xi + c_2)^2 + (a\xi + c_1)^2](b\xi + c_2 + a\xi + c_1) \\ &\quad (b\xi + c_2 - a\xi - c_1) \end{aligned}$$

$$\begin{aligned}
&= \frac{\pi}{4} [(b^4 - a^4)\xi^4 + 4(c_2b^3 - c_1a^3)\xi^3 \\
&\quad + 6(c_2^2b^2 - c_1^2a^2)\xi^2 + 4(c_2^3b - c_1^3a)\xi + (c_2^4 - c_1^4)] \\
V(\xi) &= \int_0^{\ell} A(z) dz = \int_0^1 A(\xi) \ell d\xi \\
&= \int \pi \ell (a\xi + c_1 + b\xi + c_2) (b\xi + c_2 - a\xi - c_1) d\xi \\
&= \ell \pi \int [ab\xi^2 + c_2a\xi - a^2\xi^2 - c_1a\xi + c_1b\xi + c_1c_2 - c_1a\xi - c_1^2 \\
&\quad + b^2\xi^2 + c_2b\xi - ab\xi^2 - c_1b\xi + c_2b\xi + c_2^2 - c_2a\xi - c_1c_2] d\xi \\
&= \ell \pi \int [(ab - a^2 + b^2 - ab)\xi^2 + (c_2a - c_1a + c_1b - c_1a + c_2b - c_1b + c_2b - c_2a)\xi \\
&\quad + (c_1c_2 - c_1^2 + c_2^2 - c_1c_2)] d\xi \\
&= \ell \pi \int [(b^2 - a^2)\xi^2 + 2(c_2b - c_1a)\xi + (c_2 + c_1)(c_2 - c_1)] d\xi \\
&= \pi \ell [(b^2 - a^2) \frac{\xi^3}{3} + (c_2b - c_1a)\xi^2 + (c_2 + c_1)(c_2 - c_1)\xi] \\
&= \frac{\pi \ell}{3} [(b^2 - a^2)\xi^3 + 3(c_2b - c_1a)\xi^2 + 3(c_2^2 - c_1^2)\xi]
\end{aligned}$$

$$m_1(\xi) = \rho_1 A(\xi) d\xi$$

$$w_1^w(\xi) = \rho_1 g A(\xi) d\xi$$

For the given structure described by Figure 2.2.2 and using the above relationships, the stiffness matrix for a varying geometry can be found.

$$\begin{aligned}
 K_{x_1 x_1} &= \frac{E}{\ell^3} \int_0^1 I(\xi) \psi_{x_1}^2 d\xi \\
 &= \frac{E}{\ell^3} \int_0^1 \left\{ \frac{\pi}{4} \left[(b^4 - a^4) \xi^4 + 4(c_2 b^3 - c_1 a^3) \xi^3 + 6(c_2^2 b^2 - c_1^2 a^2) \xi^2 \right. \right. \\
 &\quad \left. \left. + 4(c_2^3 b - c_1^3 a) \xi + (c_2^4 - c_1^4) \right] \right\} (-6 + 12\xi)^2 d\xi \\
 &= \left(\frac{E\pi}{4\ell^3} \right) \int_0^1 \left[(b^4 - a^4) \xi^4 + 4(c_2 b^3 - c_1 a^3) \xi^3 + 6(c_2^2 b^2 - c_1^2 a^2) \xi^2 \right. \\
 &\quad \left. + 4(c_2^3 b - c_1^3 a) \xi + (c_2^4 - c_1^4) \right] [144\xi^2 - 144\xi + 36] d\xi \\
 &= \frac{\pi E}{4\ell^3} \int_0^1 \left[144(b^4 - a^4) \xi^6 + (576(c_2 b^3 - c_1 a^3) - 144(b^4 - a^4)) \xi^5 \right. \\
 &\quad + (864(c_2^2 b^2 - c_1^2 a^2) - 576(c_2 b^3 - c_1 a^3) + 36(b^4 - a^4)) \xi^4 \\
 &\quad + (576(c_2^3 b - c_1^3 a) - 864(c_2^2 b^2 - c_1^2 a^2) + 144(c_2 b^3 - c_1 a^3)) \xi^3 \\
 &\quad + (144(c_2^4 - c_1^4) - 576(c_2^3 b - c_1^3 a) + 216(c_2^2 b^2 - c_1^2 a^2)) \xi^2 \\
 &\quad \left. + 144((c_2^3 b - c_1^3 a) - (c_2^4 - c_1^4)) \xi + 36(c_2^4 - c_1^4) \right] d\xi
 \end{aligned}$$

$$\begin{aligned}
&= \frac{\pi E}{4\ell^3} \left[\frac{144}{7} (b^4 - a^4) \xi^7 + \left(\frac{576}{6} (c_2 b^3 - c_1 a^3) - \frac{144}{6} (b^4 - a^4) \right) \xi^6 \right. \\
&\quad + \left(\frac{864}{5} (c_2^2 b^2 - c_1^2 a^2) - \frac{576}{6} (c_2 b^3 - c_1 a^3) + \frac{36}{5} (b^4 - a^4) \right) \xi^5 \\
&\quad + \left(\frac{576}{4} (c_2^3 b - c_1^3 a) - \frac{864}{4} (c_2^2 b^2 - c_1^2 a^2) + \frac{144}{4} (c_2 b^3 - c_1 a^3) \right) \xi^4 \\
&\quad + \left(\frac{144}{3} (c_2^4 - c_1^4) - \frac{576}{3} (c_2^3 b - c_1^3 a) + \frac{216}{3} (c_2^2 b^2 - c_1^2 a^2) \right) \xi^3 \\
&\quad \left. + \left(\frac{144}{2} (c_2^3 b - c_1^3 a) - (c_2^4 - c_1^4) \right) \xi^2 + 36 (c_2^4 - c_1^4) \xi \right] \Bigg|_0^1
\end{aligned}$$

$$\begin{aligned}
&= \frac{36\pi E}{\ell^3} \left[\frac{1}{7} (b^4 - a^4) + \frac{2}{3} (c_2 b^3 - c_1 a^3) - \frac{1}{6} (b^4 - a^4) + \frac{6}{5} (c_2^2 b^2 - c_1^2 a^2) \right. \\
&\quad - \frac{4}{5} (c_2 b^3 - c_1 a^3) + \frac{1}{20} (b^4 - a^4) + (c_2^3 b - c_1^3 a) - \frac{3}{2} (c_2^2 b^2 - c_1^2 a^2) \\
&\quad + \frac{1}{4} (c_2 b^3 - c_1 a^3) + \frac{1}{3} (c_2^4 - c_1^4) - \frac{4}{3} (c_2^3 b - c_1^3 a) + \frac{1}{2} (c_2^2 b^2 - c_1^2 a^2) \\
&\quad \left. + \frac{1}{2} (c_2^3 b - c_1^3 a) - \frac{1}{2} (c_2^4 - c_1^4) + \frac{1}{4} (c_2^4 - c_1^4) \right]
\end{aligned}$$

$$\begin{aligned}
&= \frac{\pi}{\ell^3} \left[\frac{33}{35} (b^4 - a^4) + \frac{21}{5} (c_2 b^3 - c_1 a^3) + \frac{36}{5} (c_2^2 b^2 - c_1^2 a^2) \right. \\
&\quad \left. + 6 (c_2^3 b - c_1^3 a) + 3 (c_2^4 - c_1^4) \right]
\end{aligned}$$

$$\begin{aligned}
 K_{x_1 x_2} &= \frac{E}{\ell^3} \int_0^1 I(\xi) \psi_{x_1}'' \psi_{x_2}'' d\xi \\
 &= \frac{E\pi}{\ell^3} \left[-\frac{33}{35} (b^4 - a^4) - \frac{21}{5} (c_2 b^3 - c_1 a^3) - \frac{36}{5} (c_2^2 b^2 - c_1^2 a^2) \right. \\
 &\quad \left. - 6(c_2^3 b - c_1^3 a) - 3(c_2^4 - c_1^4) \right]
 \end{aligned}$$

$$\begin{aligned}
 K_{x_1 \theta_1} &= \frac{E}{\ell^3} \int_0^1 I(\xi) \psi_{x_1}'' \psi_{\theta_1}'' d\xi \\
 &= \frac{\pi E}{\ell^2} \left[\frac{19}{70} (b^4 - a^4) + \frac{6}{5} (c_2 b^3 - c_1 a^3) + \frac{21}{10} (c_2^2 b^2 - c_1^2 a^2) \right. \\
 &\quad \left. + 2(c_2^3 b - c_1^3 a) + \frac{3}{2} (c_2^4 - c_1^4) \right]
 \end{aligned}$$

$$\begin{aligned}
 K_{x_1 \theta_2} &= \frac{E}{\ell^3} \int_0^1 I(\xi) \psi_{x_1}'' \psi_{\theta_2}'' d\xi \\
 &= \frac{\pi E}{\ell^2} \left[\frac{47}{70} (b^4 - a^4) + 3(c_2 b^3 - c_1 a^3) + \frac{51}{10} (c_2^2 b^2 - c_1^2 a^2) \right. \\
 &\quad \left. + 4(c_2^3 b - c_1^3 a) + \frac{3}{2} (c_2^4 - c_1^4) \right]
 \end{aligned}$$

$$K_{x_2 x_2} = \frac{E}{l^3} \int_0^1 I(\xi) \psi_{x_2}''^2 d\xi = \frac{E\pi}{l^3} \left[\frac{33}{35} (b^4 - a^4) + \frac{21}{5} (c_2 b^3 - c_1 a^3) \right. \\ \left. + \frac{36}{5} (c_2^2 b^2 - c_1^2 a^2) + 6 (c_2^3 - c_1^3 a) + c(c_2^4 - c_1^4) \right]$$

$$K_{x_2 \theta_1} = \frac{E}{l^3} \int_0^1 I(\xi) \psi_{x_2}'' \psi_{\theta_1}'' d\xi = \frac{E\pi}{l^2} \left[-\frac{19}{70} (b^4 - a^4) \right. \\ \left. - \frac{6}{5} (c_2 b^3 - c_1 a^3) - \frac{21}{10} (c_2^2 b^2 - c_1^2 a^2) - 2(c_2^3 - c_1^3 a) \right. \\ \left. - \frac{3}{2} (c_2^4 - c_1^4) \right]$$

$$K_{x_2 \theta_2} = \frac{E}{l^3} \int_0^1 I(\xi) \psi_{x_2}'' \psi_{\theta_2}'' d\xi = \frac{E\pi}{l^2} \left[-\frac{47}{70} (b^4 - a^4) - 3(c_2 b^3 - c_1 a^3) \right. \\ \left. - \frac{51}{10} (c_2^2 b^2 - c_1^2 a^2) - 4(c_2^3 - c_1^3 a) - \frac{3}{2} (c_2^4 - c_1^4) \right]$$

$$K_{\theta_1 \theta_1} = \frac{E}{l^3} \int_0^1 I(\xi) \psi_{\theta_1}''^2 d\xi = \frac{E\pi}{l} \left[\frac{3}{35} (b^4 - a^4) + \frac{2}{5} (c_2 b^3 - c_1 a^3) \right. \\ \left. + \frac{4}{5} (c_2^2 b^2 - c_1^2 a^2) + (c_2^3 - c_1^3 a) + (c_2^4 - c_1^4) \right]$$

$$K_{\theta_1 \theta_2} = \frac{E}{l^3} \int_0^1 I(\xi) \psi_{\theta_1}'' \psi_{\theta_2}'' d\xi = \frac{E\pi}{l} \left[\frac{13}{70} (b^4 - a^4) + \frac{4}{5} (c_2 b^3 - c_1 a^3) \right. \\ \left. + \frac{13}{10} (c_2^2 b^2 - c_1^2 a^2) + (c_2^3 - c_1^3 a) + \frac{1}{2} (c_2^4 - c_1^4) \right]$$

$$K_{\theta_2 \theta_2} = \frac{E}{l^3} \int_0^1 I(\xi) \psi_{\theta_2}^2 d\xi = \frac{E\pi}{l} \left[\frac{17}{35} (b^4 - a^4) + \frac{11}{5} (c_2 b^3 - c_1 a^3) \right. \\ \left. + \frac{19}{5} (c_2^2 b^2 - c_1^2 a^2) + 3 (c_2^3 b - c_1^3 a) + (c_2^4 - c_1^4) \right]$$

GEOMETRIC STIFFNESS MATRIX

Definition:

$$K_{G_{ij}} = \int_0^1 N(z) \psi_i'(z) \psi_j'(z) dz$$

Convert from "z" to "ξ" coordinates:

$$K_{G_{ij}} = \int_0^1 N(\xi) \left[\left(\frac{1}{l} \right) \psi_i'(\xi) \right] \left[\left(\frac{1}{l} \right) \psi_j'(\xi) \right] l d\xi$$

where:

$$N(\xi) = W_2 + w_{\text{column total}} - w_1(\xi) \\ = \left[\frac{W_2 + w_{\text{column total}}}{l} \right] \int_0^1 \psi_i'(\xi) \psi_j'(\xi) d\xi - \frac{1}{l} \int_0^1 w_1(\xi) \psi_i'(\xi) \psi_j'(\xi) d\xi$$

and where:

$$W_2 = \rho_2 \text{defg}$$

$$w_{\text{column total}} = \rho g V_{\text{total}}$$

$$w_1(\xi) = \rho_1 g V(\xi) = \frac{\rho_1 g \pi l}{3} [(b^2 - a^2) \xi^3 + 3(c_2 b - c_1 a) \xi^2 + 3(c_2^2 - c_1^2) \xi]$$

$$K_{G_{1j}} \text{ for constant } W_2 + w_{\text{column total}} \text{ term:}$$

$$(\text{let } W_2 + w_{\text{column total}} = W)$$

$$\begin{aligned} K_{G_{x_1 x_1}} &= \frac{W}{l} \int_0^1 (-6\xi + 6\xi^2)^2 d\xi = \frac{W}{l} \int_0^1 (36\xi^4 - 72\xi^3 + 36\xi^2) d\xi \\ &= \frac{W}{l} \left[\frac{36}{5} \xi^5 - \frac{72}{4} \xi^4 + \frac{36}{3} \xi^3 \right] \bigg|_0^1 = \underline{\underline{\frac{W}{30l} (36)}} \end{aligned}$$

$$K_{G_{x_1 x_2}} = \frac{W}{l} \int_0^1 (-6\xi + 6\xi^2) d\xi = \underline{\underline{\frac{W}{30l} (-36)}}$$

$$K_{G_{x_1 \theta_1}} = \frac{W}{l} \int_0^1 (-6\xi + 6\xi^2) (1 - 4\xi + 3\xi^2) l d\xi = \underline{\underline{\frac{W}{30l} (3l)}}$$

$$K_{G_{x_1 \theta_2}} = \frac{W}{l} \int_0^1 (-6\xi + 6\xi^2) (-2\xi + 3\xi^2) l d\xi = \underline{\underline{\frac{W}{30} (3l)}}$$

94.

$$K_{Gx_2x_2} = \frac{W}{l} \int_0^1 (6\xi - 6\xi^2)^2 d\xi = \underline{\underline{\frac{W}{30l} (36)}}$$

$$K_{Gx_2\theta_1} = \frac{W}{l} \int_0^1 (6\xi - 6\xi^2) (1-4\xi + 3\xi^2) l d\xi = \underline{\underline{\frac{W}{30l} (-3l)}}$$

$$K_{Gx_2\theta_2} = \frac{W}{l} \int_0^1 (6\xi - 6\xi^2) (-2\xi + 3\xi^2) l d\xi = \underline{\underline{\frac{W}{30l} (-3l)}}$$

$$K_{G\theta_1\theta_1} = \frac{W}{l} \int_0^1 (1 - 4\xi + 3\xi^2)^2 d\xi = \underline{\underline{\frac{W}{30l} (4l^2)}}$$

$$K_{G\theta_1\theta_2} = \frac{W}{l} \int_0^1 (1 - 4\xi + 3\xi^2) l (-2\xi + 3\xi^2) l d\xi = \underline{\underline{\frac{W}{30l} (-l^2)}}$$

$$K_{G\theta_2\theta_2} = \frac{W}{l} \int_0^1 ((-2\xi + 3\xi^2) l)^2 d\xi = \underline{\underline{\frac{W}{30l} (4l^2)}}$$

$K_{G_{1j}}$ for variable $w_1(\xi)$:

$$K_{G_{x_1 x_1}} = \frac{1}{\ell} \int_0^1 \frac{\rho_1 \pi \ell g}{3} [(b^2 - a^2) \xi^3 + 3(c_2 b - c_1 a) \xi^2 + 3(c_2^2 - c_1^2) \xi]$$

$$[36\xi^2 - 72\xi^3 + 36\xi^4] d\xi$$

$$= \frac{\rho_1 \pi g}{3} \int_0^1 [36 (b^2 - a^2) \xi^5 + 108 (c_2 b - c_1 a) \xi^4 + 108 (c_2^2 - c_1^2) \xi^3$$

$$- 72(b^2 - a^2) \xi^6 - 216 (c_2 b - c_1 a) \xi^5 - 216 (c_2^2 - c_1^2) \xi^4$$

$$+ 36 (b^2 - a^2) \xi^7 + 108 (c_2 b - c_1 a) \xi^6 + 108 (c_2^2 - c_1^2) \xi^5] d\xi$$

$$= \frac{\rho_1 \pi g}{3} [\frac{36}{6} (b^2 - a^2) \xi^6 + \frac{108}{5} (c_2 b - c_1 a) \xi^5 + \frac{108}{4} (c_2^2 - c_1^2) \xi^4$$

$$- \frac{72}{7} (b^2 - a^2) \xi^7 - \frac{216}{6} (c_2 b - c_1 a) \xi^6 - \frac{216}{5} (c_2^2 - c_1^2) \xi^5$$

$$+ \frac{36}{8} (b^2 - a^2) \xi^8 + \frac{108}{7} (c_2 b - c_1 a) \xi^7 + \frac{108}{6} (c_2^2 - c_1^2) \xi^6] \Big|_0^1$$

$$= \frac{\rho_1 \pi g}{3} [\frac{3}{14} (b^2 - a^2) + \frac{12}{35} (c_2 b - c_1 a) + \frac{9}{5} (c_2^2 - c_1^2)]$$

