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1.0. Introduction and Background

The purpose of this study is to develop and verify an analytical model for semi-submersible Mobile Offshore Drilling Units (MODUs) loading and movements in hurricanes.

In September 1992, hurricane Andrew swept through the eastern portion of the Gulf of Mexico(GOM) . Five MODUs both experienced damage and inflicted significant damage on surrounding facilities. The Zane Barnes, Zapata Saratoga, and Treasure 75 all moved very significant distance during hurricane Andrew. The storm snapped seven of the semi-submersible drilling unit Saratoga's eight anchor chains and drove the unit some 100 miles to the north until it collided with several platforms. The Zane Barnes broke loose from its eight anchors, drifted northwest some 30 miles, repeatedly colliding with several platforms and many pipelines. The anchors from the Treasure 75 reportedly collided with several platforms. The LOOP (Louisiana Offshore Oil Port) 36 inch diameter pipeline narrowly missed being snagged by the dragging anchors of one of these MODUs.

This implies that there are fundamental issues that need to be resolved regarding the policies and guidelines for manning, positioning and mooring semi-submersible drilling units in the GOM during hurricane season. Special mooring areas and mooring systems have been proposed for MODUs operation during hurricane seasons.

The objective of this study is to develop an analytical model to evaluate MODUs movements in response to the combined load effect due to hurricane winds, waves and currents, then use a Monte-Carlo simulation process to evaluate the probability of collision between the MODU and surrounding large facilities.

The model is based on: 1) available statistics and hindcast results for hurricanes in the Gulf of Mexico since the turn of the century; 2)numerical models of wind, wave, current and their load effect on a platform; and 3) probability models to include the hurricane parameter variability, hurricane model uncertainties, and the spatial geometry.

The input of the model is:

1) The location of the MODU and large facilities, e.g., (X_M, Y_M) and (X_F, Y_F); where (X_M, Y_M) are coordinates of MODU's location and (X_F, Y_F) are coordinates of surrounding large structures;

2) MODU parameters, e.g.,displacement, draft, and mooring system capacity;

3) Hurricane parameters, e.g., $\Delta P, V_F, R_M$, which are the pressure difference, storm translation speed and radius of maximum wind speed;

4) Hurricane direction parameters, e.g., X_0, φ, which are defined in Figure 7.1.

The output of the model is the probability of collision between the MODU and surrounding large facilities during the considered time period.

A computer simulation program MODUSIM was developed which is utilized to evaluate alternative mooring and securing sittings for MODUs. Reasonable simplifications and high degrees of user friendliness have been employed in development of the software to reduce the engineering effort, expertise, and costs associated with the analysis.

MODUSIM can be used to estimate the probability of MODU's mooring system failure and the probability of collision with surrounding structures after mooring failure, to predict hurricanes coming routes and estimate the failure probability with a given coming hurricane, to simulate whether the mooring system breaks and also the MODU's moving route after mooring failure with a known hurricane track, straight line or curve, to forecast the histogram of environmental conditions which is very helpful for creating MODU securing and evacuation plans.

Parametric and case studies of the MODU "Zane Barnes" in hurricane Andrew are presented based on the results from MODUSIM.

2.0. Hurricane History and Hindcast Parameters

2.1 Hurricane Statistics

The characteristics of past hurricanes in the Gulf of Mexico along the coastal area of Texas and Louisiana since the turn-of-the-century are summarized in Table 2.1. The parameters of most interest are the pressure difference (ΔP), radius of maximum wind speed(R), and storm translation speed (V_f). The table values represent the maximum values observed when the storm crossed the shelf. Only storms with R less than 100 nm (nautical mile) are considered.

The first two moments of the hurricane parameters, i.e., their mean values, standard deviations, coefficient of variation and the correlation matrix are summarized in Table 2.2.

2.2 Storm Track and Occurrence Statistics

On the basis of the statistical evaluations performed by Ward. et al.[1978] and Bea [1975], the hurricane track shelf edge crossings are assumed to be uniformly distributed. The hurricane track directions are assumed to follow a triangular distribution. The peak value is 101 degrees relative to the coast line orientation according to Reference [8].

Previous investigations(e.g., Haring and Heideman, 1978) have shown that the occurrence of hurricanes over time can be approximately modeled as a simple Poisson Process (Bea 1975). The mean occurrence rate per time is, therefore, the only parameter required of the occurrence in a specified region. From Ward, et al. (1978), the occurrence rates for hurricanes in the Gulf of Mexico regions A, B, C, D in Fig. 2.1 are respectively 0.459, 0.563, 0.587, and 0.563 per year. As the widths of the regions are 360 nautical miles, the hurricane occurrence statistics may alternatively be described by the mean rate of the storm tracks crossing the 600ft. depth contour line per year per nautical mile. For example, the occurrence rates at a point in region A, B, C, and D are correspondingly 0.00127, 0.00156, 0.00163, and 0.00156/year-nautical mile. Interpolation may be used to determine the occurrence rate at any given location on the contour line.

2.3. Hurricane Parameter Distributions

The parameters of most interested are ΔP, R and V_f. Since these three important hurricane parameters are correlated, they are modeled as jointly log-normal random variables with parameters given in Table 2.3. In other words, the logarithmic transforms of these parameters follow a jointly normal distribution.

It is pointed out that the log normal distribution has been used in almost all previous risk studies of hurricanes(e.g., Batts, et al., 1980; Russell, 1968). It is a convenient model to use, in particular, in treating correlated random quantities.

2.4 Markov-Chain Modeling of Storm Tracks

2.4.1 Introduction

The hurricane was assumed to be a storm traveling along a straight line with a given translation speed and direction in the previous study [Reference 26]. In fact, the hurricane tracks are generally curved. Based on the statistical analysis on the hurricane route history, one can determine the parameters which influence changes of hurricane's direction, and determine their probability distribution. A Markov model has been developed to describe the probabilities of changes in the storm track directions. Based on the data from the MMS, the transition probability matrix of hurricane track prediction for Gulf of Mexico hurricanes has been developed.

2.4.2 Introduction to Markov Chain

The state of a system invariably changes with respect to some parameter, for example, time or space. The transition from one state to another as a function of the parameter, or its corresponding transition probability, may generally depend on the prior states. However, if the transition probability depends only on the current state, the process of change may be modeled with the Markov process. If the state space is a countable or finite set, the process is called a Markov Chain. If the transition probability is independent of the state of the system, the process reduces to the Poisson process.

Consider a system with m possible states, namely 1, 2, , m, and changes in state can occur only at discretized values of the parameter; for example, at times $t_1, t_2, \cdots, t_n$. Let X_{n+1} denote the state of the system at t_{n+1}. In general, the probability of a future state of the system may depend on its entire history; that is, its conditional probability is:

$$P(X_{n+1} = i | X_0 = x_0, X_1 = x_1, \cdots, X_n = x_n) \tag{2.1}$$

where $|X_0 = x_0, X_1 = x_1, \cdots, X_n = x_n$ represent all previous states of the system. If the future state is governed solely by the present state of the system, that is, the conditional probability, Eq.(2.1) is

$$P(X_{n+1} = i|X_0 = x_0, X_1 = x_1, \cdots, X_n = x_n) = P(X_{n+1} = i|X_n = x_n) \qquad (2.2)$$

then the process is a Markov chain. For a discrete parameter Markov chain, the transitional probability from state i at time t_m to state j at time t_n may be denoted by

$$p_{i,j}(m,n) = p(X_n = j|X_m = i); \qquad n > m \qquad (2.3)$$

The Markov chain is homogeneous if $p_{i,j}(m,n)$ depends only on the difference $t_n - t_m$; in this case, we define

$$p_{i,j}(k) = p(X_k = j|X_0 = i) = p(X_{k+s} = j|X_s = i) \qquad s \geq 0 \qquad (2.4)$$

as the k-step transition probability function. Physically, this represents the conditional probability that a homogeneous Markov chain will go from state i to state j after k times stages. This probability can be determined from the one-step transition probabilities, namely $p_{i,j}(1)$ or simply $p_{i,j}$, between all pairs of states in the system. These transition probabilities can be summarized in a matrix for a system with m states, called the transition probability matrix

$$\mathbf{P} = \begin{bmatrix} p_{1,1} & p_{1,2} & \cdots & p_{1,m} \\ p_{2,1} & p_{2,2} & \cdots & p_{2,m} \\ \vdots & \vdots & & \vdots \\ p_{m,1} & p_{m,2} & \cdots & p_{m,m} \end{bmatrix} \qquad (2.5)$$

As the states of a system are mutually exclusive and collectively exhaustive after each transition, the probabilities in each row add up to 1.0. For a homogeneous discrete Markov chain, the probabilities of the initial states are the only other information needed to define the model behavior at any future time.

2.4.3 State Probabilities

The probabilities of the respective initial states of a system may be denoted by a row matrix

$$\mathbf{P}(0) = [p_1(0), p_2(0)\cdots p_m(0)] \tag{2.6}$$

where $p_i(0)$ is the probability that the system is initially at state i. In the special case for which the initial state of the system is known, for example, at state i, then $p_i(0) = 1.0$ and all other elements in the row matrix $P(0)$ are zero. After one transition, the probability that the system is in state j is given by the theorem of total probability as

$$p_j(1) = P(X_1 = j) = \sum_i P(X_0 = i)P(X_1 = j|X_0 = i) \tag{2.7}$$

Hence,

$$p_j(1) = \sum_i p_i(0)p_{i,j} \tag{2.8}$$

In matrix notation, the single stages probabilities become

$$\mathbf{P}(1) = \mathbf{P}(0)\mathbf{P} \tag{2.9}$$

which is also a row matrix.

