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APPROXIMATE MODELS FOR OFF-SHORE CONCRETE GRAVITY STRUCTURES

by

WILLIAM EMMERT DUVALL

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by

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ABSTRACT

APPROXIMATE 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 offshore 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 $W_2 + w_{\substack{column \\ total}}$

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

$w_{\substack{column\\total}}$ = 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 $(\frac{z}{\ell})$

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 cheapter 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 Southhampton 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 Southhampton 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 propellors 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 pro-pietary 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 paraphenalia 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 per centage 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.

NAME	OWNER	BUILDER	YARD	INSTALLATION DATE	TYPE
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 TP1	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

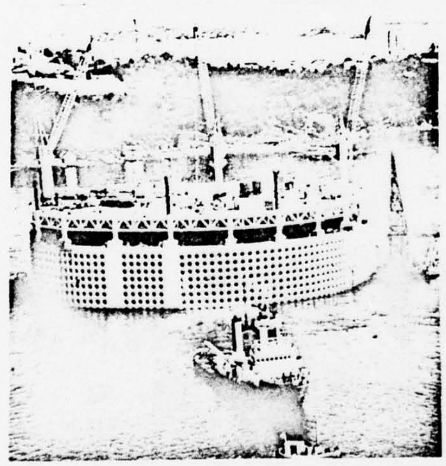

Figure 1.2.1

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-

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)

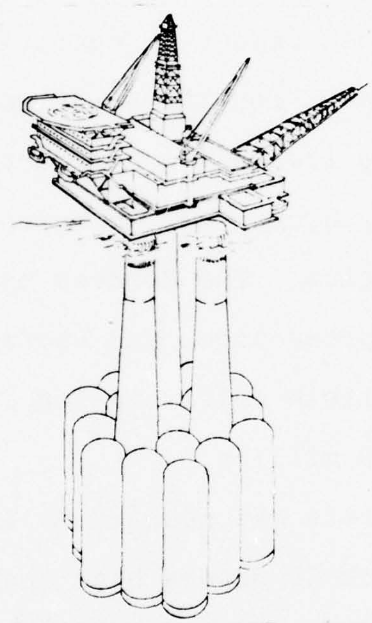

Figure 1.2.2

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

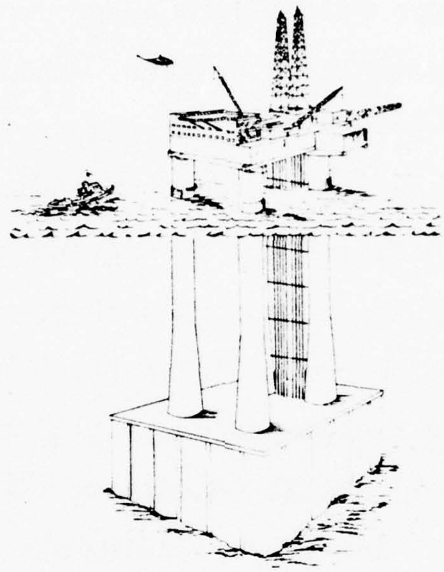

Figure 1.2.3

SEATANK

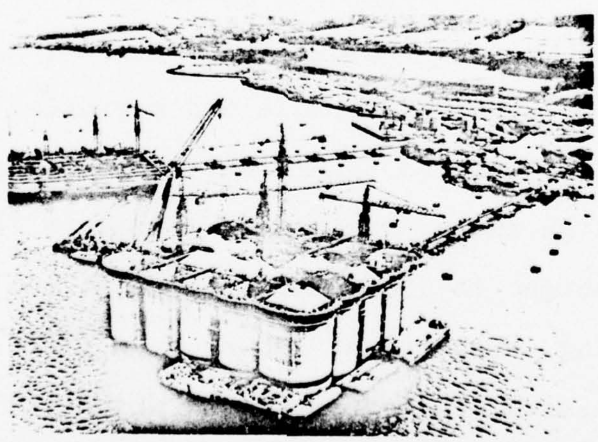

Figure 1.2.4

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 slideing 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

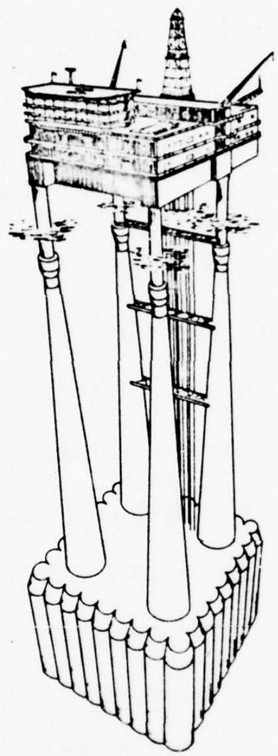

Figure 1.2.5

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)

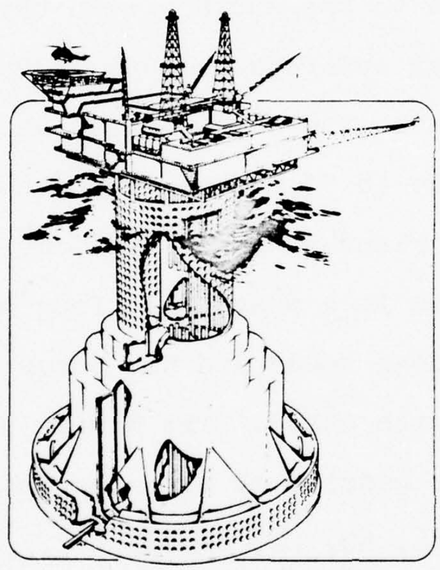

Figure 1.2.6

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).

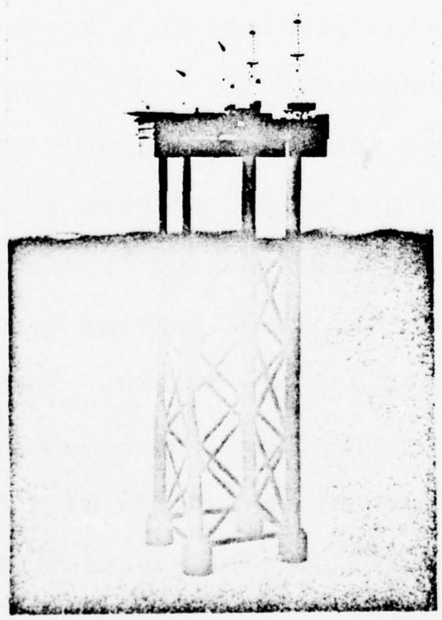

Figure 1.3.1 Raymond International's Tilt-Up/Jack-Up

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)

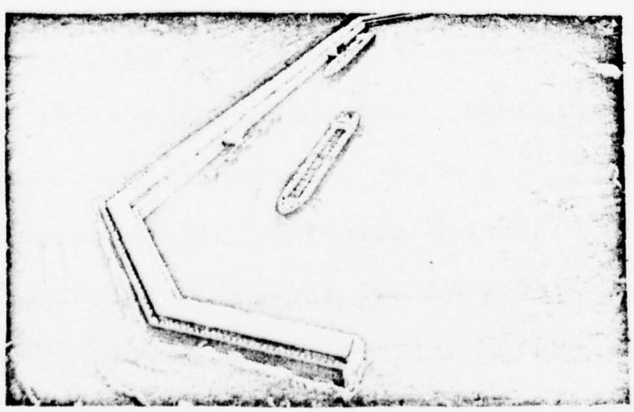

Figure 1.3.2 Breakwater/Oil Storage System

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)

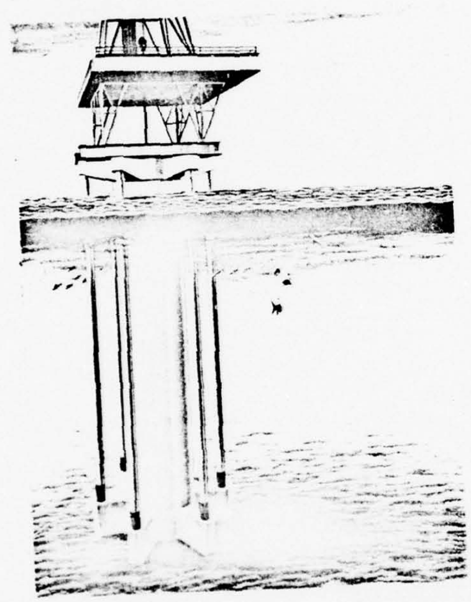

Figure 1.3.3
Prestressed Concrete Tower

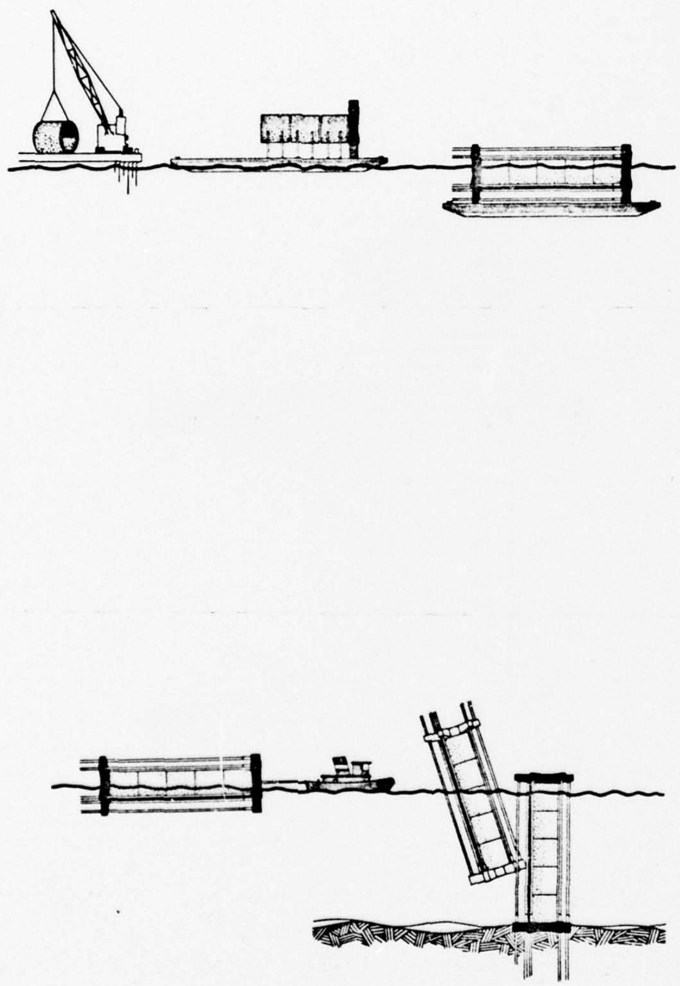

Figure 1.3.4
Dravo Ocean Structures Construction
Sequence for Prestressed, Post-Tensioned
Concrete Tower

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)

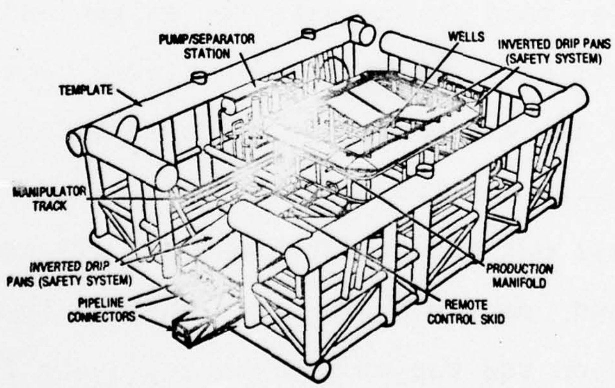

Figure 1.3.5 Exxon's Subsea Production System Module

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. (31)

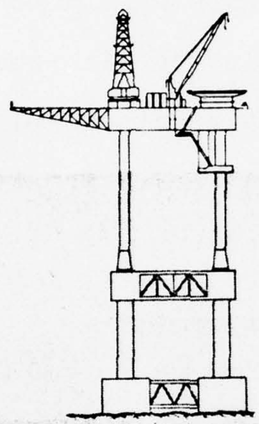

Figure 1.3.6 Gem-Hersent Steel Gravity Platform

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 Dabai "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)

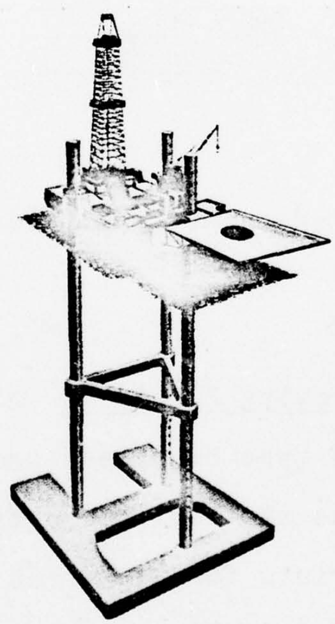

Figure 1.3.7 Bethlehem Steel's Hybrid Gravity Platform

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)

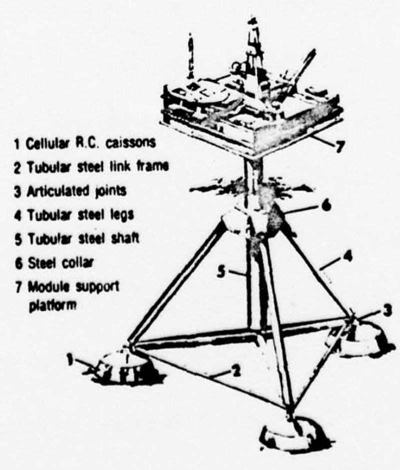

Figure 1.3.8 Pinned Hybrid With Concrete "Spuds"

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)

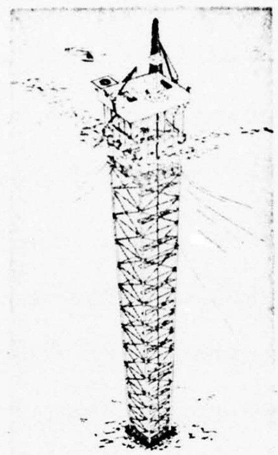

Figure 1.3.9 Exxon's Guyed, Compliant Steel Tower

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) Campenon 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)

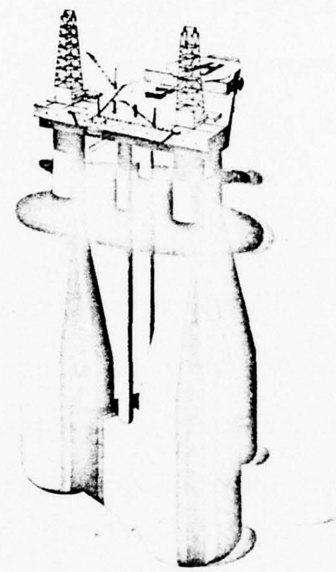

Figure 1.3.10 Selmer Tripod Concrete Gravity Platform

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)

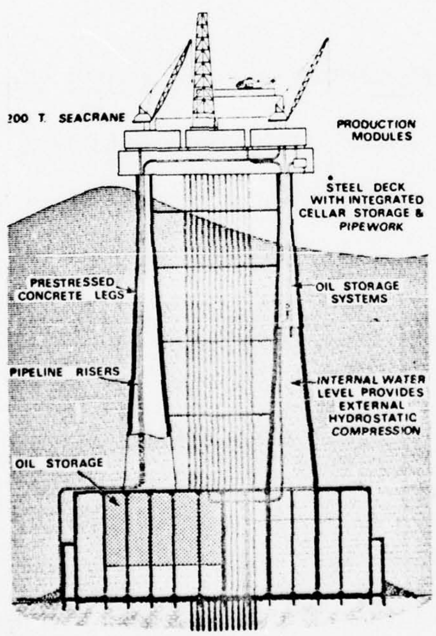

Figure 13.11 Caledonian Groups Forth 150 Concrete Gravity Platform

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) Bouyges - 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)

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

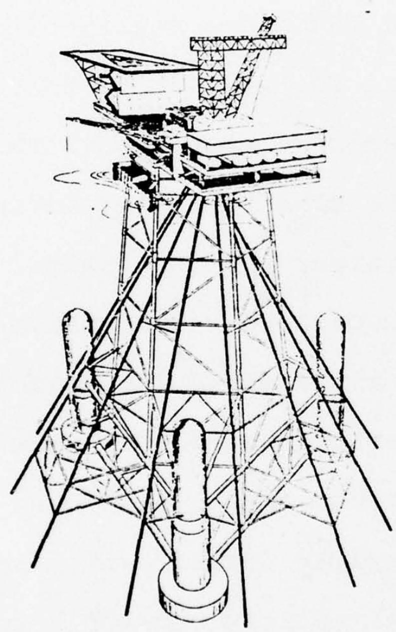

Figure 1.3.12

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)

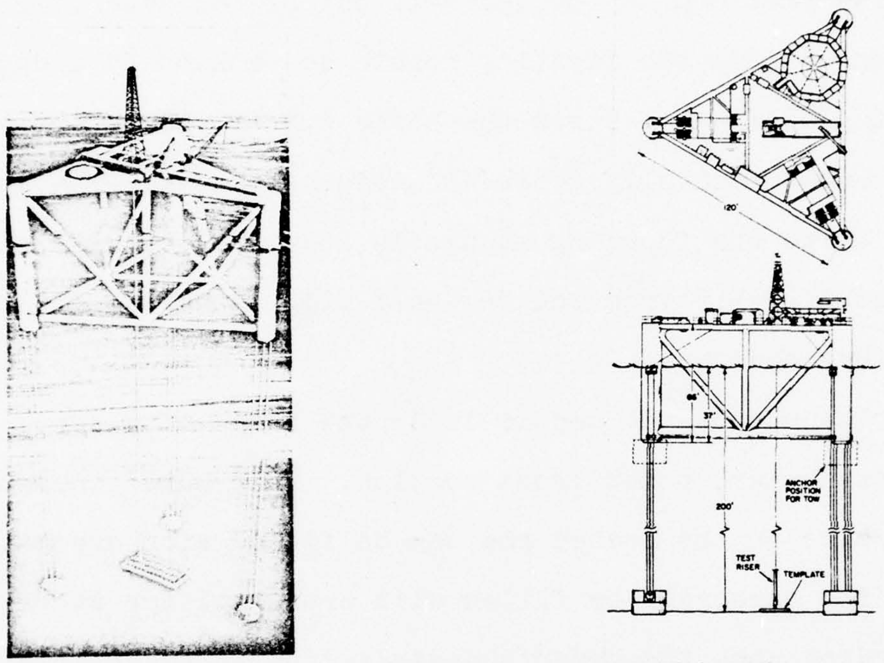

Figure 1.3.13
Deep Oil Technology's Tension Leg Platform

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)