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APPROXIMATE MODELS FOR OFF-SHORE CONCRETE GRAVITY STRUCTURES.(U)
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$$K_{Gx_1x_2} = \frac{1}{\ell} \int_0^1 w_1(\xi) \psi'_{x_1} \psi'_{x_2} d\xi = \frac{\rho_1 g \pi}{3} \left[-\frac{3}{14} (b^2 - a^2) \right. \\ \left. - \frac{12}{35} (c_2 b - c_1 a) - \frac{9}{5} (c_2^2 - c_1^2) \right]$$

$$K_{Gx_1\theta_1} = \frac{1}{\ell} \int_0^1 w_1(\xi) \psi'_{x_1} \psi'_{\theta_1} d\xi = \frac{\rho_1 g \pi \ell}{3} \left[\frac{1}{20} (b^2 - a^2) \right. \\ \left. + \frac{3}{14} (c_2 b - c_1 a) + \frac{3}{10} (c_2^2 - c_1^2) \right]$$

$$K_{Gx_1\theta_2} = \frac{1}{\ell} \int_0^1 w_1(\xi) \psi'_{x_1} \psi'_{\theta_2} d\xi = \frac{\rho_1 g \pi \ell}{3} \left[-\frac{1}{28} (b^2 - a^2) \right. \\ \left. - \frac{3}{35} (c_2^2 - c_1^2) \right]$$

$$K_{Gx_2x_2} = \frac{1}{\ell} \int_0^1 w_1(\xi) \psi'^2_{x_2} d\xi = \frac{\rho_1 g \pi}{3} \left[\frac{3}{14} (b^2 - a^2) \right. \\ \left. + \frac{12}{35} (c_2 b - c_1 a) + \frac{9}{5} (c_2^2 - c_1^2) \right]$$

$$K_{Gx_2\theta_1} = \frac{1}{\ell} \int_0^1 w_1(\xi) \psi'_{x_2} \psi'_{\theta_1} d\xi = \frac{\rho_1 g \pi \ell}{3} \left[\frac{1}{20} (b^2 - a^2) - \frac{3}{14} (c_2 b - c_1 a) \right. \\ \left. - \frac{3}{10} (c_2^2 - c_1^2) \right]$$

$$K_{Gx_2\theta_2} = \frac{1}{\ell} \int_0^1 w_1(\xi) \psi'_{x_2} \psi'_{\theta_2} d\xi = \frac{\rho_1 g \pi \ell}{3} \left[\frac{1}{28} (b^2 - a^2) + \frac{3}{35} (c_2^2 - c_1^2) \right]$$

$$K_{G\theta_1\theta_1} = \frac{1}{\ell} \int_0^1 w_1(\xi) \psi_{\theta_1}^{'2} d\xi = \frac{\rho_1 g \pi \ell^2}{3} \left[\frac{11}{840} (b^2 - a^2) + \frac{2}{35} (c_2 b - c_1 a) + \frac{1}{10} (c_2^2 - c_1^2) \right]$$

$$K_{G\theta_1\theta_2} = \frac{1}{\ell} \int_0^1 w_1(\xi) \psi'_{\theta_1} \psi'_{\theta_2} d\xi = \frac{\rho_1 g \pi \ell^2}{3} \left[-\frac{11}{840} (b^2 - a^2) - \frac{3}{70} (c_2 b - c_1 a) - \frac{1}{20} (c_2^2 - c_1^2) \right]$$

$$K_{G\theta_2\theta_2} = \frac{1}{\ell} \int_0^1 w_1(\xi) \psi_{\theta_2}^{'2} d\xi = \frac{\rho_1 g \pi \ell^2}{3} \left[\frac{13}{168} (b^2 - a^2) + \frac{9}{35} (c_2 b - c_1 a) + \frac{3}{10} (c_2^2 - c_1^2) \right]$$

The K_G matrix is assembled from the above expressions by adding directly for each element of the matrix, the terms contributed by the total column weight and the deck weight, and by subtracting the term describing the weight below any point on the column, $w_1(\xi)$.

MASS MATRIX

Definition:

$$m_{ij} = \int_0^{\ell} m_1(z) \psi_i(z) \psi_j(z) dz + M_2 \psi_i(\ell) \psi_j(\ell)$$

Convert from "z" to "ξ" coordinates:

$$\begin{aligned} m_{ij} &= \int_0^1 m_1(\xi) \psi_i(\xi) \psi_j(\xi) \ell d\xi + M_2 \psi_i(1) \psi_j(1) \\ &= \ell \int_0^1 m_1(\xi) \psi_i(\xi) \psi_j(\xi) d\xi + M_2 \psi_i(1) \psi_j(1) \end{aligned}$$

where:

$$\begin{aligned} m_1(\xi) &= \rho_1 A(\xi) = \rho_1 \pi [(b^2 - a^2) \xi^2 + 2(c_2 b - c_1 a) \\ &\quad + (c_2^2 - c_1^2)] \end{aligned}$$

$$M_2 = \rho_2 \text{def}$$

Evaluate the M_2 Term:

$$\psi_{x_1}(1) = \psi_{\theta_1}(1) = \psi_{\theta_2}(1) = 0$$

$$\psi_{x_2}(1) = 1$$

$$M_2 \psi_{x_2}^2(1) = \rho_2 \text{def}$$

$$\begin{aligned}
m_{x_1 x_1} &= \lambda \int_0^1 m_1(\xi) \psi_{x_1}^2 d\xi = \lambda \int_0^1 \rho \pi [(b^2 - a^2) \xi^2 + 2(c_2 b - c_1 a) \xi \\
&\quad + (c_2^2 - c_1^2)] [1 - 6\xi^2 + 4\xi^3 + 9\xi^4 - 12\xi^5 + 4\xi^6] d\xi \\
&= \rho \pi \lambda \int_0^1 [(b^2 - a^2) \xi^2 + 2(c_2 b - c_1 a) \xi + (c_2^2 - c_1^2) - 6(b^2 - a^2) \xi^4 \\
&\quad - 12(c_2 b - c_1 a) \xi^3 - 6(c_2^2 - c_1^2) \xi^2 + 4(b^2 - a^2) \xi^5 + 8(c_2 b - c_1 a) \xi^4 \\
&\quad + 4(c_2^2 - c_1^2) \xi^3 + 9(b^2 - a^2) \xi^6 + 18(c_2 b - c_1 a) \xi^5 + 9(c_2^2 - c_1^2) \xi^4 \\
&\quad - 12(b^2 - a^2) \xi^7 - 24(c_2 b - c_1 a) \xi^6 - 12(c_2^2 - c_1^2) \xi^5 + 4(b^2 - a^2) \xi^8 \\
&\quad + 8(c_2 b - c_1 a) \xi^7 + 4(c_2^2 - c_1^2) \xi^6] d\xi \\
&= \rho \pi \lambda \left[\frac{1}{3} (b^2 - a^2) \xi^3 + (c_2 b - c_1 a) \xi^2 + (c_2^2 - c_1^2) \xi - \frac{6}{5} (b^2 - a^2) \xi^5 \right. \\
&\quad - \frac{12}{4} (c_2 b - c_1 a) \xi^4 - \frac{6}{3} (c_2^2 - c_1^2) \xi^3 + \frac{4}{6} (b^2 - a^2) \xi^6 + \frac{8}{5} (c_2 b - c_1 a) \xi^5 \\
&\quad + \frac{4}{4} (c_2^2 - c_1^2) \xi^4 + \frac{9}{7} (b^2 - a^2) \xi^7 + \frac{18}{6} (c_2 b - c_1 a) \xi^6 + \frac{9}{5} (c_2^2 - c_1^2) \xi^5 \\
&\quad - \frac{12}{8} (b^2 - a^2) \xi^8 - \frac{24}{7} (c_2 b - c_1 a) \xi^7 - \frac{12}{6} (c_2^2 - c_1^2) \xi^6 + \frac{4}{9} (b^2 - a^2) \xi^9 \\
&\quad \left. + \frac{8}{8} (c_2 b - c_1 a) \xi^8 + \frac{4}{7} (c_2^2 - c_1^2) \xi^7 \right] \Big|_0^1 \\
&= \rho \pi \lambda \left[\left(\frac{1}{3} - \frac{6}{5} + \frac{2}{3} + \frac{9}{7} - \frac{3}{2} + \frac{4}{9} \right) (b^2 - a^2) + \left(1 - 3 + \frac{8}{5} + 3 - \frac{24}{7} + 1 \right) \right. \\
&\quad \left. (c_2 b - c_1 a) + \left(1 - 2 + 1 + \frac{9}{5} - 2 + \frac{4}{7} \right) (c_2^2 - c_1^2) \right] \\
&= \rho \pi \lambda \left[\left(\frac{19}{630} (b^2 - a^2) + \frac{6}{35} (c_2 b - c_1 a) + \frac{13}{35} (c_2^2 - c_1^2) \right) \right]
\end{aligned}$$

$$m_{x_1 x_2} = \ell \int_0^1 m_1(\xi) \psi_{x_1} \psi_{x_2} d\xi = \rho \pi \ell \left[\frac{23}{630} (b^2 - a^2) + \frac{9}{70} (c_2 b - c_1 a) \right. \\ \left. + \frac{9}{70} (c_2^2 - c_1^2) \right]$$

$$m_{x_1 \theta_1} = \ell \int_0^1 m_1(\xi) \psi_{x_1} \psi_{\theta_1} d\xi = \rho \pi \ell^2 \left[\frac{17}{2520} (b^2 - a^2) + \frac{1}{30} (c_2 b - c_1 a) \right. \\ \left. + \frac{11}{210} (c_2^2 - c_1^2) \right]$$

$$m_{x_1 \theta_2} = \ell \int_0^1 m_1(\xi) \psi_{x_1} \psi_{\theta_2} d\xi = \rho \pi \ell^2 \left[-\frac{19}{2520} (b^2 - a^2) - \frac{1}{35} (c_2 b - c_1 a) \right. \\ \left. - \frac{13}{420} (c_2^2 - c_1^2) \right]$$

$$m_{x_2 x_2} = \ell \int_0^1 m_1(\xi) \psi_{x_2}^2 d\xi = \rho \pi \ell \left[\frac{29}{126} (b^2 - a^2) + \frac{4}{7} (c_2 b - c_1 a) \right. \\ \left. + \frac{13}{35} (c_2^2 - c_1^2) \right] + \rho_2 \text{def}$$

$$m_{x_2 \theta_1} = \ell \int_0^1 m_1(\xi) \psi_{x_2} \psi_{\theta_1} d\xi = \rho \pi \ell^2 \left[\frac{5}{504} (b^2 - a^2) + \frac{1}{30} (c_2 b - c_1 a) \right. \\ \left. + \frac{13}{420} (c_2^2 - c_1^2) \right]$$

$$m_{x_2 \theta_2} = \ell \int_0^1 m_1(\xi) \psi_{x_2} \psi_{\theta_2} d\xi = \underline{\underline{\rho \pi \ell^2 \left[-\frac{13}{504} (b^2 - a^2) - \frac{1}{14} (c_2 b - c_1 a) - \frac{11}{210} (c_2^2 - c_1^2) \right]}}$$

$$m_{\theta_1 \theta_1} = \ell \int_0^1 m_1(\xi) \psi_{\theta_1}^2 d\xi = \underline{\underline{\rho \pi \ell^3 \left[\frac{1}{630} (b^2 - a^2) + \frac{1}{140} (c_2 b - c_1 a) + \frac{1}{105} (c_2^2 - c_1^2) \right]}}$$

$$m_{\theta_1 \theta_2} = \ell \int_0^1 m_1(\xi) \psi_{\theta_1} \psi_{\theta_2} d\xi = \underline{\underline{\rho \pi \ell^3 \left[-\frac{1}{504} (b^2 - a^2) - \frac{1}{140} (c_2 b - c_1 a) - \frac{1}{140} (c_2^2 - c_1^2) \right]}}$$

$$m_{\theta_2 \theta_2} = \ell \int_0^1 m_1(\xi) \psi_{\theta_2}^2 d\xi = \underline{\underline{\rho \pi \ell^3 \left[\frac{1}{252} (b^2 - a^2) + \frac{1}{84} (c_2 b - c_1 a) + \frac{1}{105} (c_2^2 - c_1^2) \right]}}$$

This completes the evolution of the expressions on the left-hand side of the equation of motion. The computer program allows us to select actual dimensions for a proposed offshore structure and to evaluate the matrices based on the above expressions. (25,51,84)

2.3 Linear Wave Theory

The right-hand side of the equation of motion is an expression for the vector of external loads imposed on the structure by the waves. The loads depend upon a number of factors including size and shape of the structure, depth of water, wave height, and wave length.

Linear Wave Theory uses a velocity potential to describe the motion of the waves. The velocity potential, ϕ , satisfies the following linearized governing equations:

1. $\nabla^2 \phi = 0$ Laplaces Equation
2. $\frac{\partial \phi}{\partial z} = 0 @ z = 0$ Bottom Boundary Condition
3. $\frac{\partial \eta}{\partial t} = \frac{\partial \phi}{\partial z} @ z = h$ Kinematic Boundary Condition
4. $\frac{\partial \phi}{\partial t} + g\eta = 0 @ z = h$ Dynamic Boundary Condition

The velocity potential is arbitrarily assumed and the boundary conditions are imposed. Laplaces Equation is then solved by the method of separation of variables, giving ϕ as a function of H , g , ω , k , z , h , x , and t .

(49, 75)

Figure 2.3.1 depicts the general situation in the ocean environment where:

$$\eta = \frac{H}{2} \cos (kx - \omega t)$$

$$\omega^2 = kg \tanh kh$$

$$\omega = \frac{2\pi}{T}$$

$$k = \frac{2\pi}{L}$$

and H = wave height

T = wave period

L = wave length

h = water depth

The assumptions which apply to linear wave theory are:

- a) ideal fluid (non-viscous)
- b) irrotational flow
- c) two dimensional motion
- d) constant depth, impermeable bottom
- e) periodic motion (Period T)
- f) small amplitude waves

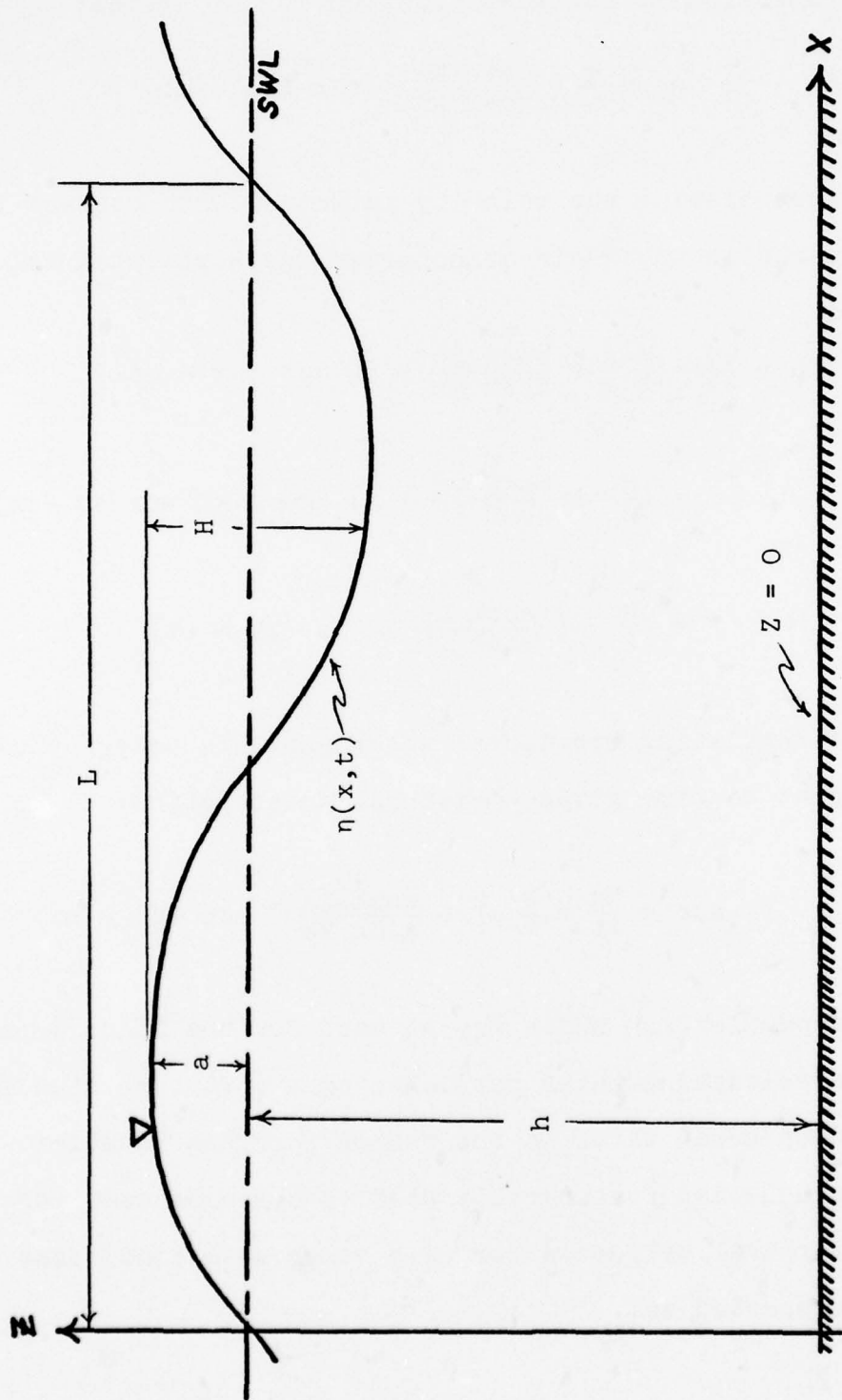


Figure 2.3.1 Parameters Used In Linear Wave Theory

The solution of Laplace's Equation for ϕ gives:

$$\phi = \frac{H}{2} \frac{g}{\omega} \left(\frac{\cosh kz}{\cosh kh} \right) \sin(kx - \omega t)$$