Similarly, the probability that the system is in state j after two transitions is given by

$$p_j(2) = \sum_k P(X_1 = k)P(X_2 = j|X_1 = k) = \sum_k p_k(1)p_{k,j} \tag{2.10}$$

or in matrix notation

$$\mathbf{P}(2) = \mathbf{P}(1)\mathbf{P} = \mathbf{P}(0)\mathbf{P}\mathbf{P} = \mathbf{P}(0)\mathbf{P}^2 \tag{2.11}$$

Therefore, by induction, it can be shown that the n-stage state probability matrix is given by

$$\mathbf{P}(n) = \mathbf{P}(n-1)\mathbf{P} = \mathbf{P}(n-2)\mathbf{P}\mathbf{P} = \cdots = \mathbf{P}(0)\mathbf{P}^n \tag{2.12}$$

2.4.4 Hurricane Tracks modeling in Gulf of Mexico

For application to hurricane tracks, the state are defined as the direction of one storm track. And the transition step size is two hours. As shown in Fig.2.2, if we divide the 0-180 to 3 blocks, then there are 3 possible states (1,2,3) and the transition probability matrix **P** is 3×3.

1--direction 0-75

2--direction 75-100

3--direction 100-180

And based on the statistic analysis of the storm track history, we also assume that, within each state of direction, the moving direction has a probabilistic distribution. They are uniform distribution in state 2 and triangular distribution in state 1 and 3. The distribution functions are shown in Fig.2.3.

The transition probabilities are estimated by calculating the times of storm track direction changes from one state to the other based on the data of the hurricane track history from MMS. The Table 2.4 shows the observed transitions in Gulf of Mexico from 1950 to 1992.

Table 2.4 Observed Transitions in Gulf of Mexico (1950 - 1992)

From\To	1	2	3	Total
1	99	12	25	136
2	10	2	4	16
3	14	4	15	33

The $P_{i,j}$ values are estimated from Table 2.4 using the formula:

$$P_{i,j} = \frac{a_{i,j}}{\sum_j a_{i,j}} \tag{2.13}$$

Table 2.5. $P_{i,j}$ Values

From\To	1	2	3
1	0.73	0.09	0.18
2	0.63	0.12	0.25
3	0.43	0.12	0.45

The resulting transition probability matrix is:

$$P=\begin{bmatrix}0.73 & 0.09 & 0.18\\ 0.63 & 0.12 & 0.25\\ 0.43 & 0.12 & 0.45\end{bmatrix} \tag{2.14}$$

2.4.5 Steady State Probabilities

We note that the state probabilities starting with two different initial states approach one another as the number of transition stages increases. In fact, the state probabilities will converge to a set of steady-state probabilities p*, which are independent of the initial states. Therefore, at steady-state condition,

$$\mathbf{P}(n+1)=\mathbf{P}(n)=\mathbf{P}^* \tag{2.15}$$

Hence,

$$\mathbf{P}(n+1)=\mathbf{P}(n)\mathbf{P} \tag{2.16}$$

$$\mathbf{P}^*=\mathbf{P}^*\mathbf{P} \tag{2.17}$$

For a Markov chain with m states, this matrix equation represents a set of simultaneous equations as follows:

$$[p_1^*\cdots p_m^*]=[p_1^*\cdots p_m^*]\begin{bmatrix}p_{1,1} & \cdots & p_{1,m}\\ \vdots & \ddots & \vdots\\ p_{m,1} & \cdots & p_{m,m}\end{bmatrix} \tag{2.18}$$

We can find that Eq.(2.18) contains one degree of freedom. The required constraint to obtain P^* is:

$$p_1^* + p_2^* + \cdots + p_m^* = 1.0 \tag{2.19}$$

Given a particular state matrix $\mathbf{P}_i$, the probabilities of being in the various possible states after n transitions are found from:

$$\mathbf{P}_{n+i} = \mathbf{P}_i \bullet \mathbf{P}^n \tag{2.20}$$

Using the hurricane route input as $P_1 = [1 \quad 0 \quad 0]$, after two hours, the probabilities matrix is :

$$P_2 = [0.73 \quad 0.09 \quad 0.18]$$
$$P_3 = [0.667 \quad 0.098 \quad 0.235]$$
$$P_4 = [0.649 \quad 0.099 \quad 0.250]$$
$$P_5 = [0.643 \quad 0.101 \quad 0.256]$$

And the P^* matrix is calculated as:

$$P^* = [0.643 \quad 0.101 \quad 0.256] \tag{2.21}$$

This implies that the hurricane route change according to state 1 about 64.3%, to state 2 about 10.1% and to state 3 about 25.6%. Also, it can be seen that the future transition probability are not strongly dependent upon the present state matrix. After only four transitions, the state probability matrix coverages to the steady-state probability matrix.

2.4.6 Hurricane Track Modeling for Texas-Mexico Coast

The hurricane route history statistics for Texas-Mexico coast line is also calculated. The result is presented as follow:

Table 2.6 Observed Transitions in Texas-Mexico Coast

From\To	1	2	3	Total
1	725	74	135	934
2	55	22	21	98
3	120	19	93	232

Table 2.7 $P_{i,j}$ Values

From\To	1	2	3
1	0.78	0.08	0.14
2	0.56	0.22	0.22
3	0.52	0.08	0.40

The transition probability matrix is:

$$P = \begin{bmatrix} 0.78 & 0.08 & 0.14 \\ 0.56 & 0.22 & 0.22 \\ 0.52 & 0.08 & 0.40 \end{bmatrix} \tag{2.22}$$

The P* matrix is calculated as:

$$P^* = [0.708 \quad 0.093 \quad 0.199] \tag{2.23}$$

From the comparation with the transition matrix of GOM, it can be found that the two matrix are close to each other. It also can be found that storms tends to move clockwise in the GOM and more straight in the Texas-Mexico coast.

2.4.7 Examples of Markov Model Hurricane Tracks

In Figure 2.4, there are ten hurricane track examples generated by MODUSIM based on Markov-Chain model. It is found that they are very close to real hurricane tracks.

Table 2.1 Hurricane Statistics

NO	STORM DATA	NAME	DP(mb)	RM(nm)	VF(kts)
1	9/6/00		76	14	10
2	8/13/01		40	33	5
3	10/8/02		19	37	8
4	9/25/06		78	43	8
5	7/13/09		60	20	10
6	9/18/09		33	22	8
7	8/15/15		63	29	12
8	9/28/15		78	31	12
9	7/4/16		50	30	14
10	8/17/16		62	25	18
11	10/17/16		49	19	10
12	9/26/17		48	40	8
13	8/5/18		53	20	15
14	9/11/19		64	20	10
15	9/12/19		66	19	10
16	9/20/20		33	28	15
17	6/20/21		64	17	7
18	8/23/26		56	27	6
19	9/19/26		59	17	13
20	6/27/29		41	13	10
21	8/12/32		71	12	8
22	8/2/33		38	25	8
23	9/2/33		64	25	10
24	6/14/34		40	37	8
25	8/4/40		41	11	8
26	9/13/41		10	20	6
27	9/21/41		51	21	10
28	8/20/42		19	16	7
29	8/28/42		62	18	12
30	9/20/42		19	15	7
31	7/25/43		41	16	8
32	8/25/45		46	18	5
33	8/23/47		23	15	5
34	9/18/47		48	23	6
35	9/2/48		23	25	9
36	10/3/49		50	20	14
37	8/28/50	Baker	25	21	12
38	9/23/56	Flossy	34	30	10
39	6/25/57	Audrey	62	19	14
40	8/8/57	Bertha	17	25	7
41	5/29/59	Arlene	14	50	5
42	7/23/59	Debra	32	28	3
43	9/14/60	Ethel	43	18	11
44	9/8/61	Carla	75	30	7
45	9/16/63	Cindy	18	30	6
46	8/6/64	Abby	16	15	9
47	10/1/64	Hilda	73	21	6

NO	STORM DATA	NAME	DP(mb)	RM(nm)	VF(kts)
48	9/9/65	Betsy	72	40	17
49	8/18/67	Beulah	62	25	8
50	6/23/68	Candy	16	25	18
51	8/16/69	Camille	105	12	14
52	8/1/70	Celia	69	9	14
53	9/14/70	Felicia	15	25	17
54	9/6/71	Fern	34	26	5
55	9/15/71	Edith	36	27	15
56	9/3/73	Delia	23	55	10
57	9/6/74	Carmen	76	15	10
58	9/22/75	Eloise	60	28	17
59	8/30/77	Anita	86	15	9
60	9/4/77	Babe	17	45	8
61	7/30/78	Amelia	9	50	5
62	7/10/79	Bob	21	40	12
63	8/30/79	Elena	9	60	8
64	9/11/79	Frederic	65	25	11
65	8/7/80	Allen	77	12	10
66	9/4/80	Danielle	14	20	10
67	9/10/82	Chris	17	25	7
68	8/16/83	Alicia	50	20	7
69	8/27/83	Barry	28	15	10
70	9/8/84	Diana	46	27.5	7
71	8/12/85	Danny	28	36.5	12
72	8/27/85	Elena	51	25	16
73	9/16/85	Gloria	66	17.5	20
74	10/25/85	Juan	32	34.5	8
75	11/15/85	Kate	40	30.5	16
76	6/24/86	Bonnie	21	40	8
77	8/14/86	Charley	28	36.5	10
78	9/20/87	Emily	56	22.5	18
79	10/9/87	Floyd	20	40.5	10
80	9/1/88	Debby	24	38.5	8
81	9/2/88	Ernesto	20	40.5	25
82	9/7/88	Florance	40	30.5	14
83	9/8/88	Gilbert	56	22.5	18
84	9/19/88	Helene	76	12.5	10
85	10/10/88	Joan	76	12.5	12
86	11/17/88	Keith	50	25.5	16
87	7/30/89	Dean	32	34.5	20
88	8/2/89	Chantal	26	37.5	10
89	8/17/89	Erin	40	30.5	18
90	8/30/89	Gabriell	76	12.5	20
91	10/12/89	Jerry	30	35.5	12
92	7/24/90	Bertha	40	30.5	12
93	8/4/90	Diana	40	30.5	14
94	8/24/90	Gustav	48	26.5	10