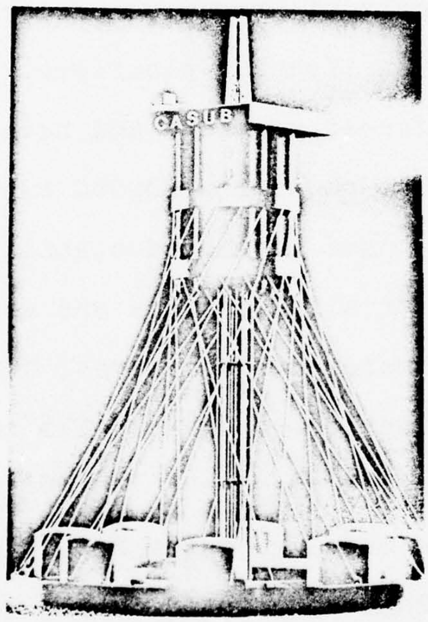

Figure 1.3.14
Cable-Stayed Submerged Buoyant Production Platform

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)

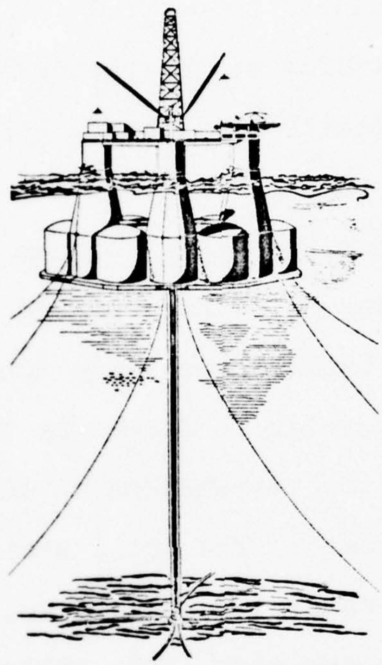

Figure 1.3.15
CONPROD Production Platform

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)

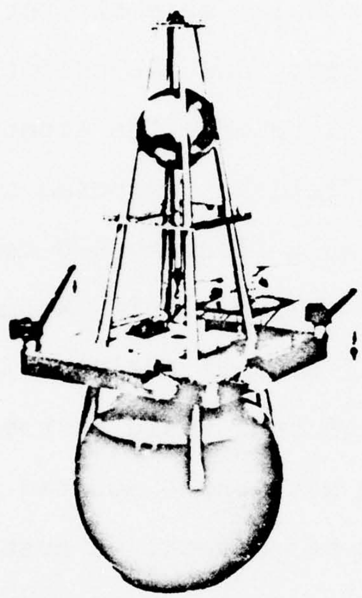

Figure 1.3.16
The Tuned Sphere Drilling Ball

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)

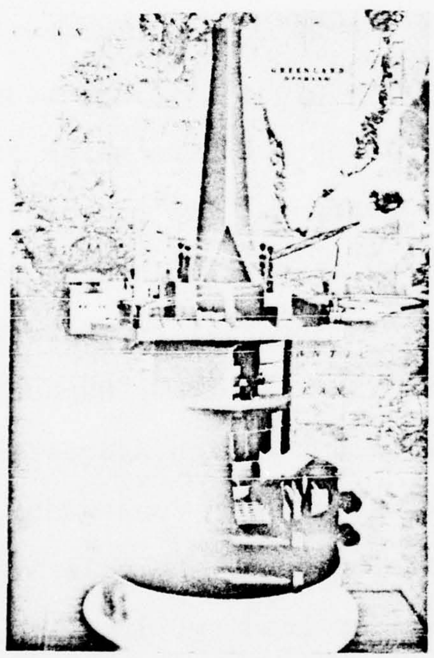

Figure 1.3.17
Trosvik Group's Big Buoy 6000

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 verticle 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)

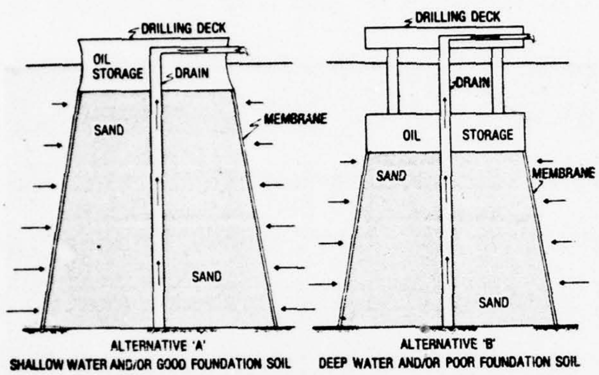

Figure 1.3.18
Golder and Associates' "Sand Bag"

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 Condeep 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)

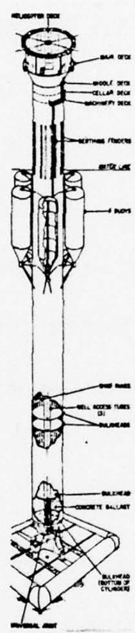

Figure 1.3.19
Typical Articulated Platform

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 [illegible]nt Field and is intended to be a temporary [illegible]. Its purpose is to maintain initial production from [illegible]atory wel[illegible] 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 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)

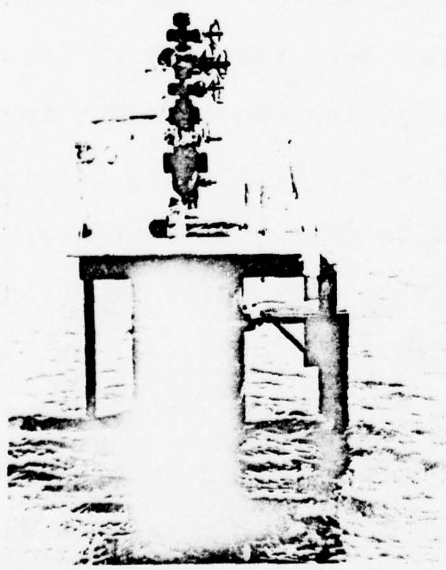

Figure 1.3.20

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. Offshore 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.

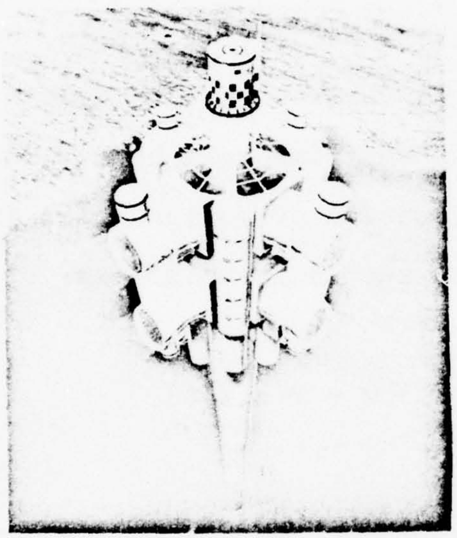

Figure 1.3.21
Lockheed's Conception of Ocean Thermal Plant

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 perdendicular 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 degress 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 $\frac{z}{\ell}$.

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.

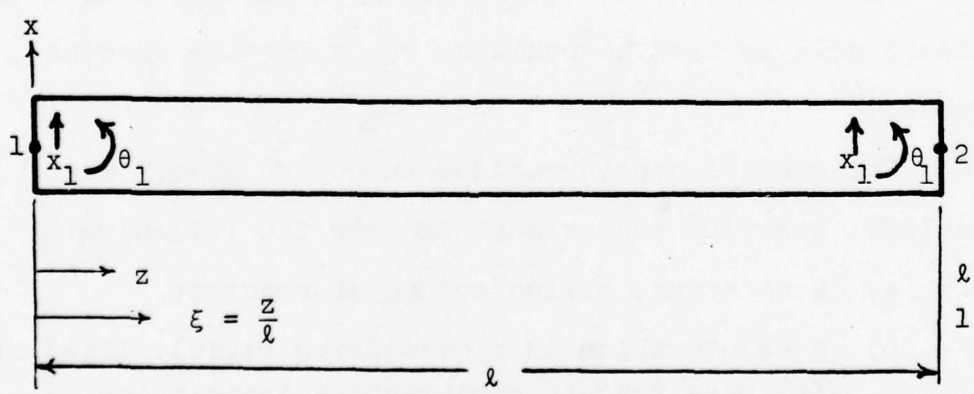

Figure 2.2.1 Simple Beam Parameters

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.

If: $\xi = \frac{z}{\ell}$, $d\xi = (\frac{1}{\ell})dz$, $\frac{d\xi}{dz} = \frac{1}{\ell}$

and: $\theta = \frac{dx}{dz} = \frac{dx}{d\xi}(\frac{d\xi}{dz}) = (\frac{1}{\ell})\frac{dx}{d\xi}$, $\frac{dx}{d\xi} = \ell\theta = x'$

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

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

and: $$x' = \alpha_1 + 2\alpha_2\xi + 3\alpha_3\xi^2$$

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

$$x_1(0) = \alpha_o$$

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

$$x_1'(0) = \alpha_1 = \ell\theta_1$$

$$x_2'(1) = \alpha_1 + 2\alpha_2 + 3\alpha_3 = \ell\theta_2$$

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

$$x = x_1(0) + \ell\theta_1\xi + (-3x_1(0) + 3x_2(1) - 2\ell\theta_1 - \ell\theta_2)\xi^2 +$$

$$+ (2x_1(0) - 2x_2(1) + \ell\theta_1 + \ell\theta_2)\xi^3$$

$$= (1 - 3\xi^2 + 2\xi^3)\ x_1(0) + (3\xi^2 - 2\xi^3)\ x_2(1) +$$

$$+ (\xi - 2\xi^2 + \xi^3)\ \ell\theta_1 + (-\xi^2 + \xi^3)\ \ell\theta_2$$

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

$$\psi_{x_1} = (1 - 3\xi^2 + 2\xi^3)$$

$$\psi_{x_2} = (3\xi^2 - 2\xi^3)$$

$$\psi_{\theta_1} = (\xi - 2\xi^2 + \xi^3)\ \ell$$

$$\psi_{\theta_2} = (-\xi^2 + \xi^3)\ \ell$$

Differentiating with respect to ξ:

$$\psi'_{x_1} = -6\xi + 6\xi^2$$

$$\psi'_{x_2} = 6\xi - 6\xi^2$$

$$\psi'_{\theta_1} = (1 - 4\xi + 3\xi^2)\ell$$

$$\psi'_{\theta_2} = (-2\xi + 3\xi^2)\ \ell$$

and:

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

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

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

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

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:

$$K_{ij} = \int_0^{\ell} EI(z)\ \psi''_i(z)\ \psi''_j(z)\ dz$$

where

$$K = \begin{bmatrix} K_{x_1x_1} & K_{x_1x_2} & K_{x_1\theta_1} & K_{x_1\theta_2} \\ & K_{x_2x_2} & K_{x_2\theta_1} & K_{x_2\theta_2} \\ & & K_{\theta_1\theta_1} & K_{\theta_1\theta_2} \\ & & & K_{\theta_2\theta_2} \end{bmatrix}$$

Convert from "z" to "ξ" co-ordinates

Using:

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

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

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

or

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

Therefore:

$$K_{ij} = \int_0^1 EI(\xi)\left[\left(\frac{1}{\ell^2}\right)\psi_i''(\xi)\right]\left[\left(\frac{1}{\ell^2}\right)\psi_j''(\xi)\right](\ell d\xi)$$

$$= \frac{E}{\ell^3}\int_0^1 I(\xi)\,\psi_i''(\xi)\,\psi_j''(\xi)\,d\xi$$

As a check, assume E and I Constant:

$$K_{x_1x_1} = \frac{EI}{\ell^3}\int_0^1 (\psi_{x_1}'')^2 d\xi = \frac{EI}{\ell^3}\int_0^1(-6 + 12\xi)^2 d\xi = \frac{EI}{\ell^3}\int_0^1(36 - 144\xi + 144\xi^2)d\xi$$

$$= \frac{EI}{\ell^3}\left[36\xi - 72\xi + 48\xi\right]_0^1 = \underline{\underline{\frac{2EI}{\ell^3}(6)}}$$

$$K_{x_1x_2} = \frac{EI}{\ell^3}\int_0^1 (-6 + 12\xi)\ (6 - 12\xi)\ d\xi = \underline{\underline{\frac{2EI}{\ell^3}\ (-6)}}$$

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

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

$$K_{x_2x_2} = \frac{EI}{\ell^3}\int_0^1 (6 - 12\xi)^2\ d\xi = \underline{\underline{\frac{2EI}{\ell^3}\ (6)}}$$

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

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

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

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

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

Stiffness Matrix (Constant E & I):

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

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
- c_1 = internal column radius at bottom of column
- c_2 = external column radius at bottom of column
- d = deck thickness
- e = deck length
- f = deck width
- ρ_1 = density of concrete

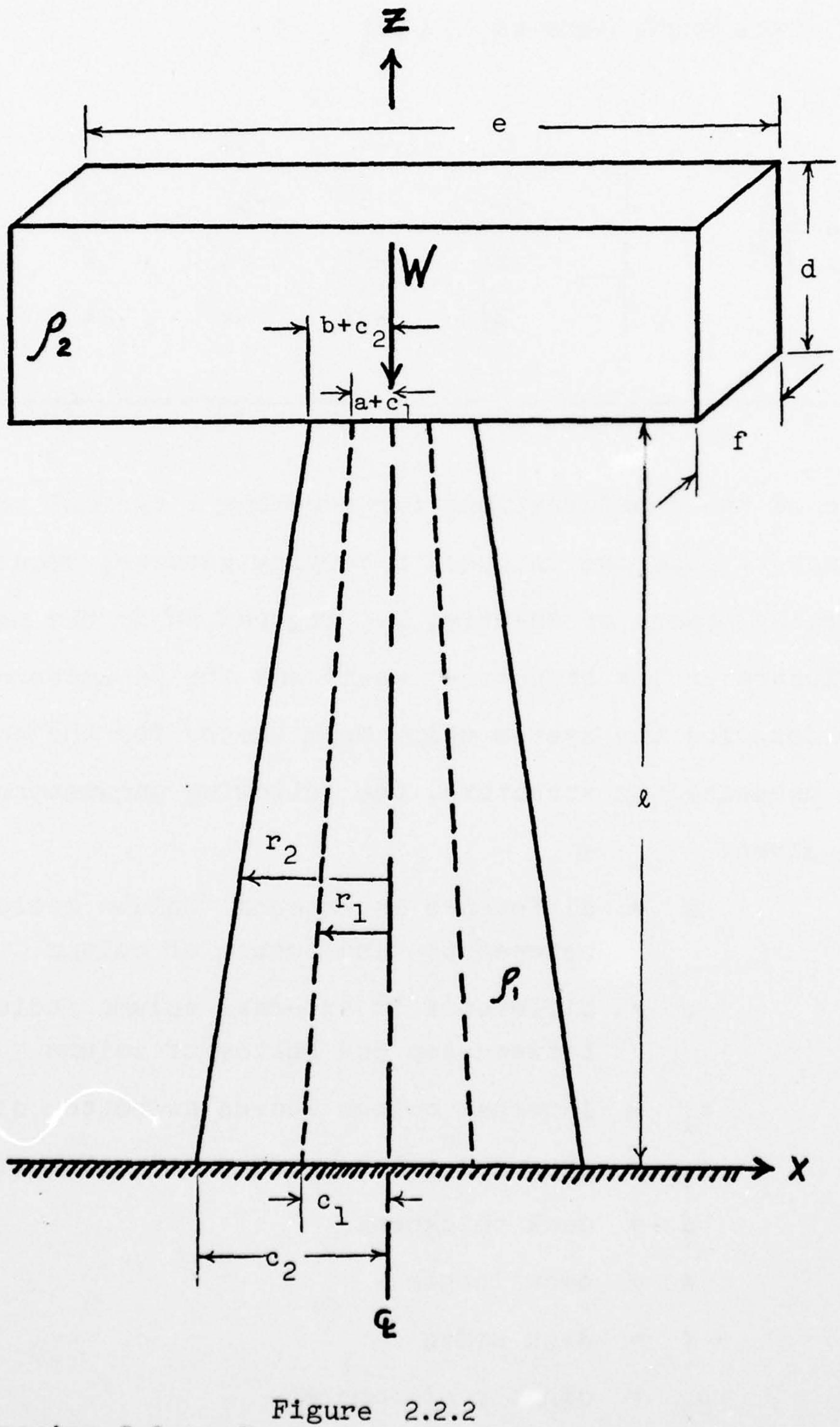

Figure 2.2.2
Tapering Column Parameters Used For Beam Theory

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:

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

$$r_1 = a(\frac{z}{\ell}) + c_1 = a\xi + c_1$$

$$r_2 = b(\frac{z}{\ell}) + c_2 = b\xi + c_2$$

$$M_2 = \rho_2 def$$

$$W_2 = \rho_2 defg$$

$$A(\xi) = \pi r_2^2 - \pi r_1^2 = \pi(r_2+r_1)(r_2-r_1) = \pi(b\xi+c_2+a\xi+c_1)(b\xi+c_2-a\xi-c_1)$$

$$= \pi[\ (b^2-a^2)\xi^2 + 2(c_2 b-c_1 a)\xi + (c_2^2-c_1^2)\ ]$$

$$I_y(\xi) = \tfrac{1}{4}\pi r_2^4 - \tfrac{1}{4}\pi r_1^4 = \frac{\pi}{4}(r_2^2 + r_1^2)\ (r_2^2 - r_1^2)$$

$$= \frac{\pi}{4}(r_2^2 + r_1^2)\ (r_2 + r_1)\ (r_2 - r_1)$$

$$= \frac{\pi}{4}(\ (b\xi + c_2)^2 + (a\xi + c_1)^2\ )\ (b\xi + c_2 + a\xi + c_1)$$

$$(b\xi + c_2 - a\xi - c_1)$$

$$= \frac{\pi}{4} [(b^4 - a^4)\xi^4 + 4(c_2 b^3 - c_1 a^3)\xi^3$$

$$+ 6(c_2^2 b^2 - c_1^2 a^2)\xi^2 + 4(c_2^3 b - c_1^3 a)\xi + (c_2^4 - c_1^4)]$$

$$V(\xi) = \int_0^{\ell} A(z)dz = \int_0^1 A(\xi)\ell d\xi$$

$$= \int \pi\ell(a\xi+c_1+b\xi+c_2)\ (b\xi + c_2 - a\xi - c_1)d\xi$$

$$= \ell\pi \int [ab\xi^2 + c_2 a\xi - a^2\xi^2 - c_1 a\xi + c_1 b\xi + c_1 c_2 - c_1 a\xi - c_1^2$$

$$+ b^2\xi^2 + c_2 b\xi - ab\xi^2 - c_1 b\xi + c_2 b\xi + c_2^2 - c_2 a\xi - c_1 c_2]d\xi$$

$$= \ell\pi \int [(ab-a^2+b^2-ab)\xi^2 + (c_2 a-c_1 a+c_1 b-c_1 a+c_2 b-c_1 b+c_2 b-c_2 a)\xi$$

$$+ (c_1 c_2-c_1^2+c_2^2-c_1 c_2)]d\xi$$

$$= \ell\pi \int [(b^2-a^2)\xi^2 + 2(c_2 b-c_1 a)\xi + (c_2+c_1)\ (c_2-c_1)]d\xi$$

$$= \pi\ell [(b^2-a^2) \frac{\xi^3}{3} + (c_2 b-c_1 a)\xi^2 + (c_2+c_1)(c_2-c_1)\xi]$$

$$= \frac{\pi\ell}{3} [(b^2-a^2)\xi^3 + 3(c_2 b-c_1 a)\xi^2 + 3(c_2^2 - c_1^2)\xi]$$