Differentiating the velocity potential with respect to distance in the x-direction gives the horizontal velocity:

$$\begin{aligned} u &= \frac{\partial \phi}{\partial x} = \frac{H}{2} \frac{g}{\omega} \left(\frac{\cosh kz}{\cosh kh} \right) [k \cos(kx - \omega t)] \\ &= \left(\frac{H}{2} \right) \left(\frac{\cosh kz}{\cosh kh} \right) (\omega \coth kh) \cos(kx - \omega t) \\ &= \left(\frac{H}{2} \right) \omega \left(\frac{\cosh kz}{\sinh kh} \right) \cos(kx - \omega t) \end{aligned}$$

Differentiating horizontal water particle velocity with respect to time gives horizontal acceleration:

$$acc = \frac{\partial u}{\partial t} = \frac{H}{2} \omega^2 \left(\frac{\cosh kz}{\sinh kh} \right) \sin(kx - \omega t)$$

An approximation which may be used for the loads imposed by accelerating water particles on a structure standing in deep ocean waves is the famous Morrison Equation. This equation is generally used to describe wave forces on vertical cylinders for deep ocean wave conditions. It is expressed as:

$$F_{\text{total}} = F_{\text{inertial}} + F_{\text{drag}}$$

where:

$$\begin{aligned} F_{\text{inertial}} &= m \cdot \text{acc} \\ &= [C_I \rho \pi r^2] (\text{acc}) \\ F_{\text{drag}} &= C_{D \text{ or } 2} u |u| \end{aligned}$$

A number of sophisticated studies have attempted to evaluate C_D and C_I . They depend upon many variables and are rather complicated unless simplifying assumptions can be made to reduce them to constants. Nath and Harleman(54) in 1967 attempted to model deep water structures very similar to those in this thesis. I will adopt their conclusions without further comment because the conditions will be approximately the same.

Nath and Harleman found that $C_I = 2.0$ (after Agerschou and Edens, 1965) was a good approximation for the given deep water conditions. After a long and complicated study of varying parameters, Nath and Harleman showed that C_D (which depends upon the Reynolds number) can be neglected and set equal to zero for the depths, tower diameter, and wave lengths included in this study. Therefore:

$$F_{\text{total}} = C_I \rho [\pi r_2^2(\xi)] \left\{ \frac{H}{2} \omega^2 \left(\frac{\cosh kl\xi}{\sinh kh} \right) \sin(kx - \omega t) \right\}$$

LOADING VECTOR

Definition:

$$P_i(z, x, t) = \int_0^h [\chi(z) \zeta(t)] \psi_i(z) dz$$

Change "z" coordinates to "ξ" coordinates:

$$\begin{aligned} P_i(\xi, x, t) &= \zeta(x, t) \int_0^{h/l} \chi(\xi) \psi_i(\xi) l d\xi \\ &= \zeta(x, t) l \int_0^{h/l} \chi(\xi) \psi_i(\xi) d\xi \end{aligned}$$

where:

$$\zeta(x, t) = \frac{C_I l \pi \frac{H}{2} \omega^2}{\sinh kh} \sin(kx - \omega t)$$

$$\chi(\xi) = r_2^2(\xi) \cosh(k l \xi)$$

In evaluating this loading vector, the integration gets extremely complicated with several terms of the form $\xi^6 \cosh \xi$. A scheme of Gaussian integration is used in

the computer program to approximate the exact integrations. As a check on the Gaussian scheme several values were inserted and a linear approximation of loading forces was made. By evaluating the area under the linear curve, total forces could be estimated. These estimated linear approximations agreed quite accurately with the Gaussian scheme using the full expression. The scheme, therefore, is working accurately and confidence can be placed in the loading vector.

Chapter 3

A COMPUTER PROGRAM TO EVALUATE DYNAMIC RESPONSE

3.1 Introduction

The computer program developed to model dynamic response is made up of two main programs, each of which must be run separately. Output of each will be used however, as input for different and later runs of each main.

The main structural program will accept the overall dimensions of the tower, the number of elements into which the tower will be divided, a finite number of frequencies, water depth, material properties, and deck properties. Using single frequencies a steady-state response can be plotted, and the natural frequencies of the first and perhaps second or third modes of the tower can be found. The frequencies at which maximum steady-state response occur can then be subjected to sensitivity analysis to determine which tower parameters such as deck load, tower diameter, concrete modulus, concrete density, tower wall thickness, or tower length, cause the greatest shifts in natural frequency. It may be that wave frequency will occur near tower natural frequency interacting strongly with the structure and causing severe resonant vibrations. A knowledge of natural frequency controlling parameters,

then, is desirable early in the planning of a concrete off-shore gravity structure.

The second main program may be run while static response of the tower is being analyzed. This program allows three options for the development of loading and wave frequency data. Option 1 allows a wave time history record, such as recordings of wave height on a wave staff at specific time intervals, to be read from data cards. This program, using a Fast Fourier Transform, will plot a wave spectrum from the card data. Option 2 is available to take the wave spectrum and condense it to a spectrum for several frequencies. This may be necessary, as wave records are normally twenty minute records at one-half record intervals. Option 3 takes a general formula from a developed wave spectrum such as the Pierson-Moscowitz or the Jonswap spectra and stores and plots this spectrum. The program then continues by taking the spectrum, however it was obtained, and "condensing" into a finite number of frequencies. Basically a complete spectrum should have an infinite number of frequencies, but for an integration in the time domain several thousand or more frequencies would have to be stored for each structural degree of freedom. This would result in excessive expense or even inability of some computers to handle a modest program. The second main program evaluates the energy under the wave spectrum

curve and makes a histogram out of it in almost the reverse (and condensed) way that it was developed. Random phase angles between $-\frac{\pi}{2}$ and $\frac{\pi}{2}$ are generated to retain probability aspects instead of "worst case", in-phase wave heights.

The output of Main Program Two, in the form of a finite number of frequencies and their corresponding wave heights and phase angles, can then be read into Main Program One. The main structural program will compute the wave loading for each frequency at each node and store this for use in the time integration subroutine where each will be needed.

This total package capability allows a wave record or standard spectrum to be applied as loading against a hollow tapering concrete column in the ocean. The output is the dynamic response of the tower from a time domain integration.

Much future work is left to other workers. The intent was to develop a broad-based general capability. A time integration was used to allow for nonlinear waves in the future, collision analysis possibilities, and concrete cracking or reinforcing steel deterioration. Steel platform analysis has already reached the point where it may be possible to pinpoint deterioration location and extent by analyzing shifts in dynamic response. Concrete must certainly be amenable to this type of analysis also.

3.2 The Subroutines

What follows will be a brief description of each subroutine. In general terms, the variables, required data, output, and limitations will be discussed.

MAIN PROGRAM - Serves only as a control element to call different subroutines and initially dimension all variables.

INPUT - Input calls the parameters to be analyzed. The number of elements, frequencies, overall dimensions, material properties, and deck loads are read from data cards.

ASMBL - This subroutine calls the matrix subroutines for each element and assembles the matrix elements for each element into a branded matrix for the whole structure. It also finds total mass and adds deck load parameters to the global matrix. ASMBL also adds the stiffness and geometric stiffness matrices.

SUBK - This is the stiffness matrix and will be a 4×4 matrix. Translation and rotation at each end of a beam in one plane only is used as shown in Chapter 2. Only the upper right-hand ten elements are used, as the matrix is symmetric.

ADD - Subroutine ADD merely adds the elements of each element matrix in a consistent manner to obtain a banded global matrix.

SUBM - Subroutine SUBM computes the mass matrix for each element and totals the mass of the entire tower.

SUBKG - This subroutine takes into account the geometric non-linearities arising from the large axial load imposed on the concrete column due to the deck load and the column's own self weight. Since integration begins from the bottom moving upward, the total column weight minus the integrated weight to the point in question becomes the axial load at that point.

In all integrations for finding matrix element values, a Gaussian integration scheme was used. Five points were more than enough to get accurate matrix element values. For each matrix a test was run comparing values obtained with those found by hand-calculated exact integrations shown in Chapter 2. The accuracy was perfect beyond the five significant figures which the computer prints.

TF - The transfer function subroutine finds the static response by calling the load subroutine at a specific frequency and wave height and by then solving the equation:

114.

$$x [(K + K_G) - \omega_m^2] = P$$

where

x = static horizontal displacement

K = stiffness matrix

K_G = geometric stiffness matrix

ω^2 = radius frequency squared

m = mass matrix

P = loading vector

RK - This subroutine solves the transcendental equation:

$$\omega^2 - kg \tanh kh$$

for k given ω^2

where:

$$\omega^2 = \frac{2\pi}{T}, \quad T = \text{wave period}$$

$$k = \frac{2\pi}{L}, \quad L = \text{wave length}$$

g = acceleration due to gravity

h = water depth

Although the deep water approximation for this equation is $\omega^2 = kg$ (only if $\frac{h}{L} > \frac{1}{2}$); we cannot always assume $\frac{h}{L} > \frac{1}{2}$ to be true. For instance, in a probabilistic study

of waves, some waves of $L < 400M$ could be present and if that were true, our 200M water depth would allow the depth assumption to be violated making $\omega^2 \neq kg$. Therefore, the transcendental equation must be solved each time.

SUBP - SUBP calculates the loading vector on the tower due to linear wave theory. A Gaussian integration scheme is used. For each element and each degree of freedom and each frequency; a load element in the vector is calculated and stored. This process is repeated for each time step in the integration in the time domain.

SOLVE - A general matrix-solving subroutine is used here to solve a system of equations. This subroutine allows solving, reduction, or reduction and back-substitution. It is of the form $[A][X] = [B]$

TIMEH = This subroutine does a step-by-step time integration in matrix form using a procedure by Wilson and Clough (93). It is a linear acceleration/constant velocity method.

AMBC - AMBC is a subroutine to do the matrix operation $[A] - [B][C]$.

MAIN PROGRAM 2 - By selecting a code number 1, 2, or 3, this subroutine allows for three options in computing a wave spectrum. Option 1 reads wave record raw data and prepares a graph. Option 2, using a Fast Fourier Transform converts this spectrum to an energy vs. frequency spectrum. Option 3 will compute energy vs. frequency from a developed wave spectrum such as the Pierson-Moscowitz or the Jonswap Wave Spectra. The MAIN 2 PROGRAM then continues and will condense these spectra to one of manageable size with a small number of frequencies.

RECORD - This routine reads data cards from a wave record and plots them on a wave height vs. time plot.

POWER - Power computes an energy vs. frequency spectrum and plots it. Wave height is related to energy by the equation $E = \frac{1}{2} \left(\frac{H}{2} \right)^2 \rho g$. Using a Fast Fourier Transform, this spectrum is obtained and plotted.

SET 0 - A subroutine to set all elements of a large matrix equal to zero.

FOUR 2 - This subroutine calls several other subroutines including BITRV, COOL 2, and FIXRL. It accomplishes a

Fourier Transform and comes as a package which I did not develop or de-bug.

SCALE - This subroutine scales the values in a Fast Fourier Transform or actually, the axis of energy and frequency which are the outputs of the FOUR 2 subroutine. All elements are multiplied by a "factor".

CONNER - Subroutine Connor is the subroutine which "condenses" a spectrum. It is given 10 or so frequencies and it selects an interval around these frequencies. Within this interval it calculates the total energy under the spectrum curve and computes a wave height corresponding to that energy. That wave height is assigned to that frequency and an output of several frequencies with several corresponding wave heights is the result. Random phase angles are also generated to maintain the probabilistic nature of the problem.

SEA - This subroutine is presently written for the JONSWAP spectrum. An equation giving energy as a function of frequency may be developed and presented by oceanographers. This equation is used to compute a wave spectrum at several hundred frequencies. A smooth spectrum curve is plotted and the condensing of the spectrum can then take place. (12)

3.3 The Model and Its Response

The concrete gravity platform to be modeled is shown in figure 3.3.1. All units will be in the MKS system. It was decided to divide the structure into four elements for analysis. Provision is made to use any number of elements by reading a data card. For the static analysis fifty frequencies were used evenly divided between .04 and .7 CPS. For the dynamic analysis ten frequencies were used. The modulus of concrete is given in tons/M^3 and was developed from 150 lb/ft^3 concrete at 5,000 PSI using the formula $E = w^{1.5}(33)\sqrt{f'_c}$. Density of concrete is found using normal conversion factors. The deck mass was calculated using the assumption of a 12,000 english ton deck supported by 3 columns. (24,94)

The static responses are shown in figures 3.3.2, 3.3.3, 3.3.4 and 3.3.5. It appears that only the two lowest modes are excited by ocean waves with frequencies .04 - .7 CPS. The static response was done with little or no damping and therefore, as the interval was refined to locate the exact response frequency, the response approached infinity. The two frequencies appear to be .07 and .175 CPS.

The next step in the analysis was to develop a wave spectrum. The JONSWAP spectrum approximating the North Sea environment has been very prominent in journals lately and

