Final Report

Assess the Effect of API RP 2A 20th Edition Criteria on the Design of Offshore Caisson-Type Platforms

Prepared for

Minerals Management Service
Contract No. 14-35-0001-30700
Task Order II

Prepared by

PMB Engineering Inc.

July 1994

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INTRODUCTION

The metocean criteria changed significantly in the API RP 2A, 20th Edition (1993) compared to its predecessor 19th Edition (1991). The new 20th Edition also differentiated the caisson platforms from conventional steel jacket platforms and classified them under "minimum structures," with specific design provisions. The likelihood of significant increase in the design load level per the new Edition raised concerns in the industry that such increased structural requirements may make some fields uneconomical.

Recognizing this, MMS selected PMB Engineering to perform an independent study to evaluate the effect of the 20th Edition over the 19th Edition designs. The project has four primary objectives:

- API Design Criteria. Identify differences in the 19th and 20th Editions criteria and establish an objective opinion as to their applicability to caisson type platform design.
- Evaluation of Caisson Design. Investigate the design of a "new" caisson using both the 19th and 20th Editions to determine differences in structure performance and material quantities.
- Comparison with Observed Behavior during Andrew. Compare the analytical predictions and the behavior of a caisson exposed to Andrew to determine whether the 19th or 20th Edition provides the better recipe of caisson performance.
- Recommendations. Make recommendations based on the findings of the study.

API Design Criteria

A comparison of the 19th and 20th Editions indicated the following differences pertaining to caissons:

- Hydrodynamic recipe
- Structure design
- Fatigue design

The hydrodynamic recipe differs in terms of recommended metocean parameters (wave height, current, etc.) for the Gulf of Mexico and hydrodynamic force computation procedures (C_d, C_m, etc.). A comparison of wave loads acting on several representative caissons indicates that 20th Edition loads are typically 40 to 50 percent higher than loads per the 19th Edition. In one case, the loads were 95 percent higher for the 20th Edition. The increase is due primarily to the addition of current values for the 20th Edition. Discussions with several industry experts regarding the 20th edition recipe indicates that most believe it is equally applicable to caissons as it is to multi leg platforms.

The primary structural design factor that is new in the 20th Edition is the requirement of an interaction ratio of 0.9 (instead of 1.0) for caissons where Class C steel is used. This change negates a previous increase in allowable bending stress allowed in the 17th Edition. It is applicable for caissons only and adjusts the allowable back to the same apparent allowable stress as has historically been used successfully.

The simplified fatigue analysis procedure applied to several example caissons provides similar or up to 15 percent higher allowable peak hot spot stresses per 20th Edition compared to those per the 19th Edition.

Caisson Design Evaluation

The design of a caisson for a 53 ft water depth was compared using the 19th and 20th Editions. Redesign of the caisson per the 20th Edition resulted in bending moments 50 percent higher than the redesign per the 19th Edition. The net result of the 20th Edition design was an increase of about 30 percent more steel.

Comparison of a Caisson Analysis with Its Behavior During Andrew

The actual caisson that was used as a basis for the previous caisson design evaluation was evaluated for ultimate strength during Andrew using a nonlinear pushover analysis. The observed caisson damage was compared to the damage predicted by the analysis at various levels of base shear based upon the 19th and 20th Editions. It was found that both Editions predict caisson damage, with the 20th providing a slightly better match of analytical versus observed conditions. However, this difference was insignificant in terms of clearly determining that the 20th Edition provides a superior approach. In addition, note that other factors such as the accuracy of the hindcast wave height, analytical modeling techniques and accuracy of the post Andrew caisson inspection also contribute to the uncertainty.

Recommendations

There are clear differences between caisson design per the 19th and 20th Editions that can lead to an increase in hydrodynamic loads of 40 to 50 percent. This may lead to an increase in steel weight in some cases 30 percent or more. The net result is more expensive caissons that in some cases may make a particular offshore development uneconomical.

The project identified no basis to believe that the 20th Edition, in particular the wave load recipe, is not applicable for design of caissons. In fact, the 20th Edition represents many years of API and industry research and is considered an acceptable approach for designing a caisson or platform in the offshore US and in some other offshore regions.

One option is to accept a lower design criteria (e.g. less than 100 yr. return period waves) for design of a caisson than for multileg platforms. Another option is to allow a certain amount of "damage" to the structure, such as a 5 degree lean, for the 100 year design condition. The rational is that caissons are typically low consequence structures which are unmanned and are generally of low environmental significance. Indeed, API allows for reduced criteria for these types of structures based upon risk analysis (RP 2A 20th Section 1.5).

It was originally anticipated that such criteria could be identified by this project. This, however, would involve detailed risk studies combined with numerous nonlinear analysis, and thus selection of a specific criteria was beyond the time and cost constraints of this project. Further, it is important that such a recommendation be developed in conjunction with the industry representatives in a joint industry project (JIP) in order to develop criteria based upon an "industry consensus."

However, this project did provide some preliminary information based upon results of the pushover analysis for the caisson that was damaged in Andrew. Pushover analysis per the 19th Edition indicated a lean angle of less than 5 degrees, whereas pushover analysis per the 20th Edition indicated a lean angle of more than 5 degrees. Assuming that the "acceptable" lean angle is 5 degrees (per preliminary findings by Barnett and Casbarian in a project for the MMS), these results indicate that the metocean criteria for the acceptable damage limit condition lies between the 19th and 20th Edition criteria. Assuming that caissons can accept a higher risk, then a reduction in the 20th Edition metocean criteria may be appropriate. The specific criteria should be based upon a thorough evaluation of acceptable risk for several caissons.

A proposed calibration effort similar to the above is currently in the planning stages by API for a possible JIP. It is recommended that this project go forward if it is felt by the MMS and the industry that there is a need to develop specific "reduced" design criteria for caissons. This criteria can then be incorporated directly into RP 2A to provide a convenient means of designing caissons.

Section 1
Introduction

1.1 BACKGROUND

There have been significant changes in the API Recommended Practice for Planning, Designing, and Constructing Fixed Offshore Platforms, RP 2A, 20th Edition (1993) compared to the 19th Edition (1991). The primary areas where changes have been made which are of relevance to this study:

- Metocean criteria
- Hydrodynamic force computation guidelines
- Minimum structures criteria

The RP 2A, 20th Edition provides the metocean parameters and hydrodynamic force coefficients based on extensive work undertaken by API over several years [Petrauskas et al, 1993]. It provides more detailed recommendations for the Gulf of Mexico locations and includes additional features for hydrodynamic force computations, which were not in the previous versions.

In the 20th Edition, a new Section 16 applicable to "Minimum Structures" has been included, which provides additional specific provisions of importance to the minimum structures. Caisson type platforms which are the focus of this study fall under this category.

The RP 2A does not differentiate between conventional steel jacket template platforms and caisson type platforms in applicability of the metocean criteria. In general, the 20th Edition metocean load level for the conventional steel jacket template platforms was found to exceed the 19th Edition load level. Some in the industry have expressed concern that the 20th Edition wave load recipe was developed primarily for multileg platforms. This has raised some concerns in the industry on direct applicability of the latest 20th Edition RP 2A criteria to the design of caisson type platforms.

1.2 OBJECTIVES

The objectives set forth for this study per the MMS Task Order II (Contract No. 14-35-0001-30700), "Assess the Effect of API RP 2A 20th Edition Criteria on the Design of Offshore Caisson-Type Platforms," are as follows (see Appendix-A):

- Task 2A: <u>Review of API design criteria:</u> Identify differences between API RP 2A 19th and 20th Editions criteria and establish objective expert opinion as to their basis and applicability to caisson platform design.

- Task 2B: Evaluate a representative caisson by two criteria: Assess an existing caisson design (representative of the Gulf of Mexico) based on both API RP 2A 19th and 20th Edition recommendations in order to determine the impact on design of these structures (i.e., amount of steel).

- Task 2C: Compare analyzed and predicted behavior of a caisson during Andrew: Compare for the available Andrew hindcast data the observed behavior of a typical caisson with analysis predictions per 19th and 20th Editions in order to determine which methodology most closely matches observed behavior.

To meet these tasks, the relevant API recommended practice given in the RP 2A, 19th and 20th Editions, which affect design of caisson type platforms, will be reviewed and their impact on caisson design will be discussed. The impact of 20th Edition guidelines on the design of a caisson will be evaluated and the post-Andrew observed behavior of a caisson will be compared with analytical predictions for the Andrew seastate.

1.3 OVERVIEW OF CAISSON TYPE PLATFORMS

API RP 2A, 20th Edition (1993) classifies caisson type platforms under "minimum structures" category and provides guidelines for their design which differ from those in its 19th Edition (1991). The structural characteristics of a caisson type platform could vary significantly. The two basic structural designs of caisson type platforms defined under "minimum structures" type in Section 1.6.4 of the RP 2A, 20th Edition are as follows:

- Free-standing caisson platform, which consists of one large tubular member supporting one or more wells.

- Well conductor(s) or free-standing caisson(s), which are utilized as structural and/or axial foundation elements by means of attachment using welded, non-welded or non-conventional welded connections.

Caissons have been installed primarily in shallow water depths (up to 75 ft) and some have been even installed in water depths greater than 100 ft. Their diameter generally varies from 3 ft to 6 ft and their penetration below seabed is generally in the range of 100 ft to 150 ft.

In addition to these basic designs, a number of other variations have been used in deeper water depths. Some designs which have been used in the past consist of: braced caisson platforms and laterally moored caisson platforms. Such designs are not part of this study. This study is limited to the shallow water free standing caissons (hereafter called Caisson) which sometimes are also called single pile caissons.

1.4 STRUCTURAL FEATURES OF CAISSON PLATFORMS

Minerals Management Service reports post Andrew damage to 145 satellite/ caisson type platforms. Out of these, 25 were completely toppled and 120 were leaning with a lean up to 45 degree. Of the 120 leaning satellites, 43 were found to be leaning more than 5 degrees [Daniels, 1993]. Some of the caissons that were damaged were installed as recently as that summer (1992).

Barnett & Casbarian, Inc. selected caisson designs from this database, which were affected by Hurricane Andrew, and obtained structural details for several cases from three operating companies (Companies A, B and C) [Barnett & Casbarian, 1994-1]. These caissons were installed in shallow water locations in the Ship Shoal, South Pelto and South Timbalier blocks. Table 1-1 summarizes the key characteristics of 11 caissons. The operating companies mentioned that the structural details of the damaged caissons follow their standard design practices for those water depths and they have several other similar caissons which were undamaged during Andrew.

Figures 1-1 through 1-3 provide the general configurations of these platforms. Several differences in the structural characteristics of these caissons are:

- Caisson Structure: Company A used uniform diameter caissons in shallower water depths and conical section designs in deeper water depths with a maximum diameter of 72 inch. Company C used uniform diameter caissons. Company B did not install any caisson and instead used the well conductor itself (30" diameter) as the primary load bearing structure. The annulus between the 30" diameter well conductor and the internal tubing was grouted.

- Boat Landings: Each company used their standard boat landing designs. The boat landing designs of the three companies varied significantly.

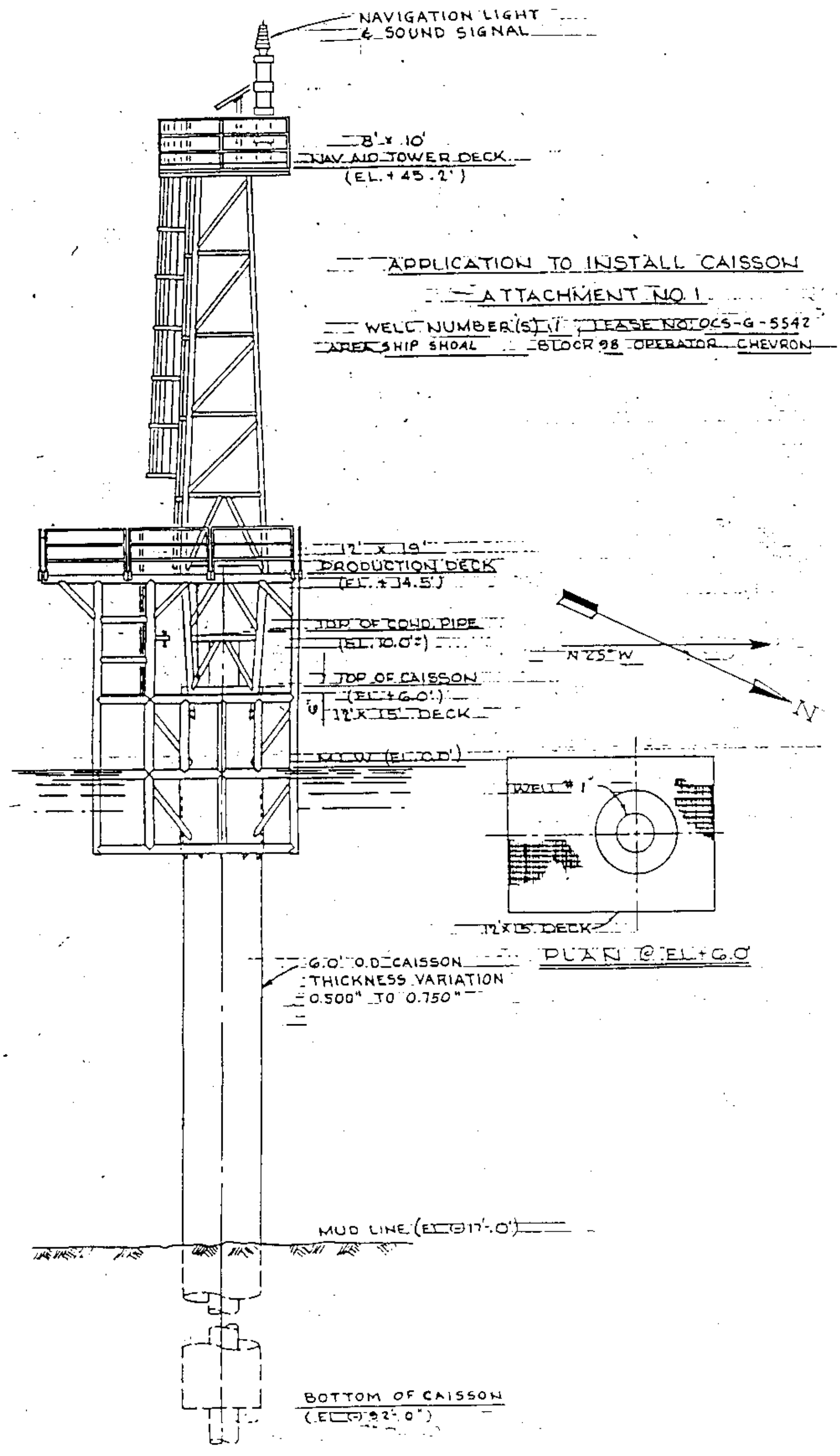
- Deck Structures: Company A provided nav-aid tower facilities on the deck in addition to the production well equipment. In one case Company A used multiple wells (2 wells located outside the caisson). Company B provided an elevated deck and Company C provided a deck structure with an integrated boat landing. The design waves per both 19th and 20th Editions of API inundate the deck and nav-aid tower structures.

- Structural Damage: The details of post hurricane Andrew damage to these caissons are also given in Table 1-1. The caissons of Company B and Company C were found leaning up to 15 degrees. Two caissons of Company A sheared at sections near the mudline and the company reported likelihood of fatigue related failure. Company A's multi-well caisson platform sheared near mudline, but the outside wells remained undamaged.

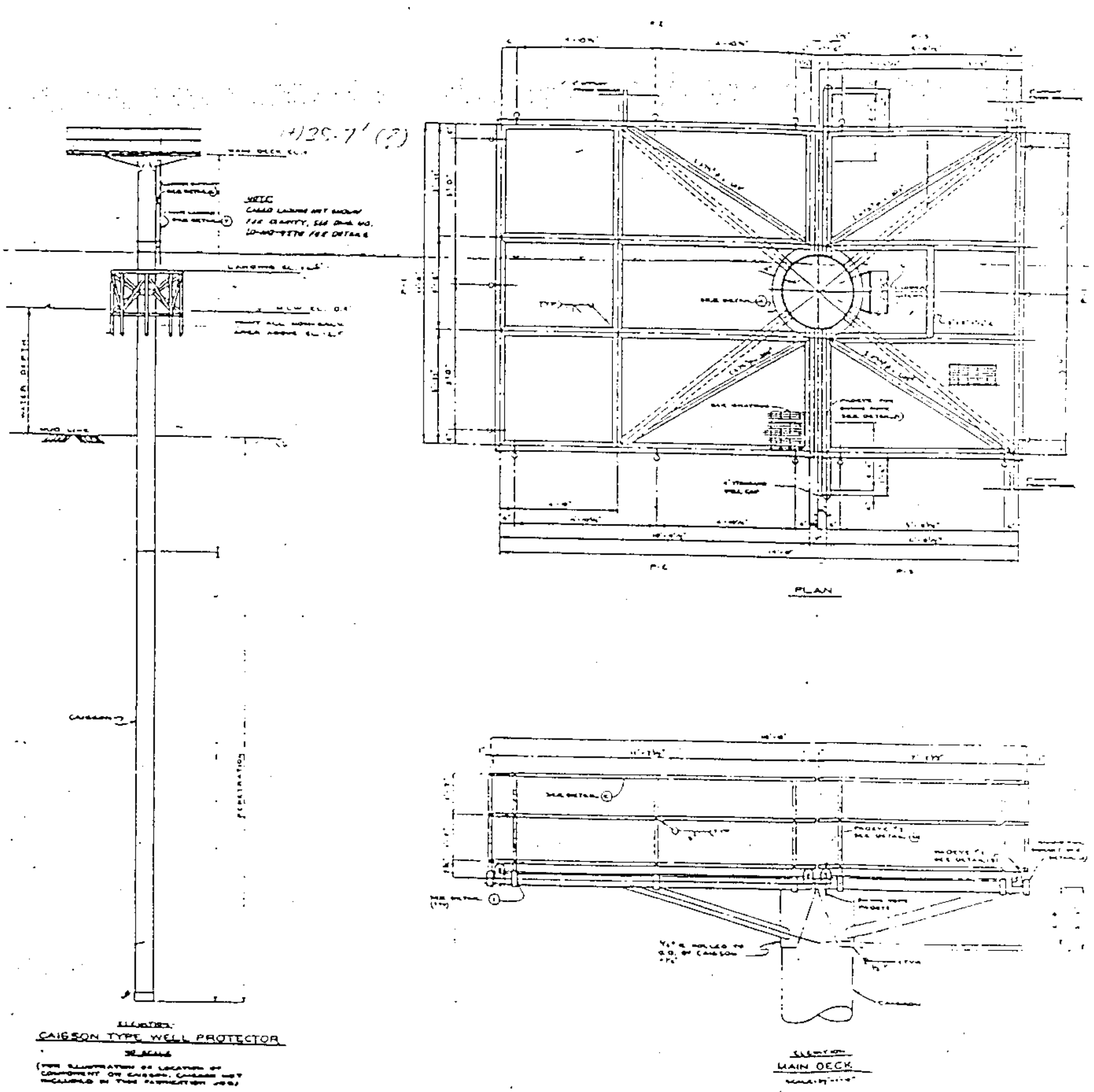
These cases were reviewed to select the most appropriate for this study. The emphasis in selection was on conventional design practice, water depth, completeness of data available, and requirement of special studies. Two caissons of Company A located in very shallow water depths (17 ft and 21 ft) with damage near mudline were not considered because RP 2A provides metocean criteria for locations with water depth more than 25 ft and site-specific studies are needed for locations with water depth less than 25 ft.