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

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

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.

$$K_{x_1x_1} = \frac{E}{\ell^3} \int_0^1 I(\xi)\, \psi''^2_{x_1} d\xi$$

$$= \frac{E}{\ell^3} \int_0^1 \left\{ \frac{\pi}{4} [\ (b^4-a^4)\xi^4 + 4(c_2b^3-c_1a^3)\xi^3 + 6(c_2^2b^2-c_1^2a^2)\xi^2 + 4(c_2^3b-c_1^3a)\xi + (c_2^4-c_1^4)\ ] \right\} (-6+12\xi)^2\, d\xi$$

$$= (\frac{E\pi}{4\ell^3}) \int_0^1 [\ (b^4-a^4)\xi^4 + 4(c_2b^3-c_1a^3)\xi^3 + 6(c_2^2b^2-c_1^2a^2)\xi^2 + 4(c_2^3b-c_1^3a)\xi + (c_2^4-c_1^4)\ ][144\xi^2-144\xi+36]d\xi$$

$$= \frac{\pi E}{4\ell^3} \int_0^1 [\ 144(b^4-a^4)\xi^6 + (\ 576\ (c_2b^3-c_1a^3) - 144(b^4-a^4)\ )\xi^5$$

$$+ (864\ (c_2^2b^2-c_1^2a^2) - 576(c_2b^3-c_1a^3) + 36(b^4-a^4)\ )\xi^4$$

$$+ (576\ (c_2^3b-c_1^3a) - 864(c_2^2b^2-c_1^2a^2) + 144(c_2b^3-c_1a^3)\ )\xi^3$$

$$+ (144\ (c_2^4-c_1^4) - 576(c_2^3b-c_1^3a) + 216(c_2^2b^2-c_1^2a^2)\ )\xi^2$$

$$+ 144(\ (c_2^3b-c_1^3a) - (c_2^4-c_1^4)\ )\xi + 36(c_2^4-c_1^4)\ ]d\xi$$

$$= \frac{\pi E}{4\ell^3} \Big[\frac{144}{7}(b^4-a^4)\xi^7 + \Big(\frac{576}{6}(c_2b^3-c_1a^3) - \frac{144}{6}(b^4-a^4)\Big)\xi^6$$

$$+ \Big(\frac{864}{5}(c_2^2b^2-c_1^2a^2) - \frac{576}{6}(c_2b^3-c_1a^3) + \frac{36}{5}(b^4-a^4)\Big)\xi^5$$

$$+ \Big(\frac{576}{4}(c_2^3b-c_1^3a) - \frac{864}{4}(c_2^2b^2-c_1^2a^2) + \frac{144}{4}(c_2b^3-c_1a^3)\Big)\xi^4$$

$$+ \Big(\frac{144}{3}(c_2^4-c_1^4) - \frac{576}{3}(c_2^3b-c_1^3a) + \frac{216}{3}(c_2^2b^2-c_1^2a^2)\Big)\xi^3$$

$$+ \Big(\frac{144}{2}(c_2^3-c_1^3a) - (c_2^4-c_1^4)\Big)\xi^2 + 36\,(c_2^4-c_1^4)\xi \Big] \Big|_0^1$$

$$= \frac{36\pi E}{\ell^3} \Big[\frac{1}{7}(b^4-a^4) + \frac{2}{3}(c_2b^3-c_1a^3) - \frac{1}{6}(b^4-a^4) + \frac{6}{5}(c_2^2b^2-c_1^2a^2)$$

$$- \frac{4}{5}(c_2b^3-c_1a^3) + \frac{1}{20}(b^4-a^4) + (c_2^3-c_1^3a) - \frac{3}{2}(c_2^2b^2-c_1^2a^2)$$

$$+ \frac{1}{4}(c_2b^3-c_1a^3) + \frac{1}{3}(c_2^4-c_1^4) - \frac{4}{3}(c_2^3b-c_1^3a) + \frac{1}{2}(c_2^2b^2-c_1^2a^2)$$

$$+ \frac{1}{2}(c_2^3b-c_1^3a) - \frac{1}{2}(c_2^4-c_1^4) + \frac{1}{4}(c_2^4-c_1^4) \Big]$$

$$= \frac{\pi}{\ell^3} \Big[\frac{33}{35}(b^4-a^4) + \frac{21}{5}(c_2b^3-c_1a^3) + \frac{36}{5}(c_2^2b^2-c_1^2a^2)$$

$$+ 6\,(c_2^3b-c_1^3a) + 3\,(c_2^4-c_1^4) \Big]$$

$$K_{x_1x_2} = \frac{E}{\ell^3} \int_0^1 I(\xi)\, \psi''_{x_1}\, \psi''_{x_2}\, d\xi$$

$$= \frac{E\pi}{\ell^3} \left[-\frac{33}{35}(b^4-a^4) - \frac{21}{5}(c_2b^3-c_1a^3) - \frac{36}{5}(c_2^2b^2-c_1^2a^2) - 6(c_2^3b-c_1^3a) - 3(c_2^4-c_1^4) \right]$$

$$K_{x_1\theta_1} = \frac{E}{\ell^3} \int_0^1 I(\xi)\, \psi''_{x_1}\, \psi''_{\theta_1}\, d\xi$$

$$= \frac{\pi E}{\ell^2} \left[\frac{19}{70}(b^4-a^4) + \frac{6}{5}(c_2b^3-c_1a^3) + \frac{21}{10}(c_2^2b^2-c_1^2a^2) + 2(c_2^3b-c_1^3a) + \frac{3}{2}(c_2^4-c_1^4) \right]$$

$$K_{x_1\theta_2} = \frac{E}{\ell^3} \int_0^1 I(\xi)\, \psi''_{x_1}\, \psi''_{\theta_2}\, d\xi$$

$$= \frac{\pi E}{\ell^2} \left[\frac{47}{70}(b^4-a^4) + 3(c_2b^3-c_1a^3) + \frac{51}{10}(c_2^2b^2-c_1^2a^2) + 4(c_2^3b - c_1^3a) + \frac{3}{2}(c_2^4-c_1^4) \right]$$

$$K_{x_2x_2} = \frac{E}{\ell^3} \int_0^1 I(\xi) \; \psi''^2_{x_2} \; d\xi = \frac{E\pi}{\ell^3} \; [\; \frac{33}{35} (b^4-a^4) + \frac{21}{5} (c_2b^3-c_1a^3)$$

$$+ \frac{36}{5} (c_2^2b^2-c_1^2a^2) + 6 \; (c_2^3-c_1^3a) + c(c_2^4-c_1^4) \;]$$

$$K_{x_2\theta_1} = \frac{E}{\ell^3} \int_0^1 I \; (\xi) \; \psi''_{x_2} \; \psi''_{\theta_1} \; d\xi = \frac{E\pi}{\ell^2} \; [- \frac{19}{70} (b^4-a^4)$$

$$- \frac{6}{5} (c_2b^3-c_1a^3) - \frac{21}{10} (c_2^2b^2-c_1^2a^2) - 2(c_2^3b-c_1^3a)$$

$$- \frac{3}{2} (c_2^4-c_1^4) \;]$$

$$K_{x_2\theta_2} = \frac{E}{\ell^3} \int_0^1 I \; (\xi) \; \psi''_{x_2} \; \psi''_{\theta_2} \; d\xi = \frac{E\pi}{\ell^2} \; [- \frac{47}{70} (b^4-a^4) -3(c_2b^3-c_1a^3)$$

$$- \frac{51}{10} (c_2^2b^2-c_1^2a^2) - 4 \; (c_a^3-c_1^3a) - \frac{3}{2} (c_2^4-c_1^4) \;]$$

$$K_{\theta_1\theta_1} = \frac{E}{\ell^3} \int_0^1 I(\xi) \; \psi''^2_{\theta_1} \; d\xi = \frac{E\pi}{\ell} [\; \frac{3}{35} (b^4-a^4) + \frac{2}{5} (c_2b^3-c_1a^3)$$

$$+ \frac{4}{5} (c_2^2b^2-c_1^2a^2) + (c_2^3b-c_1^3a) + (c_2^4-c_1^4) \;]$$

$$K_{\theta_1\theta_2} = \frac{E}{\ell^3} \int_0^1 I(\xi) \psi''_{\theta_1} \psi''_{\theta_2} \; d\xi = \frac{E\pi}{\ell} [\; \frac{13}{70} (b^4-a^4) + \frac{4}{5} (c_2b^3-c_1a^3)$$

$$+ \frac{13}{10} (c_2^2b^2-c_1^2a^2) + (c_2^3b-c_1^3a) + \frac{1}{2} (c_2^4-c_1^4) \;]$$

$$K_{\theta_2\theta_2} = \frac{E}{\ell^3}\int_0^1 I(\xi)\ \psi''^2_{\theta_2}\ d\xi = \frac{E\pi}{\ell}\Big[\ \frac{17}{35}(b^4-a^4) + \frac{11}{5}(c_2b^3-c_1a^3)$$

$$+ \frac{19}{5}(c_2^2b^2-c_1^2a^2) + 3\,(c_2^3b-c_1^3a) + (c_2^4-c_1^4)\ \Big]$$

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:

$$K_{G_{ij}} = \int_0^1 N(\xi)\ [\ (\tfrac{1}{\ell})\ \psi_i'(\xi)\ ][\ (\tfrac{1}{\ell})\ \psi_j'(\xi)\ ]\ell d\xi$$

where:

$$N(\xi) = W_2 + w_{\substack{\text{column}\\ \text{total}}} - w_1(\xi)$$

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

and where:

$$W_2 = \rho_2 defg$$

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

$$w_1(\xi) = \rho_1 gV(\xi) = \frac{\rho_1 g\pi \ell}{3} [(b^2-a^2)\xi^3$$

$$+ 3(c_2b-c_1a)\xi^2 + 3(c_2^2-c_1^2)\xi]$$

$K_{G_{ij}}$ for constant $W_2 + w_{\substack{column\\total}}$ term:

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

$$K_{Gx_1x_1} = \frac{W}{\ell} \int_0^1 (-6\xi + 6\xi^2)^2 \, d\xi = \frac{W}{\ell} \int_0^1 (36\xi^4 - 72\xi^3 + 36\xi^2) d\xi$$

$$= \frac{W}{\ell} \left[\frac{36}{5}\xi^5 - \frac{72}{4}\xi^4 + \frac{36}{3}\xi^3 \right] \Bigg|_0^1 = \underline{\underline{\frac{W}{30\ell}(36)}}$$

$$K_{G_{x_1x_2}} = \frac{W}{\ell} \int_0^1 (-6\xi + 6\xi^2) d\xi = \underline{\underline{\frac{W}{30\ell}(-36)}}$$

$$K_{Gx_1\theta_1} = \frac{W}{\ell} \int_0^1 (-6\xi + 6\xi^2)(1 - 4\xi + 3\xi^2)\ell d\xi = \underline{\underline{\frac{W}{30\ell}(3\ell)}}$$

$$K_{Gx_1\theta_2} = \frac{W}{\ell} \int_0^1 (-6\xi + 6\xi^2)(-2\xi + 3\xi^2)\ell d\xi = \underline{\underline{\frac{W}{30}(3\ell)}}$$

$$K_{G_{x_2 x_2}} = \frac{W}{\ell} \int_0^1 (6\xi - 6\xi^2)^2 \, d\xi = \frac{W}{30\ell}(36)$$

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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$$K_{Gx_1x_2} = \frac{1}{\ell}\int_0^1 w_1(\xi)\psi'_{x_1}\ \psi'_{x_2}\ d\xi = \frac{\rho_1 g\ \pi}{3}\ [\ -\ \frac{3}{14}(b^2-a^2)$$

$$-\ \frac{12}{35}(c_2b-c_1a) - \frac{9}{5}(c_2^2-c_1^2)\ \ ]$$

$$K_{Gx_1\theta_1} = \frac{1}{\ell}\int_0^1 w_1(\xi)\ \psi'_{x_1}\ \psi'_{\theta_1}\ d\xi = \frac{\rho_1 g\pi\ell}{3}\ [\frac{1}{20}(b^2-a^2)$$

$$+\ \frac{3}{14}(c_2b-c_1a) + \frac{3}{10}(c_2^2-c_1^2)\ \ ]$$

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

$$-\ \frac{3}{35}(c_2^2-c_1^2)\ \ ]$$

$$K_{Gx_2x_2} = \frac{1}{\ell}\int_0^1 w_1(\xi)\ \psi'^2_{x_2}\ \ d\xi\ = \frac{\rho_1 g\pi}{3}\ [\ \ \frac{3}{14}(b^2-a^2)$$

$$+\ \frac{12}{35}(c_2b-c_1a) + \frac{9}{5}(c_2^2-c_1^2)\ \ ]$$

$$K_{Gx_2\theta_1} = \frac{1}{\ell}\int_0^1 w_1(\xi)\ \psi'_{x_2}\ \psi'_{\theta_1}\ d\xi = \frac{\rho_1 g\pi\ell}{3}\ [-\frac{1}{20}(b^2-a^2) - \frac{3}{14}(c_2b-c_1a)$$

$$-\ \frac{3}{10}(c_2^2-c_1^2)\ \ ]$$

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

$$K_{G\theta_1\theta_1} = \frac{1}{\ell}\int_0^1 w_1(\xi)\,\psi'^2_{\theta_1}\,d\xi = \frac{\rho_1 g\pi\ell^2}{3}\left[\frac{11}{840}(b^2-a^2) + \frac{2}{35}(c_2b-c_1a)\right.$$

$$\left. + \frac{1}{10}(c_2^2-c_1^2)\right]$$

$$K_{G\theta_1\theta_2} = \frac{1}{\ell}\int_0^1 w_1(\xi)\,\psi'_{\theta_1}\,\psi'_{\theta_2}\,d\xi = \frac{\rho_1 g\pi\ell^2}{3}\left[-\frac{11}{840}(b^2-a^2) - \frac{3}{70}(c_2b-c_1a)\right.$$

$$\left. - \frac{1}{20}(c_2^2 - c_1^2)\right]$$

$$K_{G\theta_2\theta_2} = \frac{1}{\ell}\int_0^1 w_1(\xi)\,\psi'^2_{\theta_2}\,d\xi = \frac{\rho_1 g\pi\ell^2}{3}\left[\frac{13}{168}(b^2-a^2) + \frac{9}{35}(c_2b-c_1a)\right.$$

$$\left. + \frac{3}{10}(c_2^2-c_1^2)\right]$$

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:

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

$$= \ell \int_0^{1} m_1(\xi)\ \psi_i(\xi)\ \psi_j(\xi) d\xi\ + \ M_2\psi_i(1)\psi_j(1)$$

where:

$$m_1(\xi) = \rho_1 A(\xi) = \rho_1 \pi\ [\ (b^2-a^2)\xi^2 + 2(c_2 b - c_1 a)$$
$$+ (c_2^2 - c_1^2)\ \ ]$$

$$M_2 = \rho_2 def$$

Evaluate the M_2 Term:

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

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

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

$$m_{x_1x_1} = \ell \int_0^1 m_1(\xi)\psi^2_{x_1}\, d\xi = \ell \int_0^1 \rho\pi \, [\, b^2-a^2)\xi^2 + 2(c_2b-c_1a)\xi$$

$$+ (c_2^2-c_1^2) \,]\, [1-6\xi^2+4\xi^3+9\xi^4-12\xi^5+4\xi^6 \,]d\xi$$

$$= \rho\pi\ell \int_0^1 [\, (b^2-a^2)\xi^2 + 2(c_2b-c_1a)\xi + (c_2^2-c_1^2) - 6(b^2-a^2)\xi^4$$

$$- 12(c_2b-c_1a)\xi^3 - 6(c_2^2-c_1^2)\xi^2 + 4(b^2-a^2)\xi^5 + 8(c_2b-c_1a)\xi^4$$

$$+ 4(c_2^2-c_1^2)\xi^3 + 9(b^2-a^2)\xi^6 + 18(c_2b-c_1a)\xi^5 + 9(c_2^2-c_1^2)\xi^4$$

$$-12(b^2-a^2)\xi^7 - 24\,(c_2b-c_1a)\xi^6 - 12(c_2^2-c_1^2)\xi^5 + 4(b^2-a^2)\xi^8$$

$$+ 8(c_2b-c_1a)\xi^7 + 4(c_2^2-c_1^2)\xi^6 \quad]d\xi$$

$$= \rho\pi\ell \,[\, \frac{1}{3}(b^2-a^2)\xi^3 + (c_2b-c_1a)\xi^2 + (c_2^2-c_1^2)\xi - \frac{6}{5}(b^2-a^2)\xi^5$$

$$- \frac{12}{4}(c_2b-c_1a)\xi^4 - \frac{6}{3}(c_2^2-c_1^2)\xi^3 + \frac{4}{6}(b^2-a^2)\xi^6 + \frac{8}{5}(c_2b-c_1a)\xi^5$$

$$+ \frac{4}{4}(c_2^2-c_1^2)\xi^4 + \frac{9}{7}(b^2-a^2)\xi^7 + \frac{18}{6}(c_2b-c_1a)\xi^6 + \frac{9}{5}(c_2^2-c_1^2)\xi^5$$

$$- \frac{12}{8}(b^2-a^2)\xi^8 - \frac{24}{7}(c_2b-c_1a)\xi^7 - \frac{12}{6}(c_2^2-c_1^2)\xi^6 + \frac{4}{9}(b^2-a^2)\xi^9$$

$$+ \frac{8}{8}(c_2b-c_1a)\xi^8 + \frac{4}{7}(c_2^2-c_1^2)\xi^7 \quad] \Big|_0^1$$

$$= \rho\pi\ell[\, (\frac{1}{3} - \frac{6}{5} + \frac{2}{3} + \frac{9}{7} - \frac{3}{2} + \frac{4}{9})(b^2-a^2) + (1 - 3 + \frac{8}{5} + 3 - \frac{24}{7} + 1)$$

$$(c_2b-c_1a) + (1 - 2 + 1 + \frac{9}{5} - 2 + \frac{4}{7})\,(c_2^2 - c_1^2) \quad]$$

$$= \rho\pi\ell[\, (\frac{19}{630}(b^2-a^2) + \frac{6}{35}(c_2b-c_1a) + \frac{13}{35}(c_2^2-c_1^2) \quad]$$

$$m_{x_1x_2} = \ell \int_0^1 m_1(\xi)\psi_{x_1}\psi_{x_2}\, d\xi = \rho\pi\ell\left[\frac{23}{630}(b^2-a^2) + \frac{9}{70}(c_2b-c_1a) + \frac{9}{70}(c_2^2-c_1^2)\right]$$

$$m_{x_1\theta_1} = \ell \int_0^1 m_1(\xi)\psi_{x_1}\psi_{\theta_1}\, d\xi = \rho\pi\ell^2\left[\frac{17}{2520}(b^2-a^2) + \frac{1}{30}(c_2b-c_1a) + \frac{11}{210}(c_2^2-c_1^2)\right]$$

$$m_{x_1\theta_2} = \ell \int_0^1 m_1(\xi)\psi_{x_1}\psi_{\theta_2}\, d\xi = \rho\pi\ell^2\left[-\frac{19}{2520}(b^2-a^2) - \frac{1}{35}(c_2b-c_1a) - \frac{13}{420}(c_2^2-c_1^2)\right]$$

$$m_{x_2x_2} = \ell \int_0^1 m_1(\xi)\psi_{x_2}^2\, d\xi = \rho\pi\ell\left[\frac{29}{126}(b^2-a^2) + \frac{4}{7}(c_2b-c_1a) + \frac{13}{35}(c_2^2-c_1^2)\right] + \rho_2 def$$

$$m_{x_2\theta_1} = \ell \int_0^1 m_1(\xi)\psi_{x_2}\psi_{\theta_1}\, d\xi = \rho\pi\ell^2\left[\frac{5}{504}(b^2-a^2) + \frac{1}{30}(c_2b-c_1a) + \frac{13}{420}(c_2^2-c_1^2)\right]$$

$$m_{x_2\theta_2} = \ell \int_0^1 m_1(\xi)\, \psi_{x_2}\, \psi_{\theta_2}\, d\xi = \rho\pi\ell^2\Big[-\frac{13}{504}(b^2-a^2) - \frac{1}{14}(c_2b-c_1a) - \frac{11}{210}(c_2^2-c_1^2) \Big]$$

$$m_{\theta_1\theta_1} = \ell \int_0^1 m_1(\xi)\, \psi_{\theta_1}^2\, d\xi = \rho\pi\ell^3\Big[\frac{1}{630}(b^2-a^2) + \frac{1}{140}(c_2b-c_1a) + \frac{1}{105}(c_2^2-c_1^2) \Big]$$

$$m_{\theta_1\theta_2} = \ell \int_0^1 m_1(\xi)\, \psi_{\theta_1}\, \psi_{\theta_2}\, d\xi = \rho\pi\ell^3\Big[-\frac{1}{504}(b^2-a^2) - \frac{1}{140}(c_2b-c_1a) - \frac{1}{140}(c_2^2-c_1^2) \Big]$$

$$m_{\theta_2\theta_2} = \ell \int_0^1 m_1(\xi)\, \psi_{\theta_2}^2\, d\xi = \rho\pi\ell^3\Big[\frac{1}{252}(b^2-a^2) + \frac{1}{84}(c_2b-c_1a) + \frac{1}{105}(c_2^2-c_1^2) \Big]$$

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

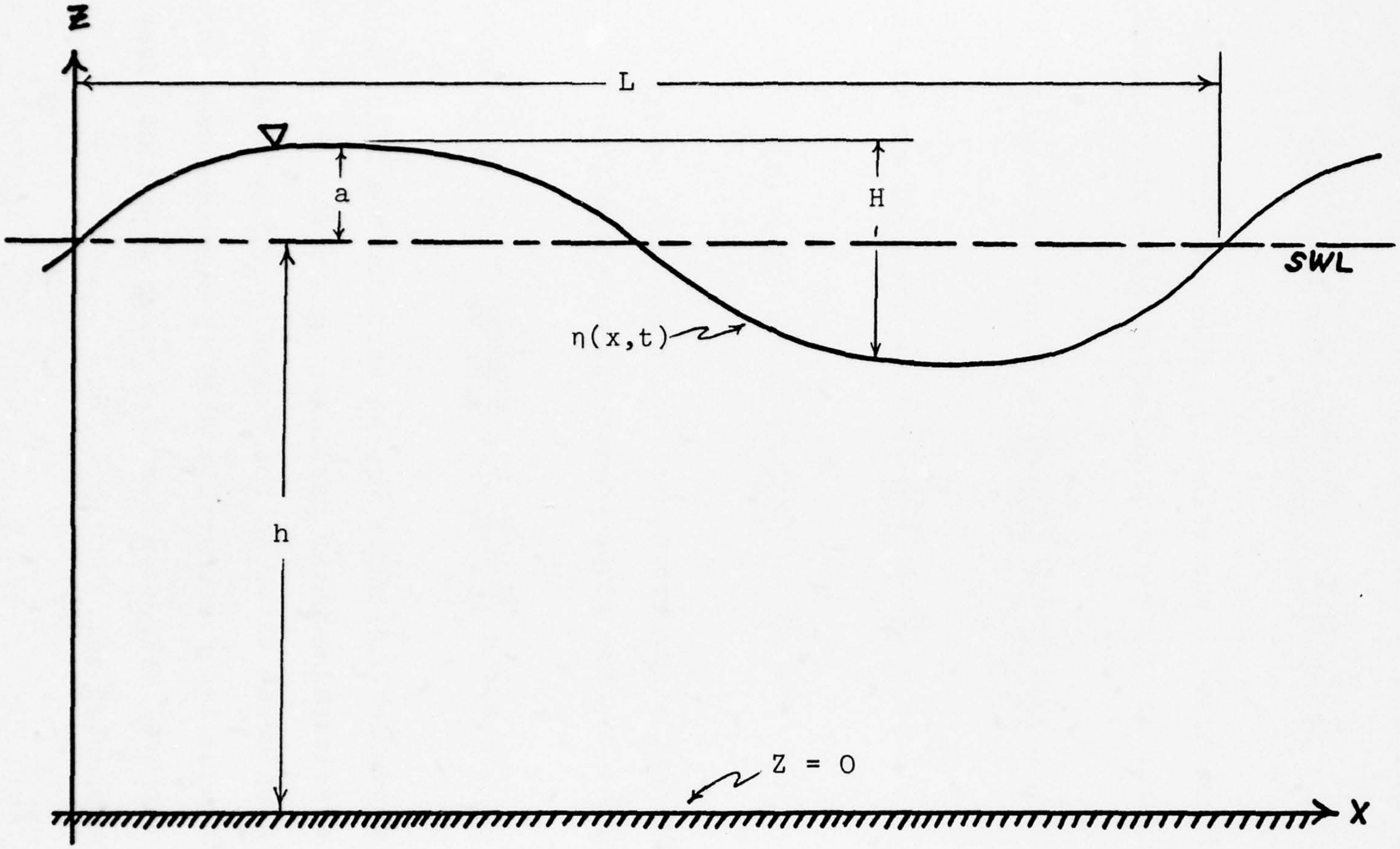

Figure 2.3.1 Parameters Used In Linear Wave Theory

The solution of Laplaces 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:

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

$$= \left(\frac{H}{2}\right)\left(\frac{\cosh kz}{\cosh kh}\right)(\omega \text{ cotanh } kh)\cos(kx - \omega t)$$

$$= \left(\frac{H}{2}\right)\omega\left(\frac{\cosh kz}{\sinh kh}\right)\cos(kx - \omega t)$$

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

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

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:

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

where:

$$F_{inertial} = m \cdot acc$$

$$= [C_I \rho \pi r_2^2] \, (acc)$$

$$F_{drag} = C_D \rho r_2 \; u|u|$$

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:

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

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:

$$P_i(\xi,x,t) = \zeta(x,t) \int_0^{h/\ell} \chi(\xi) \, \psi_i \, (\xi) \, \ell d\xi$$

$$= \zeta(x,t)\ell \int_0^{h/\ell} \chi \, (\xi) \, \psi_i \, (\xi) d\xi$$

where:

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

$$\chi \, (\xi) = r_2^2 \, (\xi) \quad \cosh \, (k \, \ell \, \xi)$$

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 ammenable 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 x 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:

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

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:

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

$k = \frac{2\pi}{L}$, L = 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 $E = \frac{1}{2}(\frac{H}{2})^2 \rho g$. 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