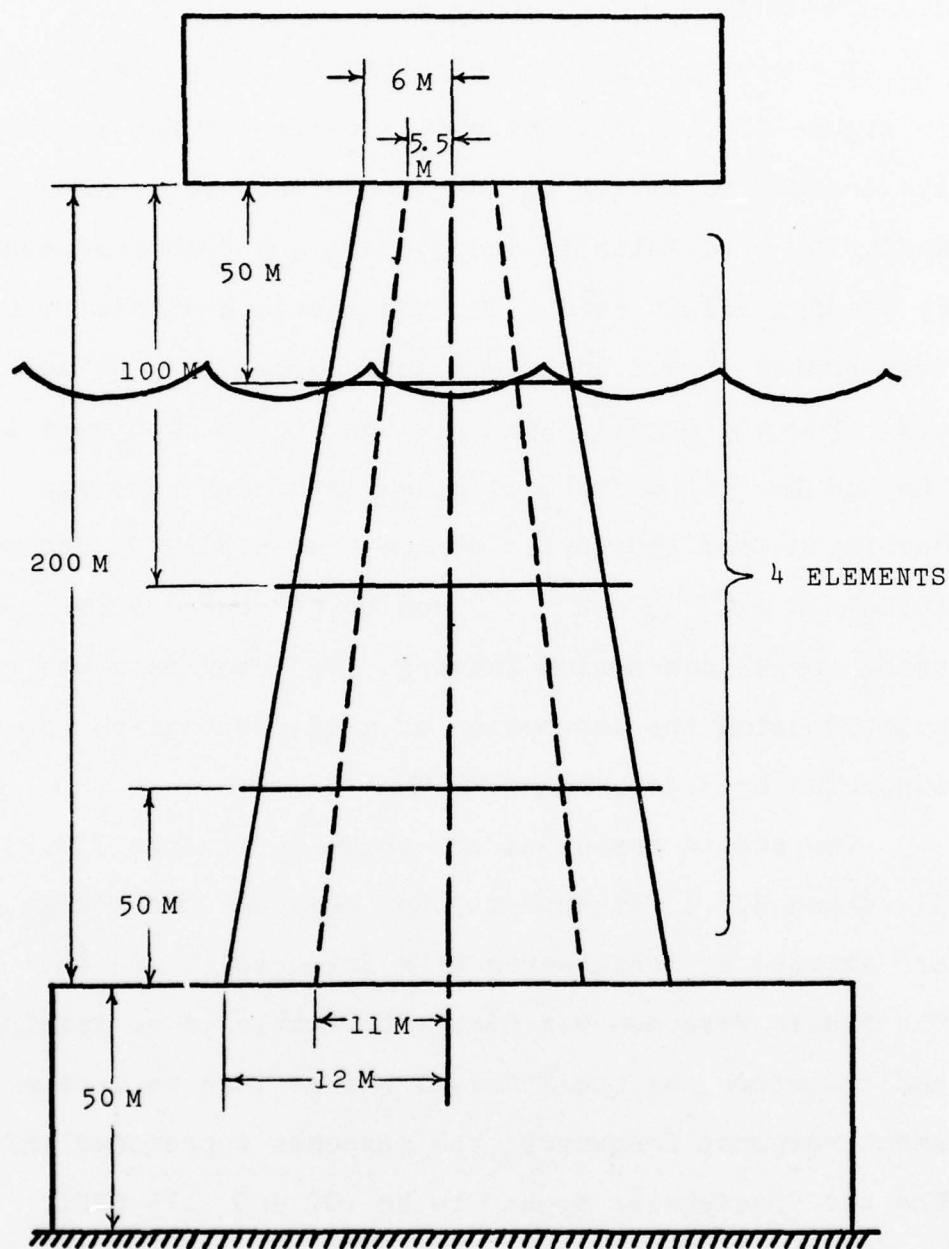


Figure 3.3.1
Dimensions And Shape of Typical Tower Used For The Computer Model

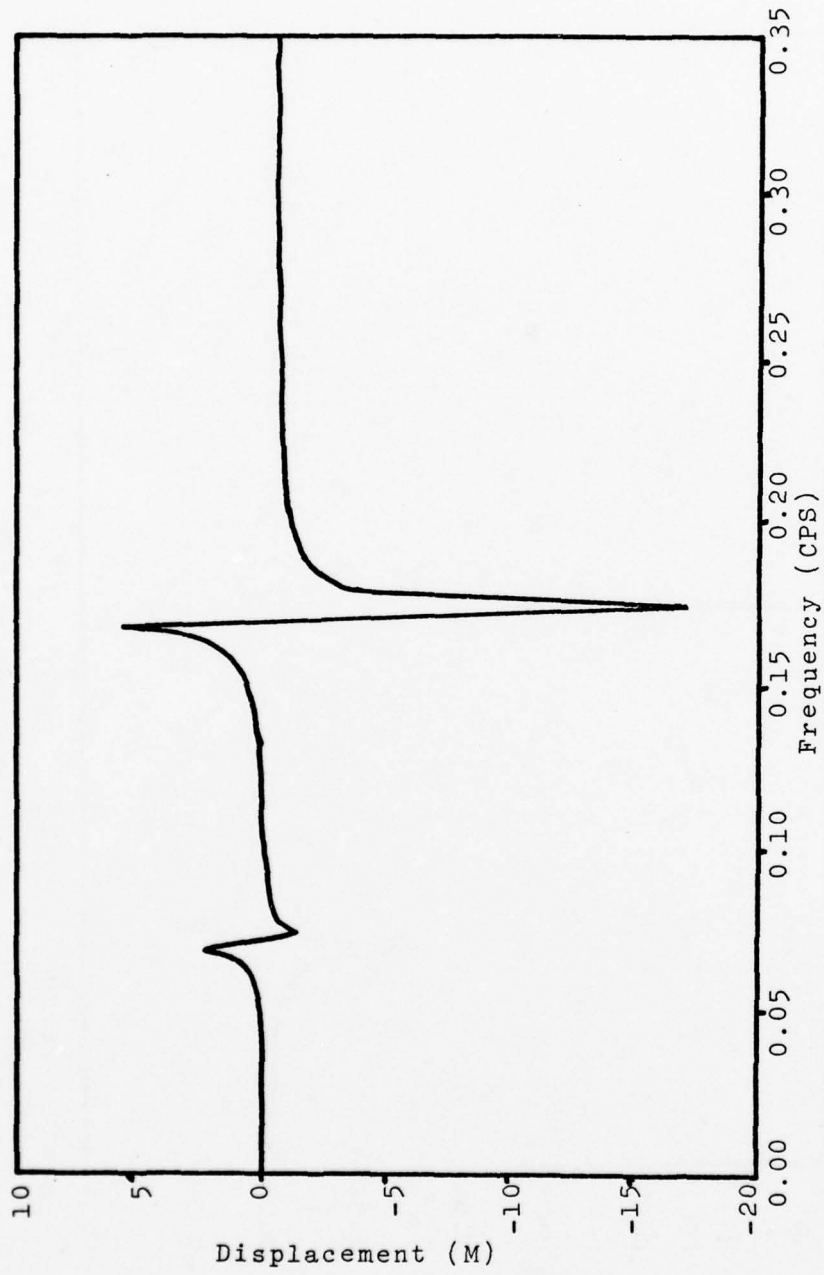


Figure 3.3.2 Displacement of Node 5 for Test Tower - Static Analysis

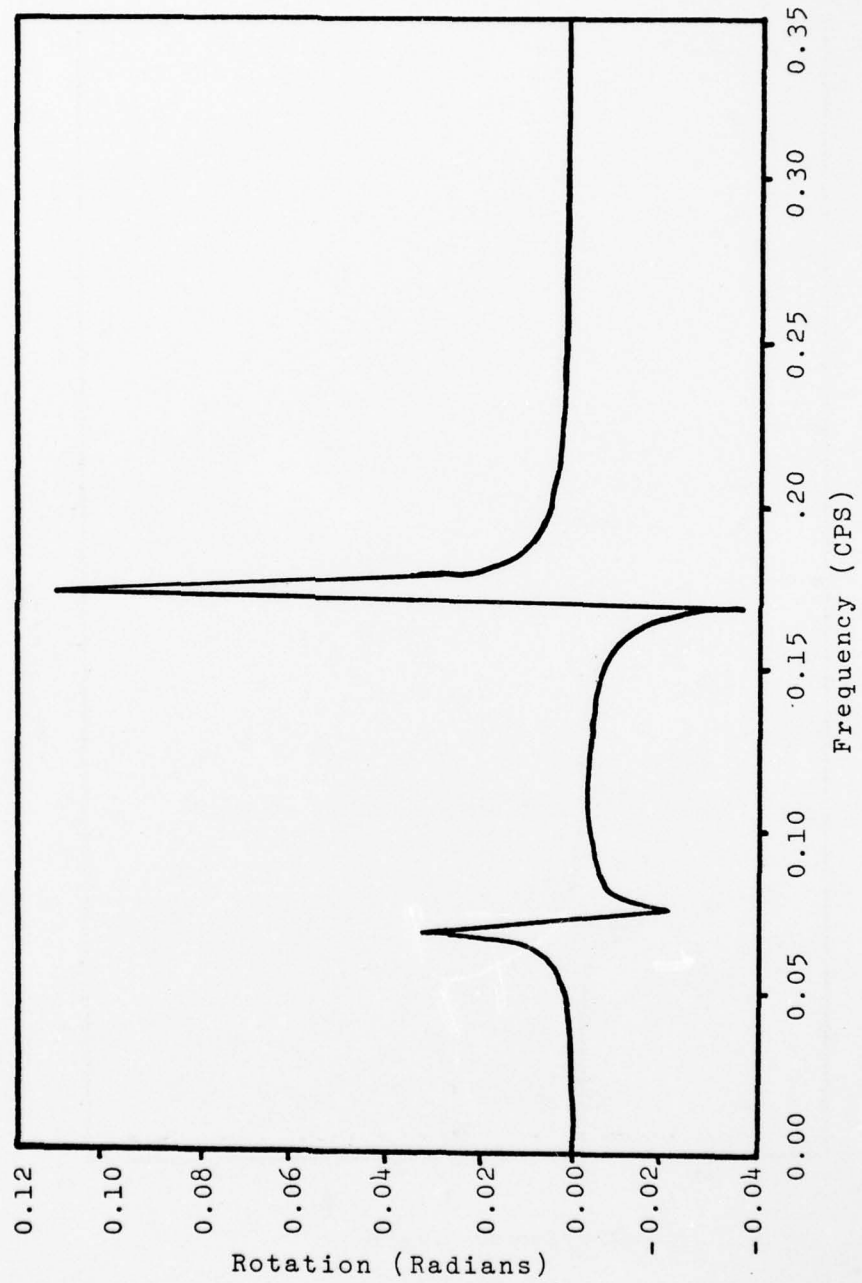


Figure 3.3.3 Rotation of Node 5 for Test Tower - Static Analysis

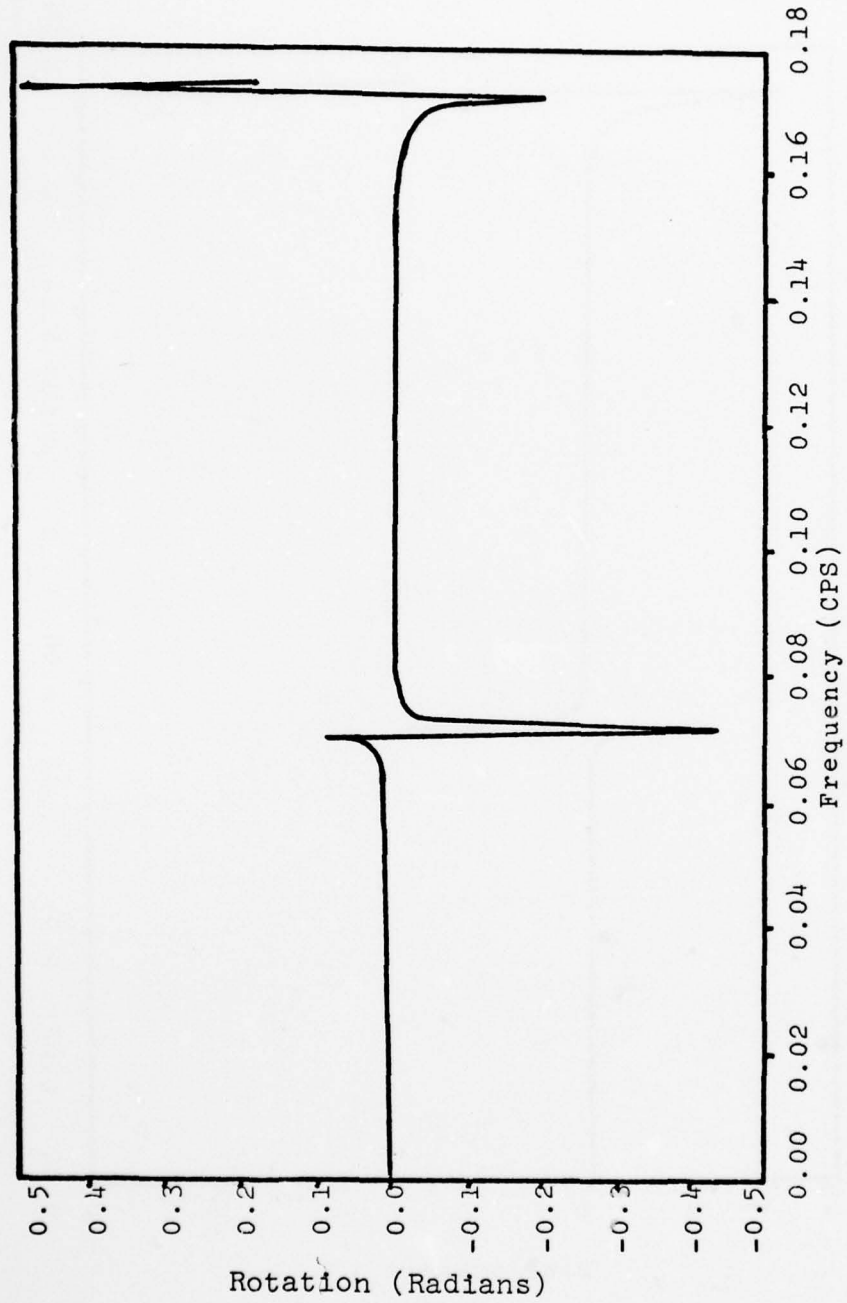


Figure 3.3.4
Narrowed Frequency Range for Static Response of Node 5 - Rotation

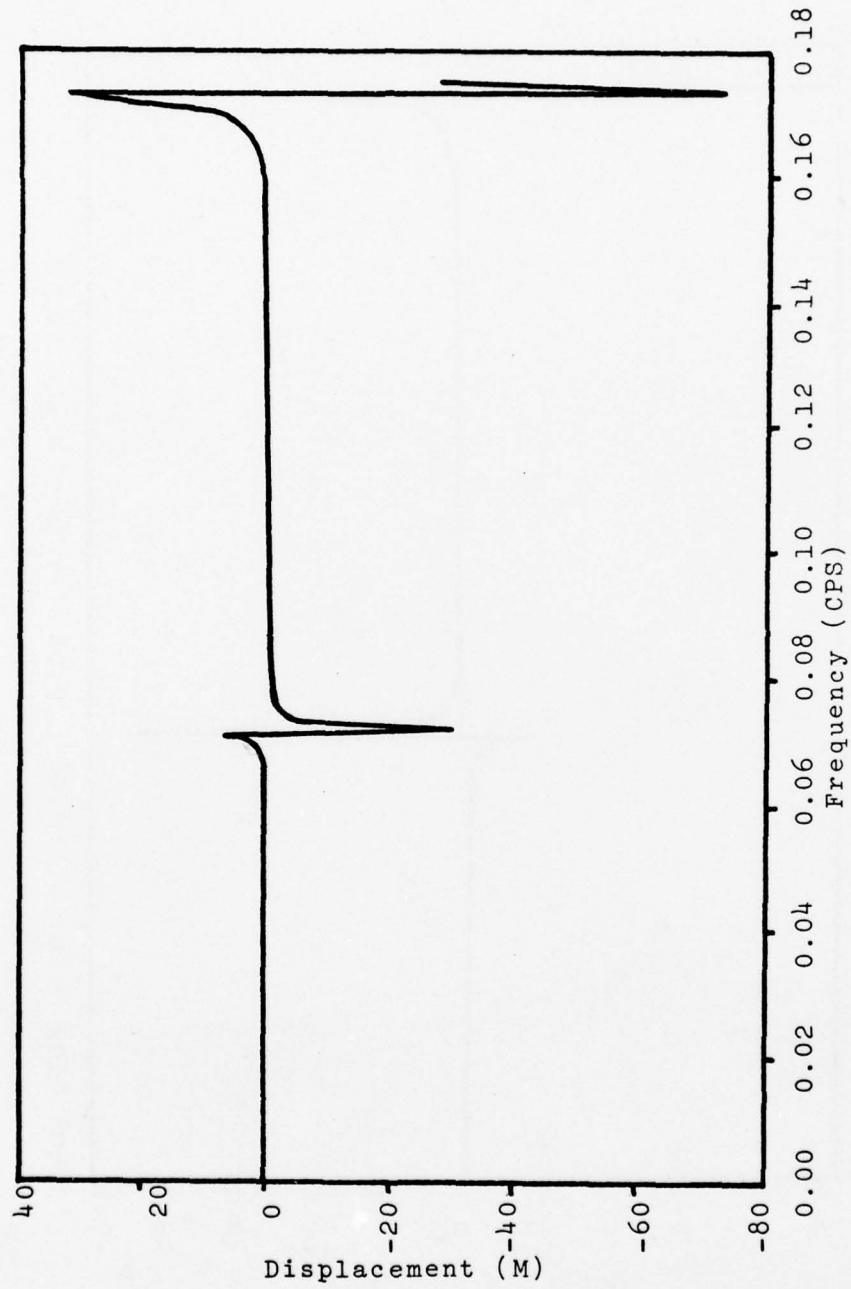


Figure 2.3.5
Narrowed Frequency Range for Static Response of Node 5 - Displacement

was selected for a first try. The JONSWAP equation relates energy and frequency in the following manner:

$$E(f) = \alpha g^2 \left(\frac{1}{2\pi}\right)^4 \left(\frac{1}{f}\right)^5 \exp \left[-1.25 \left(\frac{f_m}{f}\right)^4 \right] \gamma \exp \left[\frac{-\left(\frac{f}{f_m} - 1\right)^2}{2\sigma^2} \right]$$

where

$E(f)$ = energy (M-sec²)

α = .0081 (constant from Pierson-Moskowitz)

g = acceleration due to gravity

f = frequency

f_m = frequency at which peak energy occurs
(= .058 CPS)

γ = overshoot factor (= 3.3)

$$\begin{cases} \sigma_a = .07 & f < f_m \\ \sigma_b = .09 & f > f_m \end{cases}$$

Figure 3.3. 6 shows the plot obtained when this equation was evaluated at 240 frequencies between 0 and .24. It agrees perfectly with the Chakrabarti & Snider paper.(12)

From the spectrum shown in figure 3.3.6 a condensation was made to ten frequencies. This condensation retained all energy under the JONSWAP plot, but allocated it to ten specific frequencies to save computer storage. The fre-

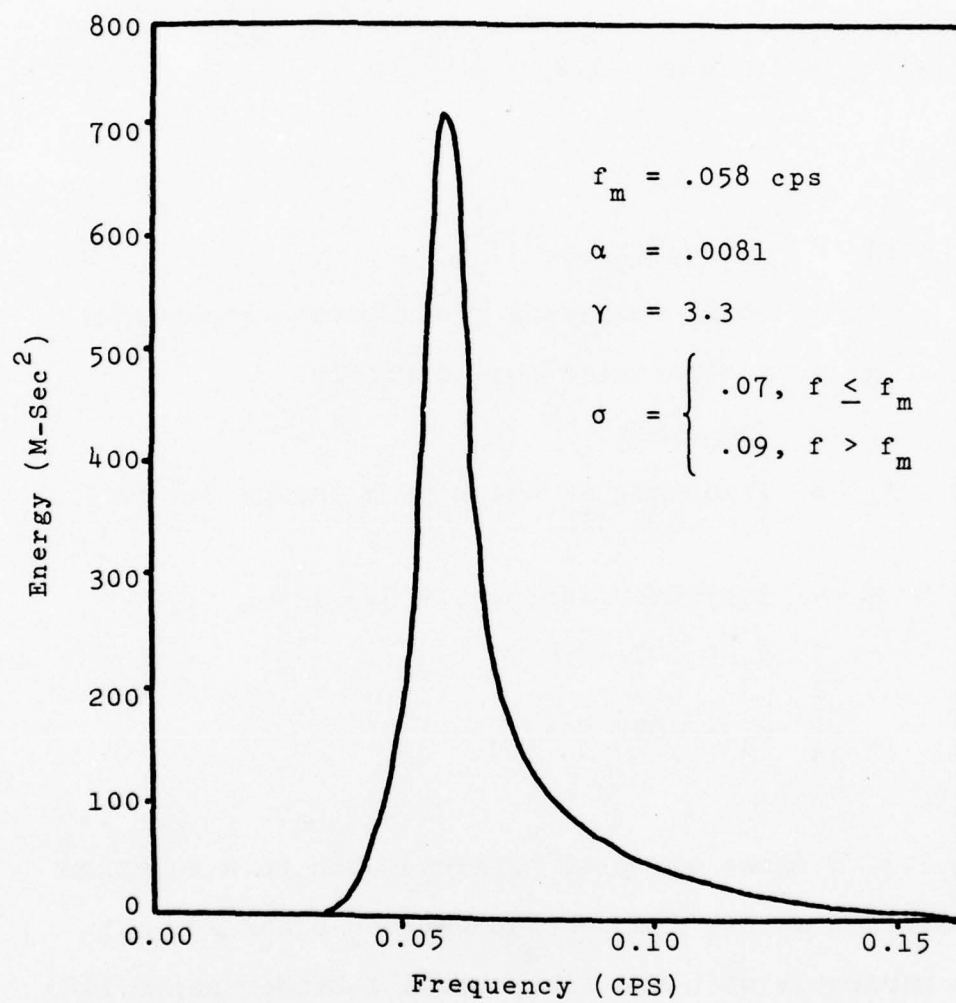


Figure 3.3.6
Typical Energy vs. Frequency Distribution for JONSWAP Wave Spectrum

quantities and wave heights with random phase angles are:

<u>FREQUENCY</u>	<u>WAVE HEIGHT</u>	<u>PHASE ANGLE</u>
.04	.5927	.4742
.0525	1.9138	- .958
.065	1.9892	- .4625
.0775	1.0963	- .0928
.09	.8322	.8751
.1005	.6138	-1.2752
.1130	.5172	.3041
.1255	.3873	.078
.138	.3208	1.0011
.1505	.231	1.5063

Figure 3.3.7 is a plot of the wave heights vs. time for the condensed spectrum. It can be seen that it models a somewhat random, confused sea. However, it is obvious that several strong frequencies tend to dominate and the wave record would be smoother for more frequencies.