NO	STORM DATA	NAME	DP(mb)	RM(nm)	VF(kts)
95	9/3/90	Isidore	38	31.5	16
96	10/3/90	Klaus	20	40.5	8
97	10/6/90	Lili	28	36.5	8
98	10/9/90	Marco	22	39.5	12
99	10/15/90	Nana	22	39.5	8
100	8/16/91	Bob	48	26.5	15
101	9/5/91	Claudett	70	15.5	12
102	10/25/91	Grace	40	30.5	10
103	9/6/92	Iniki	68	16.5	14
104	9/24/92	Charley	40	30.5	8
105	10/28/91	Unnamed	30	35.5	22
106	9/26/92	Earl	20	40.5	12
107	10/22/92	Frances	34	33.5	22
108	8/22/93	Emily	46	27.5	10
109	9/7/93	Floyd	32	34.5	25
110	9/18/93	Harvey	26	37.5	25

Table 2.2 Moment Statistics

110 Storms Represented

Statistical Parameters

Parameters	Mean Value	Variance	Std Deviation	C.O.V.
ΔP (mb)	43.2	431.4	20.77	0.48
R (nm)	26.9	104.1	10.2	0.37
V_f	11.3	22.1	4.7	0.41

Correlation Coefficient Matrix

	ΔP (mb)	R (nm)	V_f
ΔP (mb)	1.000	-0.52	0.122
R (nm)	-0.52	1.000	0.022
V_f	0.122	0.022	1.000

Table 2.3

Hurricane Parameter Distribution

76 Storms DP>30mb

Parameter	ΔP (mb)	R(nm)	V_f (kts)
Sample Size	76	76	76
Distribution	Lognormal	Lognormal	Lognormal
Mean	53.64	24.16	11.8
St. Dev.	16.14	7.85	4.5
COV.	0.3	0.32	0.38

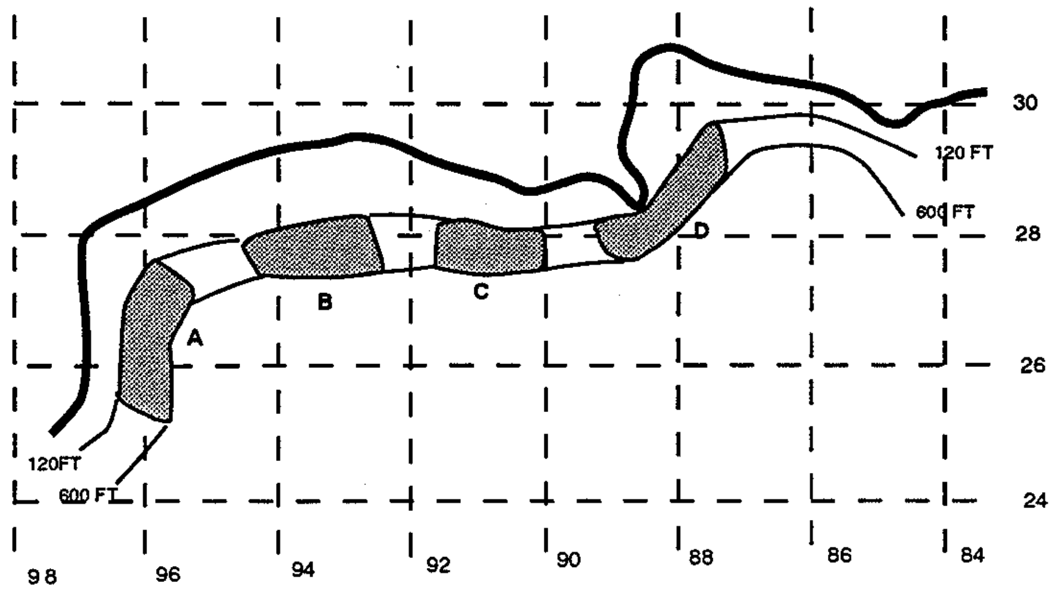


Fig. 2.1 Gulf Coastal Water Regions (Ward, et al., 1978)