The conventional description of a "caisson" platform is of a larger diameter tubular structure installed outside of a single well. Therefore the well conductor designs of Company B, with no caisson installed outside of the well, were eliminated.

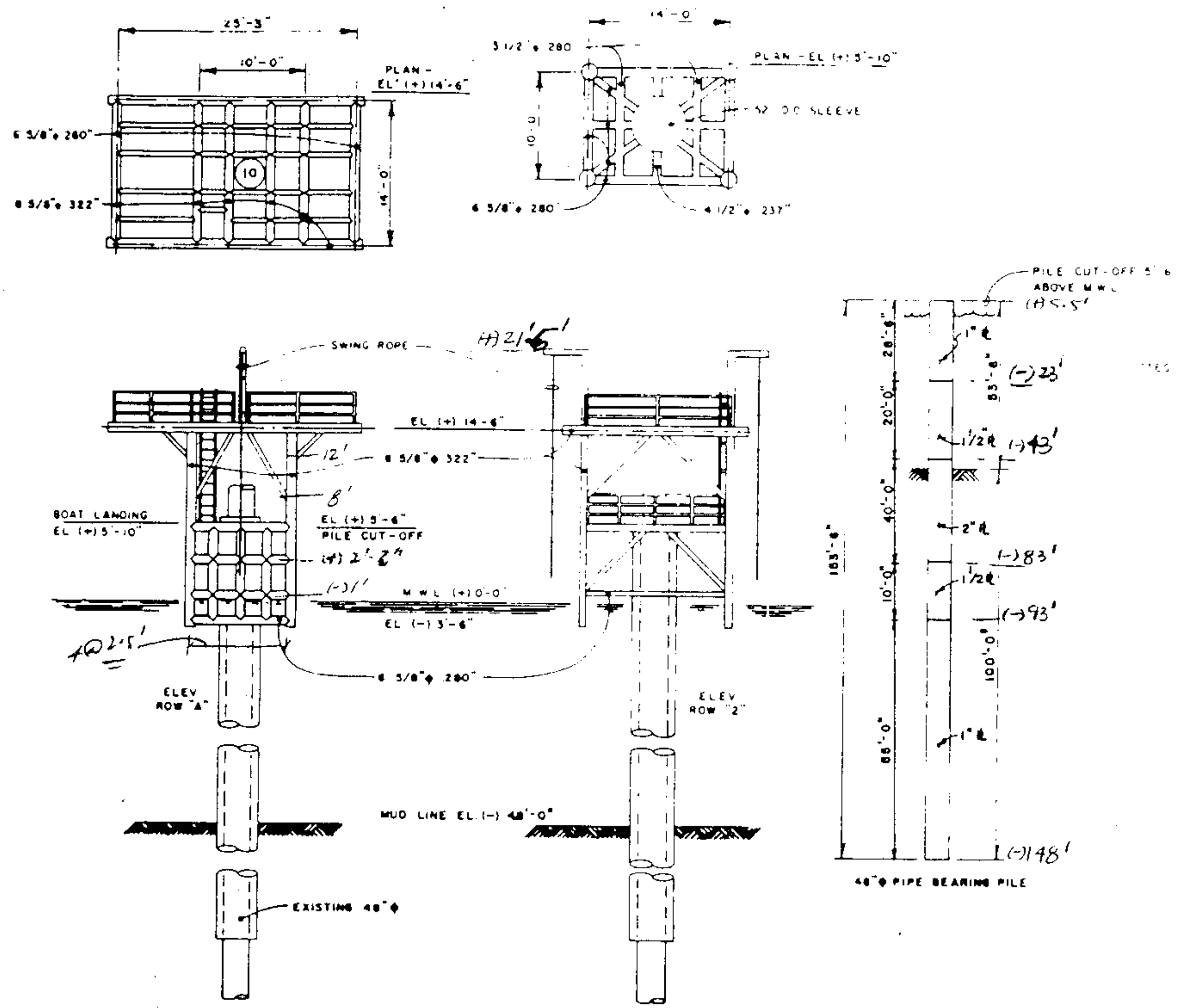
For this study, it was decided to determine metocean loads under Task 2A (differences between RP 2A 19th and 20th Editions) for typical designs of all three companies, in order to evaluate the effect of significant variations in the structural details of boat landings and deck, and in the variation in the water depth. For Task 2B (representative design case) and Task 2C (comparison with observed behavior during Andrew) the design of Company C in 48 ft water depth location was chosen due to availability of complete data for this case.



CAISSON DESIGN – COMPANY A
FIGURE 1-1



CAISSON DESIGN – COMPANY B
FIGURE 1-2



CAISSON DESIGN – COMPANY C
FIGURE 1-3

Table 1-1: Features of Selected Caisson Platforms

Company	Block Number	Year Installed	Water Depth (ft.) ##	Structural Features		Damage Description **
				Caisson Diameter	Penetration Below Seabed	
A	Ship Shoal 99	1961	21	48 inch	59 ft.	Broken at mudline
	Ship Shoal 98	1986	17	72 inch	75 ft.	No damage
	South Timbalier 52	1977	60	6 ft. to 8 ft. tapered	103 ft.	Severed 5' above mudline
	South Timbalier 51	1982	55	6 ft. to 8 ft. tapered	93 ft.	No damage
B	South Pelto 9	1985	35	30 inch	195 ft.	Leaning
	South Pelto 10	1984	35	30 inch	195 ft.	Leaning
C	Ship Shoal 113	1990	46	48 inch	100 ft.	Toppled over
	Ship Shoal 113	1988	48	48 inch	100 ft.	Leaning 48 degree
	Ship Shoal 113	1990	47	48 inch	100 ft.	Leaning 5 degree
	Ship Shoal 135	1983	53	48 inch	100 ft.	Leaning 15 degree
	Ship Shoal 136	1983	50	48 inch	100 ft.	Leaning 30 degree

Notes: ** Damage observed post hurricane Andrew
Where available, the as-is water depth is mentioned.

Section 2
API Design Criteria

2.1 INTRODUCTION

The API RP 2A, 20th Edition in "Commentary on Minimum Structures, Section 16," discusses appropriateness of owner selected criteria based on consequence level of its caisson. The specific paragraphs from the commentary Section C16.2 (page 191 of RP 2A, 20th Edition) are reproduced below:

> *Evaluation of reserve strength and redundancy should be balanced by consequence of failure. The consequences of failure of a minimum structure are usually lower since most are designed for:*
>
> 1. *Minimum topside facilities.*
> 2. *Unmanned operations.*
> 3. *One to six wells.*
> 4. *Drilling and work-over activity to be performed by a mobile drilling rig.*
>
> *It is entirely appropriate for such a structure to have lower reserve strength and less redundancy than a conventional structure. However, under no circumstances should a quarters or oil storage platform be classified as a low consequence of failure structure.*
>
> *Experience with minimum structures indicates possible hindrance of human performance, due to structural movement, from operating environmental conditions. The owner may choose to accept possible reduced operating and production efficiency. However, the owner may also choose to perform a dynamic response analysis using owner selected environmental loads. The results can be compared to a personnel comfort graph.*

The above paragraphs identify the relevance of consequences of failure of a caisson-type platform in selection of the design criteria. However, no additional guidelines for generation of a reduced criteria are given. Therefore, in general the 20th Edition metocean criteria is applicable to the caisson type platforms in the same way as for the conventional steel jacket platforms.

In the following sections, a comparison of the metocean criteria and load computation procedures will be made between the recommended practice per 19th and 20th Editions. Then the metocean criteria will be developed for the three designs of caissons for different water depths between 25 ft and 65 ft. The base shear (at mudline) will be computed for the three designs and the increase from the 19th to the 20th Editions will be determined.

In addition, the new guidelines in Section 16 of the RP 2A, 20th Edition on the design of minimum structures will be discussed for their relevance to the caisson type platforms.

2.2 ENVIRONMENTAL CRITERIA

Various parameters and quantities, which affect the API reference level design load have changed in the RP 2A, 20th Edition. The parameters that would affect the metocean load on a caisson located in the Gulf of Mexico are compared in Table 2-1 and discussed in Section 2.2.1. In Section 2.2.2, the metocean parameters and the base shear results obtained using the hydrodynamic load computation procedures per the two API editions, are presented for several caissons of the three designs.

Section 1.5 of both editions of the RP 2A provides a note on acceptability of risk analysis based approach for selection of the design metocean parameters. One relevant paragraph from this section is reproduced below:

> *As a guide, the recurrence interval for oceanographic design criteria should be several times the planned life of the platform. Experience with major platforms in the Gulf of Mexico supports the use of 100-year oceanographic design criteria. Risk analysis may justify either long or shorter occurrence intervals for design criteria. However, not less than 100-year oceanographic design criteria should be considered where the design event may occur without warning while the platform is manned and/or when there are restrictions, such as great flying distances, on the speed of personnel removal.*

The above guidelines and those in Section 16 (see last section) indicate that a owner can select metocean parameters different than the RP 2A as long as the new parameters are supported by risk analysis.

2.2.1 Comparison of the Gulf of Mexico Metocean Criteria

The difference in computation of metocean loads based on the two RP 2A editions arise from: metocean parameters (wave height, wave period, storm tide, current, etc.), wave kinematics and the hydrodynamic force coefficients used in the Morison's equation. The various parameters and coefficients which differ in the two editions are discussed below:

- <u>Wave height</u>: The two editions provide recommended wave height criteria for water depths greater than 25 ft (Figure 2-1 and Figure 2-2). The recommended maximum wave height for the 20th Edition is lower as shown in Figure 2-2. The 20th Edition recommends a further reduction in the omni-directional wave height based upon directionality (applicable for water depths greater than 40 ft). The 19th Edition recommends the same wave height for any direction. In the water depth range (up to 100 ft) of importance to caissons, the difference in wave height determined by the two editions is not significant. In shallower water depth locations, the breaking wave criteria (breaking wave height = 0.78 d, where d is sum of water depth and storm tide) governs.

- Wave period: The 19th Edition does not provide any specific values for the wave period and it recommends to obtain it based on wave height and wave steepness. The 20th Edition suggests use of a constant wave period of 13 sec. for all locations in the Gulf of Mexico. It also recommends modifying the wave period by accounting for the Doppler effect of the current present at the site.

- Storm tide: The recommended storm tides for water depth greater than 25 ft for the two editions are given in Figure 2-1 and Figure 2-2.

- Current:The 19th Edition recommends to ignore current in evaluation of the hydrodynamic loads, when the procedures given for obtaining the reference level force per Section 2.3.4g are used. The 20th Edition recommends a current magnitude of 2.1 knots (3.54 ft/sec) uniform up to 150 ft water depth with its direction dependent on platform longitude. Its component along the wave direction is taken in evaluation of the metocean load level.

- Wave kinematics factor: The API 20th Edition recommends a wave kinematics factor of 0.88 for hurricanes and of 0.95 to 1.0 for extratropical storms to account for directional spreading of wave energy. There is no such factor in the 19th Edition.

- Marine Growth: The 20th Edition recommends use of marine growth thickness of 1.5 inch up to 150 ft below the mean high water (MHW) for the Gulf of Mexico locations. The 19th Edition did not provide any specific values for the marine growth.

- Hydrodynamic force coefficients: The 19th Edition reference level force considers a constant drag coefficient (C_d) of 0.6 and inertia coefficient (C_m) varying from 1.5 to 2.0, depending on the member diameter. The 20th Edition recommends C_d of 0.65 and 1.05, and C_m of 1.05 and 1.2 for smooth and rough (marine growth roughened) members respectively.

- Other Considerations: The conductor shielding and current blockage factors introduced in the 20th Edition are not relevant to the caisson type platforms in which single- or multi-wells are located inside.

In the case of free standing caisson type platforms which are nearly symmetric in the two orthogonal directions and have small diameter boat landing and deck structural members, the directional variation of the wave height is not of much importance for the design of caisson sections for cases with zero lean angle (original design and undamaged caisson platform cases). The wave height variation with approach direction may become important for some leaning caissons.

2.2.2 Application to Caisson Designs

The metocean load difference was computed for several caissons with varying diameters, water depths, and structural configurations. In this study a single well conductor located inside of the caisson was considered. Risers provided on the outside of the caissons were neglected.

Table 2-2 presents the various metocean parameters obtained for the two RP 2A Editions for water depths of 25 ft, 36 ft, 53 ft, and 65 ft. The 20th Edition provides storm tide and guideline omni-directional wave height which are lower than those per the 19th Edition for all water depths except 25 ft case. For the 25 ft water depth case, due to lower storm tide per the 19th Edition and that the breaking wave height criteria (= 0.78 d) governs, the wave height becomes lower than that per the 20th Edition. Site specific special studies are needed below the 25 ft water depth case.

Wave load analyses were performed using these metocean parameters on the computer models generated for the typical caisson designs obtained from the three companies. Three-dimensional views of the computer models of the three designs are given in Figures 2-3 to 2-5. Table 2-3 provides the base shear values obtained from the analyses.

The results presented in the Table 2-3 indicate a significant increase in base shear using RP 2A, 20th Edition compared to the 19th Edition. For Designs B and C, the increase in base shear ranges from 38 percent to 51 percent for water depths of 36 ft and 53 ft and caisson diameter varying from 30 in. to 72 in. For the Design C with 72 in. diameter, the increase in the projected area of caisson in the wave zone leads to a higher increase in the base shear compared to that for the 48 in. diameter case.

In case of Design A, the increase in base shear using RP 2A, 20th Edition is very high (65 to 93 percent) because of the nav-aid tower installed on top of the deck.

The current (2.1 knots or 3.54 ft/sec) for the 20th Edition wave is a major factor for this increase in the base shear. Note that in all these designs, the wave crest is located above the caisson main deck and per the 20th Edition, the current is stretched up to the wave crest, which leads to significant increase in the base shear values.

2.3 STRUCTURAL DESIGN CRITERIA

This section reviews the specific guidelines provided in Section 16 of the RP 2A, 20th Edition which covers design of caisson type platforms.

The design of caissons is generally governed by moments. In the case of free standing caissons with a grouted annulus, the axial loads from tubings and casings also become important [Stahl and Baur, 1980; Imm and Stahl, 1988].

The 20th Edition allows the use of Class C steel for caissons provided the maximum interaction ratio against all design loading conditions is less than 0.90. Section 16 of the RP 2A, 20th Edition recommends a reduced allowable interaction ratio of 0.9 instead of 1.0 to account for the increase in the allowable bending stress in the 17th Edition (1987) from 0.66 Fy to 0.75 Fy, where Fy is the yield strength of steel. The industry experience with Class C steel in caissons is based on an allowable bending stress as 0.66 Fy. Therefore, API recommends using a reduced maximum interaction ratio of 0.9 for caissons instead of 1.0 used for the steel jacket platforms. Note that the 19th Edition did not distinguish between steel jacket and caisson for the allowable maximum interaction ratio.

Class C steel does not require impact testing has limited thickness (up to 2"), and the nominal yield strength varies from 30 ksi to 36 ksi for three ASTM grade steels. API allowed continued use of Class C steel for caisson type platforms due to a history of their successful use of such steel prior to 1987, when the allowable bending stress of 0.66 Fy was used [Section C16.4.2, RP 2A, 20th Edition].

Fatigue Design Criteria

The RP 2A, 20th Edition in Section 16.2.2 mentions that "For caissons with natural periods less than 2 seconds and in a water depth less than 50 ft, simplified fatigue analysis in accordance with Section C5.1 may be used in lieu of detailed fatigue analysis."

Both editions of the RP 2A provide a simplified fatigue analysis approach which has been calibrated for the design wave climate based on use of stress values obtained for the maximum design wave. Thus, the hot-spot stresses obtained using the design level wave and appropriate stress concentration factors (SCF's) are compared with the allowable peak hot-spot stresses (Sp) recommended by RP 2A.

The Sp values have changed from the 19th Edition to the 20th Edition. Figure 5.1.1-1 and Figure 5.1.1-2 (see Figure 2-6) of the 19th Edition and Figure C5.1-1 and C5.1-2 (see Figure 2-7) of the 20th Edition provides Sp values, which are based on S-N curves X and

X' respectively. The Sp values for the simplified fatigue analysis provisions were adjusted to account for the change in the metocean parameters in the 20th Edition.

Figure 2-8 compares the new and old API curves for the API X, S-N curve, "other" members, and 40 year fatigue life [Luyties, 1993]. The valley at lower water depth exists due to rapid drop with depth of the design wave height (see Figure 2-1 and Figure 2-2). Note that in deeper water depths the allowable Sp per the 19th Edition is higher than for the 20th Edition, which relates to the reduction in the wave height per 20th Edition and reduced stress level for the design wave. In shallow water the allowable Sp values have increased for some water depths for the 20th Edition case.

Table 2-4 provides the allowable peak hot-spot stress values for three water depths (25 ft, 36 ft and 50 ft) for waterline and other members obtained from both RP 2A editions for applicable API-X and -X' S-N curves. This table indicates that for the 50 ft water depth case, the allowable stress values are nearly same for the two RP 2A Editions. For the 25 ft and 36 ft water depths, the allowable stress values per the 20th Edition are 8 to 16 percent higher compared to those per the 19th Edition. The increase in Sp from applicable X to X' S-N curves is 23 to 34 percent.

2.4 OPINION SURVEY

Several industry experts involved in development of the RP 2A, 20th Edition Metocean Criteria were contacted by PMB to obtain their opinion on the applicability of the 20th Edition wave load recipe for caissons.

One industry expert indicated that they are currently performing a model test study to answer this question and to determine forces on a caisson in wave and current. At this time, it cannot be said that the applicable criteria for caissons should be less than or the same as the 100-year return period per RP 2A, 19th or 20th Editions. Their model test is aimed to evaluate, if the 20th Edition criteria is too stringent.

Another industry expert looked at the failures of caissons during Andrew and found that most of the failures occurred in zones with strong currents. This indicates that current plays a key role in caisson design.

2.5 APPLICABILITY OF API 20TH EDITION TO THE CAISSON DESIGN

The three criteria (metocean criteria, structural design criteria, fatigue check criteria) as applicable to the caisson type platforms in the Gulf of Mexico were compared and evaluated for the 19th and 20th Editions in Section 2.