Finally, figures 3.3.8 and 3.3.9 are representative outputs of the computer program's time integration for the displacement and rotation of node 5. The response was done for a period of 30 seconds. This should be approximately two full periods of the structures natural

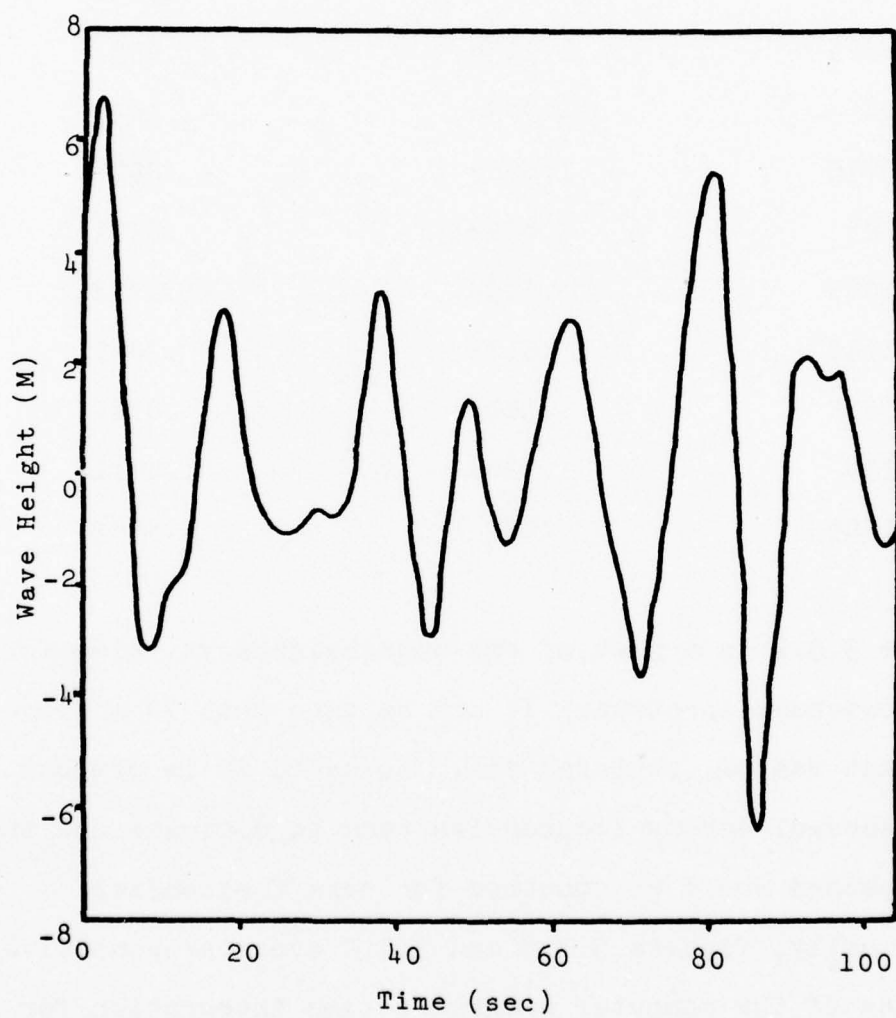


Figure 3.3.7
Typical Wave Height vs. Time Diagram Resulting From
Condensed Spectrum of 10 Frequencies

period of 14.27 sec. From the data presented in this section, a reasonable conclusion that can be made is that an approximation of dynamic response can be made in a relatively inexpensive manner. At the Joint CE/ME Computer Facility, running on the Model 80 computer this 30 second integration cost less than \$5.50.

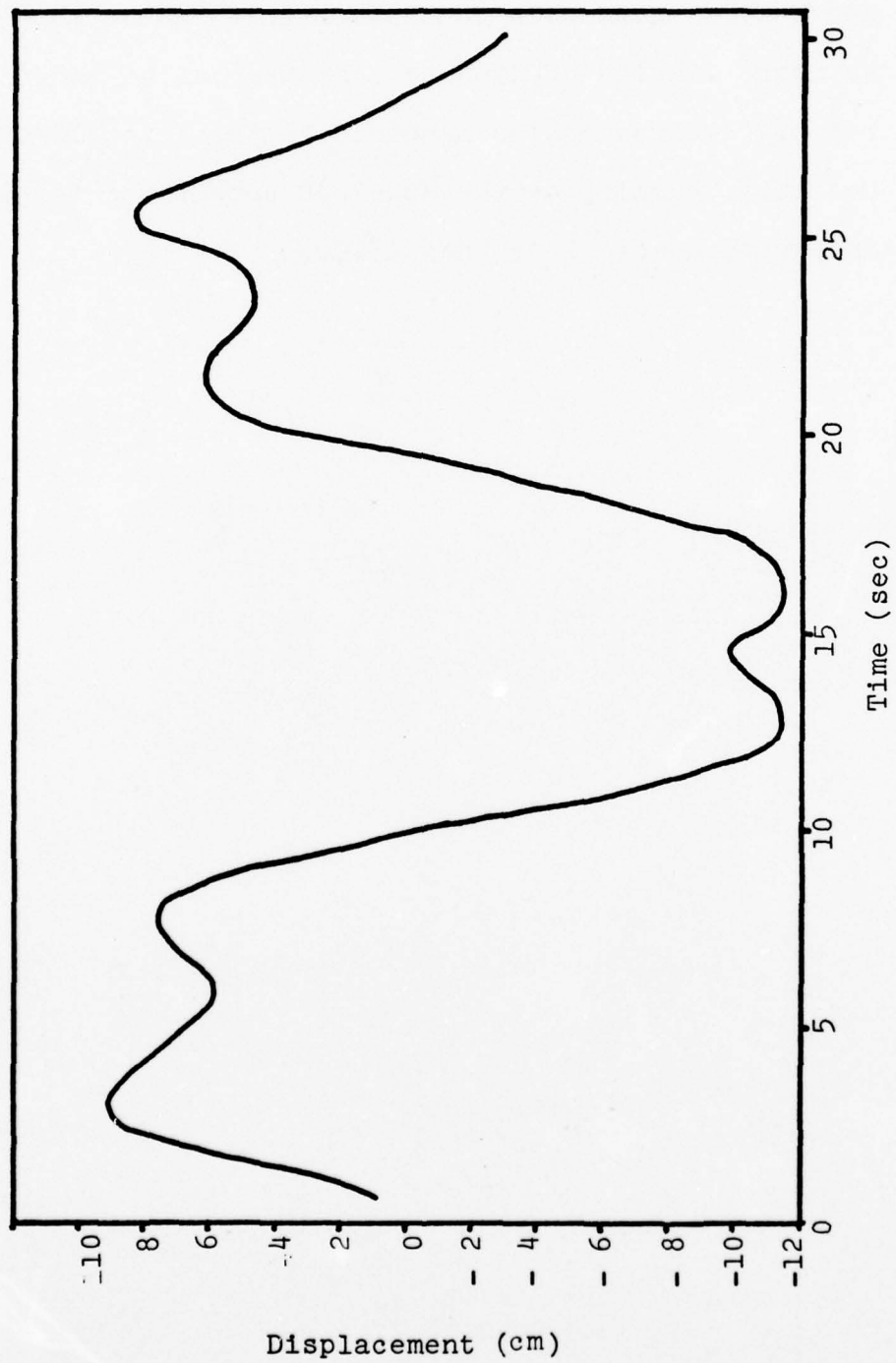


Figure 3.3.8 Displacement of Node 5

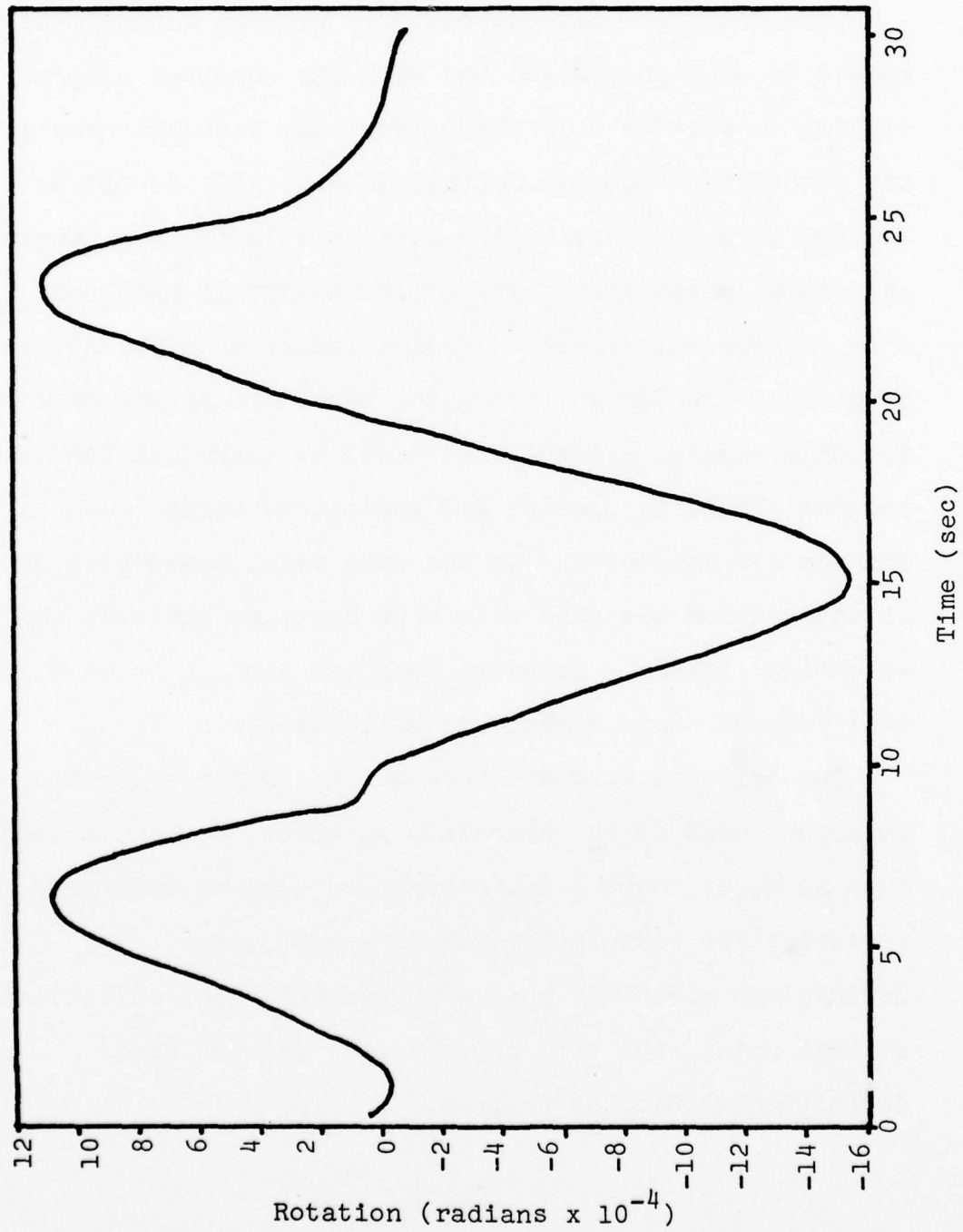


Figure 3.3.9 Rotation of Node 5

3.4 Computer Program Definitions

The following list of computer program definitions should be used in conjunction with the computer program listing in section 6.1. Each important variable name in the computer program is defined in this list to aid in debugging, rewriting, adding damping effects, or changing structural parameters. It should be kept in mind that this program was written with the intention of using two degrees of freedom at each node, translational and rotational. For this reason, maximum band width is locked at four. The program should be studied and understood before radical changes are attempted. In the same vein, a Gaussian scheme of integration was used with five Gaussian abscissas and weighting factors. Probably four and perhaps three points will give adequate computational accuracy.

The definitions given here are the major or most important uses of the symbols. At times, common letters such as A, B, C and a few others are used as interim variables for computation within a subroutine. The definitions given may not be always the exact definition at that point, but will be the major or most used definition within the program.

ACC - acceleration

ADD - subroutine to add two matrixes column-wise

AMBC - subroutine to compute A-BC

ASMBL - subroutine to assemble matrices

A - abscissa, Gaussian integration; also used as an interim variable

A1 - translation degree of freedom, bottom end of element

A2 - translation degree of freedom, top end of element

B - interim step variable (various uses)

B1 - rotational degree of freedom, bottom end of element

B2 - rotational degree of freedom, top end of element

C - interim step variable (various uses)

CI - added mass factor (inertia constant)

CONNOR - subroutine to "condense" a spectrum to one of 10 or so discrete frequencies

DEPTH - water depth

DINER - deck moment of inertia

DIS - displacement

DMASS - deck mass

DN - number of elements (real number)

DT - time interval

E - Young's Modulus of concrete (ton/M^2)

EMASS - variable which adds element and deck masses to find total column mass and deck mass

FREQ - wave frequencies

F - interim variable

F1	}	Interpolation Functions
F2		
F3		
F4		

FOUR2 - subroutine to do fast Fourier Transforms

G - acceleration due to gravity (M/sec^2)

HEIGHT - total height of tower

INPUT - subroutine to set up problem and input data

IR - read command

IW - write command

K - wave number

KODE - a code number to select one of three options in MAIN2

LENGHT - length of each element

LIM - size of banded matrix (LIM = NEQ * MBW)

MASS - coefficients within mass matrix (10 each, calculated)

MBW - maximum band width

NELEM - number of elements (integer)

NEQ - number of equations (NEQ = 2 * NNODE)

NFREQ - number of frequencies

NNODE - number of nodes (NELEM + 1)

NTIME - number of time steps to perform (integer, = Time/DT)

P - wave force / unit length

PHASE - phase angle for different frequencies of waves

PICTR - internal computer plotting command

POWER - subroutine which computes energy vs. frequency spectrum from raw wave data

Q - holding matrix for loads at different frequencies for different nodes

QMAS - mass of column from bottom to present integration

R - interim variable (various uses)

RADIUS - external radius of tower

RANDX - internal computer random number generator

REB - external radius, bottom of tower

RECORD - subroutine to read a record of raw wave data and plot it.

RET - external radius, top of tower

RIB - internal radius, bottom of tower

RIT - internal radius, top of tower

RK - function to solve equation for waves ($W2 = K * G * \tanh(K * \text{DEPTH})$)

RO - Density of concrete (ton/M^3)

ROG - $RO * G$

S - interim variable (various uses)

SCALE - subroutine to scale a matrix by multiplying each member by a factor

SEA - subroutine to plot energy vs. frequency spectrum from a given equation for a developed spectrum

SETO - subroutine to set all matrix elements equal to zero

SOLVE - subroutine to triangularize a matrix

STIFF - coefficients within stiffness matrix (10 each, calculated)

STIFG - coefficients within geometric-stiffness matrix (10 each, calculated)

SUBK - subroutine to calculate element stiffness

SUBKG - subroutine to calculate element consistent geometric stiffnesses

SUBM - subroutine to calculate element mass

SUBP - subroutine to calculate loading vector

T - wave period

TF - subroutine to find transfer function

TIME - total time of time integration

TIME H - subroutine to do time integration for dynamic response

TOWER - title of program and description

VEL - velocity

W - weighting factor, Gaussian integration; also used as an interim variable

W2 - radian frequency squared of wave

X - non-dimensional position term in interpolation functions

Z0 - Height of Caisson

Z1 - position of point at which loading is computed

Chapter 4

SUMMARY AND CONCLUSIONS

4.1 Summary

The two-fold purpose of this thesis has been to examine concrete gravity off-shore structures from a development and historical perspective and from a modeling and dynamics perspective. The two aspects are intertwined in that concrete has been moved to the forefront of off-shore work due to several of its attractive material properties. The fact that concrete is easily formed, can be cheaply produced in large quantities, and is able to provide a massive storage container with gravitational stability is the primary reason for concrete platform development. The dynamic response of steel jacket platforms has been studied, but most information is proprietary and not available. The lack of widely disseminated work on dynamic response of concrete platforms is very evident.