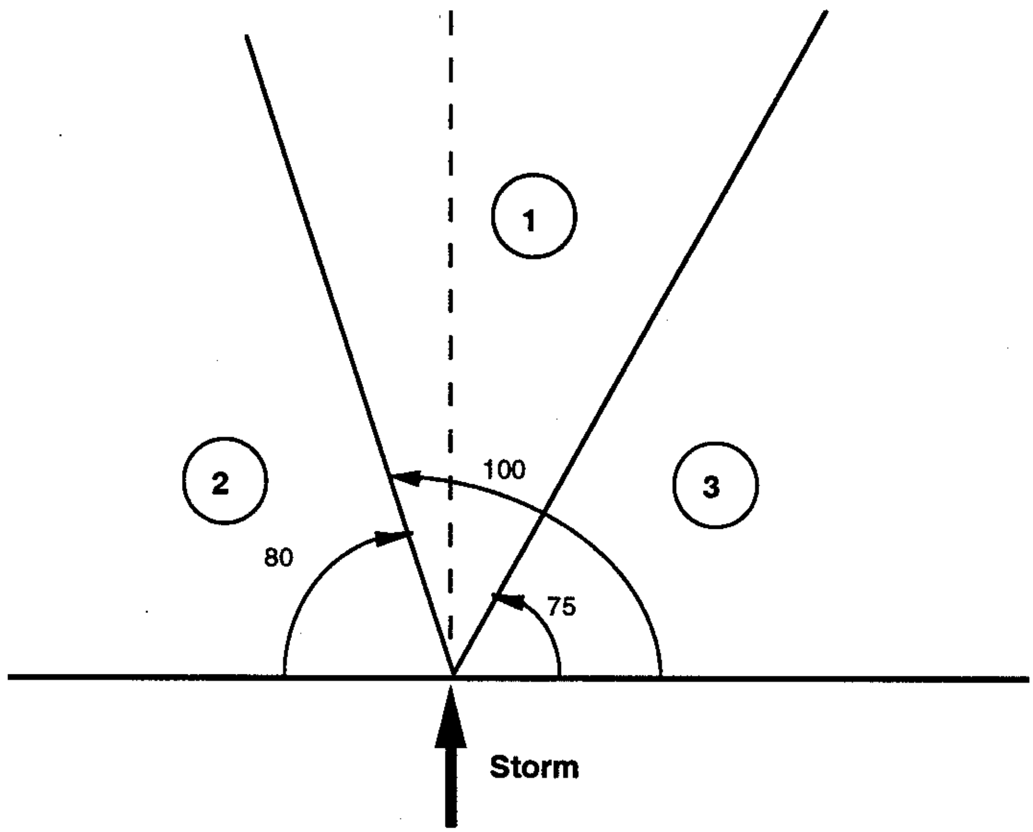


Figure 2.2. Definition of Storm Track Transimition State

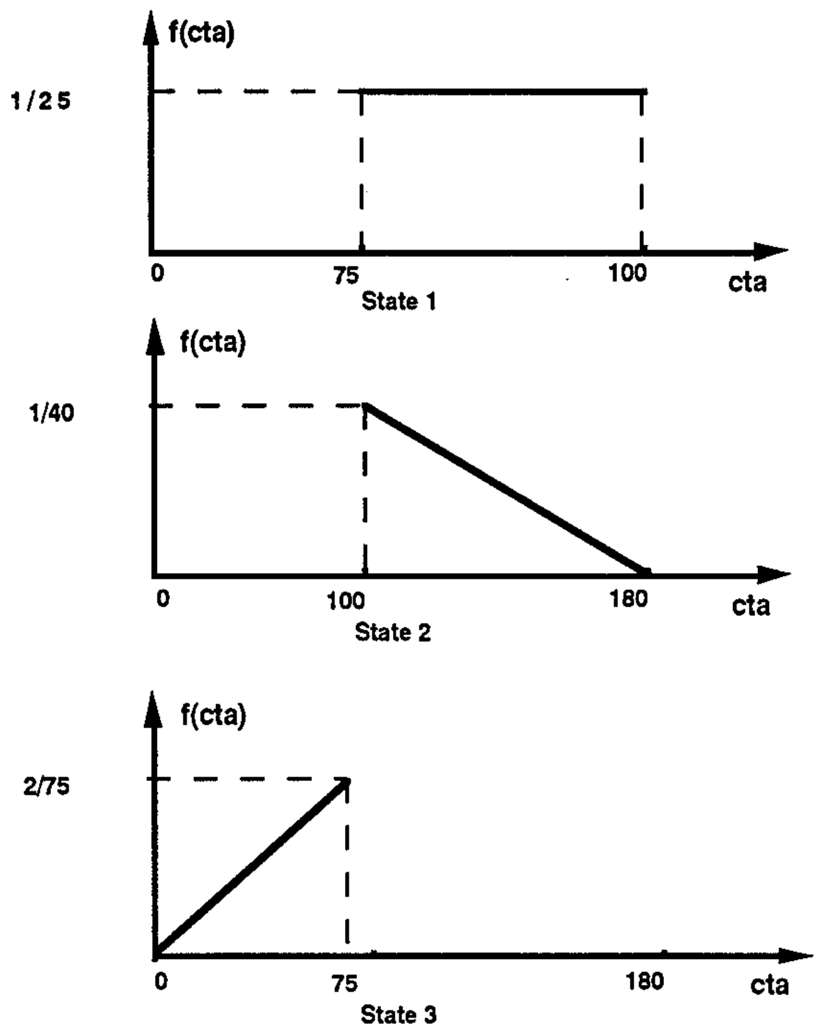
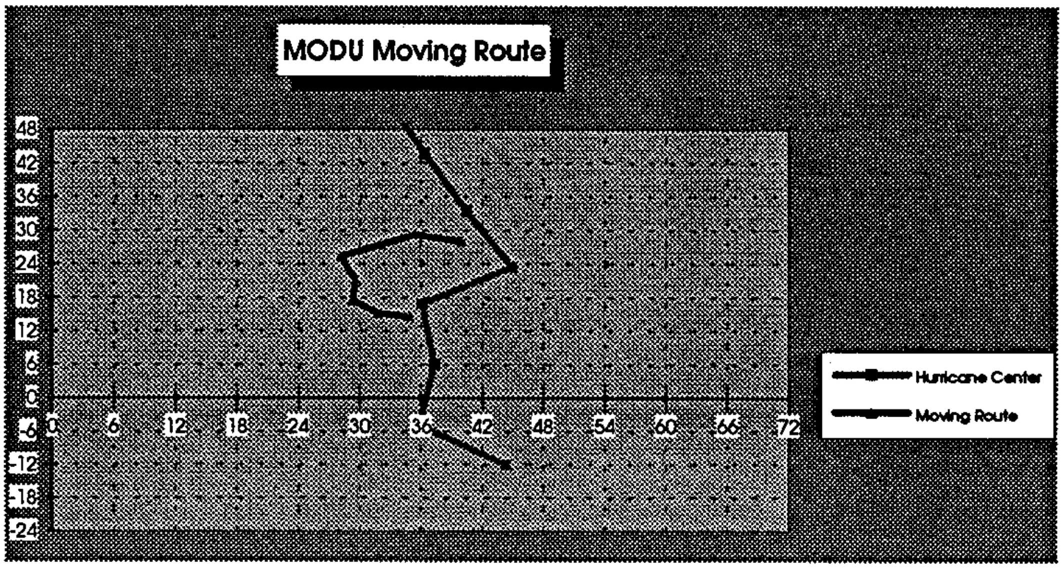
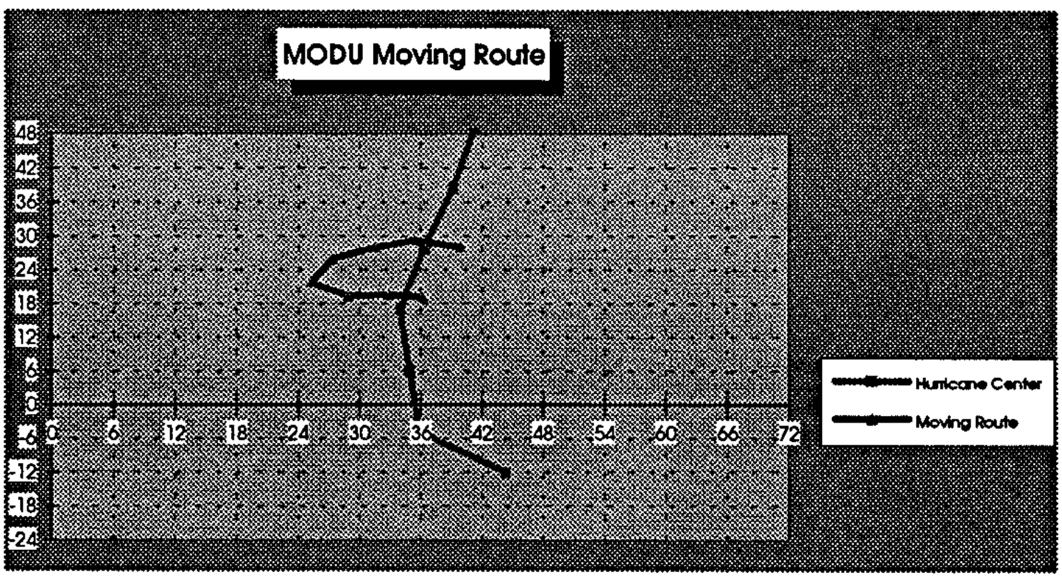


Figure 2.3 Probability Density Function of cta in State 1, 2, 3

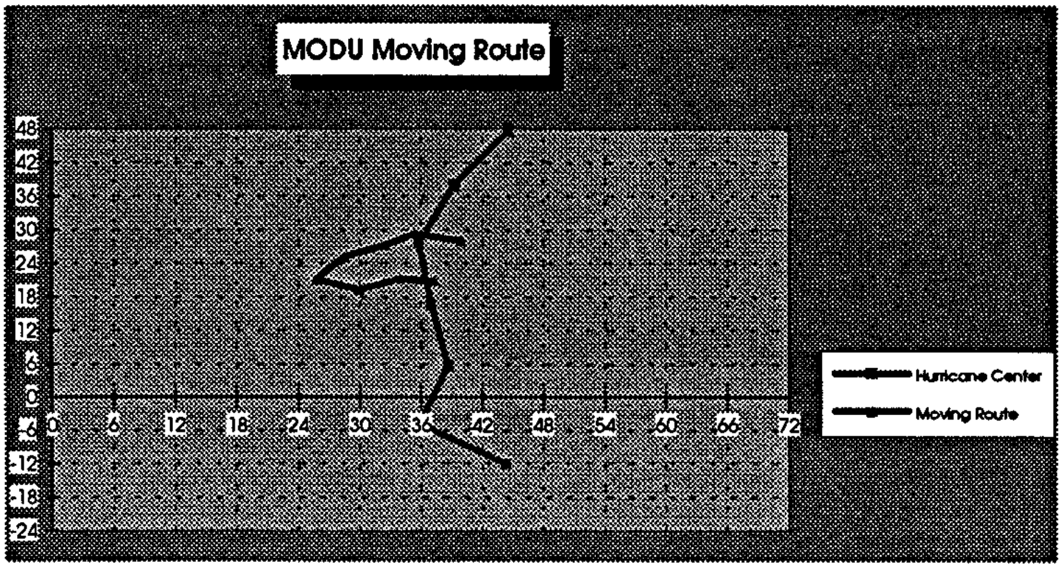


Case 1



Case 2

Figure 2.4 Examples of Markov Model Hurricane Tracks


MODU Moving Route
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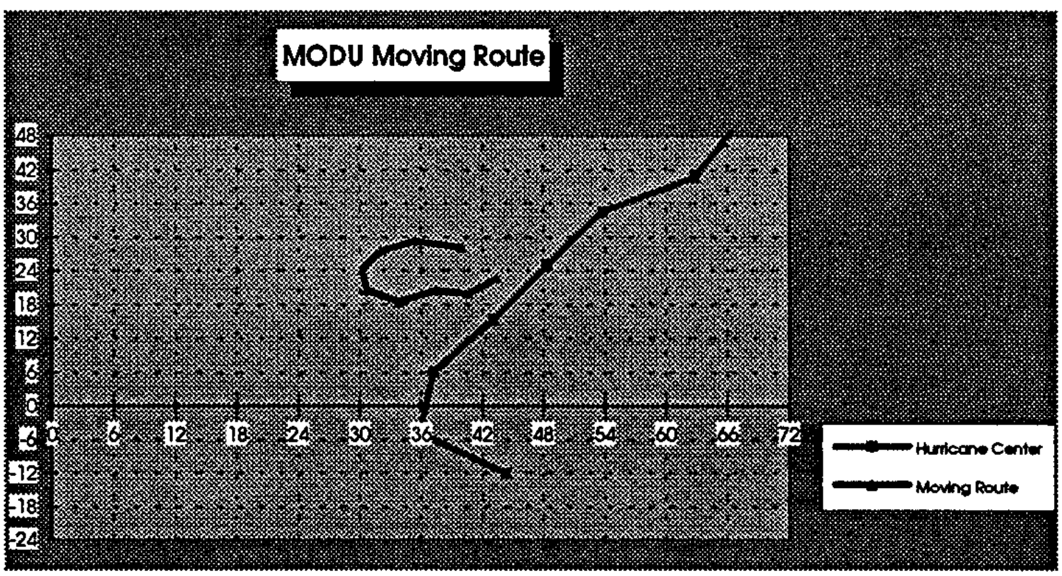
66
72
Hurricane Center
Moving Route