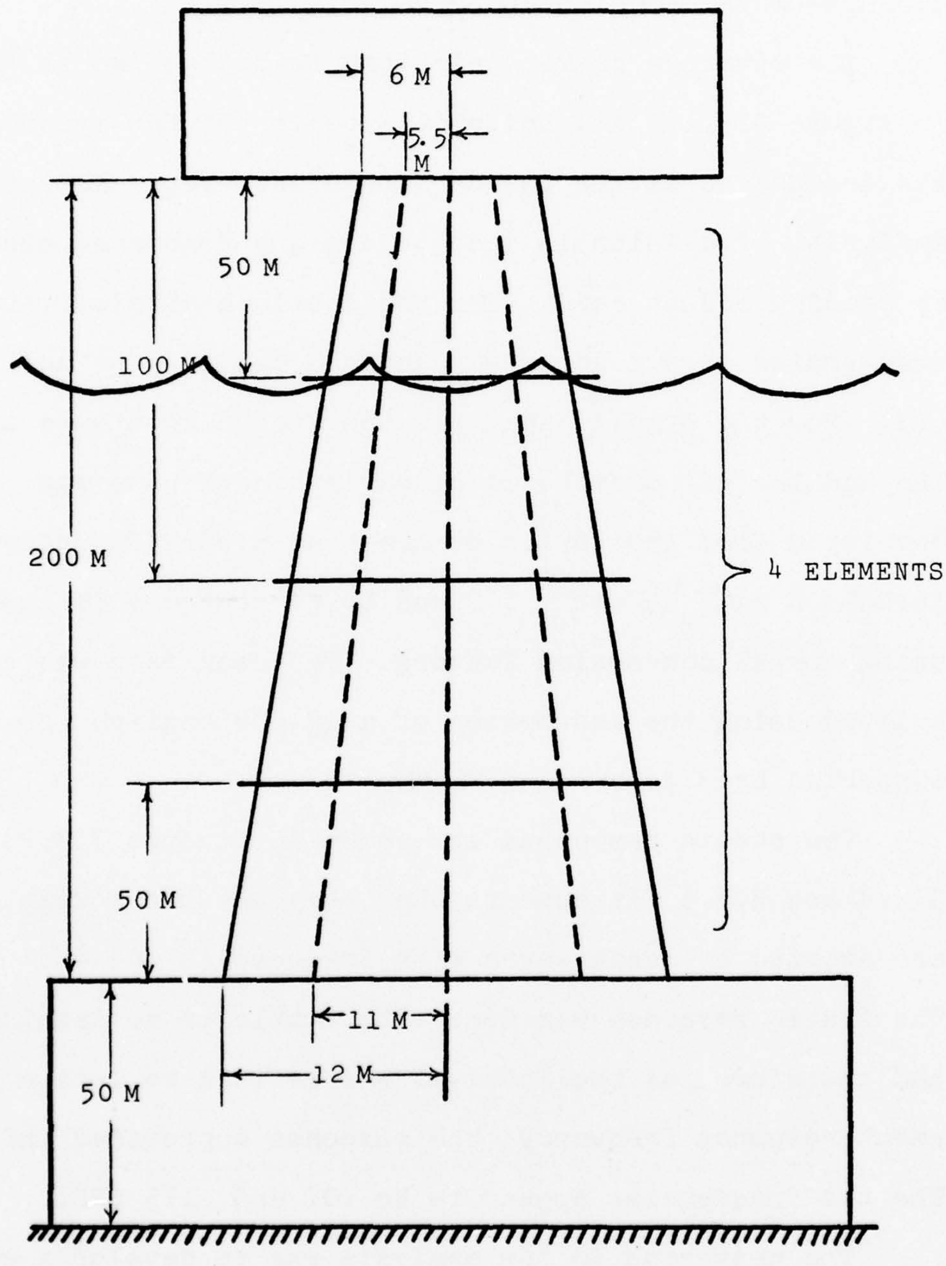

Figure 3.3.1
Dimensions And Shape of Typical Tower Used For The Computer Model

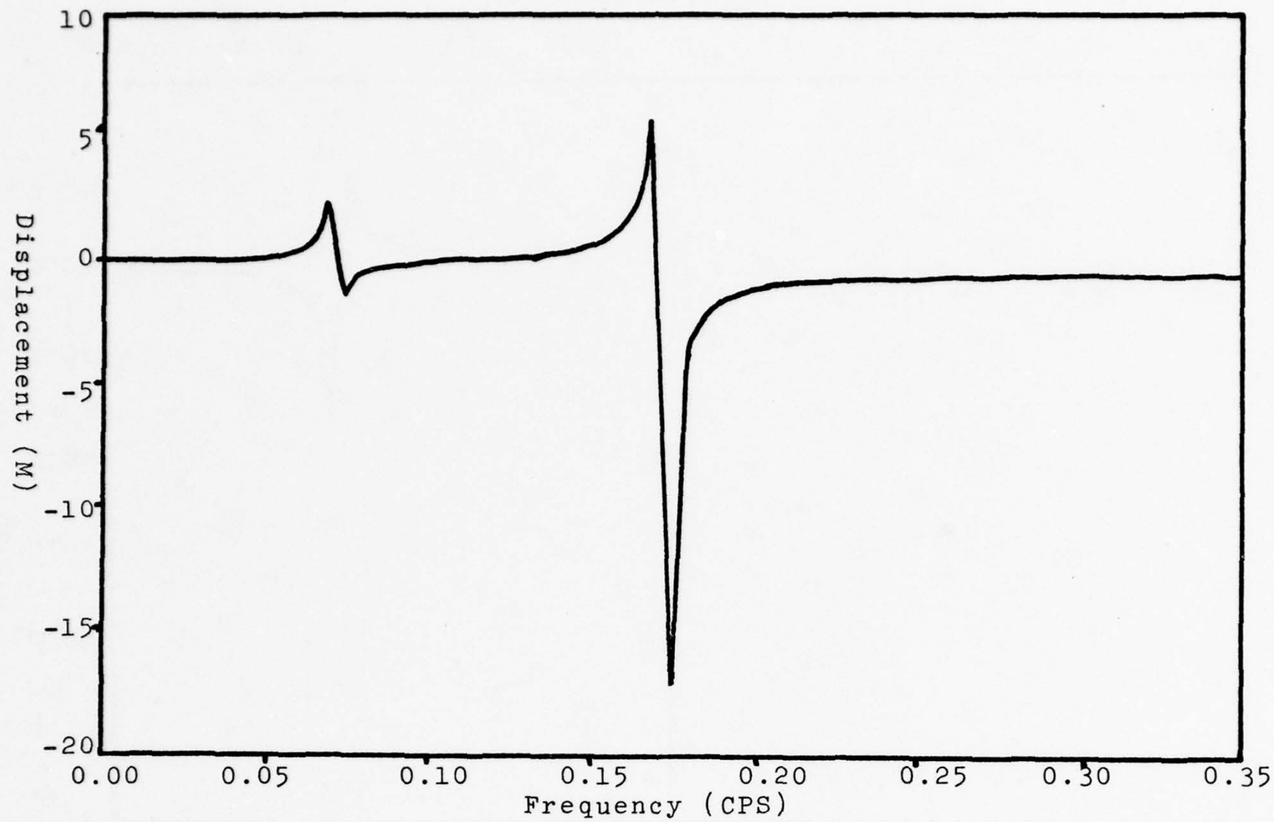

Figure 3.3.2 Displacement of Node 5 for Test Tower - Static Analysis

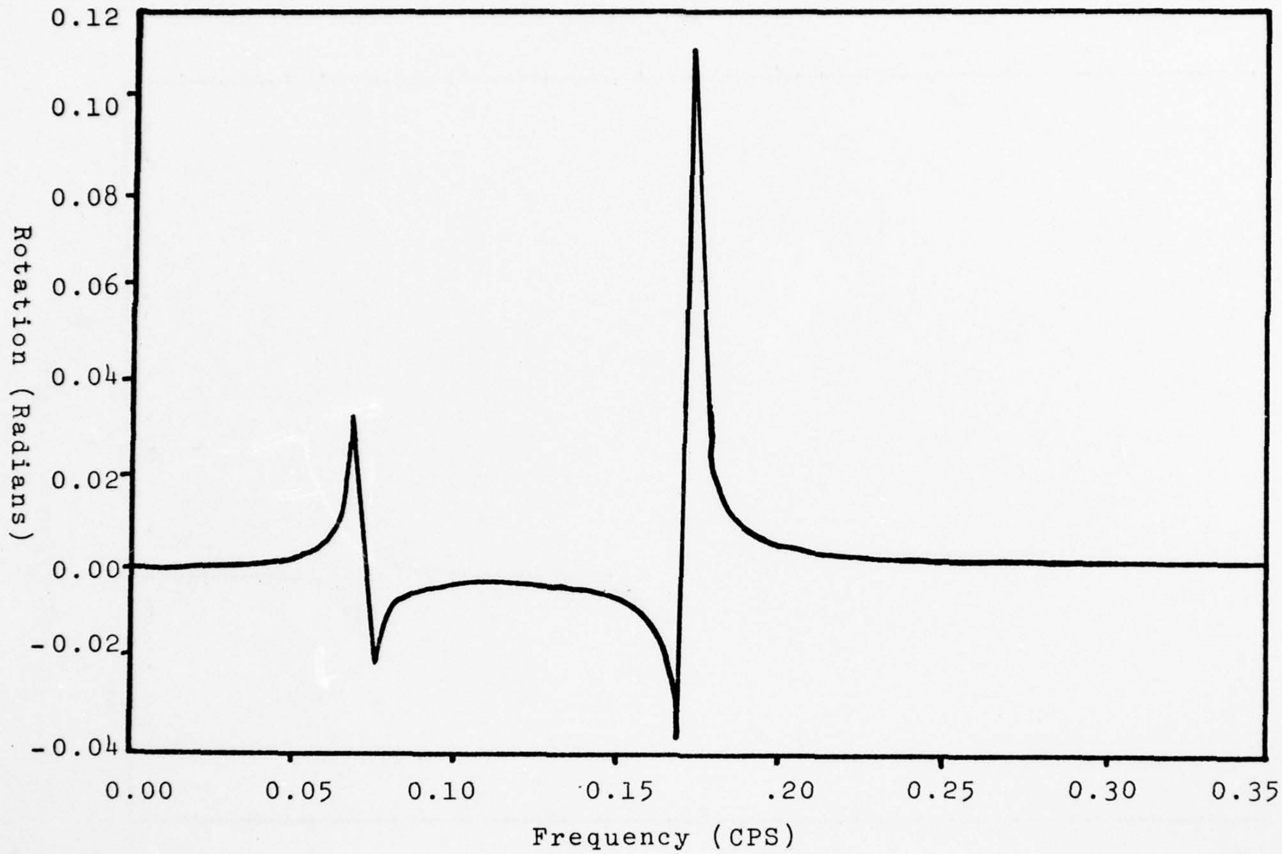

Figure 3.3.3 Rotation of Node 5 for Test Tower - Static Analysis

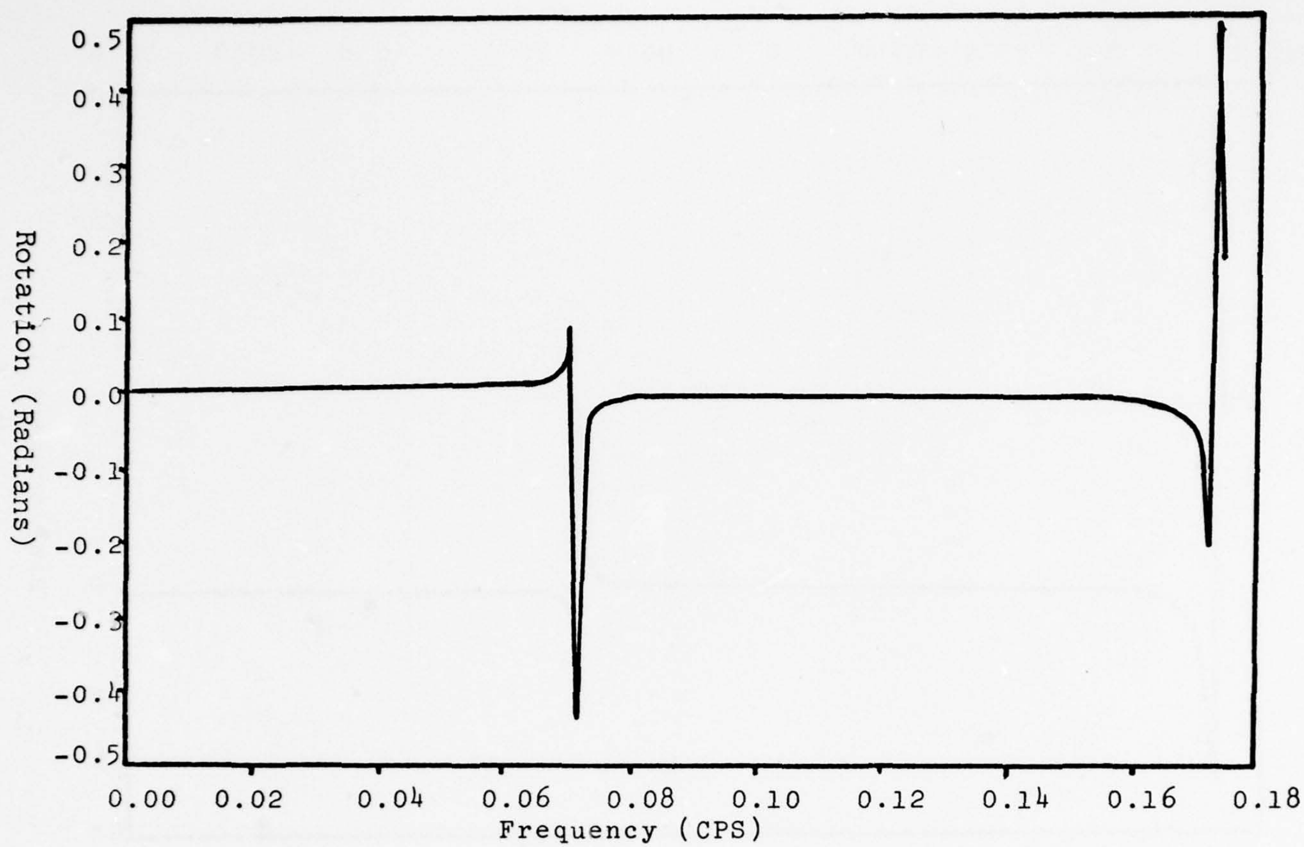

Figure 3.3.4
Narrowed Frequency Range for Static Response of Node 5 - Rotation

Figure 3.3.5
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-sec^2)

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-

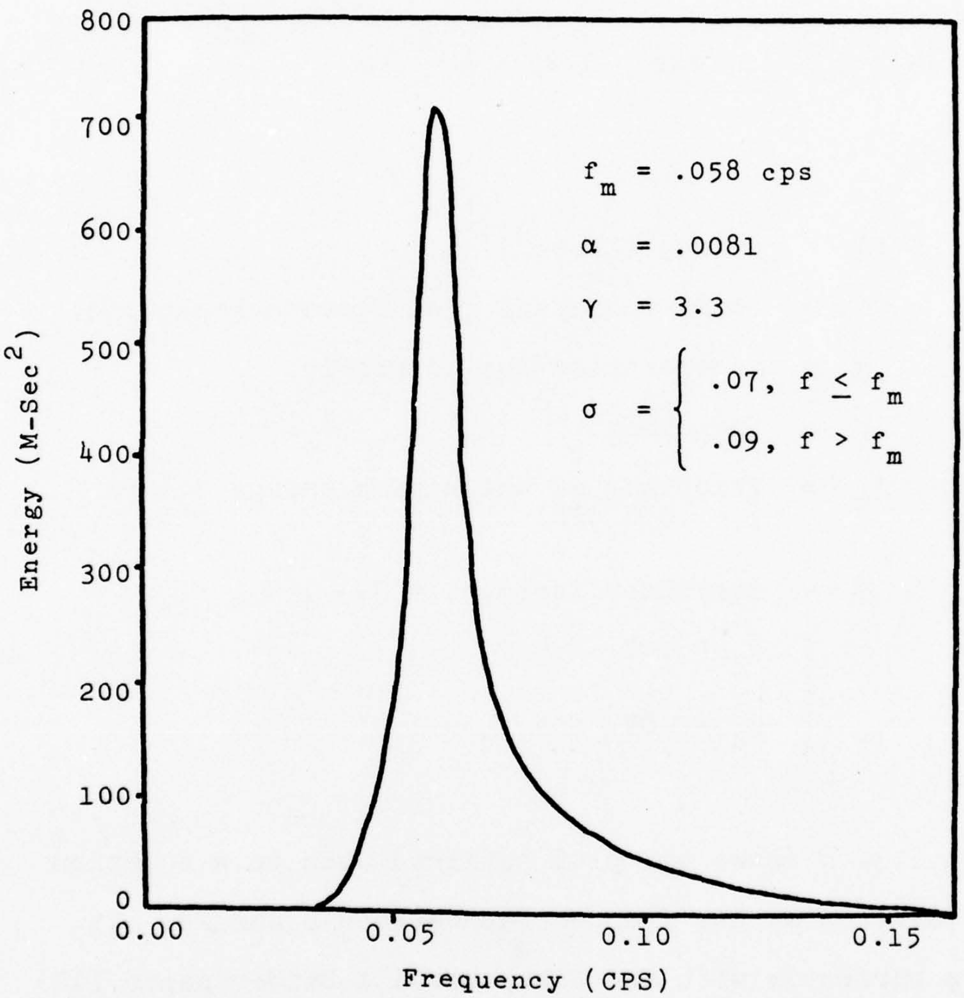

Figure 3.3.6
Typical Energy vs. Frequency Distribution for JONSWAP Wave Spectrum

quenties and wave heights with random phase angles are:

FREQUENCY	WAVE HEIGHT	PHASE ANGLE
.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

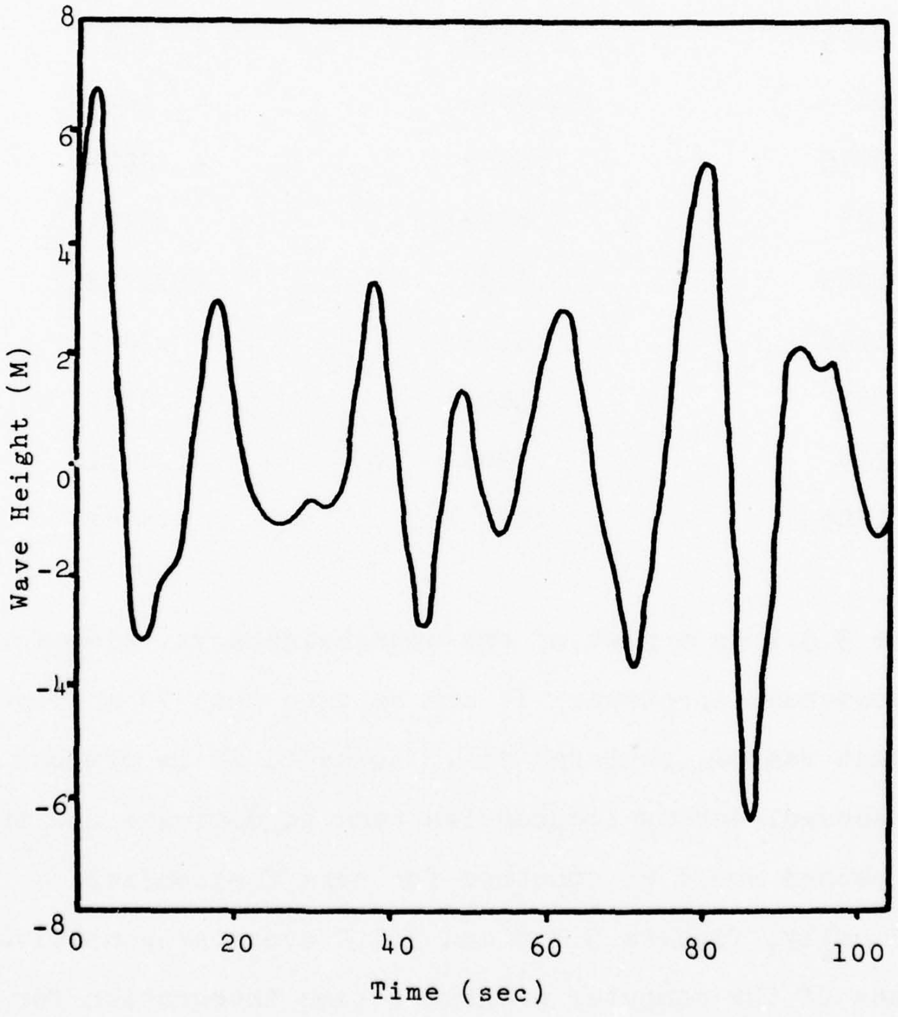

Figure 3.3.7

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.

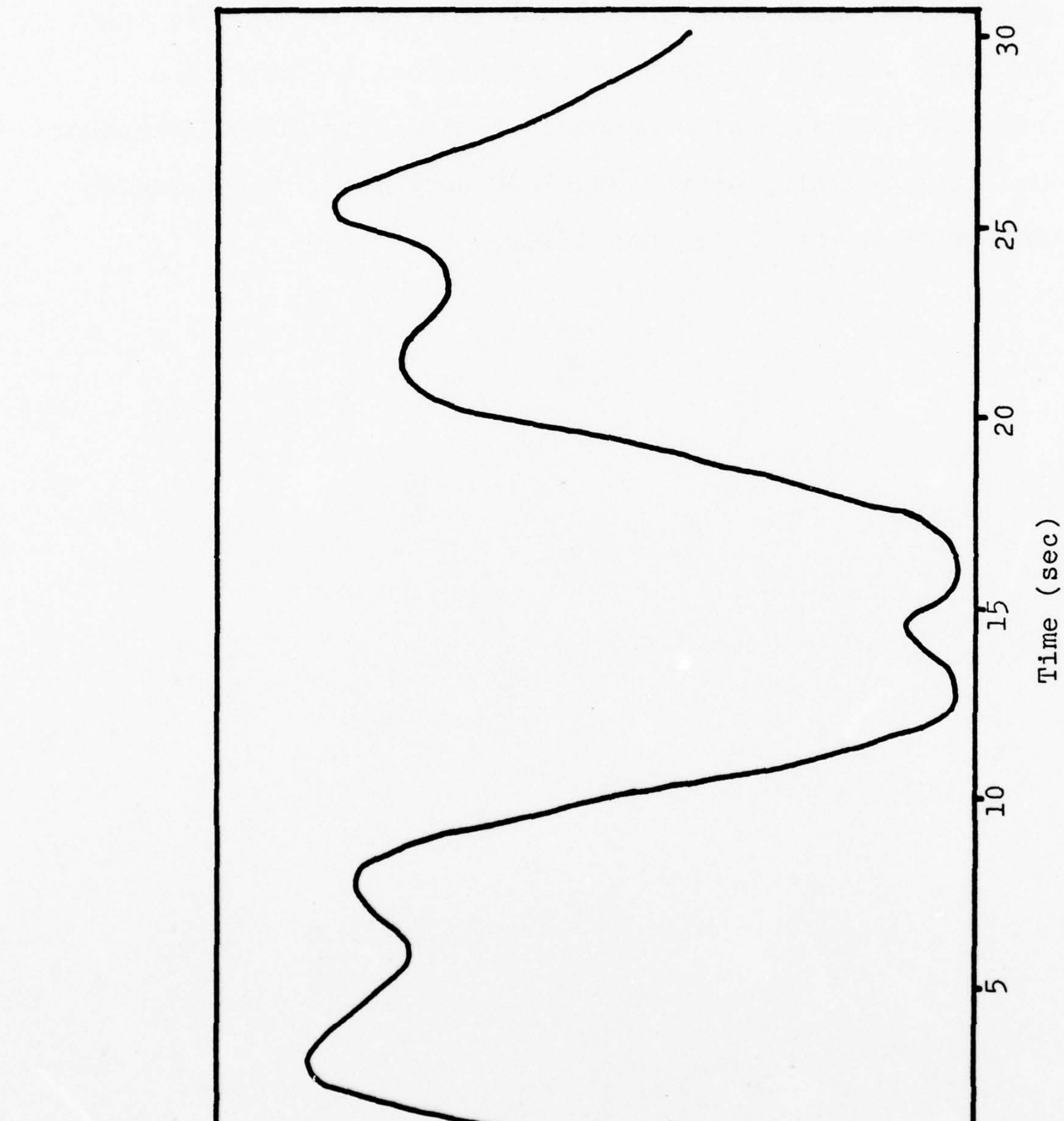

Figure 3.3.8 Displacement of Node 5

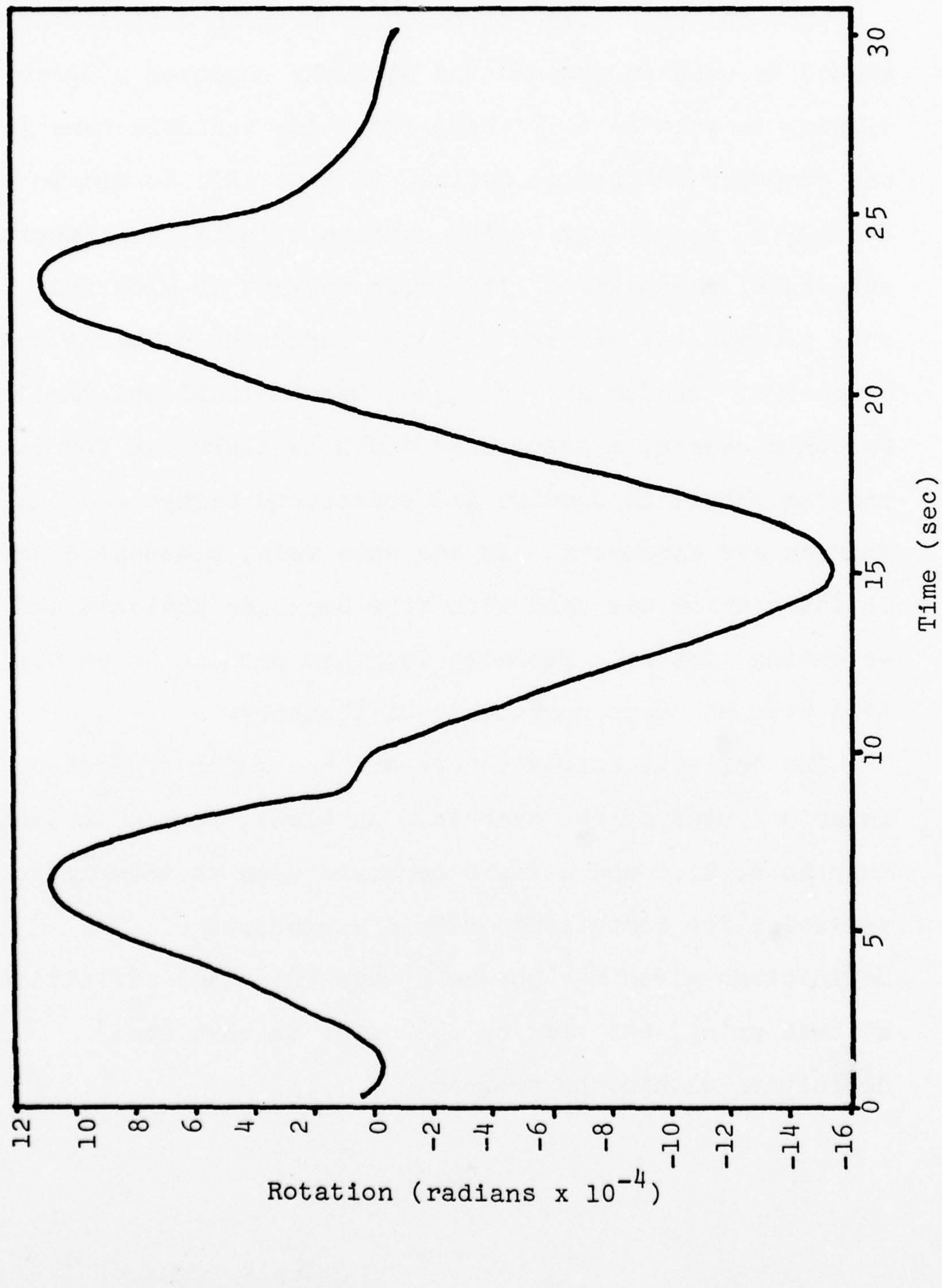

Figure 3.3.9 Rotation of Node 5

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 abcissas 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 - abcissa, 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
F2
F3
F4 } Interpolation Functions