The metocean load analysis of the three caisson designs indicated that the loads increase significantly with the 20th Edition criteria. The percentage increase in the lateral load depends upon the water depth, diameter, use of platform (facilities on deck), etc. In one design with nav-aid tower on the deck, the increase in lateral load level was very high for the shallower water locations. The general increase in the load level is noted as 40 to 50 percent.

The hurricane Andrew hindcast data for a case evaluated in this study (see Section 4) indicated the metocean parameters to be close to the RP 2A, 20th Edition criteria.

The Gulf of Mexico caisson type platforms in general have very low consequence level due to early hurricane warning system in the Gulf of Mexico and the MMS mandatory requirement of provision of SSSV valves in all tubing installations open to hydrocarbon-bearing zones. Therefore, as suggested in Section 16 of the RP 2A, 20th Edition, an operator could develop a risk based reduced criteria to meet the consequence level of particular caisson type platform.

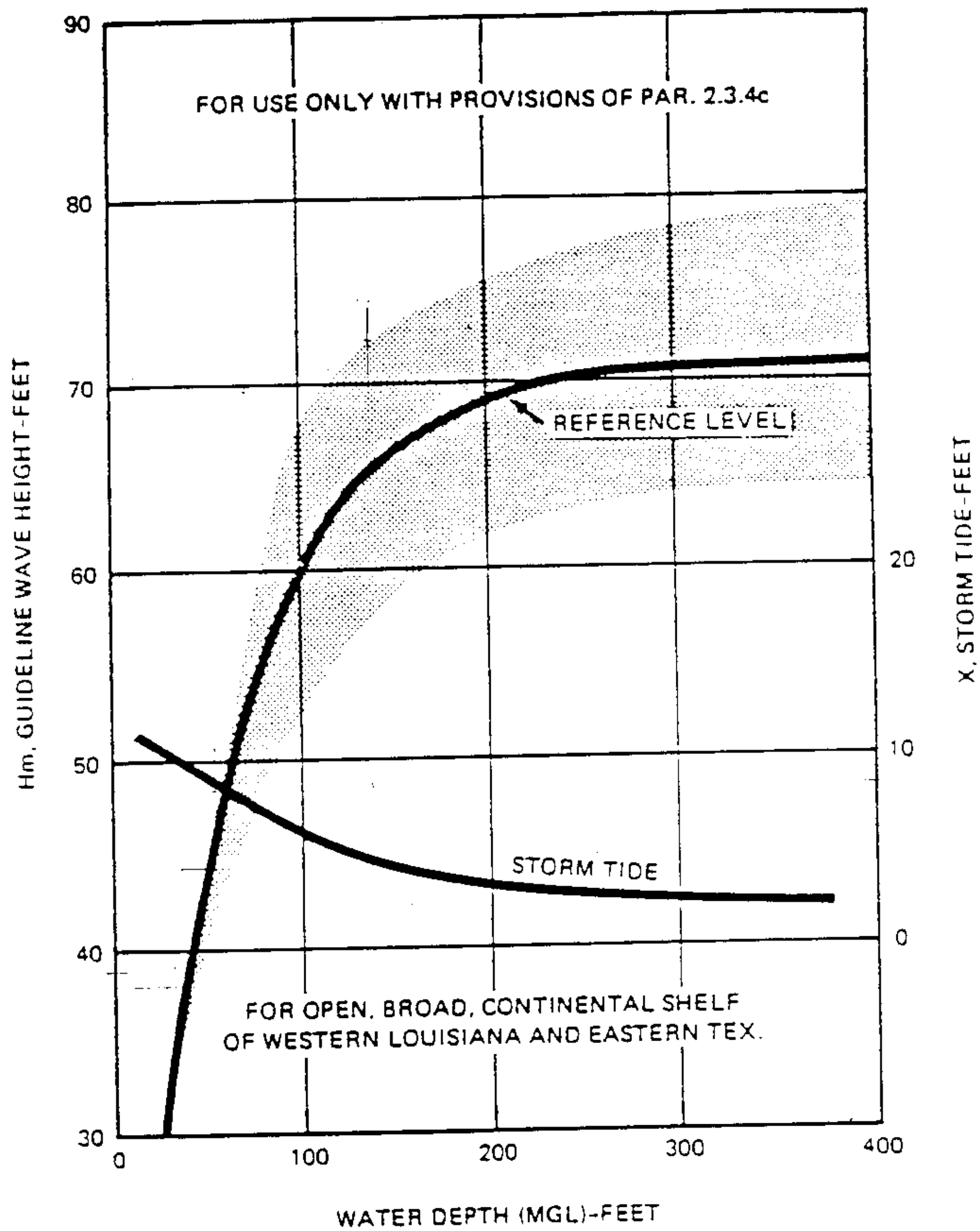
These structures have much less redundancy due to their structural characteristics. Section 16 on minimum structures does mention on acceptability of lower RSR for such systems but it does not provide any value for the acceptable lower reserve strength.

The Draft Section 17 for assessment of existing structures provides a two level criteria and reduced criteria for the design level check dependent on consequence level of facilities. The metocean parameters for insignificant consequence level case for both the design level and the ultimate strength evaluations are lower than the 20th Edition parameters.

Therefore, in lieu of a reduced criteria supported by risk analysis, the 20th Edition 100-year return period criteria for metocean parameters shall be followed to meet the safety level acceptable for all platforms. It will be prudent to have a two level criteria similar to that developed in the Draft Section 17, with the damage limited to the acceptable leaning of caisson (5 degree reported by Barnett and Casbarian) at the load level corresponding to the minimum acceptable reserve strength level. Alternately, the reduced design level criteria be calibrated to the expected lower redundancy level of such systems. In case an alternate risk based criteria is developed, the lower redundancy level of these structures shall be given due consideration in selection of the criteria. Such a reserve strength level and reduced criteria will have to decided by the government and industry.

The structural design criteria per 20th Edition limits the maximum interaction ratio to 0.9 for caissons where Class C steel is used.

The simplified fatigue analysis procedure presents revised allowable peak hot spot stress (Sp) curves due to reduced wave heights (cyclic stress component) per 20th Edition. However, for the lower water depths, applicable to the caisson type platforms, the allowable Sp values are higher for the 20th Edition. Therefore, the designs based on 20th Edition, which includes current, will have additional margin for simplified fatigue checks for caissons.



GUIDELINE WAVE HEIGHTS AND STORM TIDES FOR GULF OF MEXICO
RP 2A, 19TH EDITION
FIGURE 2-1

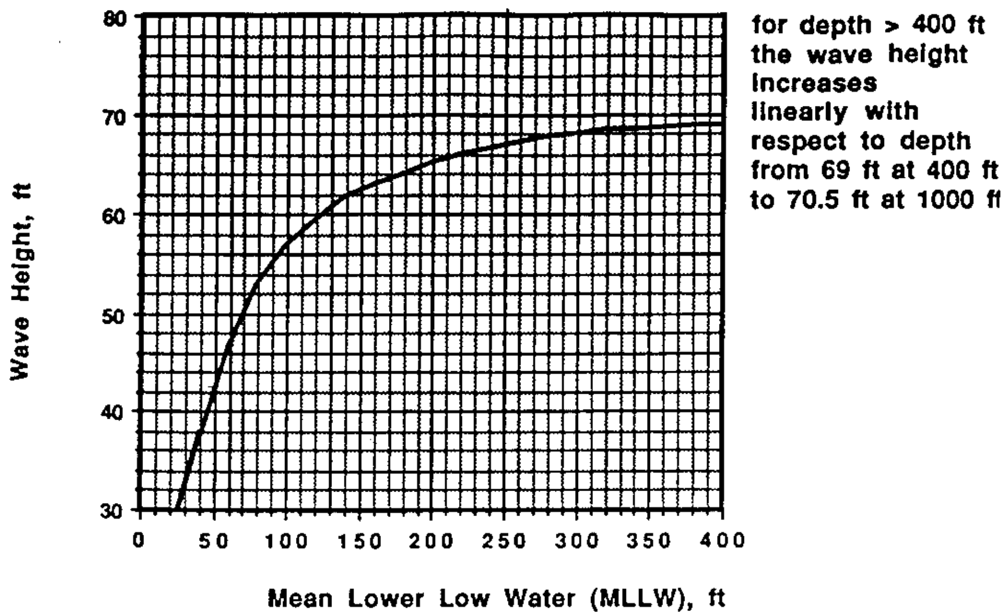


FIG. 2.3.4-3
GUIDELINE OMNIDIRECTIONAL DESIGN WAVE HEIGHT VS MLLW,
GULF OF MEXICO, NORTH OF 27° N AND WEST OF 86° W

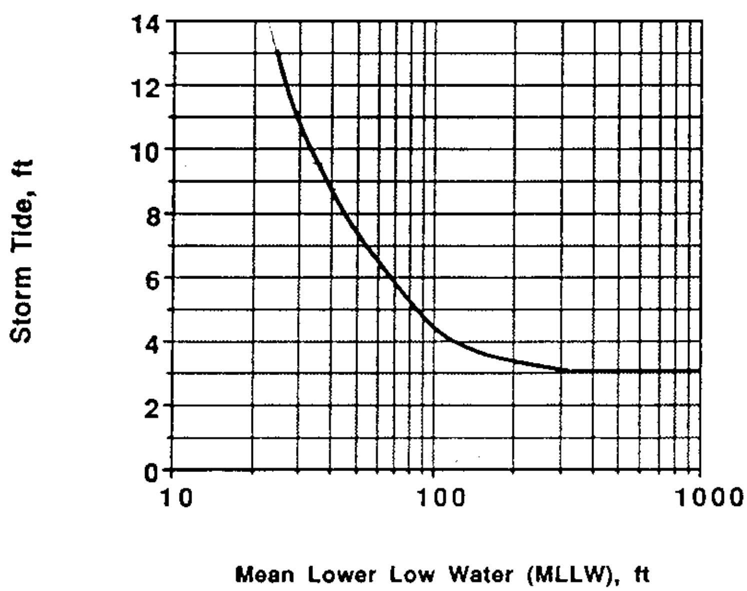
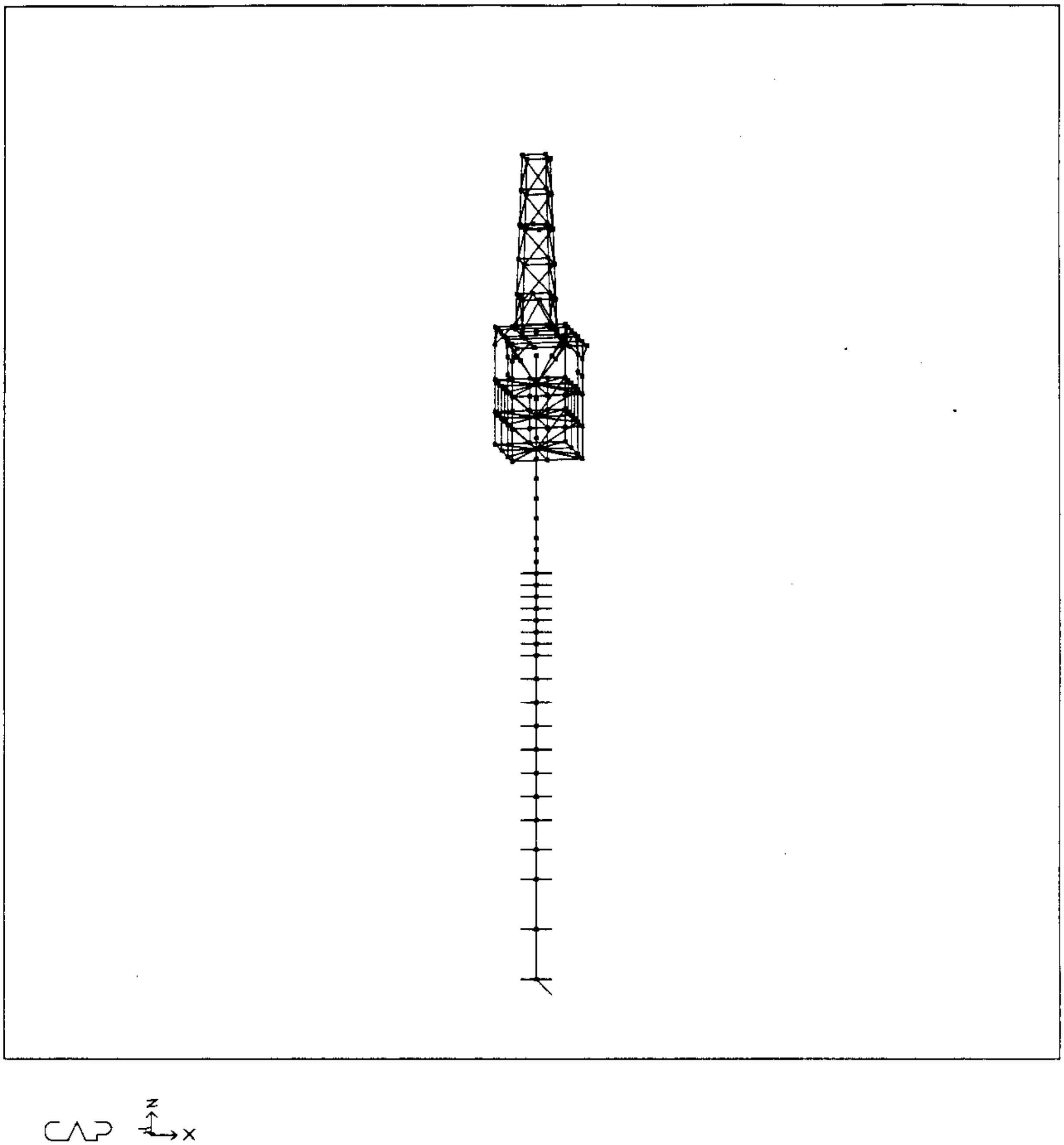


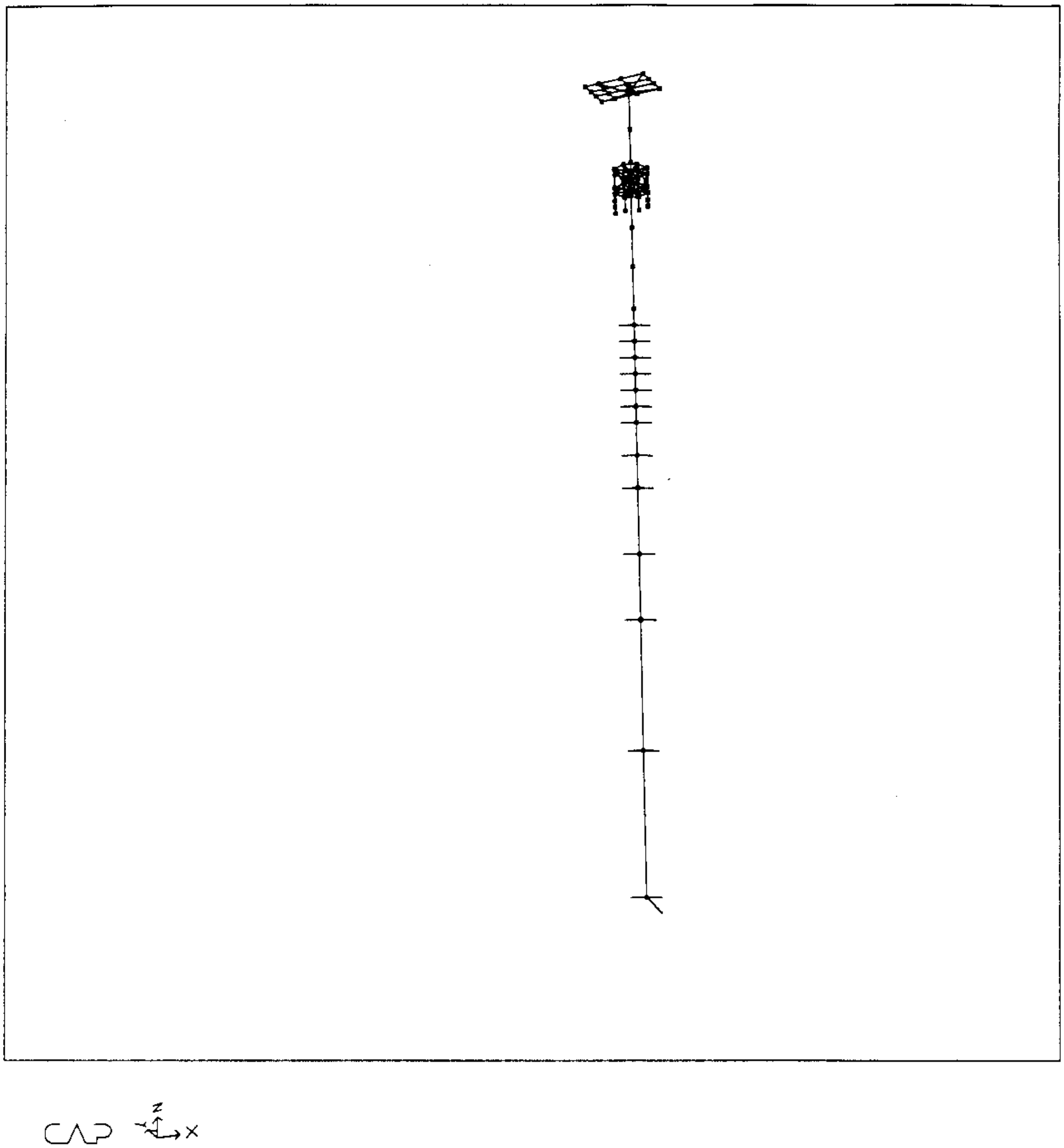
FIG. 2.3.4-7
GUIDELINE DESIGN STORM TIDE VS MLLW, GULF OF MEXICO,
NORTH OF 27° N AND WEST OF 86° W