Case 3


MODU Moving Route
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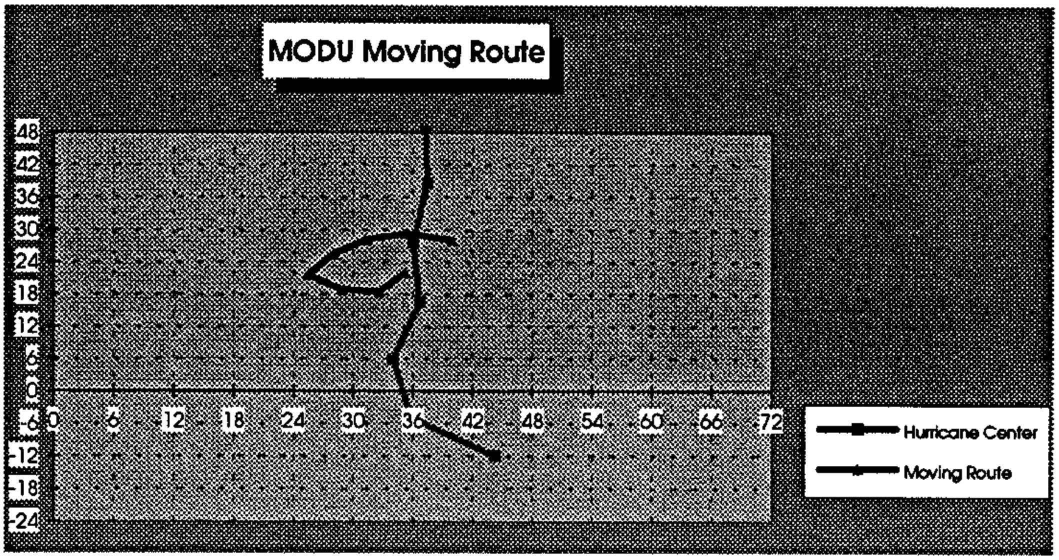
Hurricane Center
Moving Route

Case 4


MODU Moving Route
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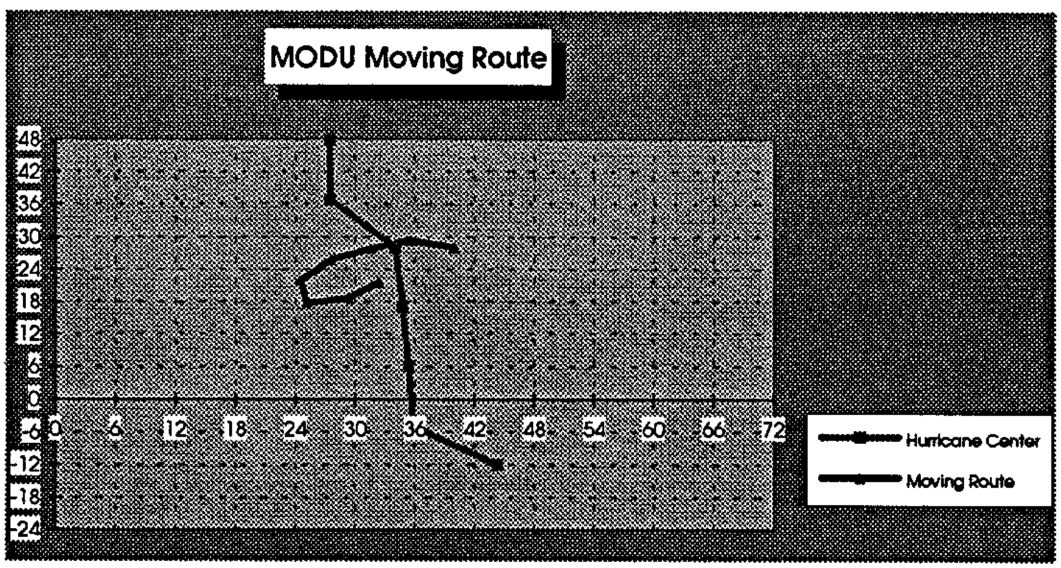
Hurricane Center
Moving Route

Case 5


MODU Moving Route
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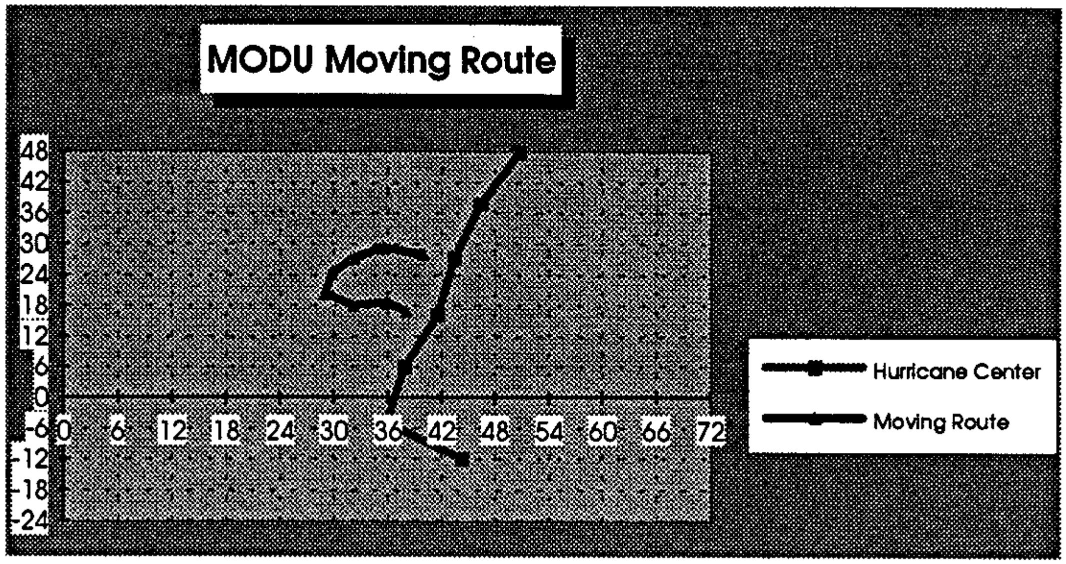
Hurricane Center
Moving Route

Case 6


MODU Moving Route
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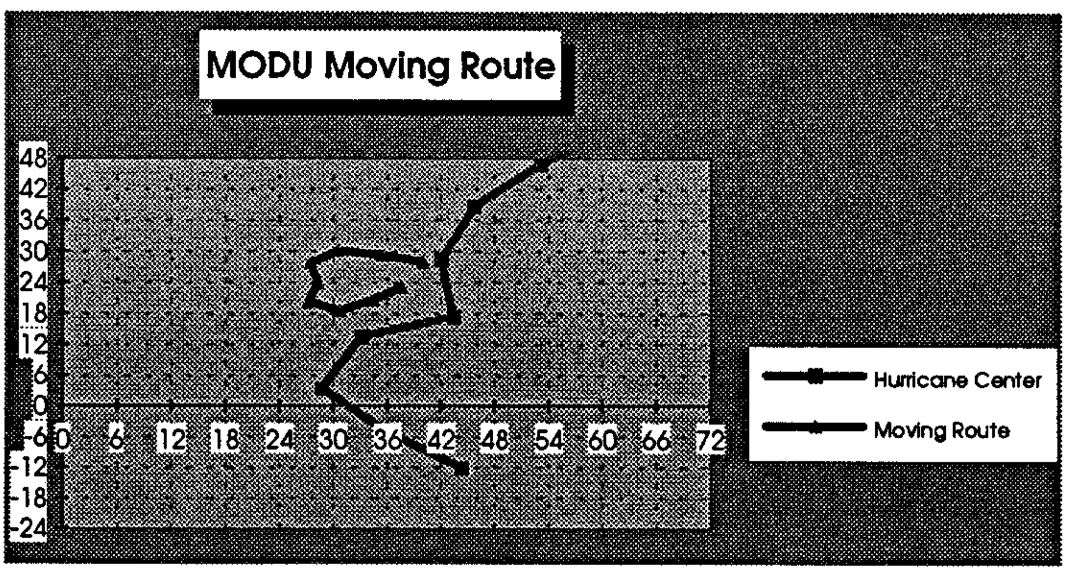
Hurricane Center
Moving Route