FOUR 2 - 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 MAIN 2

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*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

ZO - 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 deccelerated 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 crange lifts, and outfitting in a near-shore, sheltered areasagain 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

6.1 Computer Program Listing

```
C      *  MAIN PROGRAM  *                                               MP 00
       IMPLICIT  REAL  * 8 ( A-H , O-Z  )                               MP 00A
       DIMENSION  TOWER (20),  FREQ (100),          MASS (200),  STIFF(2 MP 01
      *00),   A (200),  B(50),  DIS (50),  VEL (50),  ACC (50),  R (50), MP 01A
      *S(50) , H(10) , PHASE(10), Q(500)   , F(50)                      MP 01B
       REAL*8   MASS                                                    MP 02
       DATA  IR, IW  /8,5/                                              MP 03
C                                                                       MP 04
C      INPUT DATA                                                       MP 05
       CALL INPUT  (IR, IW, TOWER, NELEM, NFREQ,                        MP 06
      *HEIGHT,ZO,REB,RET,RIB,RIT,DEPTH,E,RO,DMASS,DINER,FREQ,           MP 06A
      *H , PHASE , DT , TIME                                          ) MP 06B
C                                                                       MP 07
C      STIFFNESS AND MASS MATRICES                                      MP 08
       CALL ASMBL  (NELEM, NEQ, MBW,                                    MP 09
      *HEIGHT, REB, RET, RIB, RIT, E, RO, DMASS, DINER, STIFF,     MASS) MP 09A
C                                                                       MP 10
C      DYNAMIC OR STATIC ANALYSIS                                       MP 11
       IF  ( NFREQ  .GE.  0 )  GO  TO  12                               MP 12
       NFREQ = - NFREQ                                                  MP 12A
C      STATIC ANALYSIS IN FREQUENCY DOMAIN                              MP 13
       DO  10    I = 1, NFREQ                                           MP 13A
       CALL TF  (IW,TOWER,NELEM,HEIGHT,ZO,RET,REB, DEPTH,               MP 14
      *NEQ, MBW, STIFF, MASS, A, B, FREQ(I)                            )MP 14A
    10 CONTINUE                                                         MP 15
       STOP                                                             MP 15A
C      DYNAMIC ANALYSIS IN TIME DOMAIN                                  MP 16
    12 IF  ( NFREQ  .EQ.  0 )  STOP                                     MP 16A
       CALL TIME H  ( IW , NEQ , MBW , NFREQ , NELEM ,                  MP 16B
      *RET , REB , HEIGHT , ZO , DEPTH , DT , TIME ,                    MP 16C
      *STIFF , MASS , FREQ , A , B , H , PHASE ,                        MP 16D
      *DIS , VEL , ACC , R , S, F , Q                                 ) MP 16E
       STOP                                                             MP 17
       END                                                              MP 18
```

```
C     SUBROUTINE  INPUT                                                    SI 00
      SUBROUTINE  INPUT  (IR, IW, TOWER, NELEM, NFREQ,                     SI 01
     *HEIGHT, Z0, REB,RET,RIB,RIT, DEPTH ,E,RC,DMASS,DINER,FREQ,           SI 02
     *H , PHASE , DT , TIME                                              ) SI 02A
      IMPLICIT  REAL  * 8 ( A-H , O-Z  )                                   SI 02B
      DIMENSION  TOWER(20) , FREQ(1) , H(1) , PHASE(1)                     SI 03
C                                                                          SI 05
C     READ TOWER AND CONTROL CARD                                          SI 06
      READ  (IR, 1 )  TOWER,  NELEM,  NFREQ                                SI 07
      WRITE  (IW,2 )  TOWER,   NELEM,  NFREQ                               SI 08
C                                                                          SI 09
C     READ OVERALL DIMENSIONS                                              SI 10
      READ  (IR, 3 )  HEIGHT, Z0, REB, RET, RIB, RIT, DEPTH                SI 11
      WRITE (IW,4)  HEIGHT, Z0, REB, RET, RIB, RIT,  DEPTH                 SI 12
C                                                                          SI 13
C     READ MATERIAL PROPERTIES                                             SI 14
      READ    (IR, 3 )  E,  RC                                             SI 15
      WRITE  (IW ,5 )  E,  RC                                              SI 16
C                                                                          SI 17
C     READ DECK LOAD                                                       SI 18
      READ  (IR,3)  DMASS , DINER                                          SI 19
      WRITE  (IW,6)   DMASS, DINER                                         SI 20
C     READ FREQUENCIES                                                     SI 21
      IF  ( NFREQ .GE.  0 )  GO  TO  10                                    SI 22
C     READ FREQUENCIES FOR STATIC RESPONSE IN FREQUENCY DOMAIN             SI 23
      N = -NFREQ                                                           SI 24
      READ  ( IR , 3 )   ( FREQ(I) , I = 1,N  )                            SI 25
      WRITE  ( IW , 7 )  ( FREQ(I) , I = 1,N  )                            SI 26
      RETURN                                                               SI 27
C     READ TIME AND TIME INTERVAL PLUS CONDENSED SPECTRUM PARAMETERS       SI 28
C     FOR DYNAMIC ANALYSIS                                                 SI 28A
   10 IF  ( NFREQ  .LE.  0 )  GO  TO  12                                   SI 29
      READ  (  IR , 3 )  DT , TIME                                         SI 29A
      WRITE  ( IW , 8 )  DT , TIME                                         SI 29B
      DO  11  I = 1,NFREQ                                                  SI 30
   11 READ  ( IR , 3 )   FREQ(I) , H(I) , PHASE(I)                         SI 30A
```

```
      WRITE  ( IW , 9 ) (FREQ(1) , H(I) , PHASE(I) ,  I = 1,NFREQ  )     SI 30B
   12 RETURN                                                             SI 31
C                                                                        SI 32
    1 FORMAT   (20 A 4 ,/, 4I4  )                                        SI 33
    2 FORMAT    ('1',/,5X,  20A4,//,                                     SI 34
     * 5X, I5, ' ELEMENTS' , / , 5X, I5, ' FREQUENCIES' ,/)              SI 35
    3 FORMAT   ( 10F8.2)                                                 SI 36
    4 FORMAT (///5X, '*OVERALL DIMENSIONS*'//                            SI 37
     *5X, 'TOWER HEIGHT       ', F8.2, ' M.'/                            SI 38
     *5X, 'CAISSON HEIGHT     ', F8.2, ' M.'//                           SI 39
     *5X, 'EXTERNAL RADIUS AT THE BOTTOM    ', F7.2, ' M.'/              SI 40
     *5X, 'EXTERNAL RADIUS AT THE TOP       ', F7.2, ' M.'/              SI 41
     *5X, 'INTERNAL RADIUS AT THE BOTTOM    ', F7.2, ' M.'/              SI 42
     *5X, 'INTERNAL RADIUS AT THE TOP       ', F7.2, ' M.'//             SI 43
     *5X, 'DEPTH OF WATER    ', F8.2, ' M.'/)                            SI 44
    5 FORMAT (///5X, '*MATERIAL PROPERTIES*'//                           SI 45
     *5X, 'E  =', E10.3/5X,'RO =',  E10.3/)                              SI 46
    6 FORMAT (///5X, 'DECK MASS        ', E12.4/                         SI 47
     *                 5X, 'DECK INERTIA   ', E12.4/)                    SI 48
    7 FORMAT  (///5X, '*FREQUENCIES FOR ANALYSIS*'//(5X, 10F8.5))        SI 49
    8 FORMAT  (///5X ,  ' * TIME INTERVAL AND TOTAL TIME * '//5X ,       SI 50
     *'DELTA T =  ', F7.3/5X , 'TIME    =  ', F7.3/  )                   SI 51
    9 FORMAT  ( ///5X , ' * CONDENSED SPECTRUM PARAMETERS * '//13X ,     SI 52
     *'FREQ' , 8X , 'WAVE HEIGHT' , 3X , 'PHASE ANGLE'//(3X , 3F15.4))   SI 52A
C                                                                        SI 53
      END                                                                SI 54
```

```
C     SUBROUTINE  ASMBL                                                    SAS 00
      SUBROUTINE  ASMBL  (NELEM, NEQ, MBW,                                 SAS 01
     *HEIGHT, REB, RET, RIB, RIT, E, RO, DMASS, DINER, STIFF,        MASS)SAS 02
      IMPLICIT  REAL  * 8 ( A-H , O-Z  )                                   SAS 03
      REAL*8   MASS , LENGHT                                               SAS 04
      DIMENSION   STIFF (1) ,  MASS (1) ,   A(10)                          SAS 05
C                                                                          SAS 06
C     INITIALIZE                                                           SAS 07
      NEQ = 2*(NELEM +1 )                                                  SAS 08
      MBW = 4                                                              SAS 09
      LIM = NEQ * MBW                                                      SAS 10
      DO  10  I = 1,LIM                                                    SAS 11
      STIFF(I) = 0.                                                        SAS 12
   10 MASS (I) = 0.                                                        SAS 13
C                                                                          SAS 14
C     COMPUTE ELEMENT MATRICES AND ASSEMBLE                                SAS 15
      DN = NELEM                                                           SAS 16
      LENGHT = HEIGHT/DN                                                   SAS 17
      DA = (RET-REB)/DN                                                    SAS 18
      DB = (RIT-RIB) / DN                                                  SAS 19
      A1 = REB                                                             SAS 20
      B1 = RIB                                                             SAS 21
      EMASS = DMASS                                                        SAS 22
C                                                                          SAS 23
      DO  12   N = 1, NELEM                                                SAS 24
      A2 = A1 + DA                                                         SAS 25
      B2 = B1 + DB                                                         SAS 26
      CALL SUBK  (E,A1,B1,A2,B2,LENGHT, A  )                               SAS 27
      CALL ADD  (NEQ  ,STIFF , N , A  )                                    SAS 28
      CALL        SUBM  (RO,A1,B1,A2,B2,LENGHT, EMASS, A      )            SAS 29
      CALL ADD  (NEQ  ,MASS,   N,    A    )                                SAS 30
      A1 = A2                                                              SAS 31
   12 B1 = B2                                                              SAS 32
C                                                                          SAS 33
C     ADD DECK MASS                                                        SAS 34
      I = 2 * NELEM                                                        SAS 35
```

```
      MASS  (I+1) = MASS(I+1)  +  DMASS                              SAS 36
      MASS (I+2) = MASS (I+2) + DINER                                SAS 37
C                                                                    SAS 38
      A1 = REB                                                       SAS 39
      B1 = RIB                                                       SAS 40
      DO  14  M = 1, NELEM                                           SAS 41
      A2 = A1 + DA                                                   SAS 42
      B2 = B1 + DB                                                   SAS 43
      CALL SUBKG (RC, REB, RIB, A1, B1, A2, B2, LENGHT, EMASS, M,A ) SAS 44
      CALL ADD (NEQ, STIFF, M, A)                                    SAS 45
      A1 = A2                                                        SAS 46
   14 B1 = B2                                                        SAS 47
      RETURN                                                         SAS 48
      END                                                            SAS 49
```

```
C     SUBROUTINE  SUBK                                                   SK 00
      SUBROUTINE  SUBK  (E,A1,E1,A2,B2,LENGHT,STIFF)                     SK 01
      IMPLICIT  REAL  * 8 ( A-H , O-Z  )                                 SK 01A
      REAL*8  LENGHT                                                     SK 02
      DIMENSION  A(5), W(5),  F(4),  STIFF(1C)                           SK 03
      DATA A,W / C., -.538469,  .538469,  -.9C6180,  .906180,  .568889,  SK 04
     *2*.478629,  2*.236927             /                                SK 04A
      DO  1  I = 1,10                                                    SK 05
    1 STIFF(I) = C.                                                      SK 06
      DO  2    N = 1,5                                                   SK 07
      X = A(N)                                                           SK 08
      X = .5*(X+1.)                                                      SK 09
      F(1) = 12.*X-6.                                                    SK 10
      F(3) = -F(1)                                                       SK 11
      F(2) = (-4.+ 6.*X)*LENGHT                                          SK 12
      F(4) = (-2.+6.*X)*LENGHT                                           SK 13
      AA = A1*(1.-X)+A2*X                                                SK 14
      B = B1*(1.-X)+B2*X                                                 SK 15
      C = 0.7853981 *  (AA**4-B**4)/LENGHT**3/2.*W(N)*E                  SK 16
      IJ = 0                                                             SK 17
      DO  2  J = 1,4                                                     SK 18
      DO  2  I = 1,J                                                     SK 19
      IJ = IJ+1                                                          SK 20
    2 STIFF(IJ) = STIFF(IJ)  + C*F(I)*F(J)                               SK 21
      RETURN                                                             SK 22
      END                                                                SK 23
```

```
C     SUBROUTINE ADD                                          SA 00
      SUBROUTINE  ADD   ( NEQ , A , N , B  )                  SA 01
      IMPLICIT  REAL  * 8 ( A-H , O-Z  )                      SA 01A
      DIMENSION  A(1)  , B(1)                                 SA 02
      NN = 2*(N-1)                                            SA 03
      KL = 0                                                  SA 04
      DO   10   J=1,4                                         SA 05
      DO   10   I=1,J                                         SA 06
      II =   J-I                                              SA 07
      IJ = NEQ*II+NN+I                                        SA 08
      KL = KL+1                                               SA 09
   10 A(IJ)  = A(IJ)  + B(KL)                                 SA 10
      RETURN                                                  SA 11
      END                                                     SA 12
```

```
C     SUBROUTINE SUEM                                                            SM 00
      SUBROUTINE SUEM   (RO,A1,E1,A2,B2,LENGHT,EMASS,MASS)                       SM 01
      IMPLICIT  REAL  * 8 ( A-H , O-Z  )                                         SM 01A
      REAL*8   LENGHT , MASS                                                     SM 02
      DIMENSION  A(5), W(5),  F(4),    MASS(1C)                                  SM 03
      DATA A,W / C., -.538469,  .538469,  -.9C6180,  .906180,  .568889,          SM 04
     *2*.478629 ,    2*.236927        /                                          SM 04A
      DO  1  I = 1,10                                                            SM 05
    1 MASS (I) = C.                                                              SM 06
      DO  2    N = 1,5                                                           SM 07
      X = A(N)                                                                   SM 08
      X = .5*(X+1.)                                                              SM 09
      F(3) = X*X*(3.-2.*X)                                                       SM 10
      F(1) = 1.-F(3  )                                                           SM 11
      F(2) = X*LENGHT*(1.-2.*X+X*X)                                              SM 12
      F(4) = X*X*LENGHT*(X-1.)                                                   SM 13
      AA = A1*(1.-X)+A2*X                                                        SM 14
      B = B1*(1.-X)+B2*X                                                         SM 15
      C = 3.14159265*(AA*AA-B*B)*RO*LENGHT/2.*W(N)                               SM 16
      EMASS = EMASS+C                                                            SM 16A
      IJ = 0                                                                     SM 17
      DO  2  J = 1,4                                                             SM 18
      DO  2  I = 1,J                                                             SM 19
      IJ = IJ+1                                                                  SM 20
    2 MASS (IJ) = MASS(IJ) + C* F(I)  * F(J)                                     SM 21
      RETURN                                                                     SM 22
      END                                                                        SM 23
```

```
C                                                                        SKG 00
C     SUBROUTINE  SUBKG                                                  SKG 01
      SUBROUTINE SUBKG (RO, REB, RIB, A1, B1, A2, B2, LENGHT, EMASS, M,  SKG 02
     *                                  STIFG)                           SKG 03
      IMPLICIT  REAL  * 8 ( A-H , O-Z  )                                 SKG 03A
      REAL*8   LENGHT                                                    SKG 04
      DIMENSION  A(5),W(5),F(4),STIFG(10)                                SKG 05
      DATA A, W / -.906180, -.538469, 0. , .538469, .906180, .236927,    SKG 06
     *.478629, .568889, .478629, .236927  /                              SKG 07
      DM = M    -1                                                       SKG 08
      DO  1   I = 1,10                                                   SKG 09
    1 STIFG(I) = 0.                                                      SKG 10
      DO  2  N = 1,5                                                     SKG 11
      X = A(N)                                                           SKG 12
      X = .5*(X+1.)                                                      SKG 13
      F(1) = X*6.*(X-1.)                                                 SKG 14
      F(2) = (1.-4.*X+3.*X*X)*LENGHT                                     SKG 15
      F(3) =   -F(1)                                                     SKG 16
      F(4) = (3.*X-2.)*LENGHT*X                                          SKG 17
      A3 = (A2-A1)*X + A1                                                SKG 18
      B3 = (B2-B1)*X + B1                                                SKG 19
      QMASS = RO * 3.14159265 * ( DM + X ) * LENGHT/ 3. * (( REB * REB   SKG 20
     *+ A3*REB + A3*A3 ) - (RIB * RIB + B3*RIB + B3*B3))                 SKG 21
      P = 9.81 *  ( EMASS - QMASS )           /LENGHT * W(N) / 2.        SKG 22
      IJ = 0                                                             SKG 23
      DO  2  J = 1,4                                                     SKG 25
      DO  2  I = 1,J                                                     SKG 26
      IJ = IJ + 1                                                        SKG 27
    2 STIFG(IJ) = STIFG(IJ)  + P*F(I)*F(J)                               SKG 28
      RETURN                                                             SKG 29
      END                                                                SKG 30
```

```
C                                                                        TF 00
C     SUBROUTINE  TF                                                     TF 01
      SUBROUTINE TF  (IW,TOWER,NELEM,HEIGHT,ZO, RET,REB,DEPTH,           TF 02
     * NEQ , MEW , STIFF , MASS , A , B , FREQ                    )      TF 03
      IMPLICIT  REAL  * 8 ( A-H , O-Z  )                                 TF 03A
      REAL*8     MASS , LENGHT                                           TF 04
      DIMENSION TOWER(20), STIFF(1), MASS(1), A(1), B(10),P(4)           TF 05
      W2 = ( 6.28318531 * FREQ ) ** 2                                    TF 06
C                                                                        TF 07
C     FORM COEFFICIENT MATRIX                                            TF 08
      LIM = NEQ*MEW                                                      TF 09
      DO   1  I = 1,LIM                                                  TF 10
    1 A(I) = STIFF(I) - W2 * MASS(I)                                     TF 11
C                                                                        TF 12
C                                                                        TF 13
C     FORM LOAD VECTOR                                                   TF 14
      DO   2  I = 1,NEQ                                                  TF 15
    2 B(I) = 0.                                                          TF 16