GUIDELINE OMNIDIRECTIONAL DESIGN WAVE HEIGHT AND DESIGN STORM TIDE VS. MLLW, GULF OF MEXICO – RP 2A, 20TH EDITION

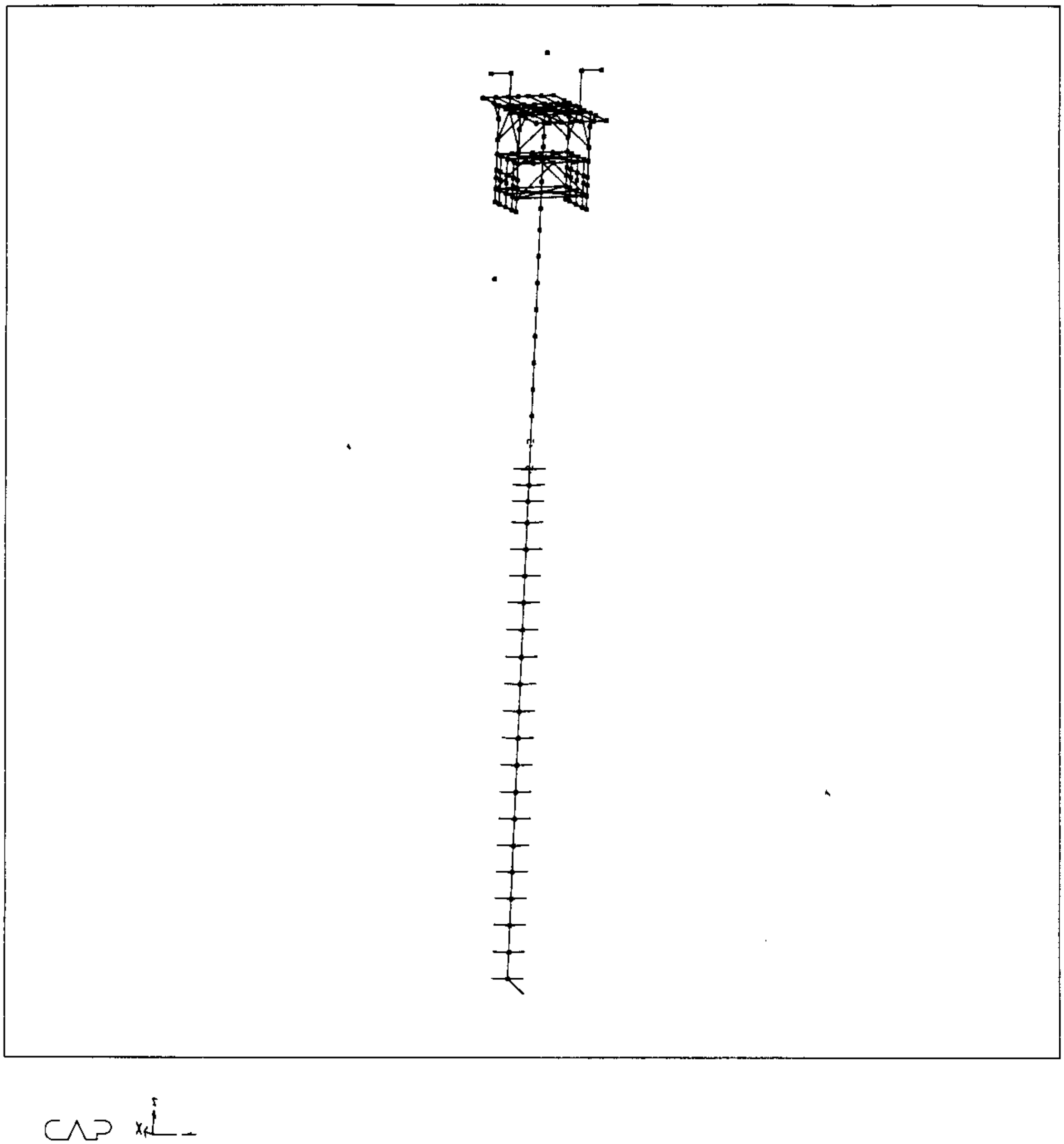
FIGURE 2-2



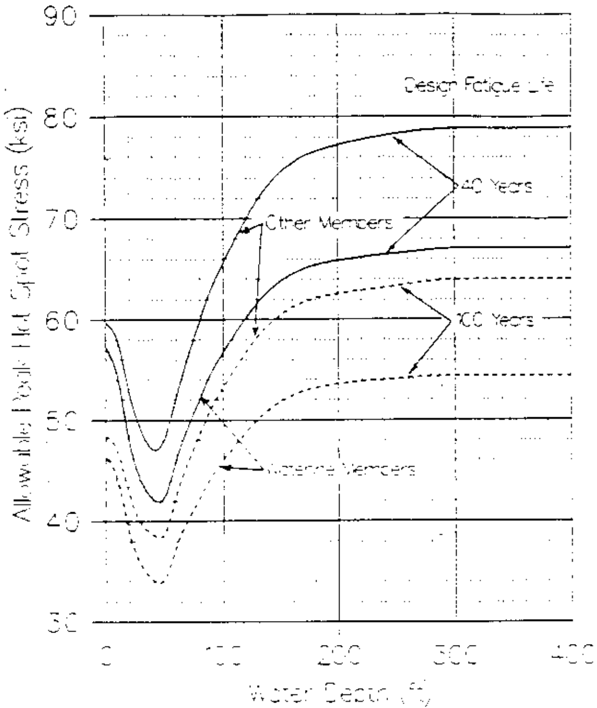
3-D COMPUTER MODEL – CAISSON DESIGN A
FIGURE 2-3



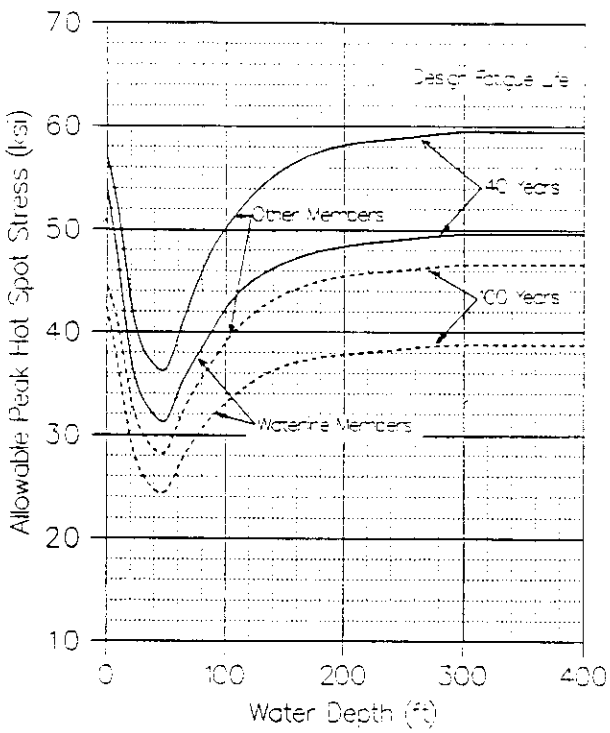
3-D COMPUTER MODEL – CAISSON DESIGN B
FIGURE 2-4



3-D COMPUTER MODEL – CAISSON DESIGN C
FIGURE 2-5

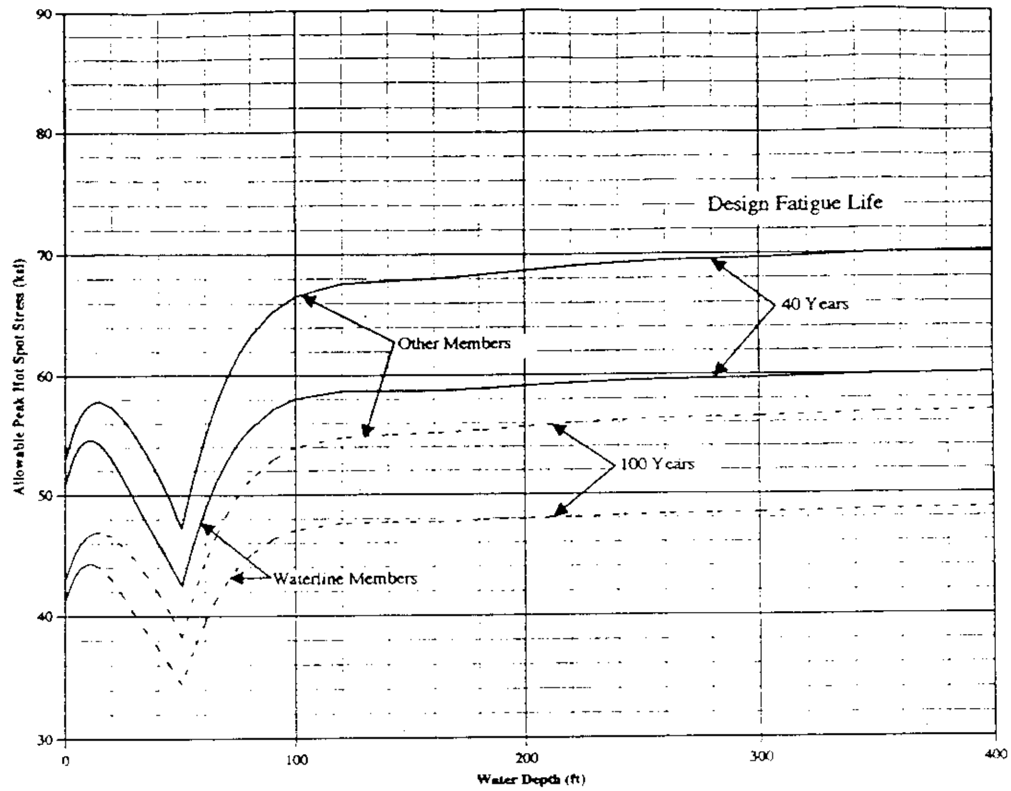


Allowable Peak Hot Spot Stress, S_p (S-N Curve X)

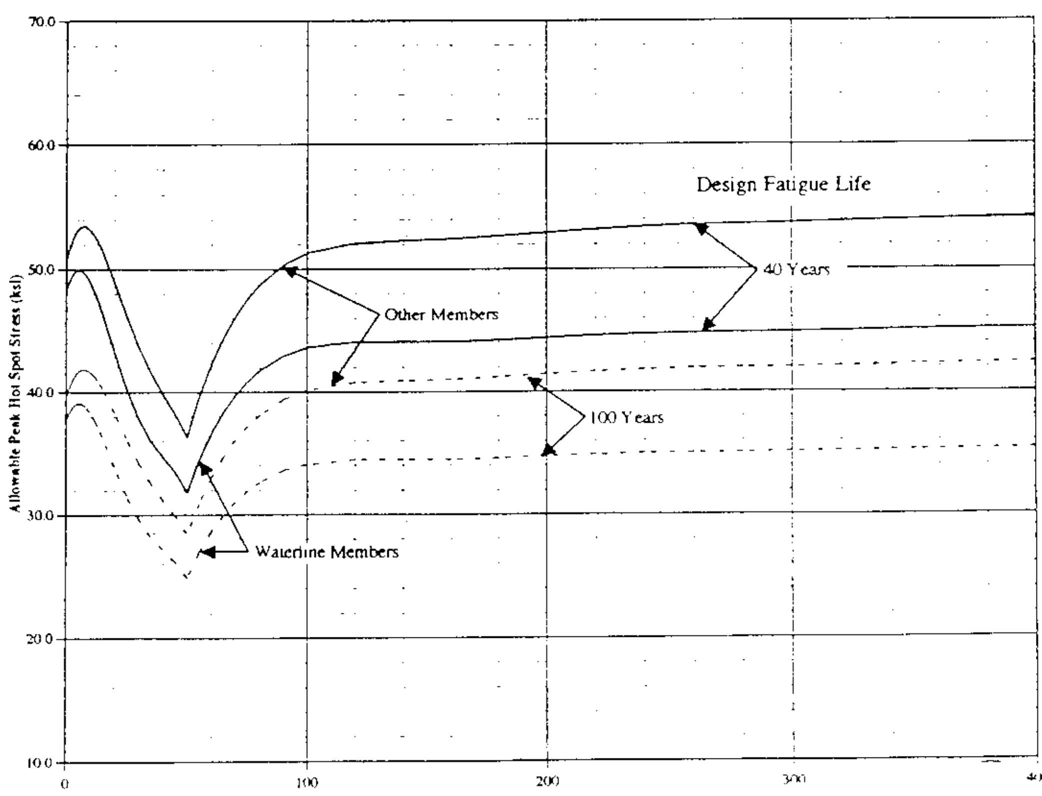


Allowable Peak Hot Spot Stress, S_p (S-N Curve X')

ALLOWABLE PEAK HOT SPOT STRESS, SP – RP 2A, 19TH EDITION
FIGURE 2-6

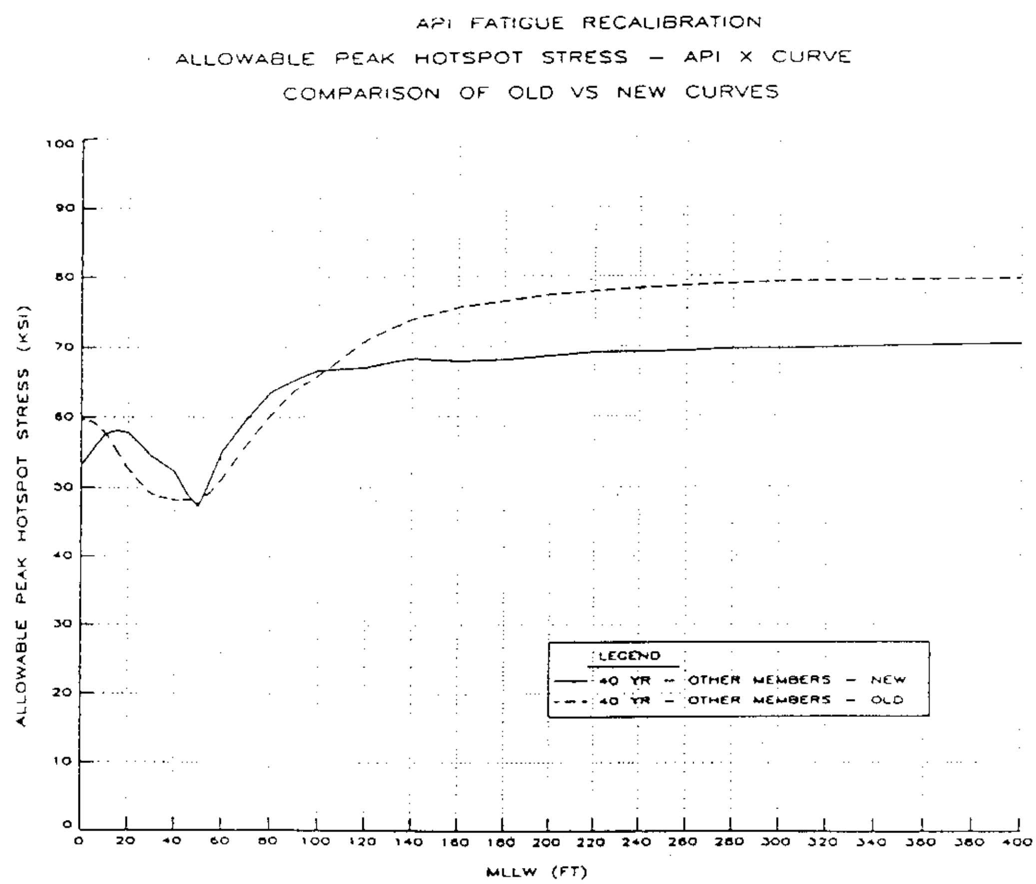


ALLOWABLE PEAK HOT SPOT STRESS, S_p (S-N CURVE X)



ALLOWABLE PEAK HOT SPOT STRESS, S_p (S-N CURVE X')

ALLOWABLE PEAK HOT SPOT STRESS, SP – RP 2A, 20TH EDITION
FIGURE 2-7



API FATIGUE RECALIBRATION, COMPARISON OF OLD AND NEW CURVES – ALLOWABLE PEAK HOT SPOT STRESS, API X CURVE (LUYTIES, 1993)

FIGURE 2-8

Table 2-1: Comparison of Wave Force Procedures - API 19th vs. 20th Editions

Item	RP2A, 19th Edition	RP2A, 20th Edition
Metocean Criteria		
Wave Height	Omni-directional	Directional Criteria
Wave Period	Unmodified	Doppler effect used
Current	None **	Function of Longitude and water depth
Marine Growth	Mentioned **	3" on dia. up to -150 ft.
Wave Force Procedure		
Current blockage factor	Not Applicable	0.7 - 1.0 based on no. of legs and wave dir.
Wave Kinematic Factor	Not Applied	0.88 for hurricanes 0.95 - 1.0 for extratropical storms
Wave Force Coefficients		
Drag Coefficient, Cd	0.6 - 1.2	0.65 (smooth tubulars)
		1.05 (rough tubulars)
Inertia Coefficient, Cm	1.3 - 2.0	1.6 (smooth tubulars)
		1.2 (rough tubulars)
Conductor Shielding Factor	1.0	Function of Spacing/ Diameter
Morison's equation	Yes	Yes

Notes:

** The current and marine growth are not used when API Reference Level Force guidelines used, i.e., Cd = 0.6 and Cm = 1.5 as per Section 2.3.4g.

Table 2-2: Comparison of Metocean Parameters - RP2A 19th vs. 20th Editions

Water Depth	Metocean Parameters	RP2A, 19th Edition	RP2A, 20th Edition (##)
25 ft	Storm Tide (ft.)	10.50	13.00
	Wave Height (ft.)	27.69 **	30.00
	Wave Directionality	omni-directional	omni-directional
	Wave Period (sec.)	13.50	14.12
	Wave Kinematic Factor	1.00	0.88
	Current (ft/sec.)	0.00	3.54
	Order of Stream Function Theory	11th	11th
36 ft.	Storm Tide (ft.)	10.00	9.60
	Wave Height (ft.)	35.9 **	35.00
	Wave Directionality	omni-directional	omni-directional
	Wave Period (sec.)	13.50	14.20
	Wave Kinematic Factor	1.00	0.88
	Current (ft/sec.)	0.00	3.54
	Order of Stream Function Theory	11th	11th
53 ft.	Storm Tide (ft.)	9.00	7.00
	Wave Height (ft.)	45.80	44.00
	Wave Directionality	omni-directional	Directional
	Wave Period (sec.)	13.50	14.10
	Wave Kinematic Factor	1.00	0.88
	Current (ft/sec.)	0.00	3.54
	Order of Stream Function Theory	9th	9th
65 ft	Storm Tide (ft.)	8.40	6.10
	Wave Height (ft.)	50.00	49.00
	Wave Directionality	omni-directional	Directional
	Wave Period (sec.)	13.50	14.03
	Wave Kinematic Factor	1.00	0.88
	Current (ft/sec.)	0.00	3.54
	Order of Stream Function Theory	9th	9th

Notes: ** Based on API breaking wave height criteria (= 0.78 d)
The apparent wave period is given for RP2A, 20th Edition Case

Table 2-3: Comparison of Base Shear Values for Different Designs

Company	Water Depth (ft.)	Caisson Diameter (inch)	Base Shear (BS)		
			RP2A, 19th Edition (KIps)	RP2A, 20th Edition (KIps)	Increase in BS (%)
A	25	48	57	110	93
	65	72	165	272	65
B	36	30	55	75	38
C	53	48	94	132	40
	53	72	178	269	51

Table 2-4: Comparison of Allowable Peak Hot Spot Stress (Sp) **

Water Depth (ft.)	S-N Curve	Member Location	Allowable Hot-Spot Peak Stress, Sp		
			RP2A, 19th Edition (Ksi)	RP2A, 20th Edition (Ksi)	Increase in Allowable Sp (%)
25	API-X'	Waterline Members	34.4	40.0	16.3
		Other Members	40.0	45.5	13.8
	API-X	Waterline Members	45.3	50.8	12.1
		Other Members	50.3	56.0	11.3
36	API-X'	Waterline Members	32.5	35.1	8.0
		Other Members	37.3	40.4	8.3
	API-X	Waterline Members	42.5	47.0	10.6
		Other Members	47.5	52.5	10.5
50	API-X'	Waterline Members	31.5	31.7	0.6
		Other Members	36.3	36.5	0.6
	API-X	Waterline Members	42.1	42.5	1.0
		Other Members	47.1	47.3	0.4

Notes: ** Applicable for the Simplified Fatigue Analysis
Design fatigue life assumed as 40 years

Section 3
Evaluation of Caisson Design

This section provides details of the re-design and evaluation of a caisson damaged during Hurricane Andrew. In this evaluation, the metocean criteria and the hydrodynamic load computation procedures per both 19th and 20th Editions of RP 2A were used. The following sections summarize the results obtained. The objective is to compare a caisson design using both the 19th and 20 Editions to determine the impact on loads, caisson performance, and steel requirement.