As can be seen from Section 1.3, the future of off-shore platforms will include deeper drilling and producing depths with correspondingly more severe ocean and weather environments. Present day costs have made it a necessity to build multi-purpose platforms, enhancing concrete's attractiveness as a construction material.

The attractive properties of concrete for floating rigs has also been established in Section 1.3. A much larger deck area and the ability to store crude oil on a semi-submersible floating platform are great advantages. Similarly, for bottom fixed structures, the ability or inability to drive piles or establish exact foundation conditions for steel jackets has decelerated their proliferation. Concrete gravity platforms can be set upon a screeded gravel pad which the platform itself can grout.

Low emplacement time and cost, the elimination of heavy at-sea crane lifts, and outfitting in a near-shore, sheltered area again favor the development of concrete gravity structures. Perhaps the ideal conditions for concrete gravity platforms are found on our own U.S. east coast. The ten to two hundred meter water depths, a large continental shelf, desired multi-purpose platform use, required storage capacity, and availability of labor and materials all enhance the prospects of a concrete gravity structure for this location. An adequate construction site with a deep enough channel may be hard to find, but certain construction techniques such as those employed in Scotland can mitigate this drawback for the U.S. east coast.

The study by computer modeling of the dynamic response of any structure can be a very expensive undertaking. With limited funds and the desire to obtain a working knowledge while accepting certain approximations, an inexpensive computer program was developed. The idealization of a concrete gravity platform as a cantilever beam atop a caisson is not an unreasonable assumption. Approximations were accepted in analyzing motion in one plane only, assuming a constant modulus for the concrete, and idealizing the wave loadings as a linear combination of waves developed from a linear potential theory.

The broad base which this computer program provides should not be ignored. The work remaining to make it more sophisticated is substantial, but the capacity for modifications has been built into the program.

Future projects to expand this program should include the following:

- 1) Damping should be included in the equations of motion. Either a viscous damping or a structural damping could be included. A first step would be to approximate a viscous damping as a per centage of stiffness. (93)

- 2) Nonlinear wave theory could be included in the wave loading subroutine to account for larger waves, breaking waves, or other aspects of wave theory.

3) A fascinating prospect is that of concrete or reinforcing steel degradation and the resulting shifts in dynamic response. Inspection by dynamic analysis is a real future possibility.

4) Damage from a ship colliding with a concrete gravity platform would be severe. Concrete cracking and the non-linearities involved could be included in this program if one were willing to alter the main program. It would be an academically untouched area of research.

It should be stated in conclusion that the ability to inexpensively analyze the dynamic or static response of a concrete gravity platform now exists, be it ever so approximate. A sophisticated dynamic analysis can be made with a little work and many modifications. This work was intended to be very broadly based so that continued improvements of the program is possible.

4.2 Conclusions

Several conclusions can be stated from this two-part study:

1. Concrete gravity structures have an outstanding future in the medium depth, multi-purpose category of off-shore construction work.
- 2) Steel jacket structures appear to have reached their limits in rigid, bottom-fixed configurations due to cost and the increasingly severe environments.
- 3) Ease of construction, near-shore outfitting, and an inexpensive and uncomplicated emplacement procedure enhance concrete gravity platforms' attractiveness.
- 4) An inexpensive computer program can model dynamic response of concrete gravity platforms if certain approximations are acceptable.
- 5) It appears that normal ocean wave frequencies will correspond to only the lowest or perhaps the two lowest natural frequencies of a large concrete gravity structure.
- 6) A reasonable approximation of ocean spectra can be made by "condensing" the energy under a spectrum to the energy surrounding several discrete frequencies. Figure 3.3.7 shows that the wave record run backwards out of the condensed spectrum is reasonable.

7) Difficulty was encountered with round-off error accumulation until the time interval was made sufficiently small that this error came under control.

8) It is still not completely understood why the time interval needs to be as small as it is. A natural frequency of 14.25 seconds should allow a time interval of .25 seconds to give good answers. The time interval was reduced to .125, .05, and finally .01 seconds before the proper accuracy was attained.

9) Storage capacity in the computer is required for each frequency present in the waves at each degree of freedom of the structure. These values must be stored and recalculated for each time step. Realization of this fact caused the "condensing" idea to be implemented.

10) A modest capability has been developed to analyze dynamic response of a concrete gravity platform.

Chapter 5

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Chapter 6

APPENDICES

```

C      * MAIN PROGRAM *
C      IMPLICIT REAL * 8 ( A-H , O-Z )
C      DIMENSION TCWER (20), FREQ (100),
C      *00), A (200), B(50), DIS (50), VEL (50), ACC (50),
C      *S(50), H(10), PHASE(10), Q(500), F(50)
C      REAL*8 MASS
C      DATA IR, IW /8.5/
C
C      INPUT DATA
C      CALL INPUT (IR, IW, TCWER, NITEM, NREFC,
C      *HEIGHT,ZC,REB,RET,RIB,RIT,DEPTH,E,RO,DMASS,DINER,FREQ,
C      *H, PHASE, LT, TIME
C
C      STIFFNESS AND MASS MATRICES
C      CALL ASMBL (NELEM, NLC, MBW,
C      *HEIGHT, REB, RET, RIB, RIT, E, RO, DMASS, DINER, STIFF,
C
C      DYNAMIC OR STATIC ANALYSIS
C      IF ( NREFC .GE. 0 ) GC TC 12
C      NREFC = - NREFC
C      STATIC ANALYSIS IN FREQUENCY DOMAIN
C      DO 10 I = 1, NREFC
C      CALL TF (IW,TOWER,NELEM,HEIGHT,ZC,RET,REB, DEPTH,
C      *NEQ, MBW, STIFF, MASS, A, B, FREQ(I)
C      10 CONTINUE
C      STOP
C      DYNAMIC ANALYSIS IN TIME DOMAIN
C      12 IF ( NREFC .EQ. 0 ) STOP
C      CALL TIME H ( IW, NEQ, MBW, NREFC, NELEM,
C      *RET, REB, HEIGHT, ZC, DEPTH, DT, TIME,
C      *STIFF, MASS, FREQ, A, E, H, PHASE,
C      *DIS, VEL, ACC, R, S, F, Q
C      STOP
C      END

```

```

C SUBROUTINE INPUT
SUBROUTINE INPUT (IR, IW, TOWER, NELEM, NPREQ,
*HEIGHT, ZO, REB, RET, RIB, FIT, DEPTH, E, RC, LMASS, DINER, FREQ,
*H, PHASE, IT, TIME
IMPLICIT REAL * 8 ( A-H, O-Z )
DIMENSION TCW(20), FREQ(1), H(1), PHASE(1)

C READ TOWER AND CONTRCI CARD
READ (IR, 1) TOWER, NELEM, NPREQ
WRITE (IW, 2) TOWER, NELEM, NPREQ

C READ OVERALL DIMENSIONS
READ (IR, 3) HEIGHT, ZO, REB, RET, RIB, FIT, DEPTH
WRITE (IW, 4) HEIGHT, ZO, REB, RET, RIB, FIT, DEPTH

C READ MATERIAL PROPERTIES
READ (IR, 5) E, RC
WRITE (IW, 5) E, RC

C READ DECK LOAD
READ (IR, 6) LMASS, LINEB
WRITE (IW, 6) LMASS, DINER
READ FREQUENCIES
IF ( NPREQ .GE. 0 ) GC TO 10
N = -NPREQ
READ (IR, 3) ( FREQ(I), I = 1, N )
WRITE (IW, 7) ( FREQ(I), I = 1, N )
RETURN

C READ TIME AND TIME INTERVAL PLUS CONDENSED SPECTRUM PARAMETERS
FOR DYNAMIC ANALYSIS
10 IF ( NPREQ .LE. 0 ) GC TO 12
READ (IR, 3) DT, TIME
WRITE (IW, 8) DT, TIME
DO 11 I = 1, NPREQ
11 READ (IR, 3) FREQ(I), H(I), PHASE(I)

```

SI 00
SI 01
SI 02
SI 02A
SI 02B
SI 03
SI 05
SI 06
SI 07
SI 08
SI 09
SI 10
SI 11
SI 12
SI 13
SI 14
SI 15
SI 16
SI 17
SI 18
SI 19
SI 20
SI 21
SI 22
SI 23
SI 24
SI 25
SI 26
SI 27
SI 28
SI 28A
SI 29
SI 29A
SI 29B
SI 30
SI 30A

```

C
WRITE ( I4 , 9 ) ( FREQ(I) , H(I) , PHASE(I) , I = 1,NFREQ )
12 RETURN
SI 30B
SI 31
SI 32
SI 33
SI 34
SI 35
SI 36
SI 37
SI 38
SI 39
SI 40
SI 41
SI 42
SI 43
SI 44
SI 45
SI 46
SI 47
SI 48
SI 49
SI 50
SI 51
SI 52
SI 52A
SI 53
SI 54

1 FORMAT (20 A 4 ,//, 4I4 )
2 FORMAT ( '1',//,5X, 2CA4,///,
* 5X, I5, ' ELEMENTS' , / , 5X, I5, ' FREQUENCIES' ,// )
3 FORMAT ( 10F8.2)
4 FORMAT (///5X, '*OVERALL DIMENSIONS*///
*5X, 'TOWER HEIGHT' , , F8.2, ' M.'//
*5X, 'CAISSON HEIGHT' , , F8.2, ' M.'//
*5X, 'EXTERNAL RADIUS AT THE BOTTOM' , , F7.2, ' M.'//
*5X, 'EXTERNAL RADIUS AT THE TOP' , , F7.2, ' M.'//
*5X, 'INTERNAL RADIUS AT THE BOTTOM' , , F7.2, ' M.'//
*5X, 'INTERNAL RADIUS AT THE TOP' , , F7.2, ' M.'//
*5X, 'DEPTH OF WATER' , , F8.2, ' M.'// )
5 FORMAT (///5X, '*MATERIAL PROPERTIES*///
*5X, 'F' = , E10.3/5X, 'RC' = , E10.3/ )
6 FORMAT (///5X, 'DECK MASS' , , F12.4/
* 5X, 'DECK INERTIA' , , E12.4/ )
7 FORMAT (///5X, '*FREQUENCIES FOR ANALYSIS*///(5X, 10F8.5))
8 FORMAT (///5X, ' * TIME INTERVAL AND TOTAL TIME * '///5X ,
* 'DELTA T' = , F7.3/5X , 'TIME' = , F7.3/ )
9 FORMAT ( ///5X , ' * CONDENSED SPECTRUM PARAMETERS * '///13X ,
* 'FREQ' , 8X , 'WAVE HEIGHT' , 3X , 'PHASE ANGLE'///(3X , 3F15.4))

C
END

```

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```

C      SUBROUTINE ASMBL
      SUBROUTINE ASMBL (NELEM, NEQ, MBW,
      *HEIGHT, REB, RET, RIB, RIT, E, RO, DMASS, DNER, STIFF,
      IMPLICIT REAL * 8 (A-H, O-Z)
      REAL*8 MASS, LENGHT
      DIMENSION STIFF (1), MASS (1), A(10)

C      INITIALIZE
      NEQ = 2*(NELEM + 1)
      MBW = 4
      LIM = NEQ * MBW
      DO 10 I = 1, LIM
      STIFF(I) = C.
10    MASS (I) = C.

C      COMPUTE ELEMENT MATRICES AND ASSEMBLE
      DN = NELEM
      LENGHT = HEIGHT/DN
      DA = (RET-RIB)/DN
      DB = (RIT-RIB) / DN
      A1 = REB
      B1 = RIB
      EMASS = DMASS

C      DO 12 N = 1, NELEM
      A2 = A1 + DA
      B2 = B1 + DB
      CALL SUBK (E,A1,B1,A2,B2,LENGHT, A )
      CALL ALD (NEQ, STIFF, N, A )
      CALL SUBM (RC,A1,E1,A2,B2,LENGHT, EMASS, A )
      CALL ALD (NEQ, MASS, N, A )
      A1 = A2
12    B1 = B2

C      ADD DECK MASS
      I = 2 * NELEM

```

SAS 00
SAS 01
SAS 02
SAS 03
SAS 04
SAS 05
SAS 06
SAS 07
SAS 08
SAS 09
SAS 10
SAS 11
SAS 12
SAS 13
SAS 14
SAS 15
SAS 16
SAS 17
SAS 18
SAS 19
SAS 20
SAS 21
SAS 22
SAS 23
SAS 24
SAS 25
SAS 26
SAS 27
SAS 28
SAS 29
SAS 30
SAS 31
SAS 32
SAS 33
SAS 34
SAS 35

MASS)

SAS 36
 SAS 37
 SAS 38
 SAS 39
 SAS 40
 SAS 41
 SAS 42
 SAS 43
 SAS 44
 SAS 45
 SAS 46
 SAS 47
 SAS 48
 SAS 49

```

C
      MASS (I+1) = MASS(I+1) + DMASS
      MASS (I+2) = MASS (I+2) + EINER
      A1 = REB
      B1 = RIB
      DO 14 M = 1, NELEM
      A2 = A1 + LA
      B2 = B1 + LB
      CALL SUBRG (RC, REB, RIB, A1, B1, A2, B2, LENGHT, EMASS, M, A)
      CALL ADD (NEC, STIFF, N, A)
      A1 = A2
      B1 = B2
14  RETURN
      END

```

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```

C
SUBROUTINE SUBK (E,A1,E1,A2,B2,LENGHT,STIFF)
SUBROUTINE SUBK (E,A1,E1,A2,B2,LENGHT,STIFF)
IMPLICIT REAL * 8 ( A-H , O-Z )
REAL*8 LENGHT
DIMENSION A(5), W(5), F(4), STIFF(1C)
DATA A,W / C., -.538469, .538469, -.906180, .906180, .568889,
*2*.478629, 2*.236927 /
DO 1 I = 1,10
1 STIFF(I) = C.
DO 2 N = 1,5
X = A(N)
X = .5*(X+1.)
F(1) = 12.*X-6.
F(3) = -F(1)
F(2) = (-4.+ 6.*X)*LENGHT
F(4) = (-2.+6.*X)*LENGHT
AA = A1*(1.-X)+A2*X
B = B1*(1.-X)+B2*X
C = 0.7853981 * (AA**4-E**4)/LENGHT**3/2.*W(N)*E
IJ = 0
DO 2 J = 1,4
DO 2 I = 1,J
IJ = IJ+1
2 STIFF(IJ) = STIFF(IJ) + C*F(I)*F(J)
RETURN
END

```

SK 00
SK 01
SK 01A
SK 02
SK 03
SK 04
SK 04A
SK 05
SK 06
SK 07
SK 08
SK 09
SK 10
SK 11
SK 12
SK 13
SK 14
SK 15
SK 16
SK 17
SK 18
SK 19
SK 20
SK 21
SK 22
SK 23

SA 00
SA 01
SA 01A
SA 02
SA 03
SA 04
SA 05
SA 06
SA 07
SA 08
SA 09
SA 10
SA 11
SA 12

```

C
SUBROUTINE ADD
SUBROUTINE ADD ( NEQ, A, N, B )
IMPLICIT REAL * 8 ( A-E, O-Z )
DIMENSION A(1) , B(1)
NN = 2*(N-1)
KL = 0
DO 10 J=1,4
DO 10 I=1,J
II = J-I
IJ = NEQ*II+NN+I
KL = KL+1
10 A(IJ) = A(IJ) + B(KL)
RETURN
END

```

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```

C
SUBROUTINE SUEM
SUBROUTINE SUEM (RO,A1,E1,A2,E2,LENGHT,EMASS,MASS)
IMPLICIT REAL * 8 ( A-H , O-Z )
REAL*8 LENGHT , MASS
DIMENSION A(5), W(5), F(4), MASS(10)
DATA A,W / C., -.538469, .538469, -.906180, .906180, .568889,
*2*.478629, 2*.236927 /
DO 1 I = 1,10
1 MASS (I) = C.
DO 2 N = 1,5
X = A(N)
X = .5*(X+1.)
F(3) = X*X*(3.-2.*X)
F(1) = 1.-F(3)
F(2) = X*LENGHT*(1.-2.*X+X*X)
F(4) = X*X*LENGHT*(X-1.)
AA = A1*(1.-X)+A2*X
B = B1*(1.-X)+E2*X
C = 3.14159265*(AA*AA-E*E)*RO*LENGHT/2.*W(N)
EMASS = EMASS+C
IJ = 0
DO 2 J = 1,4
DO 2 I = 1,J
IJ = IJ+1
2 MASS (IJ) = MASS(IJ) + C* F(I) * F(J)
RETURN
END

```

SM 00
SM 01
SM 01A
SM 02
SM 03
SM 04
SM 04A
SM 05
SM 06
SM 07
SM 08
SM 09
SM 10
SM 11
SM 12
SM 13
SM 14
SM 15
SM 16
SM 16A
SM 17
SM 18
SM 19
SM 20
SM 21
SM 22
SM 23

```

C
C
SUBROUTINE SUBKG
SUBROUTINE SUBKG (RC, REE, RIB, A1, B1, A2, B2, LENGHT, EMASS, M,
*
* IMPLICIT REAL * 8 ( A-H, O-Z )
REAL*8 LENGHT
DIMENSION A(5), W(5), F(4), STIFG(10)
DATA A, W / -.906180, -.538469, 0., .538469, .906180, .236927,
*.478629, .568889, .478629, .236927 /
DM = M - 1
DO 1 I = 1, 10
1 STIFG(I) = C.
DO 2 N = 1, 5
X = A(N)
X = .5*(X+1.)
F(1) = X*6.*(X-1.)
F(2) = (1.-4.*X+3.*X*X)*LENGHT
F(3) = -F(1)
F(4) = (3.*X-2.)*LENGHT*X
A3 = (A2-A1)*X + A1
B3 = (B2-B1)*X + B1
QMASS = RO * 3.14159265 * ( DM + X ) * LENGHT/ 3. * (( REB * REB
*+ A3*HEB + A3*A3 ) - (FIE * RIB + B3*EIF + B3*B3))
P = 9.81 * ( EMASS - QMASS )
IJ = 0
DO 2 J = 1, 4
DO 2 I = 1, J
IJ = IJ + 1
2 STIFG(IJ) = STIFG(IJ) + F*F(I)*F(J)
RETURN
END

```

SKG 00
 SKG 01
 SKG 02
 SKG 03
 SKG 03A
 SKG 04
 SKG 05
 SKG 06
 SKG 07
 SKG 08
 SKG 09
 SKG 10
 SKG 11
 SKG 12
 SKG 13
 SKG 14
 SKG 15
 SKG 16
 SKG 17
 SKG 18
 SKG 19
 SKG 20
 SKG 21
 SKG 22
 SKG 23
 SKG 25
 SKG 26
 SKG 27
 SKG 28
 SKG 29
 SKG 30

161.