      DN = NELEM                                                         TF 17
      LENGHT = HEIGHT/DN                                                 TF 19
      DA = ( RET-REB)/DN                                                 TF 21
      A1 = REB                                                           TF 23
      DO   4  N = 1,NELEM                                                TF 24
      A2 = A1 + DA                                                       TF 25
      CALL SUBP  (N, A1, A2, LENGHT, ZO, DEPTH, W2, [illegible] )        TF 26
      J = 2*(N-1)                                                        TF 27
      DO   3  I = 1,4                                                    TF 28
      J = J+1                                                            TF 29
    3 B(J) = B(J)   +  P(I)                                              TF 30
    4 A1 = A2                                                            TF 31
C                                                                        TF 32
C     IMPOSE DISPLACEMENT BOUNDARY CONDITIONS                            TF 33
      DO   5  I = 1, LIM, NEQ                                            TF 34
      A(I) = 0.                                                          TF 35
    5 A(I+1) = 0.                                                        TF 36
      B(1) = 0.                                                          TF 37
```

```
      B(2) = 0.                                                         TF 38
C                                                                       TF 39
C     SOLVE SYSTEM OF EQUATIONS                                         TF 40
      CALL SOLVE  ( 0, IW, NEQ, MBW, 1, A, B  )                         TF 41
C                                                                       TF 42
C     PRINT OUT STEADY - STATE RESPONSE                                 TF 43
      WRITE   (IW,6)   TOWER, FREQ                                      TF 44
      I2 = NEQ                                                          TF 45
      NNODE = NELEM + 1                                                 TF 46
      DO  7  I = 1,NNODE                                                TF 47
      J = NNODE-I+1                                                     TF 48
      WRITE  (IW,8)  J, B(I2-1), B(I2)                                  TF 49
    7 I2 = I2-2                                                         TF 50
    6 FORMAT ('1'/5X,20A4//5X,'*STEADY-STATE RESPONSE AT ',F8.3, ' CPS*'TF 51
     *//5X,'NODE', 6X, 'DISPLACEMENT', 10X, 'ROTATION'/)                TF 52
    8 FORMAT  (5X,I4, 2(3X, E15.5))                                     TF 53
      RETURN                                                            TF 54
      END                                                               TF 55
```

```
C                                                                   RK 00
C     FUNCTION RK                                                   RK 01
      DOUBLE PRECISION FUNCTION  RK  ( W2 , G , DEPTH   )           RK 02
      IMPLICIT  REAL  * 8 ( A-H , O-Z  )                            RK 02A
      RK = W2/G                                                     RK 03
      IF  ( W2  .EQ.  0. )  RETURN                                  RK 04
      IF  ( RK * DEPTH  .LT.  10. )  GO  TO  8                      RK 05
      RK = 10. / DEPTH                                              RK 05A
      RETURN                                                        RK 05B
    8 A2 = 0.                                                       RK 06
      DK = ( 2. - RK ) / 10.                                        RK 07
   10 A1 = A2                                                       RK 08
      B = RK * DEPTH                                                RK 09
      A2 = W2 - RK * G *DSINH (B) /DCOSH(B)                         RK 10
      IF  ( A2  .EQ.  0.  )  RETURN                                 RK 11
      RK = RK + DK                                                  RK 12
      IF  ( A1/A2  .GE.  0. )  GO  TO  10                           RK 13
      RK = RK - 1.5 * DK                                            RK 14
      DK = DK / 2.                                                  RK 15
   12 IF  ( DK/RK  .LT.  1.E-4 )  RETURN                            RK 16
      B = RK * DEPTH                                                RK 17
      A3 = W2 - RK * G *DSINH(B) /DCOSH(B)                          RK 18
      IF  ( A3  .EQ.  0. )  RETURN                                  RK 19
      DK = DK / 2.                                                  RK 20
      IF  ( A3 / A1  .GT.  0. )  GO  TO  14                         RK 21
      RK = RK - DK                                                  RK 22
      A2 = A3                                                       RK 23
      GO  TO  12                                                    RK 24
   14 RK = RK + DK                                                  RK 25
      A1 = A3                                                       RK 26
      GO  TO  12                                                    RK 27
      END                                                           RK 28
```

```
C       SUBROUTINE SUEP                                                      SP 00
        DOUBLE PRECISICN FUNCTION  DCOSH    (A)                              SP 01
        B =DEXP(A)                                                           SP 02
        DCOSH   =   .5*(B+1./B)                                              SP 03
        RETURN                                                               SP 04
        END                                                                  SP 05
        DOUBLE PRECISION FUNCTION  DSINH (A)                                 SP 06
        B =DEXP (A)                                                          SP 07
        DSINH   =   .5*(B-1./B )                                             SP 08
        RETURN                                                               SP 09
        END                                                                  SP 10
        SUBROUTINE SUEP ( N, A1, A2, LENGHT, ZC, DEPTH, W2,     P)           SP 11
        IMPLICIT  REAL  * 8 ( A-H , O-Z  )                                   SP 11A
        REAL*8   LENGHT , K                                                  SP 12
        DIMENSION  A(5), W(5),                                     P(4)      SP 13
        DATA A,W / 0., -.538469,  .538469,  -.906180,  .906180,  .568889,    SP 14
      * 2*.478629,  2*.236927        /                                       SP 15
        DATA  CI, RC,  G /2.,  1. , 9.81  /                                  SP 16
        K = RK   ( W2 , G, DEPTH )                                           SP 16A
C                                                                            SP 17
        DO   1  I = 1,4                                                      SP 18
      1 P(I) = 0.                                                            SP 19
        Z1 = ZC + LENGHT *DFLOAT (N-1 )                                      SP 20
        C = 1.5707963 * CI * RC * W2 /DSINH ( K*DEPTH)                       SP 22
        DO  2  I = 1,5                                                       SP 23
        X = A(I)                                                             SP 24
        X = .5 *  (X + 1. )                                                  SP 25
        RADIUS = A1 * (1.-X) + A2 * X                                        SP 26
        Z = Z1 + LENGHT * X                                                  SP 27
        IF  ( Z.  GT.  DEPTH  )  RETURN                                      SP 28
        F = C * RADIUS ** 2 *DCOSH (K*Z)     * W(I) / 2.*LENGHT              SP 29
        H = X*X*(3.-2.*X)                                                    SP 30
        P(1) = P(1) + (1.-H) * F                                             SP 31
        P(2) = P(2) + (X*LENGHT*(1.-2.*X + X*X))*F                           SP 32
        P(3) = P(3) + H * F                                                  SP 33
        P(4) = P(4) + X*X*LENGHT*(X-1.) * F                                  SP 34
```

```
2 CONTINUE                                                              SP 35
  RETURN                                                                SP 36
  END                                                                   SP 37
```

```
C       SUBROUTINE SCLVE
        SUBRCUTINE SCLVE (IC,IW,NEQ,MBW,NLS,A,B)
        IMPLICIT  REAL  * 8 ( A-H , C-Z  )
        DIMENSION A(1),B(1)
C
C       * SOLVES SYMMETRIC SYSTEM OF EQUATIONS USING GAUSSIAN REDUCTICN *
C       IO      OPERATION INDICATCR    0 SOLVES SYSTEM A*X=B
C                                      1 REDUCES MATRIX A
C                                      2 REDUCES AND BACKSUBSTITUTES B
C       NEQ     NUMBER OF EQUATICNS
C       MBW     MAXIMUM BANDWIDTH
C       NLS     NUMBER OF SYSTEMS
C       A       SUARE BANDED SYMMETRIC POSITIVE DEFINITE MATRIX
C               STORED AS MCNCDIMENSIONAL ARRAY    NEQ*MBW
C               ELEMENT A(I,J)  IS STORED IN  A(I+(J-I)*NEQ)
C       B       RECTANGULAR ARRAY, STORED CCLUMNWISE
C*************************************************************************
C
C       REDUCTION CF A. CRIGINAL ARRAY IS DESTRCYED
C
        IF (IO.EQ.2) GO TO 20
        NRD = NEQ-1
        DO   18   I = 1,NRD
        D = A(I)
        IF   ( D. EQ. 0.  )   GO   TO   18
        IJ=I
        DO 16 J=2,MBW
        IJ=IJ+NEQ
        IF (A(IJ).EQ.0.) GO TO 16
        C=A(IJ)/D
        IK=IJ
        JK=I+J-1
        DO 14 K=J,MBW
        A(JK)=A(JK)-C*A(IK)
        IK=IK+NEQ
   14   JK=JK+NEQ
```

```
   16 CONTINUE                                              SS 35
   18 CONTINUE                                              SS 36
      IF (IO.EQ.1) RETURN                                   SS 37
C                                                           SS 38
C     REDUCTION OF B. ORIGINAL ARRAY IS DESTROYED           SS 39
C                                                           SS 40
   20 NRE=NEQ-1                                             SS 41
      DO 26 I=1,NRE                                         SS 42
      D=A(I)                                                SS 43
      IF (D.EQ.0.) GO TO 26                                 SS 44
      IJ=I                                                  SS 45
      DO 24 J=2,MBW                                         SS 46
      IJ=IJ+NEQ                                             SS 47
      IF (A(IJ).EQ.0.) GO TO 24                             SS 48
      C=A(IJ)/D                                             SS 49
      IK=I                                                  SS 50
      JK=I+J-1                                              SS 51
      DO 22 K=1,NLS                                         SS 52
      B(JK)=B(JK)-C*B(IK)                                   SS 53
      IK=IK+NEQ                                             SS 54
   22 JK=JK+NEQ                                             SS 55
   24 CONTINUE                                              SS 56
   26 CONTINUE                                              SS 56A
C                                                           SS 57
C     BACKSUBSTITUTION. RESULTS STORED IN B.                SS 58
C                                                           SS 59
      I=NEQ                                                 SS 60
   30 IF (A(I).EQ.0.) GO TO 34                              SS 61
      IK=I                                                  SS 62
      DO 32 K=1,NLS                                         SS 63
      B(IK)=B(IK)/A(I)                                      SS 64
   32 IK=IK+NEQ                                             SS 65
   34 I=I-1                                                 SS 66
      IF (I.EQ.0) RETURN                                    SS 67
      IJ=I                                                  SS 68
      DO 38 J=2,MBW                                         SS 69
```

```
      IJ=IJ+NEQ                                                        SS 70
      IF (A(IJ).EQ.0.) GO TO 38                                        SS 71
      IK=I                                                             SS 72
      JK=I+J-1                                                         SS 73
      DO 36 K=1,NLS                                                    SS 75
      B(IK)=B(IK)-A(IJ)*B(JK)                                          SS 76
      IK=IK+NEQ                                                        SS 77
   36 JK=JK+NEQ                                                        SS 78
   38 CONTINUE                                                         SS 79
      GO TO 30                                                         SS 80
C                                                                      SS 81
      END                                                              SS 82
```

```
C
C     SUBROUTINE TIME H
      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, P , Q                              )
      IMPLICIT  REAL  * 8 ( A-H , C-Z  )
      REAL*8   MASS , LENGHT
      DIMENSION  DIS( 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
      C2 = DT * DT / 6.
      LIM = NEQ * MBW
      DO  50  I = 1,LIM
   50 A(I) = MASS(I) + C2 * STIFF(I)
C
C     PRESCRIBE FIRST TWO DOF AS ZERO
      DO  51  I = 1, LIM , NEQ
      A(I)  = 0.
   51 A(I+1) = 0.
C
C     TRIANGULARIZE MATRIX
      CALL SOLVE  ( 1, IW, NEQ , MBW, 1 , A, B)
C
C     FORM VECTOR OF APPLIED FORCES
      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
```

```
      A1 = REB
      W2 =(6.28318531 * FREQ(N) )   **  2
      DO  7  I = 1,NELEM
      A2 = A1 + DA
      CALL SUBP  ( I , A1 , A2 , LENGHT , Z0 , DEPTH , W2 , P         )
      J = 2 * (I-1)
      DO  8  M = 1,4
      J = J + 1
    8 Q( J , N ) =    Q( J , N )  +  P(M)     * H(N)
    7 A1 = A2
C
C     INITIALIZE DISPLACEMENTS, VELOCITIES, AND ACCELERATIONS
      DO  52  I = 1,NEQ
      DIS (I) = 0.
      VEL (I) = 0.
   52 ACC (I) = 0.
      TIME = 0.
C
      C1 = DT / 2.
      C2 = DT * DT / 3.
      C3 = C2 / 2.
C
C     TIME INTEGRATION (LINEAR ACCELERATION METHOD). NO DAMPING
      DO  62  N = 1,NTIME
      TIME = TIME + DT
C
      DO  9  I = 1,NEQ
    9 B(I) = 0.
C
      DO  11  J = 1,NFREQ
      C =DCOS  ( 6.28318531 * FREQ(J) * TIME - PHASE(J) )
      DO  11  I = 1,NEQ
   11 B(I) = B(I) + C * Q( I,J )
C
      DO  55  I = 1,NEQ
      R(I) = VEL(I) + C1 * ACC(I)
```

```
      S(I) =  DIS(I) + DT * VEI(I) + C2 * ACC(I)
   55 ACC(I) = B(I)
C
      CALL AMBC  (NEQ, MBW, 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
      DO  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 , 'ACCELERATICN' , 6X , 'VELCCITY' , 5X ,
     *'DISPLACEMENT'/  )
    3 FORMAT  ( 6X , I4 , 4E16.4  )
C
      RETURN
      END
```

```
C     SUBRCUTINE AMEC                                                   AM 00
      SUBROUTINE AMBC  (NEÇ, MBW, A, B, C  )                            AM 01
      IMPLICIT  REAL  * 8 ( A-H , O-Z  )                                AM 01A
      DIMENSION  A(1), B(1), C(1)                                       AM 02
      LIM = MBW - 1                                                     AM 03
      DO   1  I = 1,NEQ                                                 AM 04
      A(I)  = A(I)  - B(I)  * C(I)                                      AM 05
      M = I                                                             AM 06
      DO   1  J = 1,LIM                                                 AM 07
      K = I + J                                                         AM 08
      M = M + NEÇ                                                       AM 09
      IF   ( K  .LE.  NEQ )     A(I) = A(I)  - B(M) *C(K)               AM 10
      K = I-J                                                           AM 11
      L = M-J                                                           AM 12
      IF   ( K  .GT. 0     )    A(I) = A(I)  - B(L) *C(K)               AM 13
    1 CONTINUE                                                          AM 14
      RETURN                                                            AM 15
      END                                                               AM 16
```

```
C                                                                   MP2 00
C     MAIN PROGRAM 2                                                MP2 01
      DIMENSION  ABC(20) , A(4096) , B(2048) , FREQ(20) , H(20)     MP2 02
      DATA  IR , IW  / 8 , 5 /                                      MP2 03
      READ  ( IR , 1 )  KCDE                                        MP2 04
      GO  TO  ( 10 , 10 , 20 )  ,  KCDE                             MP2 05
C                                                                   MP2 06
   10 CALL RECCRD  ( IR , IW , ABC , N , A , DT  )                  MP2 07
      CALL  POWER  ( N , A , B , DT , DF )                          MP2 08
      IF  ( KCDE  .EQ.  1 )  STCP                                   MP2 09
      CALL CCNNCR  (IR, IW, C, N, DF, A, M, FREQ, H, B  )           MP2 10
      STOP                                                          MP2 11
   20 CALL SEA  ( IR , IW , N , A , DF  )                           MP2 12
      CALL CCNNOR  ( IR, IW, 1, N, DF, A, M, FREQ, H, B  )          MP2 13
      STCP                                                          MP2 14
    1 FORMAT  ( I4 )                                                MP2 15
      END                                                           MP2 16
```

```
C                                                                 SR 00
C        SUBROUTINE RECORD                                        SR 01
         SUBROUTINE RECORD  ( IR , IW , ABC , N , A , DT )        SR 02
         DIMENSION  ABC (20) , CARD (10)                          SR 03
         EQUIVALENCE  ( CARD (1) , CHECK )                        SR 04
         READ  ( IR , 1 )   ABC , DT                              SR 05
         WRITE  ( IW , 2 )   ABC , DT                             SR 06
       1 FORMAT  ( 20A4 / F8.3 )                                  SR 07
       2 FORMAT  (//5X , 20A4// 5X , 'DELTA T =' , E12.3/)        SR 08
C                                                                 SR 09
         N = 0                                                    SR 10
      10 READ  ( IR , 3 )  CARD                                   SR 11
       3 FORMAT  ( 10F8.3 )                                       SR 12
         IF  ( CHECK  .EQ.  123. )  GO  TO  14                    SR 13
         DO  12  I = 1,10                                         SR 14
         N = N + 1                                                SR 15
      12 A(N) = CARD (I)                                          SR 16
      14 TIME = DT * FLOAT (N)                                    SR 17
         CALL PICTR  ( A,1,ABC,SCALE,1,N,0,-1,2,1,TIME,1)         SR 18
         PAUSE                                                    SR 19
         RETURN                                                   SR 20
         END                                                      SR 21
```

```
C                                                                   SPO 00
C     SUBROUTINE  POWER                                             SPC 01
      SUBROUTINE POWER  ( N , A , B , DT , DF )                     SPC 02
      DIMENSION  A(1) , B(1)                                        SPC 03
      ROG = 9.81                                                    SPO 04
      CALL SETO   ( A(N+1) , 4096-N )                               SPO 05
      N = 2048                                                      SPC 06
      CALL FOUR2  ( A , 4096 , 1 , -1 , 0 )                         SPC 07
      CALL SCALE  ( A , 4096 , IT )                                 SPC 08
      DF = 1. /  DT/ FLOAT (4096 )                                  SPC 09
      J = 1                                                         SPC 10
      DO  10  I = 1 , 2048                                          SPO 11
      AR = A(J)                                                     SPC 12
      AI = A( J+1 )                                                 SPO 13
      A(I) = .5 * ( AR * AR + AI * AI  )  *  ROG                    SPC 14
      B(J) = ATAN  ( AI / AR )                                      SPO 15
   10 J = J + 2                                                     SPO 16
      FMAX = 1024. * DF                                             SPC 17
      CALL PICTR  ( A,1,ABC,SCALE,1,1024,0,-1,2,1,FMAX,1 )          SPO 18
      PAUSE                                                         SPC 19
      RETURN                                                        SPO 20
      END                                                           SPC 21
```

```
C                                                                 SO 00
C      SUBROUTINE SETO                                            SO 01
       SUBROUTINE SETO   ( A , N )                                SO 02
       DIMENSION  A(1)                                            SO 03
       DO   1   I =  1,N                                          SO 04
     1 A(I)  =  C.                                                SO 05
       RETURN                                                     SO 06
       END                                                        SO 07
```