3.1 STRUCTURAL DETAILS OF SELECTED CAISSON

The caisson design of Company C in 53 ft water depth in the Ship Shoal location was used for the comparison. The original design drawings show that 48 ft water depth was considered at the design stage, whereas the actual water depth at the caisson location is now determined as 53 ft. In this study, the actual water depth of 53' has been used.

Figure 1-3 provides the structural details of the original 1983 design. It consists of 48 inch uniform diameter tubular installed with 100 ft penetration. The caisson was damaged during Andrew and a 15 degree tilt was reported. The operating company developed a repair plan and re-designed a new 72 inch diameter uniform caisson to meet the RP 2A, 20th Edition criteria. The 48 inch diameter caisson was straightened and the new 72 inch diameter caisson was installed over it. New boat landings and deck structure were installed. The elevation of the new deck is 20.5 ft compared to 14.5 ft above MWL for the original design. Figure 3-1 provides details of the new caisson.

For Task 2B, assessment of existing caisson design, the characteristics of the re-designed 72 inch diameter caisson were considered as the base case. The details of analysis and results are presented in the following sections.

3.2 METOCEAN PARAMETERS AND COMPUTER MODEL

The metocean parameters obtained from the two RP 2A editions are presented in Table 3-1. The storm tide and maximum wave height are higher by approximately 2 ft for the 19th Edition. The apparent wave period for the 20th Edition is 14.1 sec (including the doppler effect). A current of 3.54 ft/sec (2.1 knots) is to be considered at a 268 degree approach direction per the 20th Edition. The 19th Edition has no current. A uniform marine growth thickness of 1.5" has been used for both cases.

The design of the caisson per the two RP 2A editions is repeated to obtain section requirements at different elevations. Note that other practical considerations such as underdrive/overdrive tolerance, availability of sections, and other miscellaneous details have not been considered. No risers were considered. The boat landings and deck structure designs shown in Figure 3-1 were used. A nominal yield strength of steel of 36 ksi and use of Class C steel was assumed. Degraded soil-pile capacity was used to develop the p-y nonlinear soil springs.

Note that the focus of this study is to determine conceptual level sizing per the two editions and to determine the percentage increase in the steel requirement for the primary caisson. Thus, no attempt was made to re-design the boat landings and deck structure. The designs of the boat landings and deck structure could also vary due to the 20th Edition and could lead to some increase in the steel tonnage.

Complete 3-dimensional computer models of the caisson with its boat landings and deck structure were developed using CAP [PMB Engineering, 1994] as shown in Figure 3-2. Soil-structure interaction was characterized by non-linear soil spring elements. The caisson and all other structural elements were characterized by linear elastic beam elements. The design load on deck was assumed as 0.23 ksf, same as in the original design. Total topside load was 92 Kips.

3.3 INPLACE ANALYSIS

3.3.1 Inplace Analysis — API 19th Edition

Linear elastic inplace analysis of the caisson model was performed for the RP 2A, 19th Edition metocean parameters as in the Table 3-1. The diameter and thicknesses at various elevations of the caisson were established by repeated analysis. In order to reduce the projected area in the wave zone, the submerged portion of the caisson was designed as a conical section as shown in Figure 3-3. The upper part (up to Elev. -13') consists of 42 inch diameter tubulars and the bottom part (from Elev. -43') of 60 inch diameter tubulars. The tapered section is provided from Elev. (-) 13' to Elev. (-) 43' with a thickness of 1.25 inch. The penetration of 120 ft below seabed was determined for this design.

Table 3-2 summarizes the results obtained from this analysis. The maximum loads at the mudlevel (at Elev. -53 ft) are: base shear of 160 kips and overturning moment of 9,827 kips-ft. The maximum bending moment of 12,739 kips occurs in the foundation at 30 ft below the seabed. The axial load is 160 kips.

The bending moment diagram for the caisson is shown in Figure 3-4. The wall thicknesses of sections have been assumed at an increment of 0.25 in. The profile of maximum moment values at which the allowable interaction ratio is reached for different sections have also been plotted.

The maximum wall thickness required is 2 inch and is required from 20 ft to 45 ft below the seabed. The lateral displacement at the deck level (Elev. + 20.5 ft) is 4.6 ft and is 1.2 ft at the seabed. The tilt of caisson was evaluated using the deck displacement and the caisson length from the deck to the mudline, thus ignoring the displacement of caisson at seabed. In practice, it is more likely that the tilt will be computed in this way. The tilt angle is 3.6 degree.

The total steel weight of the primary steel of this caisson is 138 kips.

3.3.2 Inplace Analysis Results - API 20th Edition

Design and analysis of caisson was repeated to obtain appropriate diameters and thicknesses at various elevations using the RP 2A, 20th Edition criteria. The conceptual sizing of the caisson is shown in Figure 3-5. The upper part (up to Elev. -13') of the caisson consists of 48 inch diameter tubulars and the bottom part (from Elev. -43') of 72 inch diameter tubulars. The conical section is provided from Elev. (-) 13' to Elev. (-) 43' with a thickness of 1.25 inch. The penetration of 130 ft below seabed has been determined for this design.

Table 3-2 summarizes results obtained from this analysis. At the mudlevel (Elev. -53 ft) the: base shear and overturning moment are 247 kips and 13,721 kips-ft respectively. The maximum bending moment of 18,976 kips occurs at 35 ft below the seabed.

The bending moment diagram for the caisson is shown in Figure 3-6. The wall thicknesses of sections have been assumed at an increment of 0.25 inch. The profile of maximum moment values at which the interaction ratio will be 0.9 (limit when Class C steel used for caissons) for the different sections have also been plotted.

The maximum wall thickness is 2 inches and is required from 15 ft to 55 ft below the seabed. The lateral displacement at the deck level (Elev. + 20.5 ft) is 4.4 ft and is 1.3 ft at the seabed. The tilt angle is estimated as 3.4 degree.

The total steel weight of the primary steel of this caisson is 181 kips.

3.4 FATIGUE ASSESSMENT

3.4.1 Fatigue Assessment - API 19th Edition

A simplified fatigue analysis per Section 5.1 of RP 2A was performed on the design developed in Section 3.3.1. A linear elastic analysis was performed for the design wave criteria per Table 3-1, with no dead and live loads in order to determine cyclic stresses at various elevations of the caisson.

The SCF values were computed for the different connections: butt welds between the same diameter tubulars with same or different wall thicknesses and at the connections of the uniform diameter tubulars to the conical section.

In case of the uniform diameter tubular section connections, an out-of-alignment of 0.2t (where t is the minimum wall thickness) or maximum of 0.25 inch per Section 3 of the API Spec 2B [API, 1977] was used. Based on this magnitude of the out-of-alignment and using a SCF formulation per Maddox [1991], the SCF values over the length of caisson were obtained to vary between 1.4 to 1.64 for welds with uniform thicknesses and between 1.4 to 1.55 for welds with varying thicknesses. The welds with wall thicknesses of 1.75 inch and 2.0 inch were estimated to have lower values of these ranges.

For the connection between the uniform diameter section with the conical section, the SCF is computed using the formula given in Section 3.4.1c of the RP 2A. The SCF in this case is obtained as 1.12 and 1.15 at the upper and the lower ends of the conical section. Note that in this case, the RP 2A formula does not consider an out-of-alignment of sections. Therefore, the values computed for uniform sections with out of alignment were used.

The allowable peak hot-spot stress (Sp) of 31.8 ksi and 36.5 ksi were obtained from Figure 2-6 (Figure 5.1.1-2 of RP 2A) for welds without profile control (API X', S-N curve applicable) and for the waterline members and other members respectively. The allowable Sp values increase to 42 ksi and 48 ksi per Figure 2-6 (Figure 5.1.1-1 of RP 2A) for welds with profile control (API X, S-N curve applicable).

In case of a caisson type platform, the hot spot stress is entirely due to the bending moment. The maximum bending moment of 12020 kips-ft is estimated at 25 ft below the seabed in the 2 inch section. The maximum bending stress of 31 ksi is obtained at 5 ft below the seabed at the weld between 1.25 inch and 1.5 inch thick sections with 60 inch diameter. Considering a maximum allowable out of alignment at this section of 0.25 inch, the SCF is estimated as 1.5. The hot spot stress thus becomes 46 ksi which exceeds 36.5 ksi (allowable Sp for welds without profile control) and is lower than 48 ksi (allowable Sp for welds with profile control).

Figure 3-6 presents the cyclic bending stress profile and the hot-spot stress profile obtained from the analysis. The hot-spot stresses based on the simplified fatigue analysis method at the different connections over the length of caisson with high bending moment values range between 32 ksi to 46 ksi. Therefore, the allowable Sp of 36.5 ksi per 19th Edition is not met for a major part of the caisson length when weld profile control is not implemented. For this design, the hot spot stresses over part of the caisson are estimated within the allowable Sp of 48 ksi with controlled welding (reducing out of alignment) and with weld profile control.

3.4.2 Fatigue Assessment - API 20th Edition

Linear elastic analysis was performed for the design developed in Section 3.3.2 for the RP 2A, 20th Edition design metocean criteria with no current and no dead and live loads in order to determine the maximum cyclic stress at various elevations of the caisson.

The SCF values were computed at the different connections using the same methods as discussed in the previous section. The SCF values over the length of caisson range between 1.4 to 1.64 for welds with uniform thickness case and between 1.4 to 1.55 for welds with varying thickness. In case of the welds between the uniform diameter sections with the conical section, the SCF is obtained as 1.18 and 1.22 at the upper and the lower ends of the conical section.

The allowable Sp of 31.8 ksi and 36.5 ksi were obtained from Figure 2-7 (Figure C5.1-2 of the RP 2A) for welds without profile control for the waterline members and other members respectively. For welds with profile control, the allowable Sp increased to 43 ksi and 47.5 ksi for the waterline and other members respectively.

The maximum bending moment of 11,790 kips-ft occurs at 30 ft below the seabed in the 2 inch section. The maximum bending stress of 20 ksi is obtained at welds 5 ft above and 5 ft below the seabed for the 60 inch diameter sections. Considering a maximum allowable out of alignment at this section of 0.25 inch, the SCF is estimated as 1.6. The hot spot stress thus becomes 46 ksi which exceeds 32 ksi (allowable Sp for welds without profile control) and is lower than allowable Sp of 36.5 ksi (for welds with profile control).

Figure 3-7 presents the cyclic bending stress profile and the hot-spot stress profile obtained from the analysis. The hot-spot stresses at the different welds over the length of caisson with high bending moment values by simple approach range between 22 ksi to 32 ksi. Therefore, the allowable Sp of 36.5 ksi per 20th Edition for weld without profile control is met for total length of caisson.

3.5 COMPARISON OF RESULTS

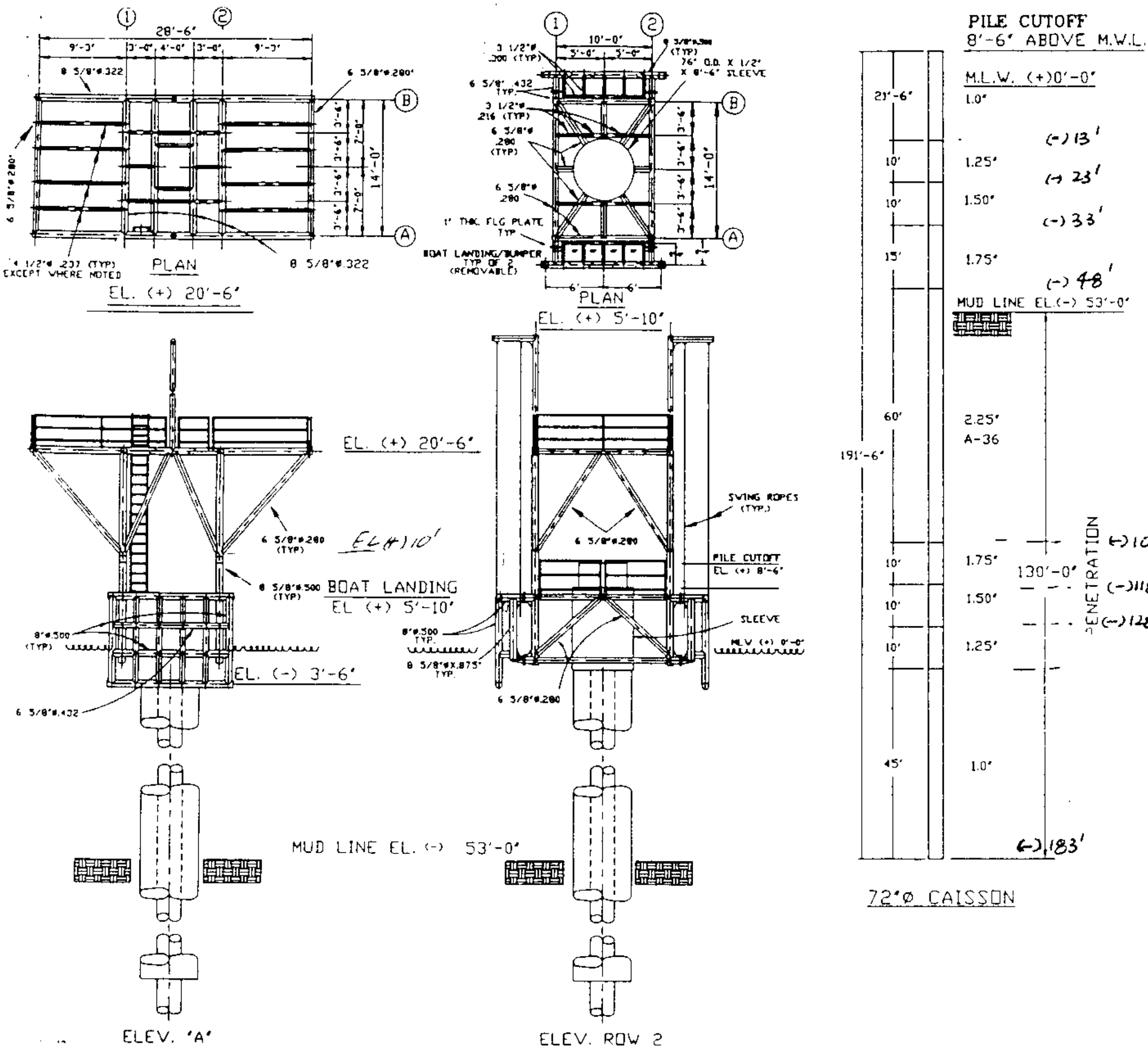
In the preceding sections, the design of a caisson in 53 ft water depth per the 19th and 20th editions has been presented. The results obtained are summarized in this section.

The caisson design was developed with tapered sections in the submerged part in order to reduce metocean loads. The total lateral loads obtained at the seabed are 160 kips per the 19th Edition and 247 kips per the 20th Edition. Therefore the lateral loads increase by 54 percent for the 20th Edition case. The increase in the maximum bending moment in the caisson at 30 ft or 35 ft below seabed is of the order of 49 percent (20th Edition higher).

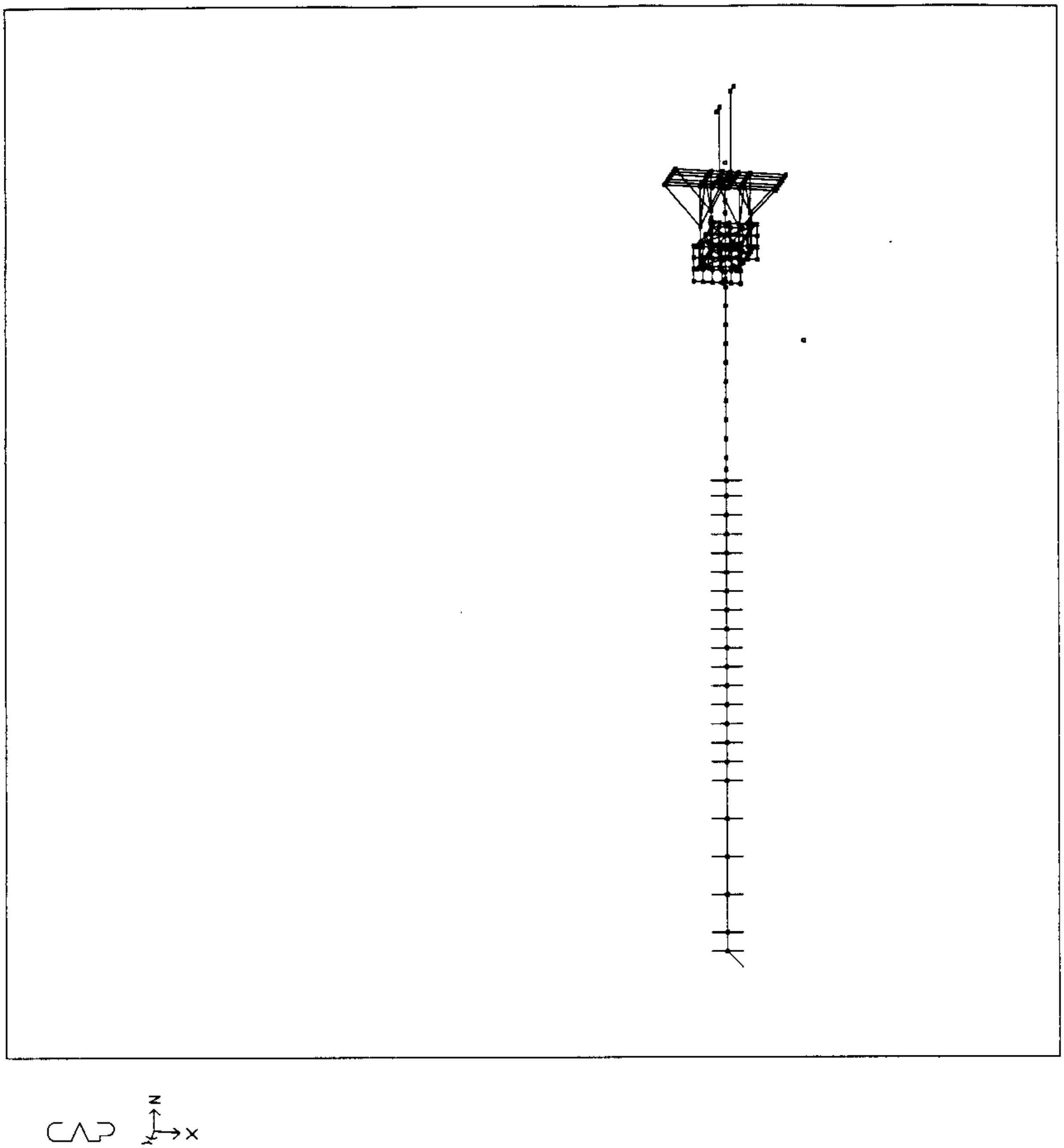
The steel weight increases from 138 kips for the 19th Edition to 181 kips for the 20th Edition, i.e., an increase of 31 percent.