Case 7


MODU Moving Route
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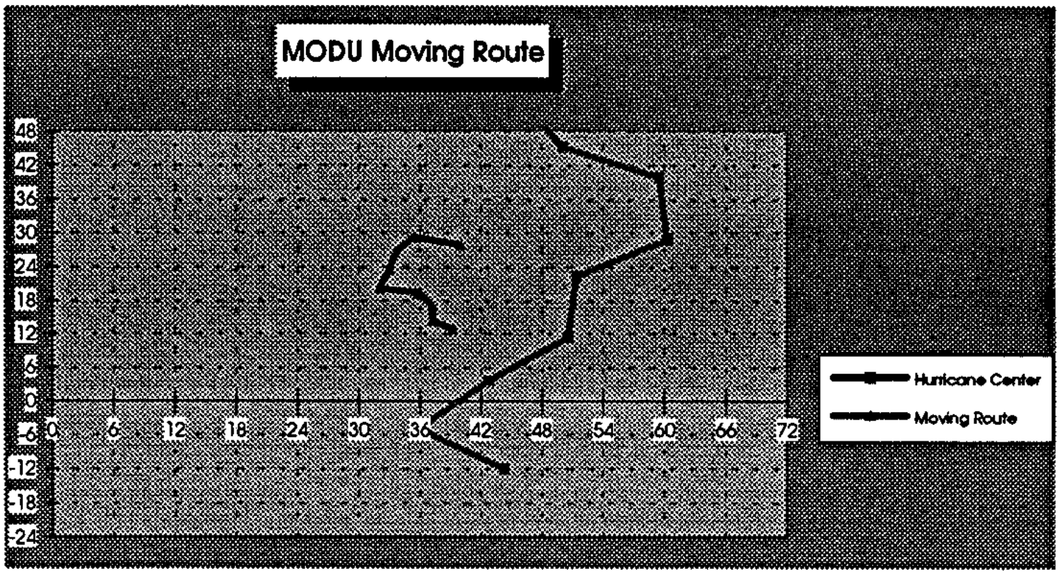
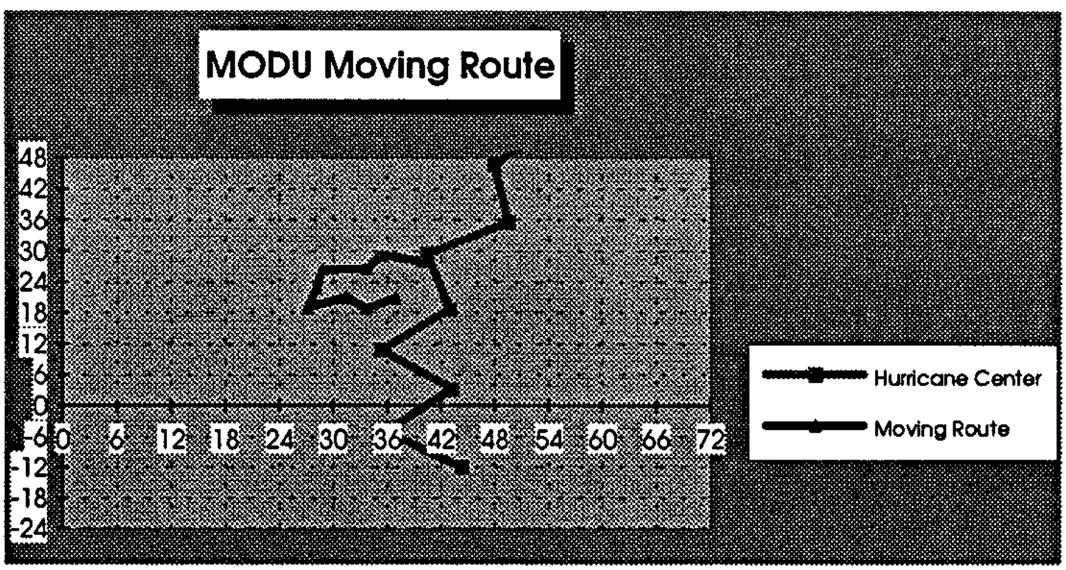
Hurricane Center
Moving Route

Case 8



Case 9



Case 10

3.0. Hurricane Wave Heights and Return Period

3.1. Hurricane Models

The hurricane is assumed to be a storm traveling along a straight line with a given translation speed and direction or a curve with direction changed by Markov-chain modeling. The wind field is governed primarily by the three parameters ΔP, R and V_f and the Coriolis force. The changes in the storm parameters after shelf edge crossing are not considered, i.e., the intensity of the hurricane is assumed to be stationary during passage over the continental shelf. The wind and wave field based on parametric expressions of more sophisticated numerical models. These parametric models which were provided by Reference[15] give the wind velocity, significant wave height, and wave direction as function of the hurricane parameters and the site position relative to the storm center. The current field is based on a one-dimensional numerical model which is a simplified version of the three-dimensional numerical model by Reference[15]. The models are briefly described in the following, details can be found in Cooper (1988).

3.1.1 Wind Field

The wind speed (in m/s) and direction β (polar angle in degree) as functions of the position relative to the storm center in polar coordinates r and θ are given by

$$W = W_m (r / R)^a \qquad \text{for} \quad r/R > 1 \qquad (3.1)$$

$$W = 1.047 W_m [1 - \exp(-3.1 r / R)] \qquad \text{for} \quad r/R < 1 \qquad (3.2)$$

in which

$$W_m = 0.885(5.6\sqrt{\Delta P} - 0.5Rf) + V_f \cos\theta \qquad (3.3)$$

$$a = -0.38 + 0.08\cos\theta \qquad (3.4)$$

where, f = Coriolis parameter in rad/s, ΔP in mb, V_f in m/s, and R in m

$$\beta_{Wind} = \theta + \alpha + 90^0 \qquad (3.5)$$

in which α is the deflection angle given by:

$$\alpha = 22 + 10\cos\theta \qquad (3.6)$$

3.1.2. Wave Field

The parametric model for significant wave height H_{SM}, at a given location can be expressed as a " 25 percentile rule" or:

$$H_{sm} = 0.25V_m \qquad (3.7)$$

In which V_m is the local wind speed in m/s. The equation for the average wave direction ϕ (polar angle in degree) is:

$$\phi = \alpha + a(r/R)^b + \theta - 90^0 \qquad (3.8)$$

in which

$$a = 144 + 39\cos\theta - 25\sin\theta - 15\cos 2\theta \tag{3.9}$$

$$b = -0.08 \tag{3.10}$$

The r.m.s. errors are of the order of 10 to 20 degrees.

The equation for peak period, $T_P(s)$, is:

$$T_P = aW^b \tag{3.11}$$

where,

$$a = 8.0 - 3.5\cos\theta + 2.7\sin\theta \tag{3.12}$$

$$b = 0.143 + 0.138\cos\theta - 0.074\sin\theta \tag{3.13}$$

3.1.3. Current Field

The following parametric model has been developed for the expected maximum current velocity (U_m, m/s, average velocity in upper 30-meter thick mixed layer), concurrent in time with the occurrence of the expected maximum wave:

$$U_m = \varepsilon V_m \tag{3.14}$$

Where $\bar{\varepsilon} = 0.02 - 0.03$, V_m is the 10m elevation, 10 minute average wind speed at the time that the cyclone crosses the site. The current direction is assumed the same as the wave direction.

3.1.4. Surge of Sea Surface

The surge of the sea surface due to hurricane in deep water is determined as:

$$\Delta h = 0.03 H_{max.} \tag{3.15}$$

where, $H_{max} = f(\Delta p)$, is the maximum wave height due to the hurricane in deep water.

3.2. Expected Maximum Wave Heights, Given Significant Wave Heights

The expected maximum wave height, H_m, could be estimated from the short term wave height distribution based on 1000 waves (expressing a 3-hour duration of the maximum sea state intensity at the location):

$$H_m = \zeta H_{sm} \sqrt{\frac{\ln N}{2}} \tag{3.16}$$

where $\bar{\zeta} = 0.93$, $V_\zeta = 8\%$

Thus, the expected maximum wave height could be estimated as:

$$H_m = 1.73 H_s \tag{3.17}$$

3.3 Shoaling Effect

Storm waves tend to be attenuated by a variety of processes as they propagate across the relatively shallow depths of the Texas and Louisiana Continental Shelves. As a wave propagates from deep to shallow water, its height and length change. The transformed wave height, H, at shallow water depth relative to the original deep water wave height, H_0, can be computed from:

$$\frac{H}{H_0} = \left(\frac{V_o}{V}\right)^{\frac{1}{2}} \left(\frac{b_o}{b}\right)^{\frac{1}{2}} \tag{3.18}$$

Where V is the group velocity of the waves, b is the distance between pairs of adjacent wave rays, and the subscript o refers to deep water condition.

The term $\left(\frac{V_o}{V}\right)^{\frac{1}{2}}$ is also known as the shoaling coefficient, k. The shoaling coefficient is given according to linear wave theory by

$$K's = \left(\frac{1}{\left(1+\frac{2kh}{\sinh 2kh}\right)\tanh kh}\right)^{\frac{1}{2}} \tag{3.19}$$

Where h is the water depth and k is the wave number. where, $L = \frac{gT^2}{2\pi}\tanh\left(\frac{2\pi d}{L}\right)$

Eckart(1952) gives an approximate expression for equation (3.19), which is correct to within about 5 percent. This expression is given by:

$$L = \frac{gT^2}{2\pi}\sqrt{\tanh\left(\frac{4\pi^2 d}{T^2 g}\right)} \tag{3.20}$$

$$T = 2.7\sqrt{H_{meter}} \tag{3.21}$$

K's is then given explicitly as a function of wave length and water depth.

The term $(\frac{b_o}{b})^{\frac{1}{2}}$ in the shoaling equation represents the relative spacing of adjacent wave rays and is also defined as the refraction coefficient, K_R. Physically, the relative spacing between wave rays represents the local wave energy density. It is generally assumed that the wave energy contained between wave orthogonal is conserved as the wave front progresses. Various graphical and numerical methods are available to compute wave refraction. In this study, the graphical procedure was adopted. However, most of the wave paths were near normal to the smoothed depth contours; thus, the wave refraction effects proved to be insignificant.

The shoaling effect of the current is defined as [Reference(16)]:

$$U = (2.5 - \frac{1.5}{250} d) U_D \tag{3.22}$$

where U_D is the current velocity at 250ft depth of water (Fig. 3.1).

The shoaling effect of the surge of the sea surface is defined as:

$$\Delta h' = \Delta h \bullet k \tag{3.23}$$

where k is the shoaling effect parameter.

$$K = (1 + \frac{3(300 - h)}{290}) \tag{3.24}$$

and, Δh is the surge in deep water (>=300ft).