```

C C SUBROUTINE TF
C SUBROUTINE TF (IW,TCWR,NELEM,HEIGHT,ZC, RET,REB,DEPTH,
* NEQ, MEW, STIFF, MASS, A, B, FREC
IMPLICIT REAL * 8 ( A-H, O-Z )
REAL*8 MASS, LENGHT
DIMENSION TCWR(20), STIFF(1), MASS(1), A(1), B(10),P(4)
W2 = ( 6.28318531 * FREC ) ** 2

C C FORM COEFFICIENT MATRIX
C LIM = NEQ*NEW
C DO 1 I = 1,LIM
1 A(I) = STIFF(I) - W2 * MASS(I)

C C FORM LOAD VECTOR
C DO 2 I = 1,NEQ
2 B(I) = 0.
C DN = NELEM
C LENGHT = HEIGHT/DN
C DA = ( RFT-FEB)/DN
C A1 = REB
C DO 4 N = 1,NELEH
C A2 = A1 + 1A
C CALL SUBP (N, A1, A2, LENGHT, Z0, DEPTH, W2,
J = 2*(N-1)
C DO 3 I = 1,4
C J = J+1
3 B(J) = B(J) + P(I)
4 A1 = A2

C C IMPOSE DISPLACEMENT ECUNARY CONDITIONS
C DO 5 I = 1, LIM, NEQ
C A(I) = 0.
C 5 A(I+1) = 0.
C B(1) = 0.

```

```

C
C
C
      B(2) = 0.
      SOLVE SYSTEM OF EQUATIONS
      CALL SOLVE ( 0, IW, NFQ, MBW, 1, A, B )
      PRINT OUT STEADY - STATE RESPONSE
      WRITE (IW,6) TOWER, FREQ
      I2 = NFQ
      NNODE = NELEM + 1
      DO 7 I = 1,NNODE
      J = NNODE-I+1
      WRITE (IW,8) J, E(I2-1), B(I2)
7 I2 = I2-2
6 FORMAT ('1',5X,20A4//5X,'*STEADY-STATE RESPONSE AT ',F8.3, ' CPS*',TF 51
*//5X,'NODE', 6X, 'DISPLACEMENT', 10X, 'ROTATION'//)
8 FORMAT (5X,I4, 2(3X, F15.5))
      RETURN
      END

```

```

TF 38
TF 39
TF 40
TF 41
TF 42
TF 43
TF 44
TF 45
TF 46
TF 47
TF 48
TF 49
TF 50
TF 51
TF 52
TF 53
TF 54
TF 55

```

RK 00
RK 01
RK 02
RK 02A
RK 03
RK 04
RK 05
RK 05A
RK 05B
RK 06
RK 07
RK 08
RK 09
RK 10
RK 11
RK 12
RK 13
RK 14
RK 15
RK 16
RK 17
RK 18
RK 19
RK 20
RK 21
RK 22
RK 23
RK 24
RK 25
RK 26
RK 27
RK 28

```

C
C
      FUNCTION RK
      DOUBLE PRECISION FUNCTION RK ( W2 , G , DEPTH )
      IMPLICIT REAL * 8 ( A-H , O-Z )
      RK = W2/G
      IF ( W2 .EQ. 0. ) RETURN
      IF ( RK * DEPTH .LT. 1C. ) GO TO 8
      RK = 1C. / DEPTH
      RETURN
      8 A2 = 0.
      DK = ( 2. - RK ) / 10.
      10 A1 = A2
      B = RK * DEPTH
      A2 = W2 - RK * G * DSINH (E) / DCOSH (E)
      IF ( A2 .EQ. 0. ) RETURN
      RK = RK + DK
      IF ( A1/A2 .GE. 0. ) GO TO 10
      RK = RK - 1.5 * DK
      DK = DK / 2.
      12 IF ( RK/RK .LT. 1.E-4 ) RETURN
      B = RK * DEPTH
      A3 = W2 - RK * G * DSINE (E) / ECCSH (B)
      IF ( A3 .EQ. 0. ) RETURN
      DK = DK / 2.
      IF ( A3 / A1 .GT. 0. ) GO TO 14
      RK = RK - DK
      A2 = A3
      GO TO 12
      14 RK = RK + DK
      A1 = A3
      GO TO 12
      END

```

```

C      SUBROUTINE SUBP
DOUBLE PRECISION FUNCTION DCOSH (A)
      B =DEXP(A)
      DCOSH = .5*(B+1./B)
      RETURN
END
C      DOUBLE PRECISION FUNCTION DSINH (A)
      B =DEXP (A)
      DSINH = .5*(B-1./B )
      RETURN
END
C      SUBROUTINE SUBP ( N, A1, A2, LENGHT, ZC, DEPTH, W2, P)
IMPLICIT REAL * 8 ( A-H , O-Z )
      REAL*8 LENGHT , K
      DIMENSION A(5), W(5),
      DATA A,W / 0., -.538469, .538469, -.906180, .906180, .568889,
      * 2*.478629, 2*.236927 /
      DATA CI, KC, G / 2., 1., 9.81 /
      K = RK ( W2 , G, DEPTH )

      DO 1 I = 1,4
1 P(I) = 0.
      Z1 = ZC + LENGHT *DFLOAT (N-1 )
      C = 1.5707963 * CI * RC * W2 /DSINH ( K*DEPTH)
      DC 2 I = 1,5
      X = A(I)
      X = .5 * (X + 1. )
      RADIUS = A1 * (1.-X) + A2 * X
      Z = Z1 + LENGHT * X
      IF ( Z. GT. LENGHT ) RETURN
      F = C * RADIUS ** 2 *DCCSH (K*Z)
      H = X*X*(3.-2.*X)
      P(1) = P(1) + (1.-H) * F
      P(2) = P(2) + (X*LENGHT*(1.-2.*X + X*X))*F
      P(3) = P(3) + H * F
      P(4) = P(4) + X*X*LENGHT*(X-1.) * F

```

SP 00
 SP 01
 SP 02
 SP 03
 SP 04
 SP 05
 SP 06
 SP 07
 SP 08
 SP 09
 SP 10
 SP 11
 SP 11A
 SP 12
 SP 13
 SP 14
 SP 15
 SP 16
 SP 16A
 SP 17
 SP 18
 SP 19
 SP 20
 SP 22
 SP 23
 SP 24
 SP 25
 SP 26
 SP 27
 SP 28
 SP 29
 SP 30
 SP 31
 SP 32
 SP 33
 SP 34

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165.

SP 35
SP 36
SP 37

2 CONTINUE
RETURN
END

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```

C          SUBROUTINE SCOLVE
C          SUBROUTINE SOLVE (IO,IA,NBQ,MBW,NLS,A,B)
C          IMPLICIT REAL * 8 ( A-H , C-Z )
C          DIMENSION A(1),B(1)
C
C          * SOLVES SYMMETRIC SYSTEM OF EQUATIONS USING GAUSSIAN REDUCTION *
C          IO      OPERATION INDICATOR  0 SOLVES SYSTEM A*X=B
C          1 REDUCES MATRIX A
C          2 REDUCES AND BACKSUBSTITUTES B
C
C          NEQ      NUMBER OF EQUATIONS
C          MBW      MAXIMUM BANDWIDTH
C          NLS      NUMBER OF SYSTEMS
C          A        SQUARE Banded SYMMETRIC POSITIVE DEFINITE MATRIX
C                   STORED AS MCNCLIMENSIONAL ARRAY  NEQ*MBW
C                   ELEMENT A(I,J) IS STORED IN A(I+(J-I)*NEQ)
C          B        RECTANGULAR ARRAY, STORED COLUMNWISE
C          *****
C          REDUCTION OF A. ORIGINAL ARRAY IS DESTROYED
C
C          IF (IO.EQ.2) GO TO 20
C          NRD = NEQ-1
C          DO 18 I = 1,NRD
C             D = A(I)
C             IF ( D.EQ. 0. ) GC TO 18
C             IJ=I
C             DO 16 J=2,NEW
C                IJ=IJ+NEQ
C                IF (A(IJ).EQ.0.) GO TO 16
C                C=A(IJ)/D
C                IK=IJ
C                JK=I+J-1
C                DO 14 K=J,NEW
C                   A(JK)=A(JK)-C*A(IK)
C                   IK=IK+NEQ
C                   JK=JK+NEQ
C
C          14

```

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167.

```

C
C
C
16 CONTINUE
18 CONTINUE
IF (IO.EQ.1) RETURN
REDUCTION OF B. ORIGINAL ARRAY IS DESTROYED
20 NRE=NEQ-1
DO 26 I=1,NRE
D=A(I)
IF (L.EQ.0.) GO TO 26
IJ=I
DO 24 J=2,NRE
IJ=IJ+NEQ
IF (A(IJ).EQ.0.) GO TO 24
C=A(IJ)/E
IK=I
JK=I+J-1
DO 22 K=1,NIS
B(JK)=B(JK)-C*B(IK)
IK=IK+NEQ
22 JK=JK+NEQ
24 CONTINUE
26 CONTINUE
BACKSUBSTITUTION. RESULTS STORED IN B.
C
C
C
I=NEQ
30 IF (A(I).EQ.0.) GO TO 34
IK=I
DO 32 K=1,NIS
B(IK)=B(IK)/A(I)
32 IK=IK+NEQ
34 I=I-1
IF (I.EQ.0) RETURN
IJ=I
DO 38 J=2,NRE
```

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168.

SS 70
SS 71
SS 72
SS 73
SS 75
SS 76
SS 77
SS 78
SS 79
SS 80
SS 81
SS 82

```
IJ=IJ+NEQ
IF (A(IJ).EQ.0.) GO TO 38
IK=I
JK=I+J-1
DO 36 K=1,NLS
E(IK)=B(IK)-A(IJ)*E(JK)
IK=IK+NEQ
36 JK=JK+NEQ
38 CONTINUE
GO TO 30
END
```

C

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169.

```

C C
C SUBROUTINE TIME H
C SUBROUTINE TIME H ( IW, NEQ, MBW, NFREQ, NELEM,
  *RET, REB, HEIGHT, ZC, DEPTH, DT, TIME,
  *STIFF, MASS, FREQ, A, B, H, PHASE,
  *DIS, VEL, ACC, R, S, F, C
  )
C IMPLICIT REAL * 8 ( A-H, C-Z )
C REAL*8 MASS, LENGHT
C DIMENSION LIS( 1 ), VEL ( 1 ), ACC ( 2 ), MASS ( 1 ), STIFF ( 1 ),
  *A( 1 ), R( 1 ), S( 1 ), B( 1 ), FREQ( 1 ), H( 1 ), PHASE( 1 ),
  *Q( NEQ, NFREQ ), P( 1 )
C NTIME = TIME / DT
C
C FORM MATRIX OF COEFFICIENTS
C C2 = LT * LT / 6.
C LIM = NEQ * MBW
C DO 50 I = 1, LIM
  50 A( I ) = MASS( I ) + C2 * STIFF( I )
C
C PRESCRIBE FIRST TWO LCF AS ZERO
C DO 51 I = 1, LIM, NEQ
  A( I ) = 0.
  51 A( I+1 ) = 0.
C
C TRIANGULARIZE MATRIX
C CALL SOLVE ( 1, IW, NEQ, MBW, 1, A, E )
C
C FORM VECTOR CF APPLIED FORCES
C DO 5 M = 1, NFREQ
  DO 5 N = 1, NEQ
    5 Q( N, M ) = C.
  DN = NELEM
  LENGHT = HEIGHT / DN
  DA = ( RET - REB ) / DN
  DO 7 N = 1, NFREQ

```

TH 00
TH 01
TH 02
TH 03
TH 04
TH 05
TH 06
TH 07
TH 08
TH 09
TH 10
TH 11
TH 12
TH 13
TH 14
TH 15
TH 16
TH 17
TH 18
TH 19
TH 20
TH 21
TH 22
TH 23
TH 24
TH 25
TH 26
TH 27
TH 28
TH 29
TH 30
TH 31
TH 32
TH 33
TH 34
TH 35

[illegible]

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171.

TH 72
TH 73
TH 74
TH 75
TH 76
TH 77
TH 78
TH 79
TH 80
TH 81
TH 82
TH 83
TH 84
TH 85
TH 86
TH 87
TH 88
TH 89
TH 90
TH 91
TH 92
TH 93
TH 94
TH 95
TH 96

```

      S(I) = DIS(I) + DT * VEL(I) + C2 * ACC(I)
55 ACC(I) = B(I)
C
      CALL AMBC (NEQ, MEW, ACC, STIFF, S)
      ACC(1) = 0.
      ACC(2) = 0.
      CALL SOLVE ( 2, IW, NEQ, MBW, 1, A, ACC)
C
      DO 56 I = 1, NEQ
      VEL (I) = F(I) + C1 * ACC(I)
56 DIS(I) = S(I) + C3 * ACC(I)
C
      IF ( N/50*50-N .NE. 0 ) GO TO 62
C
      WRITE ( IW, 2)      TIME
      DC 60 I = 1, NEQ
      60 WRITE (IW, 3)  I, B(I), ACC(I), VEL(I), DIS(I)
      62 CONTINUE
C
      2 FORMAT (//5X, ' TIME =', F8.2//, 9X, 'I', 8X,
      *'FORCE', 8X, 'ACCELERATION', 6X, 'VELOCITY', 5X,
      *'DISPLACEMENT'/)
      3 FORMAT ( 6X, I4, 4E16.4 )
C
      RETURN
      END

```

AM 00
AM 01
AM 01A
AM 02
AM 03
AM 04
AM 05
AM 06
AM 07
AM 08
AM 09
AM 10
AM 11
AM 12
AM 13
AM 14
AM 15
AM 16

```

C  SUBROUTINE AMEC
   SUBROUTINE AMBC (NEQ, MEW, A, B, C )
   IMPLICIT REAL * 8 ( A-H, O-Z )
   DIMENSION A(1), B(1), C(1)
   LIM = MBW - 1
   DO 1 I = 1, NEQ
     A(I) = A(I) - B(I) * C(I)
     M = I
     DO 1 J = 1, LIM
       K = I + J
       M = M + NEQ
       IF ( K .LE. NEQ ) A(I) = A(I) - B(M) * C(K)
       K = I - J
       L = M - J
       IF ( K .GT. 0 ) A(I) = A(I) - E(L) * C(K)
1  CONTINUE
   RETURN
   END

```

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173.

MP2 00
MP2 01
MP2 02
MP2 03
MP2 04
MP2 05
MP2 06
MP2 07
MP2 08
MP2 09
MP2 10
MP2 11
MP2 12
MP2 13
MP2 14
MP2 15
MP2 16

```

C
C  MAIN PROGRAM 2
  DIMENSION AEC(20) , A(4C56) , B(2048) , FREQ(20) , H(20)
  DATA IR , IW , 8 , 5 /
  READ ( IR , 1 ) KCLE
  GO TO ( 10 , 10 , 20 ) , KCDE

C
  10 CALL RECCRE ( IR , IW , ABC , N , A , IT )
  CALL POWER ( N , A , E , DT , DF )
  IF ( KCLE .EQ. 1 ) STCF
  CALL CCNNOF ( IR , IW , C , N , DF , A , M , FREQ , H , B )
  STOP

  20 CALL SEA ( IR , IW , A , A , DF )
  CALL CCNNOF ( IR , IW , 1 , N , DF , A , M , FREQ , H , B )
  STOP
  1 FORMAT ( I4 )
  END

```

SR 00
SR 01
SR 02
SR 03
SR 04
SR 05
SR 06
SR 07
SR 08
SR 09
SR 10
SR 11
SR 12
SR 13
SR 14
SR 15
SR 16
SR 17
SR 18
SR 19
SR 20
SR 21

```

C
C
SUBROUTINE EFCCRD
SUBROUTINE RECORD ( IR , IW , ABC , N , A , DT )
DIMENSION AEC (20) , CARD (10)
EQUIVALENCE ( CARD (1) , CHECK )
READ ( IR , 1 ) AEC , IT
WRITE ( IW , 2 ) AEC , IT
1 FORMAT ( 2CA4 / F8.3 )
2 FORMAT ( //5X , 2CA4// 5X , 'DELTA T = ' , E12.3// )

C
N = 0
10 READ ( IR , 3 ) CARD
3 FORMAT ( 1CF8.3 )
IF ( CHECK .EQ. 123. ) GO TO 14
DO 12 I = 1,10
N = N + 1
12 A(N) = CARD (I)
14 TIME = DT * FLOAT (N)
CALL PICTR ( A,1,ABC,SCALE,1,N,0,-1,2,1,TIME,1)
PAUSE
RETURN
END

```

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175.