The diameters of caisson varies from 60 inch per the 19th Edition to 72 inch per the 20th Edition. The maximum deck displacement and corresponding lean angles for both cases are similar.

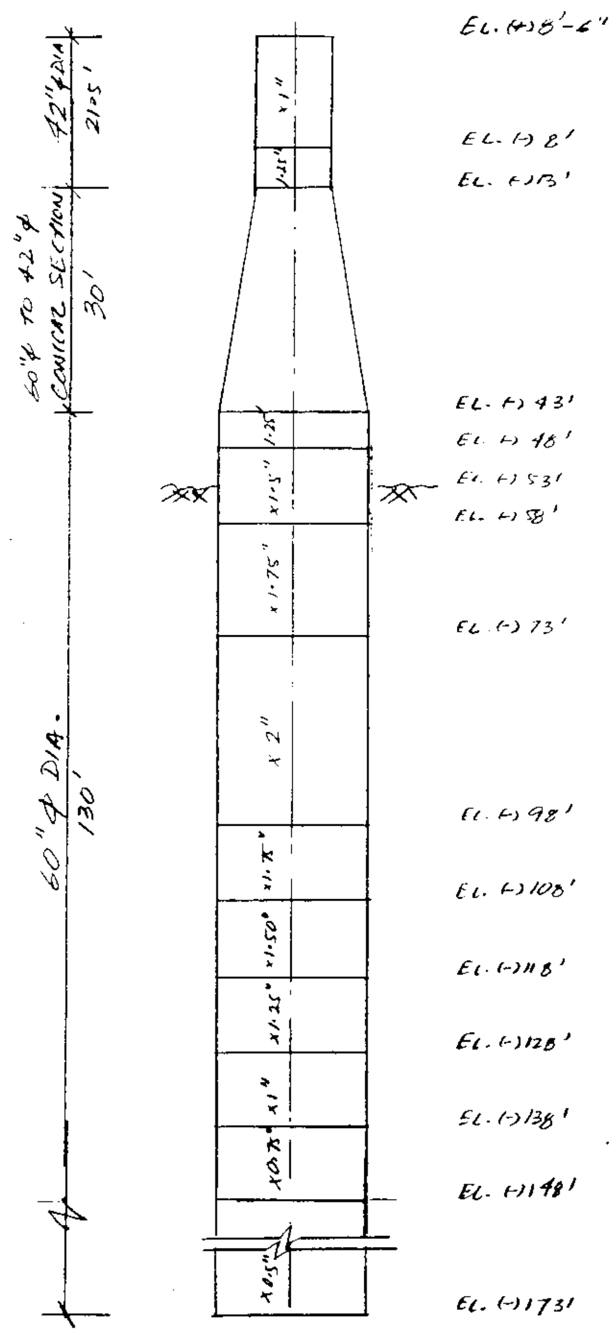
The simplified fatigue analysis results indicate that the 19th Edition design is more sensitive to fatigue than the 20th Edition design. In case of the 19th Edition design, the peak hot spot stress (Sp) is obtained as 46 ksi, which exceeds the allowable Sp for welds without profile control but is below the limit of 48 ksi for welds with profile control. Note that the hot spot stresses would reduce with a lower alignment tolerance. In case of the 20th Edition design, the peak Sp of 32 ksi is obtained which meets the allowable Sp limit of 36.5 ksi for welds without profile control.