The wind velocity in shallow water is assumed the same as in deep water. (See Fig. 3.1)

3.4. Expected Maximum Wave Heights and Return Period

From the assumptions and the procedure above, the expected maximum deep water (300ft) wave heights in Gulf of Mexico is:

$$H_m = C(\Delta P_m)^{\frac{1}{2}} \psi \zeta H_{sm} \sqrt{\frac{\ln N}{2}} \tag{3.25}$$

where $\overline{C} = 4.4$ $V_C = 6\%$

$\overline{\psi} = 0.25$ $V_\psi = 10\%$

$\overline{\zeta} = 0.93$ $V_\zeta = 8\%$

$\overline{\Delta P} = 46.38$ $V_{\Delta P} = 68\%$

Assume H_m is log normal distribution, we have

$$\overline{H_m} = \overline{C}(\overline{\Delta P})^{\frac{1}{2}} \overline{\psi} \overline{\zeta} \sqrt{\frac{\ln \overline{N}}{2}} \tag{3.26}$$

$$V_{H_m}^2 = V_C^2 + (\frac{1}{2} V_{\Delta P})^2 + V_\psi^2 + V_\zeta^2 + (\frac{1}{2} V_{\frac{\ln N}{2}})^2 \tag{3.27}$$

The average return period (ARP) was computed using Equation

$$ARP = \frac{1}{\lambda[1 - F(H_{e\max})]} \tag{3.28}$$

where $F(H_{emax})$ is the cumulative percentage of H_{emax} values equal to or less than a given value, and λ is the average number of important wave-generating hurricanes affecting this area each year. A value of $\lambda = \frac{76}{93} = 0.817$ was used.

With the same procedure, we can get the ARP of Maximum wind velocity and current velocity. See Fig.3.2.

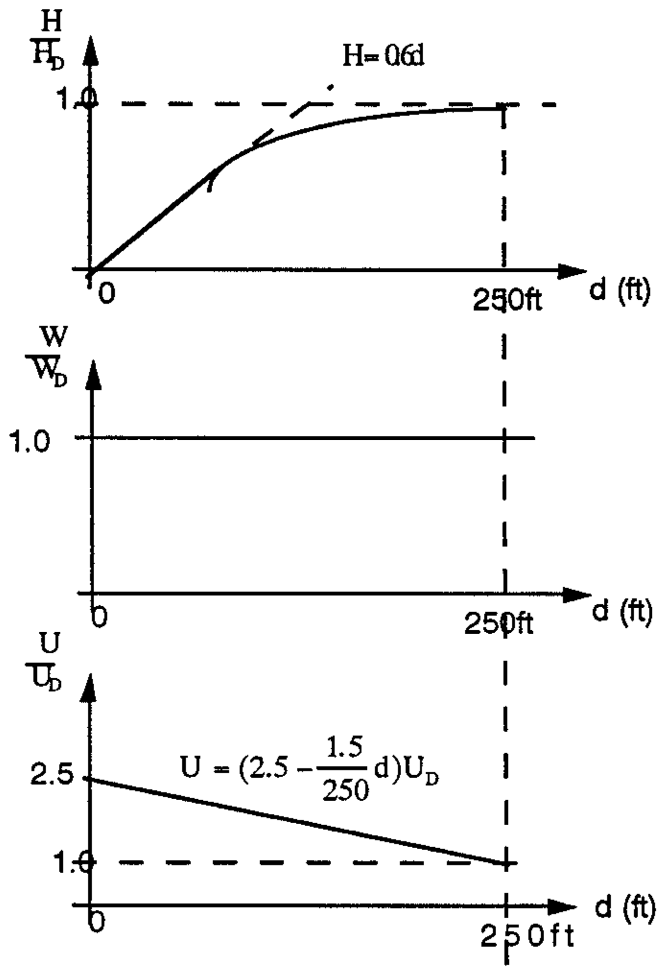


Fig. 3.1 Shoaling Effect

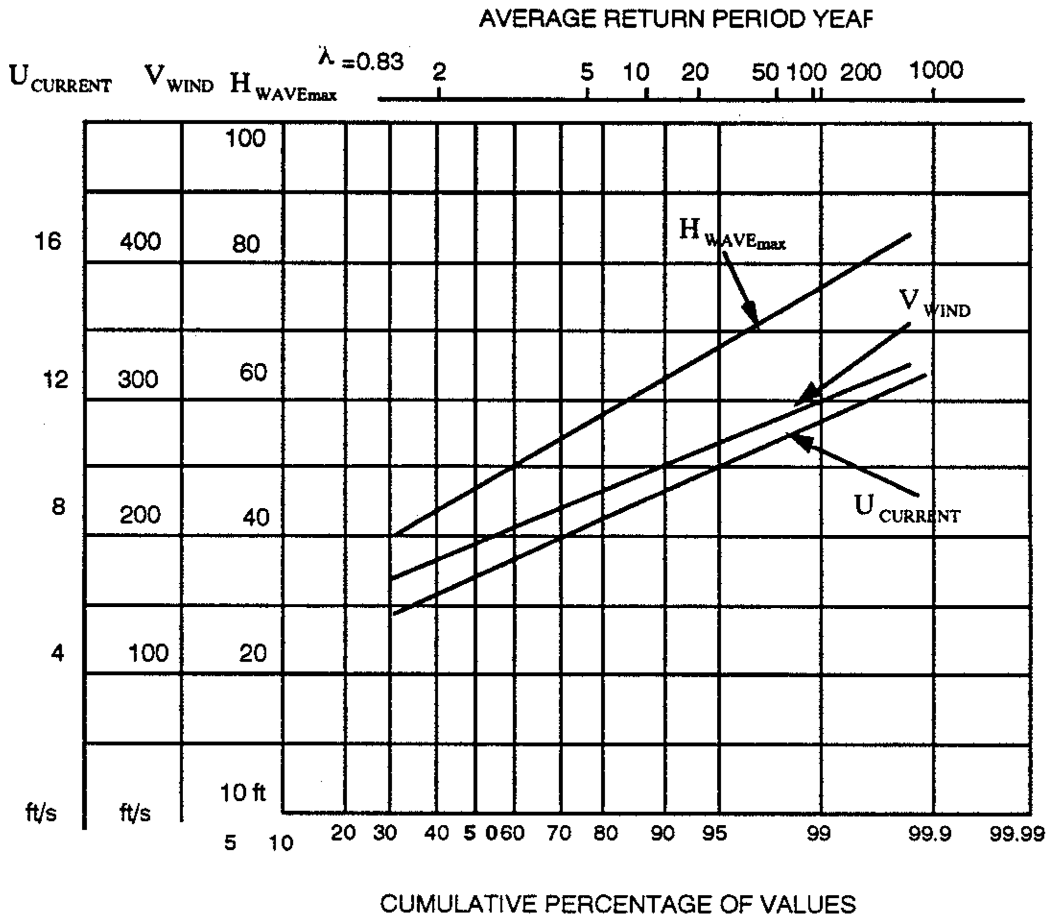


Fig. 3.2 Environmental Loading Return Period

4.0. Hurricane Loading

There are three major hurricane loads on an MODU: wind load, and hydrodynamic wave and current load (Figure 4.1).

4.1 Characterization of Wind Load

The wind force acting on a moored floating MODU can be determined using Equation (4.1):

$$F_w = C_w \sum (C_s C_h A) V_w^2 \qquad (4.1)$$

where:

F_w = wind force, lb. (N)

$C_w = 0.0034 lb / (ft^2 \bullet kt^2)(0.615 N \sec^2 / m^4)$

C_s = shape coefficient

C_h = height coefficient

A = vertical projected area of each surface exposed to the wind, $ft^2 (m^2)$

V_w = local wind speed, knots(m/sec)

The projected area exposed to the wind should include all columns, deck members, deck houses, trusses, crane booms, derrick substructure and drilling derrick as well as that portion of the hull above the water line. (Except as noted below, no shielding should be considered.)

In calculating wind areas, the following procedures should be followed:

- The projected area of all columns are included

- The blocked-in projected area of several deck houses are used instead of calculating the area of each individual unit. However, when this is done, a shape factor, C_s, of 1.10 is used.

- Isolated structures such as derricks and cranes are calculated individually.

- Open truss work commonly used for derrick mast and booms are approximated by taking 60 percent of the projected block area of one face.

- Areas are calculated for the appropriate hull draft for the given operating condition.

- Wind velocity increases with height above the water. In order to account for this change, a height coefficient, C_h, is included. The height coefficient, C_h, can be found in Table.

4.2 Characterization of Current Forces

Current forces are normally treated as steady state forces in a mooring analysis. Current force acting on semisubmersible hulls can be calculated as:

$$F_{cs} = C_{ss}(C_d A_c + C_d A_f)U_c^2 \qquad (4.2)$$

where:

F_{cs} = current force, lb(N)

C_{ss} = current force coefficient for semisubmersible hulls

$=2.85 lb/(ft^2 \bullet kt^2)(515.62 N\sec^2/m^4)$

C_d = drag coefficient (dimensionless)

=0.6 for circular members; 1.0 for members having flat surfaces.

A_c = summation of total projected areas of all cylindrical members below the waterline. $ft^2(m^2)$

A_f = summation of projected areas of all members having flat surfaces below the waterline. $ft^2(m^2)$

4.3 Characterization of Wave Forces

Interactions between ocean waves and a floating vessel results in forces acting on the vessel which can be conveniently split into three categories(Fig. 4.2):

(1) First order forces which oscillate at the wave frequencies. They induce first order motions which are also known as high frequency or wave frequency motions.