SP0 00
SPC 01
SPC 02
SPC 03
SP0 04
SP0 05
SPC 06
SP0 07
SPC 08
SPC 09
SPC 10
SP0 11
SPC 12
SP0 13
SPC 14
SP0 15
SP0 16
SPC 17
SP0 18
SPC 19
SP0 20
SPC 21

C
C
SUBROUTINE FCWER
SUBROUTINE FCWER (N , A , B , DT , DF)
DIMENSION A(1) , B(1)
ROG = 9.81
CALL SETC (A(N+1) , 4096-N)
N = 2048
CALL FCUR2 (A , 4096 , 1 , -1 , 0)
CALL SCALE (A , 4096 , IT)
DF = 1. / IT / FLGAT (4096)
J = 1
DO 10 I = 1 , 2048
AR = A(J)
AI = A(J+1)
A(I) = .5 * (AR * AR + AI * AI) * ROG
B(J) = ATAN (AI / AR)
10 J = J + 2
FMAX = 1024. * DF
CALL PICTR (A,1,AEC,SCALE,1,1024,0,-1,2,1,FMAX,1)
PAUSE
RETURN
END

SO 00
SO 01
SO 02
SO 03
SO 04
SO 05
SO 06
SO 07

C
C
SUBROUTINE SETO
SUBROUTINE SETO (A , N)
DIMENSION A(1)
DO 1 I = 1, N
1 A(I) = C.
RETURN
END

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177.

```

SUBROUTINE FCUR2 (DATA,L,NDIM,ISIGN,IFCRM)
  DIMENSION DATA(1), N(1)
  N(1)=L
  NTOT=1
  DO 10 IDIM=1,NDIM
    NTOT=NTCT*N(IDIM)
    IF (IFCRM) 7C,20,20
  10  NREM=NTOT
  20  DO 60 IDIM=1,NDIM
    NREM=NREM/N(IDIM)
    NPREV=NTCT/(N(IDIM)*NREM)
    NCURR=N(IDIM)
    IF (IDIM-1+IFCRM) 30,3C,4C
  30  NCURR=NCURR/2
  40  CALL BITRV (DATA,NPREV,NCURR,NREM)
    CALL CCOL2 (DATA,NPREV,NCURR,NREM,ISIGN)
    IF (IDIM-1+IFCRM) 50,5C,6C
  50  CALL FIXRL (DATA,N(1),NREM,ISIGN,IFORM)
    NTOT=(NTCT/N(1))*(N(1)/2+1)
  60  CONTINUE
    RETURN
  70  NTOT=(NTOT/N(1))*(N(1)/2+1)
    NREM=1
    DO 100 JDIM=1,NDIM
      IDIM=NDIM+1-JDIM
      NCURR=N(IDIM)
      IF (IDIM-1) 80,80,90
  80  NCURR=NCURR/2
      CALL FIXRL (DATA,N(1),NREM,ISIGN,IFCRM)
      NTOT=NTCT/(N(1)/2+1)*N(1)
      NPREV=NTCT/(N(IDIM)*NREM)
  90  CALL BITRV (DATA,NPREV,NCURR,NREM)
      CALL CCOL2 (DATA,NPREV,NCURR,NREM,ISIGN)
      NREM=NREM*N(IDIM)
  100 RETURN
    END

```

FF2 00
FF2 29
FF2 29
FF2 30
FF2 31
FF2 32
FF2 33
FF2 34
FF2 35
FF2 36
FF2 37
FF2 38
FF2 39
FF2 40
FF2 41
FF2 42
FF2 43
FF2 44
FF2 45
FF2 46
FF2 47
FF2 48
FF2 49
FF2 50
FF2 51
FF2 52
FF2 53
FF2 54
FF2 55
FF2 56
FF2 57
FF2 58
FF2 59
FF2 60
FF2 61
FF2 62-

[illegible]

```

SUBROUTINE CCCL2 (DATA,NFEV,N,NREM,ISIGN)
DIMENSION DATA(1)
TWOPI=6.2831853072*FICAT (ISIGN)
IPO=2
IP1=IPC*NPFEV
IP4=IP1*N
IP5=IP4*NREM
IP2=IP1
NPART=N
IF (NPART-2) 50,30,20
NPART=NPART/4
GO TO 10
IP3=IP2*2
DO 40 I1=1,IF1,IPC
DO 40 I5=I1,IF5,IP3
JC=I5
J1=J0+IP2
TEMPR=DATA (J1)
TEMPI=DATA (J1+1)
DATA (J1)=DATA (J0)-TEMPR
DATA (J1+1)=DATA (J0+1)-TEMPI
DATA (JC)=DATA (J0)+TEMPR
DATA (JC+1)=DATA (J0+1)+TEMPI
GO TO 140
IP3=IP2*4
THETA=TWOPI/FLOAT (IP3/IP1)
SINTH=SIN (THETA/2.)
WSTPR=-2.*SINTH*SINTH
WSTPI=SIN (THETA)
WR=1.
WI=0.
DO 130 I2=1,IF2,IP1
IF (I2-1) 70,70,60
W2R=WR*WF-WI*WI
W2I=2.*WR*WI
W3R=W2R*WR-W2I*WI

```

```

70 W3I=W2R*WI+W2I*WR
   I1MAX=I2+IE1-IP0
   DO 120 I1=I2,I1MAX,IP0
   DO 120 I5=I1,IP5,IP3
   JC=I5
   J1=JC+IP2
   J2=J1+IP2
   J3=J2+IP2
   IF (I2-1) 9C,90,80
80 TEMPR=DATA(J1)
   DATA(J1)=W2R*TEMPR-W2I*DATA(J1+1)
   DATA(J1+1)=W2R*DATA(J1+1)+W2I*TEMPR
   TEMPR=DATA(J2)
   DATA(J2)=W3R*TEMPR-W3I*DATA(J2+1)
   DATA(J2+1)=W3R*DATA(J2+1)+W3I*TEMPR
   TEMPR=DATA(J3)
   DATA(J3)=W3R*TEMPR-W3I*DATA(J3+1)
   DATA(J3+1)=W3R*DATA(J3+1)+W3I*TEMPR
   TOR=DATA(JC)+IATA(J1)
   TCI=DATA(JC+1)+DATA(J1+1)
   T1R=DATA(JC)-IATA(J1)
   T1I=DATA(JC+1)-DATA(J1+1)
   T2R=DATA(J2)+IATA(J3)
   T2I=DATA(J2+1)+DATA(J3+1)
   T3R=DATA(J2)-IATA(J3)
   T3I=DATA(J2+1)-DATA(J3+1)
   DATA(JC)=TCR+T2R
   DATA(JC+1)=TCI+T2I
   DATA(J2)=TCR-T2R
   DATA(J2+1)=TCI-T2I
   IF (ISIGN) 10C,100,110
100 T3R=-T3R
   T3I=-T3I
110 DATA(J1)=T1R-T3I
   DATA(J1+1)=T1I+T3R
   DATA(J3)=T1R+T3I

```


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181.

90
91
92
93
94
95
96
97-

C02
C02
C02
C02
C02
C02
C02
C02

120 DATA (J3+1)=T1J-T3R
TEMPR=WR
WR=WSTR*TEMPR-WSTPI*WI+JIMPR
130 WI=WSTR*WI+WSTPI*TFNEF+WJ
140 IP2=IP3
150 IF (IP3-IP4) 50,150,150
RETURN
END

```

SUBROUTINE FIXRL (DATA,N,NREM,ISIGN,IFORM)
REAL*8 ZR,ZI
DIMENSION DATA(2)
TWOPI=6.283185307*FICAT(ISIGN)
IPO=2
IP1=IPC*(N/2)
IP2=IP1*NREM
IF (IFORM) 1C,70,70
J1=IP1+1
DATA(2)=DATA(J1)
IF (NREM-1) 7C,70,20
J1=J1+IPC
I2MIN=IP1+1
DO 60 I2=I2MIN,IP2,IP1
DATA(I2)=DATA(J1)
J1=J1+IPC
IF (N-2) 5C,50,30
I1MIN=I2+IEC
I1MAX=I2+IE1-IPC
DO 40 I1=I1MIN,I1MAX,IEO
DATA(I1)=DATA(J1)
DATA(I1+1)=DATA(J1+1)
J1=J1+IPC
DATA(I2+1)=DATA(J1)
J1=J1+IPC
DO 80 I2=1,I2,IP1
TEMPR=DATA(I2)
DATA(I2)=DATA(I2)+DATA(I2+1)
DATA(I2+1)=TEMPR-TEMPR
IF (N-2) 2CC,200,90
THETA=TWOPI/FICAT(N)
SINTH=SIN(THETA/2.)
ZSTPF=-2.*SINTH*SINTH
ZSTPI=SIN(THETA)
ZR=(1.-ZSTPI)/2.
ZI=(1.+ZSTPF)/2.

```

***** CARD ELIMINATED *****

10 C

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183.

```

100 IF (IFCRM) 100,110,110
    ZR=1.-ZR
110 ZI=-ZI
    I1MIN=IPC+1
    I1MAX=IPO*(N/4)+1
    DO 190 I1=I1MIN,I1MAX,IPC
    DO 180 I2=I1,IP2,IP1
    I2CNJ=IPC*(N/2+1)-2*I1+I2
    IF (I2-I2CNJ) 150,120,120
    IF (ISIGN*(2*IFORM+1)) 130,140,140
120 IF (DATA(I2+1))=-DATA(I2+1)
130 DATA(I2+1) 170,180,180
140 IF (IFCRM) 170,180,180
150 DIFE=DATA(I2)-DATA(I2CNJ)
    DIFI=DATA(I2+1)+DATA(I2CNJ+1)
    TEMPR=LIFR*2R-DIFI*ZI
    TEMPI=DIFR*ZI+DIFI*ZR
    DATA(I2)=DATA(I2)-TEMPR
    DATA(I2+1)=DATA(I2+1)-TEMPI
    DATA(I2CNJ)=DATA(I2CNJ)+TEMPR
    DATA(I2CNJ+1)=DATA(I2CNJ+1)-TEMPI
    IF (IFCRM) 160,180,180
160 DATA(I2CNJ)=DATA(I2CNJ)+DATA(I2CNJ)
    DATA(I2CNJ+1)=DATA(I2CNJ+1)+DATA(I2CNJ+1)
170 DATA(I2)=DATA(I2)+DATA(I2)
    DATA(I2+1)=DATA(I2+1)+DATA(I2+1)
180 CONTINUE
    TEMPR=ZR-.5
    ZR=2STFE*TEMPR-ZSTFI*ZI+ZF
190 ZI=ZSTPR*ZI+ZSTPI*TEMPR+ZI
200 IF (IFCRM) 270,210,210
210 I2=IP2+1
    I1=I2
    J1=IPO*(N/2+1)*NREM+1
    GO TO 250
220 DATA(J1)=DATA(I1)
    DATA(J1+1)=DATA(I1+1)
    FIX 58
    FIX 59
    FIX 60
    FIX 61
    FIX 62
    FIX 63
    FIX 64
    FIX 65
    FIX 66
    FIX 67
    FIX 68
    FIX 69
    FIX 70
    FIX 71
    FIX 72
    FIX 73
    FIX 74
    FIX 75
    FIX 76
    FIX 77
    FIX 78
    FIX 79
    FIX 80
    FIX 81
    FIX 82
    FIX 83
    FIX 84
    FIX 85
    FIX 86
    FIX 89
    FIX 91
    FIX 92
    FIX 93
    FIX 94
    FIX 95
    FIX 96
```

FIX 97
 FIX 98
 FIX 99
 FIX 100
 FIX 101
 FIX 102
 FIX 103
 FIX 104
 FIX 105
 FIX 106
 FIX 107
 FIX 108
 FIX 109
 FIX 110
 FIX 111

I1=I1-IP0
 J1=J1-IP0
 IF (I2-I1) 220,240,240
 DATA (J1)=DATA(I1)
 DATA (J1+1)=0.
 I2=I2-IP1
 J1=J1-IPC
 DATA (J1)=DATA (I2+1)
 DATA (J1+1)=0.
 I1=I1-IPC
 J1=J1-IPC
 IF (I2-I1) 260,260,230
 DATA (2)=0.
 RETURN
 END

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 240
 250
 260
 270

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185.

SSC 00
SSC 01
SSC 02
SSC 03
SSC 04
SSC 05
SSC 06
SSC 07

C
C
SUBROUTINE SCALE
SUBROUTINE SCALE (A , N , FACTOR)
DIMENSION A (1)
DO 1 I = 1 , N
1 A (I) = A (I) * FACTOR
RETURN
END


```

C
C
SUBROUTINE CCNCH
SUBROUTINE CCNCH ( IF, I*, IO, N, LF, A, M, FREQ, H, B )
DIMENSION A(1), FREQ(1), H(1), B(1)
ROG = 9.81
READ ( IR, 1 ) M, ISEED, ( FREQ(I), I = 1, M )
1 FORMAT ( 2I4 / ( 10F8.3 ) )
FR = DF
J = 1
DO 14 I = 1, M
H(I) = 0.
IF ( J .GT. N ) GC TC 14
IF ( I .LT. M ) FL = .5*(FREQ(I) + FREQ(I+1) )
10 IF ( I .EQ. M ) GC TO 12
IF ( FR .GT. FL ) GC TC 14
12 H(I) = H(I) + A(J)
FR = FR + IF
J = J + 1
IF ( J - N ) 10, 10, 14
14 H(I) = SQRT ( 8. * DF / ROG * H(I) )

IF ( IO .NE. 0 ) GC TO 18
DO 16 I = 1, M
J = FREQ(I) / DF
16 B(I) = B(J)
GO TC 24

18 DO 20 I = 1, M
CALL RANDX ( ISEED, IY, FI )
ISEED = IY
20 B(I) = 3.14159265 * (FI - .5)

24 WRITE ( IW, 2 ) ( I, FREQ(I), H(I), B(I), I = 1, M )
2 FORMAT ( ///5X, ' * CONDENSED WAVE SPECTRUM * ', //8X,
* ' POSITION', 9X, ' FREQ', 8X, ' WAVE HEIGHT', 3X, ' PHASE ANGLE',
*// ( 7X, I5, 3X, 3F15.4 ) )

```

SC 00
SC 01
SC 02
SC 03
SC 04
SC 05
SC 06
SC 07
SC 08
SC 09
SC 10
SC 11
SC 12
SC 13
SC 14
SC 15
SC 16
SC 17
SC 18
SC 19
SC 20
SC 21
SC 22
SC 23
SC 24
SC 25
SC 26
SC 27
SC 28
SC 29
SC 30
SC 31
SC 32
SC 33
SC 34
SC 35

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187.

SC 36
SC 37
SC 38
SC 39
SC 40
SC 41
SC 42
SC 43
SC 44
SC 45
SC 46
SC 47
SC 48

```
DT = .25
TIME = 0.
DO 26 J = 1,600
TIME = TIME + DT
A(J) = 0.
DO 26 I = 1,M
ALFA = 6.283186 * TIME * FREQ(I) - E(I)
26 A(J) = A(J) + H(1) * SIN(ALFA)

C
CALL PICTR ( A, 1, AEC, SCALE, 1, 600, 0, -1, 2, 1, TIME, 1 )
PAUSE
RETURN
END
```

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```

C
C
SUBROUTINE SEA
SUBROUTINE SEA ( IR , IW , N , A , DF )
DIMENSION A(1)
DATA ALFA , G , PI / .0081 , 9.81 , 3.14159265 /
READ ( IR , 1 ) FREQM , GAMMA , SIGMA1 , SIGMA2 , DF , FMAX
1 FORMAT ( 6F8.3 )
WRITE ( IW , 2 ) FREQM , GAMMA , SIGMA1 , SIGMA2 , DF , FMAX
2 FORMAT ( //5X , * JCNSWAP PARAMETERS * , //
*5X , 'FREQUENCY AT PEAK ' , F8.3 /
*5X , 'GAMMA ' , F8.3 /
*5X , 'SIGMA 1 ' , F8.3 /
*5X , 'SIGMA 2 ' , F8.3 /
*5X , 'FREQUENCY INTERVAL ' , F8.3 /
*5X , 'MAX. FREQUENCY ' , F8.3 / )
N = FMAX / IF * .5
C1 = ALFA * G * G / ( 2. * PI ) ** 4
FREQ = 0.
SIGMA = SIGMA1
DO 10 I = 1 , N
FREQ = FREQ + DF
IF ( FREQ .GT. FREQM ) SIGMA = SIGMA2
S = - ( FREQ/FREQM - 1. ) ** 2 / ( 2. * SIGMA * SIGMA )
R = 0.
IF ( S .GT. -170. ) R = GAMMA ** EXP ( S )
S = - 1.25 * ( FREQM/ FREQ ) ** 4
A(I) = 0.
IF ( S .GT. -170. ) A(I) = C1 * R * EXP(S) / FREQ ** 5
10 CONTINUE
CALL PICTR ( A , 1 , AEC , SCALE , 1 , N , 0 , -1 , 2 , 1 , FMAX , 1 )
PAUSE
RETURN
END
SEA 00
SEA 01
SEA 02
SEA 03
SEA 04
SEA 05
SEA 05A
SEA 06
SEA 06A
SEA 06B
SEA 06C
SEA 06D
SEA 06E
SEA 06F
SEA 06G
SEA 07
SEA 08
SEA 09
SEA 10
SEA 11
SEA 12
SEA 12A
SEA 12B
SEA 12C
SEA 13
SEA 13A
SEA 13B
SEA 13C
SEA 14
SEA 15
SEA 16
SEA 17
SEA 18

```

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