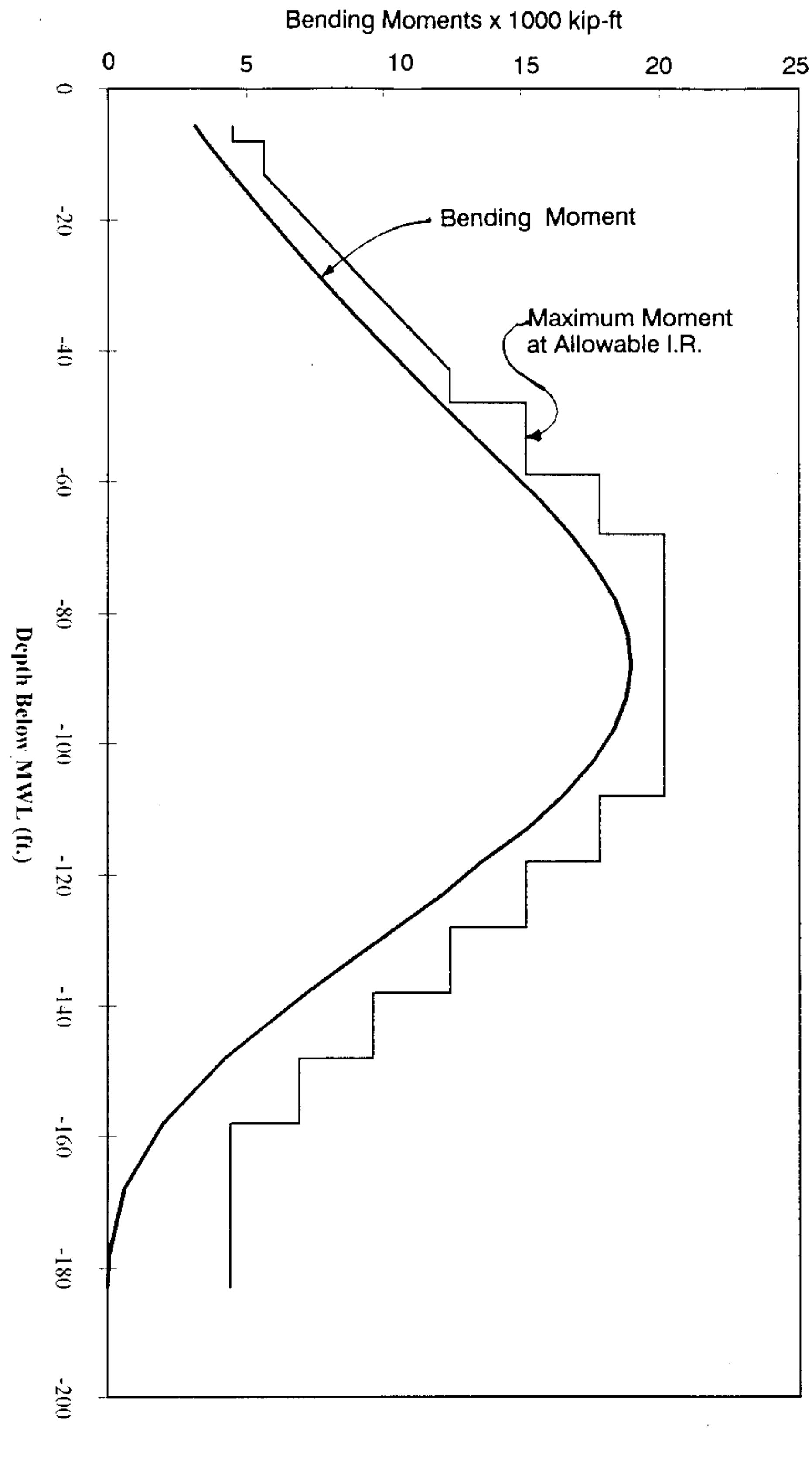
STRUCTURAL DETAILS – 72-INCH DIAMETER CAISSON
FIGURE 3-1



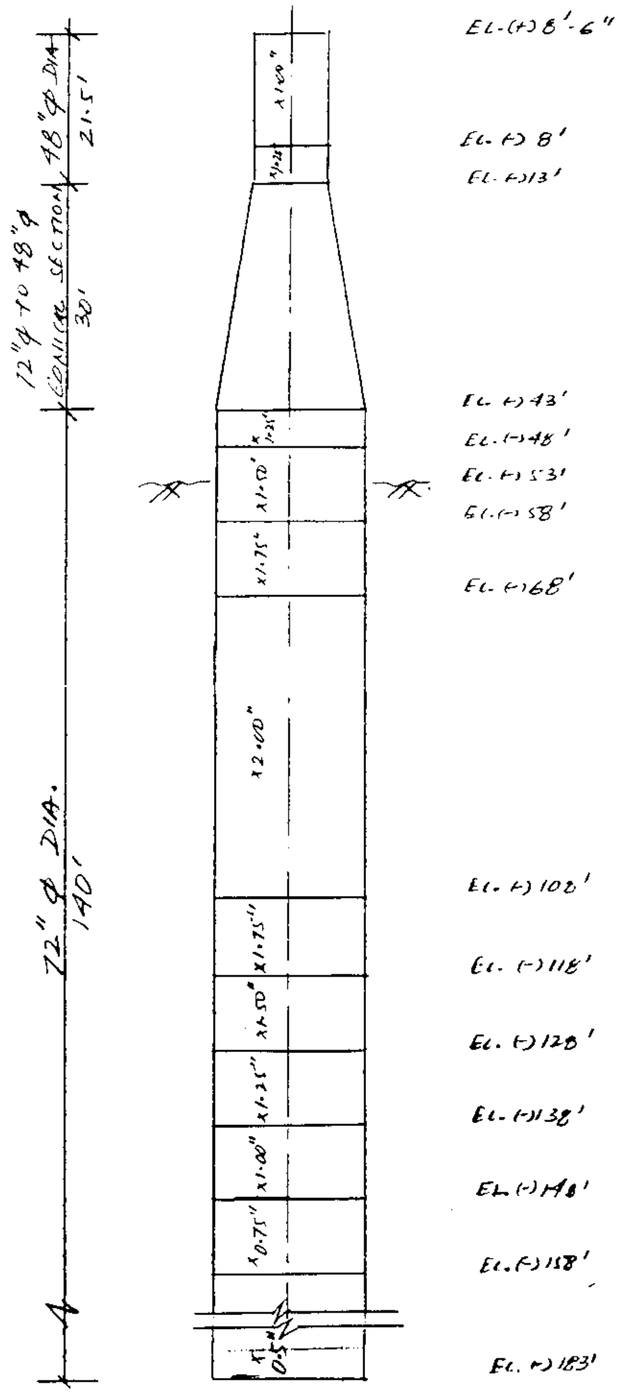
3-D COMPUTER MODEL – CAISSON DESIGN EVALUATION
FIGURE 3-2



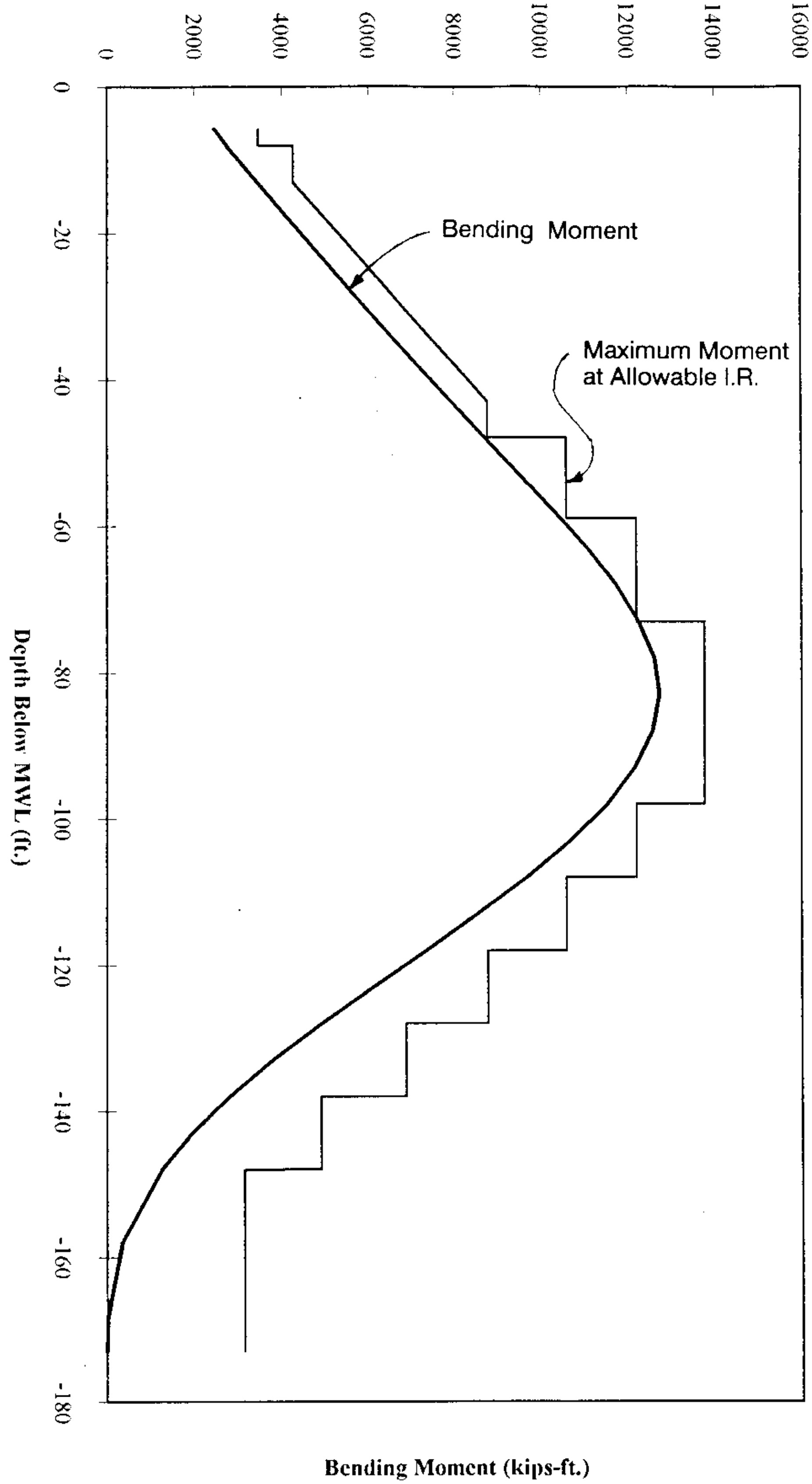
CAISSON CONCEPTUAL DESIGN – RP 2A, 19TH EDITION
FIGURE 3-3



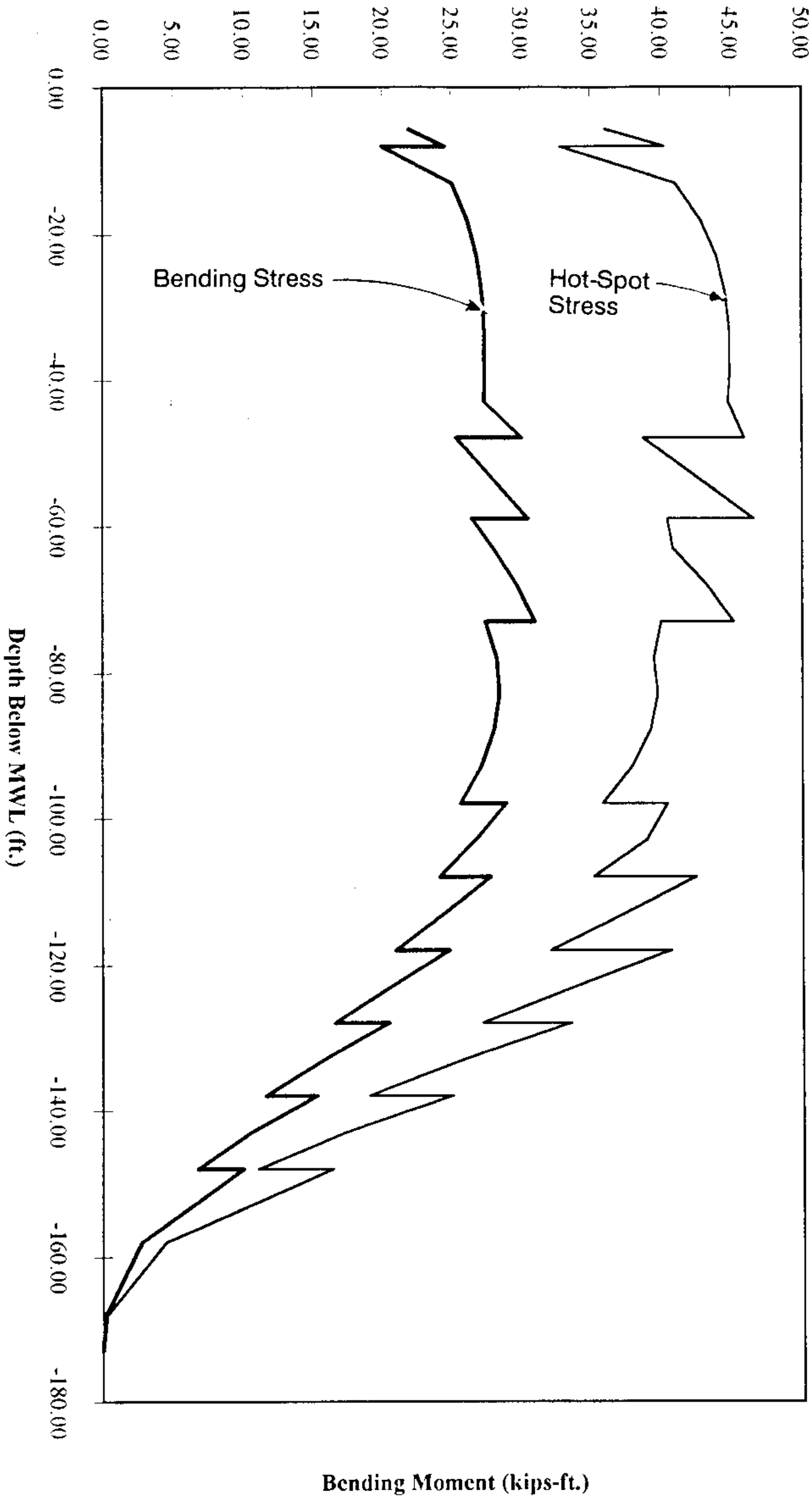
DESIGN MOMENT AND CAPACITY PROFILES – RP 2A, 19TH EDITION
FIGURE 3-4



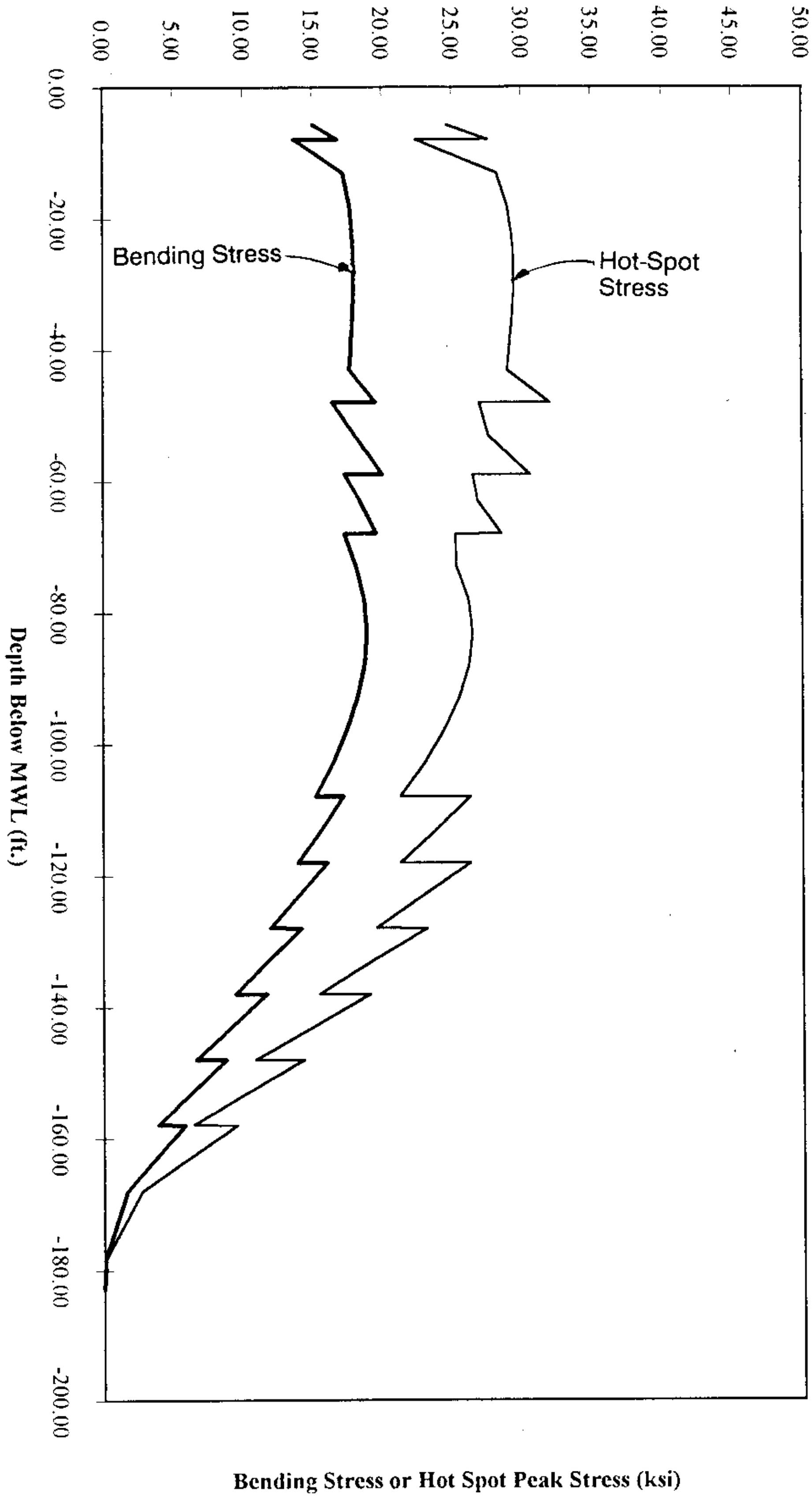
CAISSON CONCEPTUAL DESIGN – RP 2A, 20TH EDITION
FIGURE 3-5



DESIGN MOMENT AND CAPACITY PROFILES – RP 2A, 20TH EDITION
FIGURE 3-6



BENDING STRESS AND PEAK HOT SPOT STRESS PROFILES
RP 2A 19TH EDITION
FIGURE 3-7



BENDING STRESS AND PEAK HOT SPOT STRESS PROFILES
RP 2A 20TH EDITION
FIGURE 3-8

Table 3-1: Comparison of Metocean Parameters and Other Coefficients

Item	Units	RP2A, 19th Edition	RP2A, 20th Edition
Metocean Criteria			
Storm Tide	ft.	9.00	7.00
Wave Height	ft.	45.80	44.00
Wave Direction		Omni-Directional	at 290 degree
Wave Period	sec	13.50	14.10
Current Magnitude	ft/sec	0.00	3.54
Current Direction		-	at 246 degree
Marine Growth	inch	3" on dia.	3" on dia.
Wave Force Procedure			
Wave Kinematic Factor		1.00	0.88
Wave Force Coefficients			
Drag Coefficient, Cd		0.60	0.65 (smooth tubulars)
			1.05 (rough tubulars)
Inertia Coefficient, Cm		1.50	1.6 (smooth tubulars)
			1.2 (rough tubulars)
Order of Stream Function Theory		9th	9th

Notes:

** The current and marine growth are not used when API Reference Level Force guidelines used. i.e., Cd = 0.6 and Cm = 1.5 as per Section .

Table 3-2: Comparison of Design per RP2A, 19th and 20th Editions

Item	Units	RP2A, 19th Edition	RP2A, 20th Edition	%ge Change
Base Forces				
Shear Force	kips	160.00	247.00	54.38
Overturning Moment (OTM)	kips-ft.	9827.00	13721.00	39.63
Vertical Load	kips	165.00	170.00	3.03
Maximum Pile Forces				
at Elevation		30 ft. below seabed	35 ft. below seabed	
Bending Moment	kips-ft.	12739.00	18976.00	48.96
Axial Force	kips	165.00	170.00	3.03
Displacements				
at Deck Level (+) 14.5'	ft.	4.64	4.40	-5.17
at Seabed	ft.	1.03	1.30	26.21
Lean Angle	degrees	3.60	3.40	
Design				
Caisson Diameter: at waterline	inch	42.00	48.00	14.29
at seabed	inch	60.00	72.00	20.00
Penetration Below Seabed	ft.	120.00	130.00	8.33
Steel Weight	kips	138.00	181.00	31.16

Section 4
Comparison of Behavior of a Caisson During Andrew

The original design for the Company C caisson located in 48 ft water depth (Figure 4-1) was used for comparison of the observed and analytical predictions. The platform was found leaning by 15 degrees after Andrew. The operating company reported actual water depth at the platform site of 53 ft instead of 48 ft, which was considered in the original design. In this evaluation, the corrected water depth of 53 ft was used.

The caisson is constructed of 48 in. diameter tubulars with wall thicknesses varying from 1 in. to 2 in. The deck structure is at Elev.(+) 14.5' above the MLW level. The penetration of caisson is 95 ft.

The following sub-sections provide the hurricane Andrew seastate parameters obtained from the hindcast data, the capacity analysis results and the linear elastic analysis results for the caisson. The analyses were performed following guidelines per the 19th and 20th Editions.

4.1 NONLINEAR COMPUTER MODEL

A 3-D nonlinear model was generated for this caisson in its as-installed condition. Nonlinear elements were limited to the caisson structure and the soil springs. The boat landings and deck structural members were modeled as linear beam elements.

The material yield stress of 42 ksi was used to represent the mean yield stress instead of the nominal yield stress value of 36 ksi [Chen and Ross, 1977].

The recommended shear strength values were used for the soil layers. Recent tests have indicated that under the extreme (hurricane) load level state with large displacements at the pilehead level, the static lateral soil strength is a better measure. Therefore, the virgin soil-pile capacity was used to develop p-y nonlinear soil springs.

4.2 ANDREW HINDCAST DATA

The Andrew metocean conditions at the caisson were based upon the Oceanweather hindcast [Oceanweather, 1992] which provides seastate data for up to 23 storm hours for each grid point. Two grid points in the vicinity of caisson were identified and metocean condition interpolated for the specific caisson site based upon the procedure used in the Andrew JIP (PMB, 1993). The maximum wave occurred during storm hour 8 (Table 4-1).

The storm surge associated with the maximum wave during storm is 1.6 ft lower than that from either RP 2A edition. Note that the storm surge from the hindcast data is higher for hours past the maximum wave. The hindcast maximum wave height of 38.6 ft is lower than that from the either RP 2A edition. The hindcast current is 3.5 ft/sec at 234 degree, which has same magnitude as that obtained from the RP 2A, 20th Edition but the direction varies. Recall that there is no current specified in the 19th Edition.

4.3 COMPARISON OF METOCEAN LOADS

Table 4-1 also shows the resulting base shear values for Andrew and for the 19th and 20th Editions. In the case of Andrew, the seastate parameters per the hindcast were used but the procedures per 19th and 20th Editions were used for computation of the hydrodynamic loads. The base shears obtained using Andrew seastate parameters and other provisions of the 19th and 20th Editions criteria are 125 and 132 kips, respectively. The load level is similar for the Andrew seastate for both 19th and 20th Editions. This may be due to cancellation of an increase in loads due to higher hydrodynamic coefficients increase by the reduction in loads from the wave kinematic factor of 0.88 for the 20th Edition case.

The base shear value is 99 kips when the metocean parameters per the 19th Edition are used. The base shear for the Andrew seastate is 26 percent higher than that for the 19th Edition due primarily to current. The lateral load level is 158 kips, when the metocean parameters per the 20th Edition are used. This load level is 20 percent higher than the load level for Andrew seastate due to higher wave height for 20th Edition case.

4.4 CAPACITY ANALYSIS RESULTS

A pushover load pattern was generated for the Andrew seastate parameters and using the 20th Edition procedures. It was felt that there will be little difference using the 19th or 20th Edition for the pushover load pattern. The analysis was performed using CAP software [PMB Engineering, 1994].

The pushover analysis indicate that the first yield of a section occurs at 40 ft below the seabed in 1 inch wall thickness section at a lateral load level of 109 kips. This section becomes fully plastic at a lateral load level of 128 kips. The first yielding and full plastic section then extends to other sections of the caisson foundation. This analysis indicates higher bending moment values at larger depths below the seabed than in the original design.

At the formation of a fully plastic condition, the displacement at the deck level is of the order of 5.0 ft The rotation at first yield is determined as 0.002 radians. The rotation value increases to 0.006 radians, the limiting value for the 48 inch diameter section with 1 inch wall thickness at which the moment capacity starts reducing. At this rotation, the deck displacement is 6.4 ft with a lateral load of 143 kips, thus the section cannot sustain any more bending.

The lean angle at this state is approximately as 5.4 degree. Therefore, the ultimate capacity of the caisson is estimated as 143 kips, which is marginally higher than the Andrew load level of 132 kips.

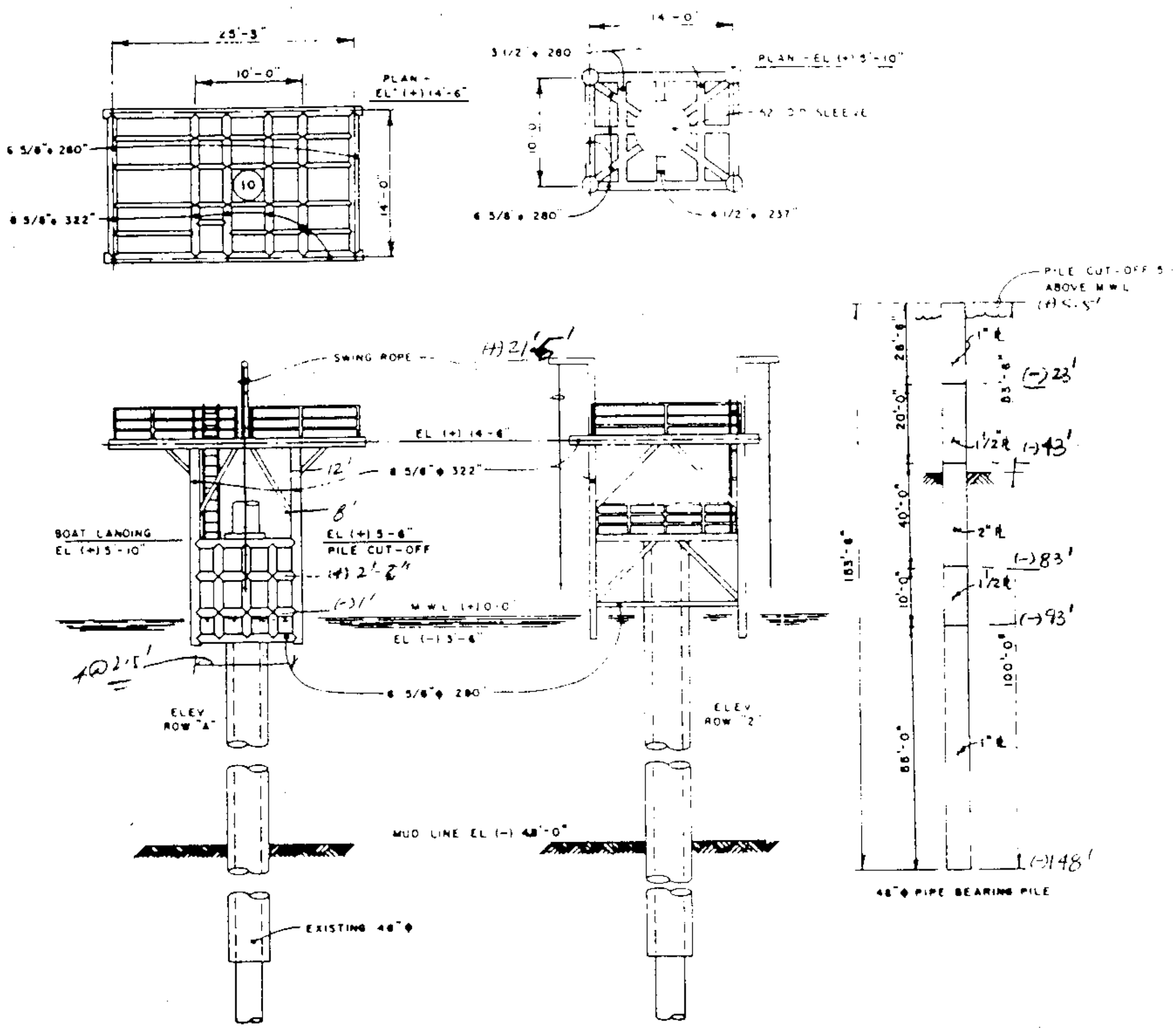
Following the formation of a fully plastic hinge in the caisson, the increase in rotation will be rapid under similar load level. Therefore, the analysis has predicted that the damage is likely to exceed 5 degrees and could match the observed damage of 15 degrees leaning.

4.5 LINEAR ANALYSIS RESULTS

A linear 3-D model was developed for the original design (Figure 4-1) of the caisson. Linear elastic analysis was performed for the 19th and 20th editions metocean parameters and criteria.

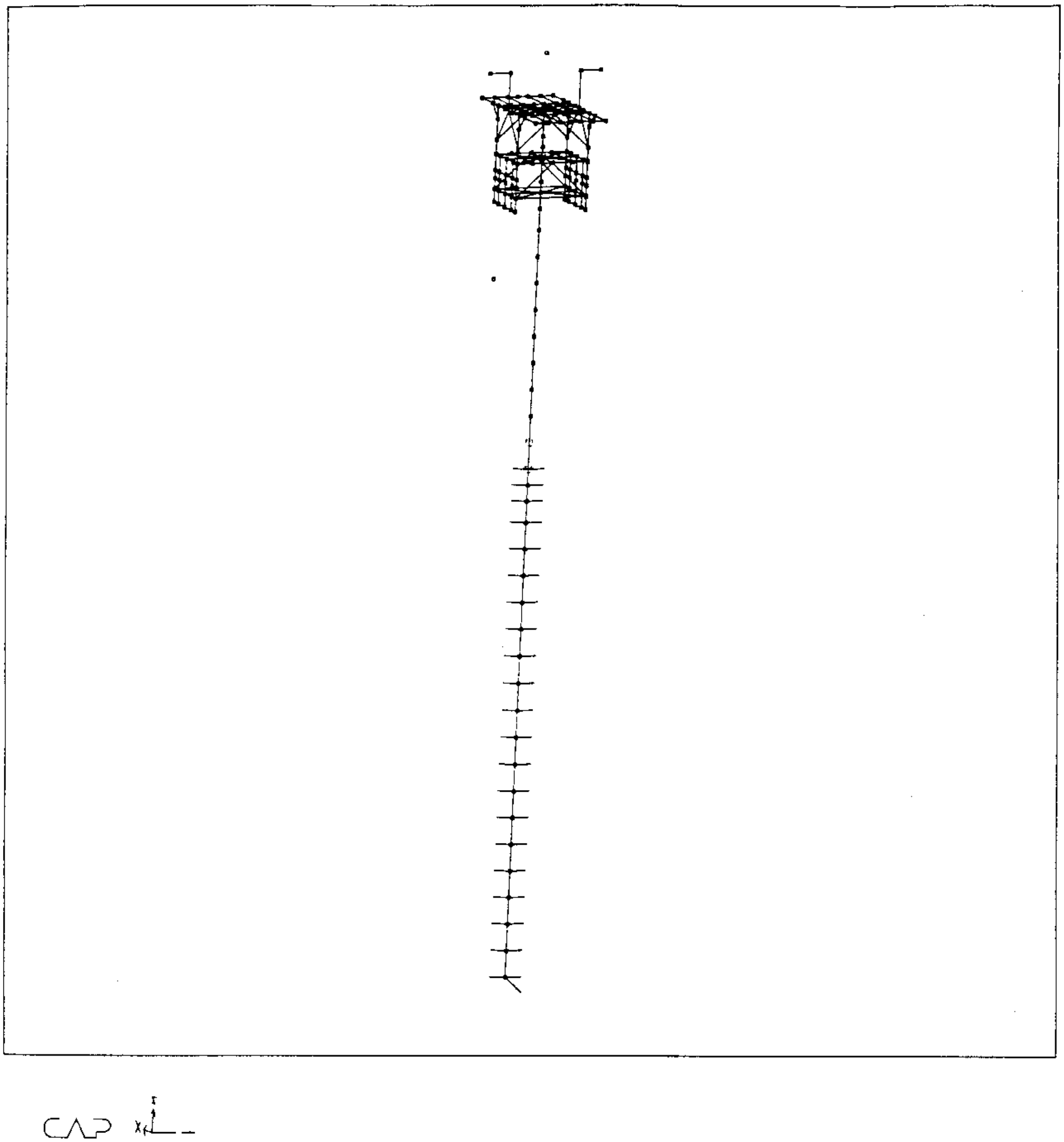
Figure 4-4 presents the bending stress profile over the caisson length per the 19th Edition guidelines. The maximum bending moment occurs at 25 ft below the seabed in the 2 in. thick section. The interaction ratio at this section is 0.72. The maximum interaction ratio of 1.15 is estimated in the 1-in. thick section at 40 ft below the seabed. The RP 2A design stress check indicates that the original design of the caisson exceeds API criteria (maximum allowable interaction ratio of 1.0) over 6 ft length from 40 ft to 46 ft below the seabed. The interaction ratio of 0.9 is exceeded over 20 ft of caisson.