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```
      SUBROUTINE FOUR2 (DATA,L,NDIM,ISIGN,IFORM)                        FF2 00
      DIMENSION DATA(1), N(1)                                           FF2  29
      N(1)=L                                                            FF2 29
      NTOT=1                                                            FF2  30
      DO 10 IDIM=1,NDIM                                                 FF2  31
10    NTOT=NTOT*N(IDIM)                                                 FF2  32
      IF (IFORM) 70,20,20                                               FF2  33
20    NREM=NTOT                                                         FF2  34
      DO 60 IDIM=1,NDIM                                                 FF2  35
      NREM=NREM/N(IDIM)                                                 FF2  36
      NPREV=NTOT/(N(IDIM)*NREM)                                         FF2  37
      NCURR=N(IDIM)                                                     FF2  38
      IF (IDIM-1+IFORM) 30,30,40                                        FF2  39
30    NCURR=NCURR/2                                                     FF2  40
40    CALL BITRV (DATA,NPREV,NCURR,NREM)                                FF2  41
      CALL COOL2 (DATA,NPREV,NCURR,NREM,ISIGN)                          FF2  42
      IF (IDIM-1+IFORM) 50,50,60                                        FF2  43
50    CALL FIXRL (DATA,N(1),NREM,ISIGN,IFORM)                           FF2  44
      NTOT=(NTOT/N(1))*(N(1)/2+1)                                       FF2  45
60    CONTINUE                                                          FF2  46
      RETURN                                                            FF2  47
70    NTOT=(NTOT/N(1))*(N(1)/2+1)                                       FF2  48
      NREM=1                                                            FF2  49
      DO 100 JDIM=1,NDIM                                                FF2  50
      IDIM=NDIM+1-JDIM                                                  FF2  51
      NCURR=N(IDIM)                                                     FF2  52
      IF (IDIM-1) 80,80,90                                              FF2  53
80    NCURR=NCURR/2                                                     FF2  54
      CALL FIXRL (DATA,N(1),NREM,ISIGN,IFORM)                           FF2  55
      NTOT=NTOT/(N(1)/2+1)*N(1)                                         FF2  56
90    NPREV=NTOT/(N(IDIM)*NREM)                                         FF2  57
      CALL BITRV (DATA,NPREV,NCURR,NREM)                                FF2  58
      CALL COOL2 (DATA,NPREV,NCURR,NREM,ISIGN)                          FF2  59
100   NREM=NREM*N(IDIM)                                                 FF2  60
      RETURN                                                            FF2  61
      END                                                               FF2  62-
```

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```
      SUBROUTINE BITRV (DATA,NPREV,N,NREM)                              BIT   1
      DIMENSION DATA(1)                                                 BIT   8
      IP0=2                                                             BIT   9
      IP1=IP0*NPREV                                                     BIT  10
      IP4=IP1*N                                                         BIT  11
      IP5=IP4*NREM                                                      BIT  12
      I4REV=1                                                           BIT  13
      DO 60 I4=1,IP4,IP1                                                BIT  14
      IF (I4-I4REV) 10,30,30                                            BIT  15
10    I1MAX=I4+IP1-IP0                                                  BIT  16
      DO 20 I1=I4,I1MAX,IP0                                             BIT  17
      DO 20 I5=I1,IP5,IP4                                               BIT  18
      I5REV=I4REV+I5-I4                                                 BIT  19
      TEMPR=DATA(I5)                                                    BIT  20
      TEMPI=DATA(I5+1)                                                  BIT  21
      DATA(I5)=DATA(I5REV)                                              BIT  22
      DATA(I5+1)=DATA(I5REV+1)                                          BIT  23
      DATA(I5REV)=TEMPR                                                 BIT  24
20    DATA(I5REV+1)=TEMPI                                               BIT  25
30    IP2=IP4/2                                                         BIT  26
40    IF (I4REV-IP2) 60,60,50                                           BIT  27
50    I4REV=I4REV-IP2                                                   BIT  28
      IP2=IP2/2                                                         BIT  29
      IF (IP2-IP1) 60,40,40                                             BIT  30
60    I4REV=I4REV+IP2                                                   BIT  31
      RETURN                                                            BIT  32
      END                                                               BIT  33-
```

```
      SUBROUTINE CCCL2 (DATA,NPREV,N,NREM,ISIGN)                        C02   1
      DIMENSION DATA(1)                                                 C02  15
      TWOPI=6.2831853072*FLOAT(ISIGN)                                   C02  16
      IP0=2                                                             C02  17
      IP1=IP0*NPREV                                                     C02  18
      IP4=IP1*N                                                         C02  19
      IP5=IP4*NREM                                                      C02  20
      IP2=IP1                                                           C02  21
      NPART=N                                                           C02  22
10    IF (NPART-2) 50,30,20                                             C02  23
20    NPART=NPART/4                                                     C02  24
      GO TO 10                                                          C02  25
30    IP3=IP2*2                                                         C02  27
      DO 40 I1=1,IP1,IP0                                                C02  28
      DO 40 I5=I1,IP5,IP3                                               C02  29
      J0=I5                                                             C02  30
      J1=J0+IP2                                                         C02  31
      TEMPR=DATA(J1)                                                    C02  32
      TEMPI=DATA(J1+1)                                                  C02  33
      DATA(J1)=DATA(J0)-TEMPR                                           C02  34
      DATA(J1+1)=DATA(J0+1)-TEMPI                                       C02  35
      DATA(J0)=DATA(J0)+TEMPR                                           C02  36
40    DATA(J0+1)=DATA(J0+1)+TEMPI                                       C02  37
      GO TO 140                                                         C02  38
50    IP3=IP2*4                                                         C02  40
      THETA=TWOPI/FLOAT(IP3/IP1)                                        C02  41
      SINTH=SIN(THETA/2.)                                               C02  42
      WSTPR=-2.*SINTH*SINTH                                             C02  43
      WSTPI=SIN(THETA)                                                  C02 44
      WR=1.                                                             C02  46
      WI=0.                                                             C02  47
      DO 130 I2=1,IP2,IP1                                               C02  48
      IF (I2-1) 70,70,60                                                C02  49
60    W2R=WR*WR-WI*WI                                                   C02  50
      W2I=2.*WR*WI                                                      C02  51
      W3R=W2R*WR-W2I*WI                                                 C02  52
```

```
      W3I=W2R*WI+W2I*WR                                                 CO2  53
 70   I1MAX=I2+IP1-IP0                                                  CO2  54
      DO 120 I1=I2,I1MAX,IP0                                            CO2  55
      DO 120 I5=I1,IP5,IP3                                              CO2  56
      J0=I5                                                             CO2  57
      J1=J0+IP2                                                         CO2  58
      J2=J1+IP2                                                         CO2  59
      J3=J2+IP2                                                         CO2  60
      IF (I2-1) 90,90,80                                                CO2  61
 80   TEMPR=DATA(J1)                                                    CO2  63
      DATA(J1)=W2R*TEMPR-W2I*DATA(J1+1)                                 CO2  64
      DATA(J1+1)=W2R*DATA(J1+1)+W2I*TEMPR                               CO2  65
      TEMPR=DATA(J2)                                                    CO2  66
      DATA(J2)=WR*TEMPR-WI*DATA(J2+1)                                   CO2  67
      DATA(J2+1)=WR*DATA(J2+1)+WI*TEMPR                                 CO2  68
      TEMPR=DATA(J3)                                                    CO2  69
      DATA(J3)=W3R*TEMPR-W3I*DATA(J3+1)                                 CO2  70
      DATA(J3+1)=W3R*DATA(J3+1)+W3I*TEMPR                               CO2  71
 90   T0R=DATA(J0)+DATA(J1)                                             CO2  72
      T0I=DATA(J0+1)+DATA(J1+1)                                         CO2  73
      T1R=DATA(J0)-DATA(J1)                                             CO2  74
      T1I=DATA(J0+1)-DATA(J1+1)                                         CO2  75
      T2R=DATA(J2)+DATA(J3)                                             CO2  76
      T2I=DATA(J2+1)+DATA(J3+1)                                         CO2  77
      T3R=DATA(J2)-DATA(J3)                                             CO2  78
      T3I=DATA(J2+1)-DATA(J3+1)                                         CO2  79
      DATA(J0)=T0R+T2R                                                  CO2  80
      DATA(J0+1)=T0I+T2I                                                CO2  81
      DATA(J2)=T0R-T2R                                                  CO2  82
      DATA(J2+1)=T0I-T2I                                                CO2  83
      IF (ISIGN) 100,100,110                                            CO2  84
100   T3R=-T3R                                                          CO2  85
      T3I=-T3I                                                          CO2  86
110   DATA(J1)=T1R-T3I                                                  CO2  87
      DATA(J1+1)=T1I+T3R                                                CO2  88
      DATA(J3)=T1R+T3I                                                  CO2  89
```

```
120   DATA(J3+1)=T1I-T3R                                      CO2  90
      TEMPR=WR                                                CO2  91
      WR=WSTPR*TEMPR-WSTPI*WI+TEMPR                           CO2  92
130   WI=WSTPR*WI+WSTPI*TEMPR+WI                              CO2  93
140   IP2=IP3                                                 CO2  94
      IF (IP3-IP4) 50,150,150                                 CO2  95
150   RETURN                                                  CO2  96
      END                                                     CO2  97-
```

```
      SUBROUTINE FIXRL (DATA,N,NREM,ISIGN,IFORM)                        FIX   1
      REAL*8 ZR,ZI                                                      FIX  02
      DIMENSION DATA(2)                                                 FIX  03
      TWOPI=6.283185307*FLOAT(ISIGN)                                    FIX  24
      IP0=2                                                             FIX  25
      IP1=IP0*(N/2)                                                     FIX  26
      IP2=IP1*NREM                                                      FIX  27
      IF (IFORM) 10,70,70                                               FIX  28
   10 J1=IP1+1                                                          FIX  30
C     DATA(2)=DATA(J1)        ******** CARD ELIMINATED *********        FIX  31
      IF (NREM-1) 70,70,20                                              FIX  32
   20 J1=J1+IP0                                                         FIX  33
      I2MIN=IP1+1                                                       FIX  34
      DO 60 I2=I2MIN,IP2,IP1                                            FIX  35
      DATA(I2)=DATA(J1)                                                 FIX  36
      J1=J1+IP0                                                         FIX  37
      IF (N-2) 50,50,30                                                 FIX  38
   30 I1MIN=I2+IP0                                                      FIX  39
      I1MAX=I2+IP1-IP0                                                  FIX  40
      DO 40 I1=I1MIN,I1MAX,IP0                                          FIX  41
      DATA(I1)=DATA(J1)                                                 FIX  42
      DATA(I1+1)=DATA(J1+1)                                             FIX  43
   40 J1=J1+IP0                                                         FIX  44
   50 DATA(I2+1)=DATA(J1)                                               FIX  45
   60 J1=J1+IP0                                                         FIX  46
   70 DO 80 I2=1,IP2,IP1                                                FIX  47
      TEMPR=DATA(I2)                                                    FIX  48
      DATA(I2)=DATA(I2)+DATA(I2+1)                                      FIX  49
   80 DATA(I2+1)=TEMPR-DATA(I2+1)                                       FIX  50
      IF (N-2) 200,200,90                                               FIX  51
   90 THETA=TWOPI/FLOAT(N)                                              FIX  52
      SINTH=SIN(THETA/2.)                                               FIX  53
      ZSTPR=-2.*SINTH*SINTH                                             FIX  54
      ZSTPI=SIN(THETA)                                                  FIX 55
      ZR=(1.-ZSTPI)/2.                                                  FIX  56
      ZI=(1.+ZSTPR)/2.                                                  FIX  57
```

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

```
      I1=I1-IPO                                                         FIX  97
      J1=J1-IPO                                                         FIX  98
230   IF (I2-I1) 22C,240,240                                            FIX  99
24C   DATA(J1)=DATA(I1)                                                 FIX 100
      DATA(J1+1)=C.                                                     FIX 101
25C   I2=I2-IP1                                                         FIX 102
      J1=J1-IPC                                                         FIX 103
      DATA(J1)=DATA(I2+1)                                               FIX 104
      DATA(J1+1)=C.                                                     FIX 105
      I1=I1-IPC                                                         FIX 106
      J1=J1-IPC                                                         FIX 107
      IF (I2-1) 26C,26C,23C                                             FIX 108
26C   DATA(2)=C.                                                        FIX 109
27C   RETURN                                                            FIX 110
      END                                                               FIX 111
```

```
C                                                               SSC 00
C      SUBROUTINE SCALE                                         SSC 01
       SUBROUTINE SCALE  ( A , N , FACTOR )                     SSC 02
       DIMENSION  A(1)                                          SSC 03
          DO  1  I =1 , N                                       SSC 04
     1 A(I) = A(I) * FACTOR                                     SSC 05
       RETURN                                                   SSC 06
       END                                                      SSC 07
```

```
C                                                                           SC 00
C     SUBROUTINE CONNOR                                                     SC 01
      SUBROUTINE CONNOR  ( IR , IW , IO , N, DF, A, M, FREQ, H, B)          SC 02
      DIMENSION  A(1) , FREQ(1) , H(1) , B(1)                               SC 03
      ROG = 9.81                                                            SC 04
      READ  ( IR , 1 )  M, ISEED,  ( FREQ(I) , I = 1,M )                    SC 05
    1 FORMAT  ( 2I4 / ( 10F8.3) )                                           SC 06
      FR = DF                                                               SC 07
      J = 1                                                                 SC 08
      DO  14  I = 1,M                                                       SC 09
      H(I) = 0.                                                             SC 10
      IF  ( J  .GT.  N )   GO  TO  14                                       SC 11
      IF  ( I  .LT.  M )  FL = .5*(FREQ(I) + FREQ(I+1) )                    SC 12
   10 IF  ( I  .EQ.  M )   GO  TO  12                                       SC 13
      IF  ( FR  .GT.  FL )   GO  TO  14                                     SC 14
   12 H(I) = H(I)  +  A(J)                                                  SC 15
      FR = FR + DF                                                          SC 16
      J = J + 1                                                             SC 17
      IF  ( J - N )  10 , 10 , 14                                           SC 18
   14 H(I) = SQRT  ( 8. * DF / ROG * H(I) )                                 SC 19
C                                                                           SC 20
      IF  ( IO  .NE.  0 )   GO  TO  18                                      SC 21
      DO  16  I = 1,M                                                       SC 22
      J = FREQ(I) / DF                                                      SC 23
   16 B(I) = B(J)                                                           SC 24
      GO  TO  24                                                            SC 25
C                                                                           SC 26
   18 DO  20  I = 1,M                                                       SC 27
      CALL RANDX  ( ISEED , IY , FI  )                                      SC 28
      ISEED = IY                                                            SC 29
   20 B(I) = 3.14159265 * (FI - .5)                                         SC 30
C                                                                           SC 31
   24 WRITE  ( IW , 2 )  ( I , FREQ(I) , H(I) , B(I) ,  I = 1,M )           SC 32
    2 FORMAT  ( ///5X,  '  * CONDENSED  WAVE  SPECTRUM *  ', //8X,          SC 33
     *  'POSITION',  9X , 'FREQ',8X, 'WAVE HEIGHT',3X,'PHASE ANGLE',        SC 34
     *// ( 7X,I5,3X,3F15.4))                                                SC 35
```

```
      DT = .25                                                        SC 36
      TIME = 0.                                                       SC 37
      DO  26   J = 1,600                                              SC 38
      TIME = TIME + DT                                                SC 39
      A(J) = 0.                                                       SC 40
      DO  26  I = 1,M                                                 SC 41
      ALFA = 6.283186  *  TIME  *  FREQ(I) - E(I)                     SC 42
   26 A(J) = A(J)  +  H(I) * SIN(ALFA)                                SC 43
C                                                                     SC 44
      CALL PICTR ( A, 1, ABC, SCALE, 1, 600, 0, -1, 2, 1, TIME, 1 )   SC 45
      PAUSE                                                           SC 46
      RETURN                                                          SC 47
      END                                                             SC 48
```

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

6.2 LIST OF FIGURES

LIST OF FIGURES
(Continued)

LIST OF FIGURES
(Continued)

AD-A052 639   MASSACHUSETTS INST OF TECH CAMBRIDGE DEPT OF CIVIL E--ETC F/G 11/2
APPROXIMATE MODELS FOR OFF-SHORE CONCRETE GRAVITY STRUCTURES.(U)
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6.3 List of Tables