Figure 4-5 presents the bending stress profile over the caisson length per the 20th Edition guidelines. The maximum bending moment occurs at 25 ft below the seabed in the 2-in. thick section. The interaction ratio at this section is 1.1. The maximum interaction of 1.90 is estimated in the 1 in. thick section at 40 ft below the seabed. The RP 2A design stress check indicates that the original design of the caisson also exceeds API criteria (maximum allowable interaction ratio of 0.9) over 60 ft length from 4 ft to 64 ft below the seabed.

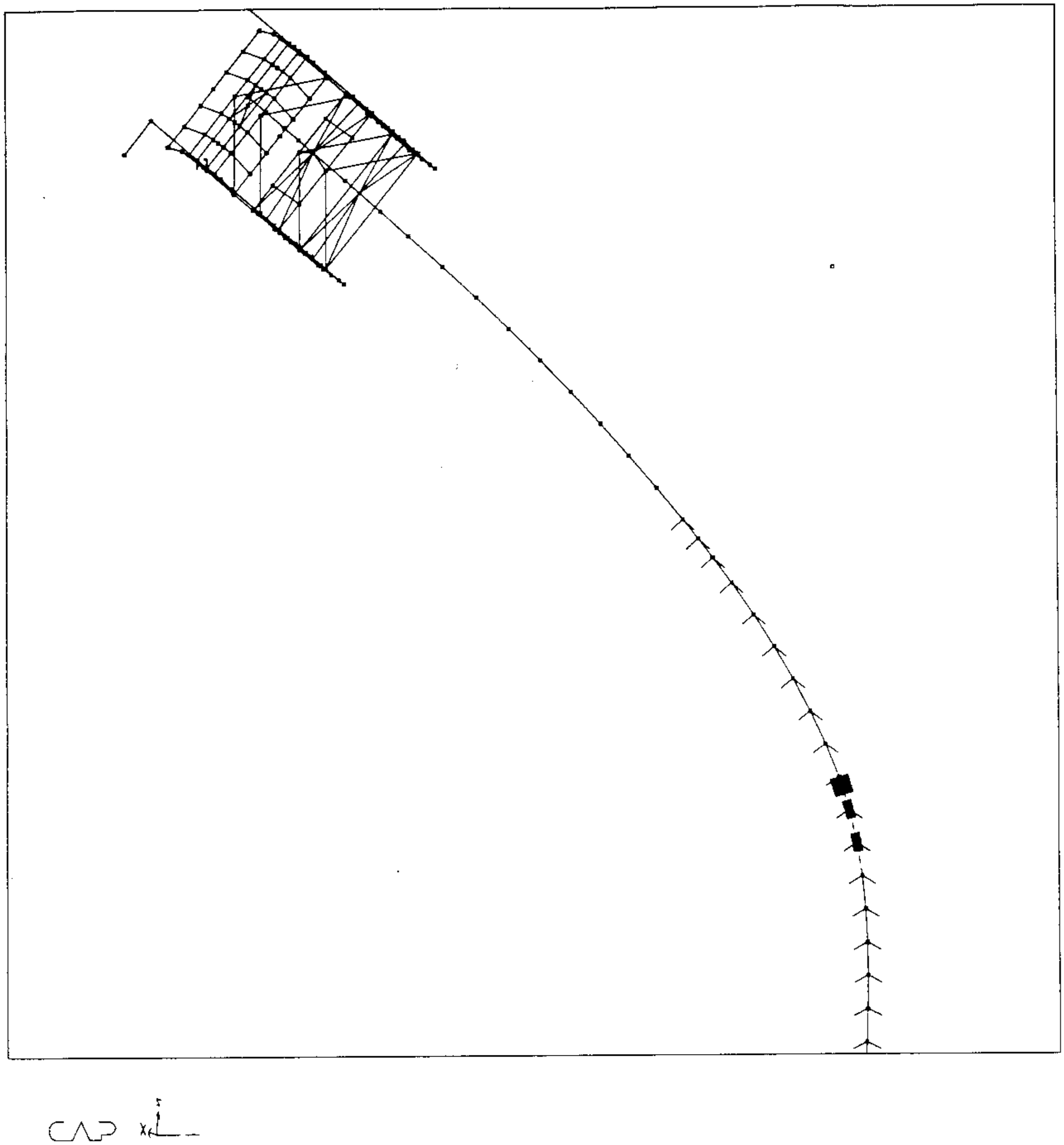


STRUCTURAL DETAILS – 48-INCH DIAMETER CAISSON DAMAGED DURING ANDREW

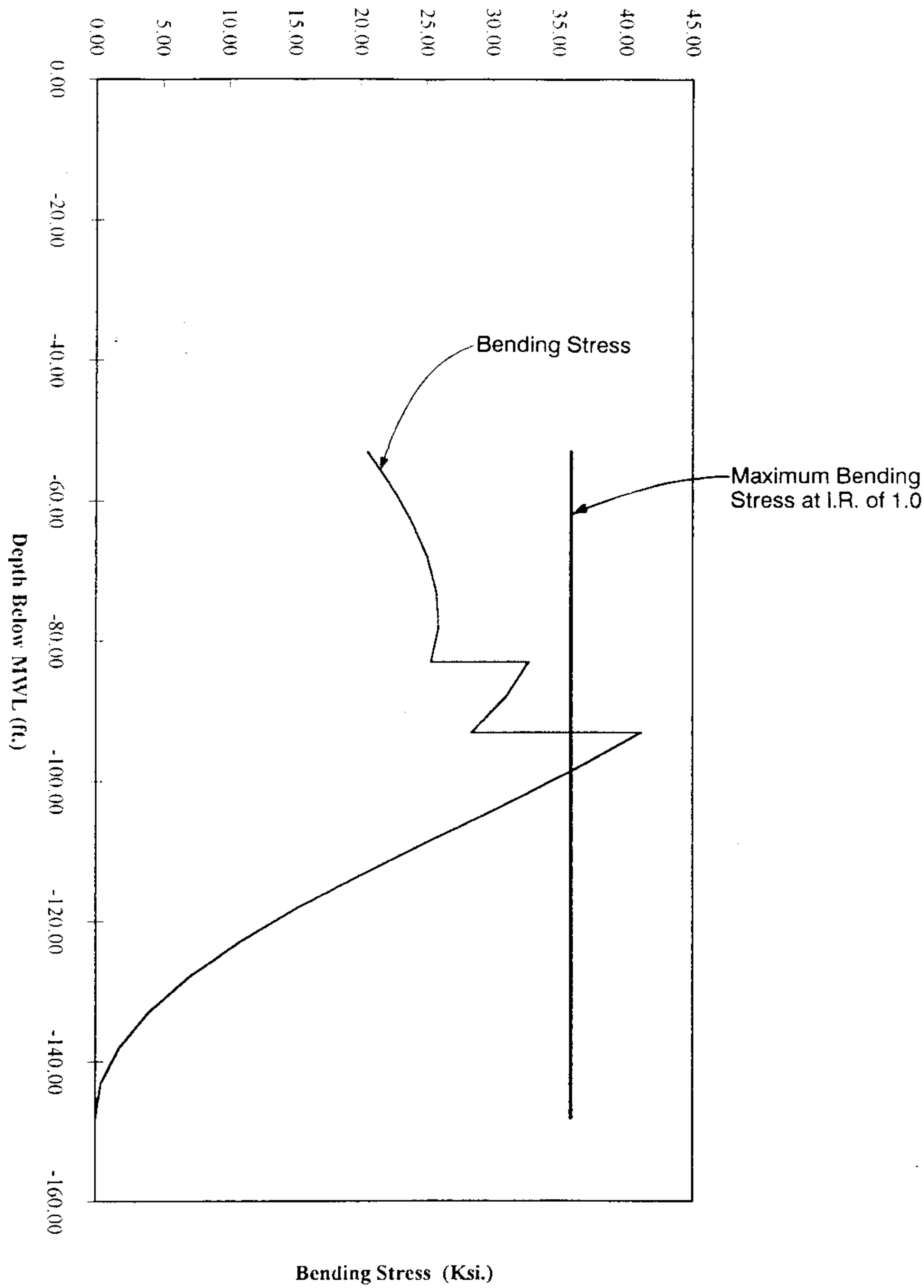
FIGURE 4-1



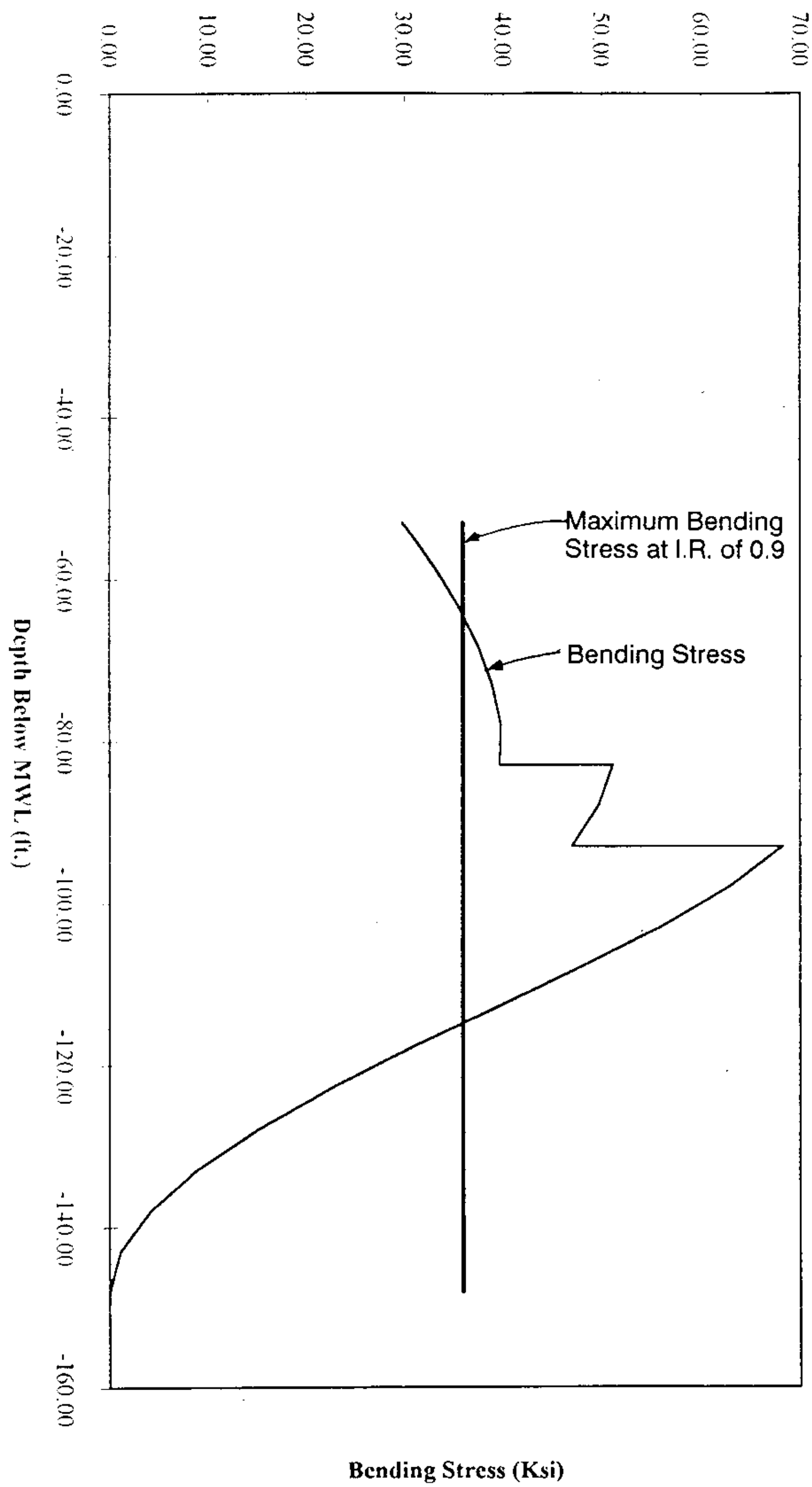
3-D COMPUTER MODEL – PUSHOVER ANALYSIS
FIGURE 4-2



PUSHOVER ANALYSIS RESULTS – NONLINEAR EVENTS AND DEFLECTED SHAPE
FIGURE 4-3



LINEAR ELASTIC ANALYSIS RESULTS - BENDING STRESS PROFILE
RP 2A, 19TH EDITION
FIGURE 4-4



LINEAR ELASTIC ANALYSIS RESULTS - BENDING STRESS PROFILE
RP 2A, 20TH EDITION
FIGURE 4-5

Table 4-1: Comparison of Metocean Parameters and Loads

Item	Units	Andrew Seastate Storm Hour 8	RP2A, 19th Edition	RP2A, 20th Edition
Metocean Criteria				
Storm Tide	ft.	3.00	9.00	7.00
Wave Height	ft.	38.60	45.80	44.00
Wave Direction	degree	193 from North	Omni-Directional	290 from North
Wave Period	sec	13.00	13.50	14.10
Current Magnitude	ft/sec	3.50	0.00	3.54
Current Direction	degree	234 from North	-	246 from North
Marine Growth	inch	3 inch on dia.	3 inch on dia.	3 inch on dia.
Analysis Results				
Base Shear	Kips	125 for 19th Ed. Case 132 for 20th Ed. Case	99.00	158.00

Section 5
Recommendations

There are clear differences between caisson design per the 19th and 20th Editions that can lead to an increase in hydrodynamic loads of 40 to 50 percent. This may lead to an increase in steel weight in some cases 30 percent or more. The net result is more expensive caissons that in some cases may make a particular offshore development uneconomical.

The project identified no basis to believe that the 20th Edition, in particular the wave load recipe, is not applicable for design of caissons. In fact, the 20th Edition represents many years of API and industry research and is considered an acceptable approach for designing a caisson or platform in the offshore US and in some other offshore regions.

One option is to accept a lower design criteria (e.g. less than 100 yr. return period waves) for design of a caisson than for multileg platforms. Another option is to allow a certain amount of "damage" to the structure, such as a 5 degree lean, for the 100 year design condition. The rational is that caissons are typically low consequence structures which are unmanned and are generally of low environmental significance. Indeed, API allows for reduced criteria for these types of structures based upon risk analysis (RP 2A 20th Section 1.5).

It was originally anticipated that such criteria could be identified by this project. This, however, would involve detailed risk studies combined with numerous nonlinear analysis, and thus selection of a specific criteria was beyond the time and cost constraints of this project. Further, it is important that such a recommendation be developed in conjunction with the industry representatives in a joint industry project (JIP) in order to develop criteria based upon an "industry consensus."

However, this project did provide some preliminary information based upon results of the pushover analysis for the caisson that was damaged in Andrew. Pushover analysis per the 19th Edition indicated a lean angle of less than 5 degrees, whereas pushover analysis per the 20th Edition indicated a lean angle of more than 5 degrees. Assuming that the "acceptable" lean angle is 5 degrees (per preliminary findings by Barnett and Casbarian in a project for the MMS), these results indicate that the metocean criteria for the acceptable damage limit condition lies between the 19th and 20th Edition criteria. Assuming that caissons can accept a higher risk, then a reduction in the 20th Edition metocean criteria may be appropriate. The specific criteria should be based upon a thorough evaluation of acceptable risk for several caissons.

A proposed calibration effort similar to the above is currently in the planning stages by API for a possible JIP. It is recommended that this project go forward if it is felt by the MMS and the industry that there is a need to develop specific "reduced" design criteria for caissons. This criteria can then be incorporated directly into RP 2A to provide a convenient means of designing caissons.

Section 6
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Appendix A
MMS Task Order II (Contract No. 14-35-0001-30700)

TASK ORDER NO. 2

Assess the Effect of API RP2A 20th Edition Criteria on the Design of Offshore Caisson-Type Platforms

- **Background**

  There have been significant changes in the design criteria between the API RP2A 19th and 20th editions that have raised some questions in the industry regarding their direct application on the design of caisson-type platforms. As a result, the work statement outlines an independent study to assess the applicability of the new criteria on caisson design and comparison with the previous guidelines.

- **Proposed Study Objective**

  Review and compare API RP2A 19th and 20th editions criteria specifically applicable to Gulf of Mexico caisson platform design. Assess impact of 20th edition on a typical design representative of the Gulf of Mexico. Make recommendations commensurate with the findings of the study.

REQUIRED TASKS

- **Task 2A Review API Design Criteria**

  Objective:

  Identify differences between API 19th and 20th edition criteria and establish objective expert opinion as to their basis and applicability to caisson platform design.

  Scope:

  Review and compare applicable design criteria specified in the two API editions and identify main differences. Consult with experts, both in-house and around the industry, knowledgeable with the development and establishment of the API recommendations to obtain their opinion. Based on this survey, formalize an objective opinion on the applicability of the present (20th edition) API RP2A recommendations to caisson design.

  Deliverables:

  A section to be included in the final report highlighting the findings of this review/survey.

o TASK 2B: REPRESENTATIVE DESIGN CASE

Objective:

Assess an existing caisson design (representative of the Gulf of Mexico) based on both API 19th and 20th edition recommendations.

Scope:

Obtain a recent available design of a caisson platform considered typical of Gulf of Mexico application. An existing design (data/drawings) will be provided to the contractor not later than the first week of the study by the MMS or their designated representative (e.g. Barnett and Casparian) for this application. It will be of a caisson for which performance data (survived, damaged, failed) are available for Hurricane Andrew (see Task 3). Perform an in-place analysis based on 19th edition criteria and determine steel and foundation requirements. A simplified deterministic fatigue assessment will also be made. Repeat in-place analysis/conceptual design based on 20th edition recommendations. Identify and comment on differences/effects in design (steel weight, foundation requirements, deflections) based upon the 19th versus 20th edition.

Deliverables:

Conceptual design level caisson size (weight estimate), foundation requirements and deflections under extreme in-place conditions for one typical caisson application based on 19th and 20th edition recommendations.

o TASK 2C COMPARE A TYPICAL DESIGN PER API PREDICTIONS WITH HINDCAST DATA FROM HURRICANE ANDREW

Objective:

Compare available Andrew hindcast data with analysis predictions per 19th and 20th editions for a typical caisson (Task 2).

Scope:

Obtain Hurricane Andrew performance data for an existing typical caisson (preferably the one made available in Task 2). Compare available observed data with analytical predictions based upon the 19th and 20th editions by repeating the in-place analyses performed in Task 2 for the site-specific Andrew metocean conditions (available from the PMB Andrew JIP, for which the MMS was a participant). Identify differences/similarities between observed response and that predicted by application of 19th and 20th edition criteria.

Deliverables:

Comparison of a typical caisson behavior during Hurricane Andrew and predictions per 19th and 20th edition recommendations.

TASK 2D: FINAL REPORT

Prepare and issue final study report documenting the work performed and findings from Tasks 1 through 3.