(2) Second order forces with frequencies below wave frequencies. They induce second order motions which are also known as low frequency motions.

(3) Steady component of the second order forces which is known as mean wave drift force.

4.3.1 Wave Frequency MODU Motions

The motions of the MODU at the frequency of the waves is an important contribution to the total mooring system loads, particularly in shallow water. These wave frequency motions can be obtained from regular or random wave model test data, or computer analysis using either time or frequency domain techniques. The method used in this work is based on the widely used Morison Equation.

The total hydrodynamic force per unit length, F, is comprised of a drag force, F_d, and an inertia force, F_i:

$$F = F_d + F_i \tag{4.3}$$

where,

$$F_d = C_d(\rho / 2)(D)u|u| \qquad F_d = K_d u|u| \tag{4.4}$$

and,

$$F_i = C_m(\rho \pi D^2 / 4)a \tag{4.5}$$

$$F_i = K_m(a)$$

The total lateral force can be calculated by integrating the local forces over the entire structure. Since the cylinder considered here has very large diameter, it is in inertia force dominant.

Storm seas are generally directional seas. Directional seas can be considered as comprising of numerous unidirectional seas. The forces calculated in the directional seas are the product of a directional spreading factor and the forces calculated by the uni-directional wave theory. The wave data used here is all directional wave height. The directional spreading factor is assumed to be one. To calculate wave kinematics, Airy wave theory and Stokes 5th order theory are used.

a. Airy Wave Theory

For uni-directional (long-crested) waves, water particle horizontal velocities, u_w and accelerations, a_w are

$$u_w = (\pi H / T)e^{kz} \cos(\theta) \tag{4.6}$$

and,

$$a_w = (2\pi^2 H / T^2)e^{kz} \sin(\theta) \tag{4.7}$$

where k is the wave number($k = 2\pi / L$), z is the vertical coordinate which is zero at the still water level and positive upward, and θ is the wave phase angle ($\theta = kx - \omega t$, ω is the wave circular frequency, $\omega = 2\pi / T$, x is the horizontal coordinate measured from the wave crest, and t is the time coordinate).

b.Stokes 5th Theory

Using equations given by Skjelbreia and Hendrickson (1961) and Fenton (1985), a computer program was developed to determine the wave kinematics (Preston, 1994). Given the wave height **H**, period **T** and water depth **d**, the vertical profile of maximum horizontal velocities beneath the wave crest are estimated as:

$$\frac{u}{c} = K_{ds} \sum_{n=1}^{5} n\Phi'_n \cosh(nks) \qquad (4.8)$$

where K_{ds} is a coefficient that recognizes the effects of directional spreading and wave irregularity on the Stokes wave theory based velocities. **k** is the wave number and **s** is the vertical coordinate counting positive upward from the sea floor. **c** is the wave celerity and given as:

$$\frac{c^2}{gd} = \frac{\tanh(kd)}{kd}[1 + \lambda^2 C_1 + \lambda^4 C_2] \qquad (4.9)$$

The crest elevation η is estimated as:

$$k\eta = \sum_{n=1}^{5} \eta'_n C_n \qquad (4.10)$$

Φ'_n and η'_n are given functions of λ and kd. C_n are known functions of kd only, given by Skjelbreia and Hendrickson (1961). The wave number k is obtained by implicitly solving equation given by Fenton (1985):

$$\frac{2\pi}{T(gk)^{0.5}} - C_0 - (\frac{kH}{2})^2 C_2 - (\frac{kH}{2})^4 C_4 = 0 \qquad (4.11)$$

The parameter λ is then calculated using the equation given by Skjelbreia and hendrickson(1961):

$$\frac{2\pi d}{gT^2} = \frac{d}{L}\tanh(kd)[1+\lambda^2 C_1 + \lambda^4 C_2] \tag{4.12}$$

The specified variation of current velocities with depth is stretched to the wave crest and modified to recognize the effects of structure blockage on the currents. The total horizontal; water velocities are taken as the sum of the wave horizontal velocities and the current velocities.

4.3.2 Mean Wave Drift Force

The mean wave drift force is induced by the steady component of the second order wave forces. The determination of mean drift force requires motions analysis computer programs or model tests. Design curves for estimating mean wave drift forces for semisubmersibles are provided in Reference[12] (Fig. 4.3). The curves are applicable to typical MODU type vessels.

4.3.3 Low Frequency Vessel Motions

Low frequency motions are induced by the low frequency component of the second order wave forces which in general are quite small compared to the first order forces. Sometimes the second order forces are amplified through resonance into motions which can become very large and neglecting low frequency motions can provide non-conservative answers. But due to the difficulty in predicting the magnitude of resulting low frequency tensions, their effect is neglected.

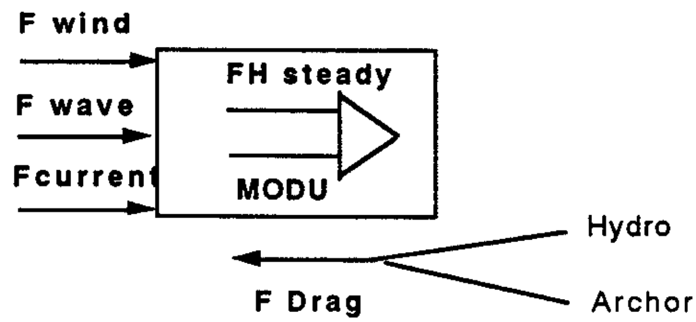


Fig. 4.1 Loading on MODU

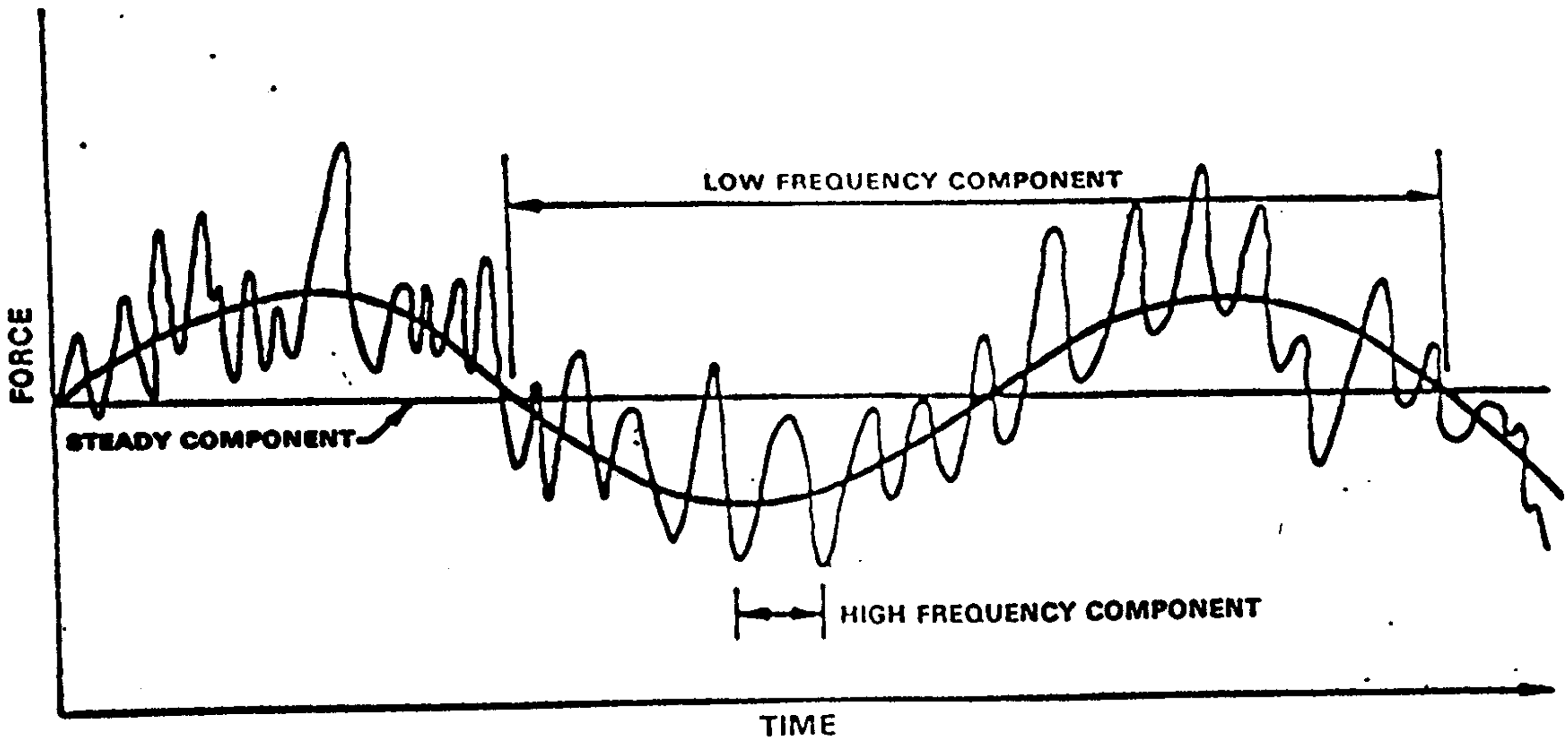


Figure 4.2 Wave Force Components

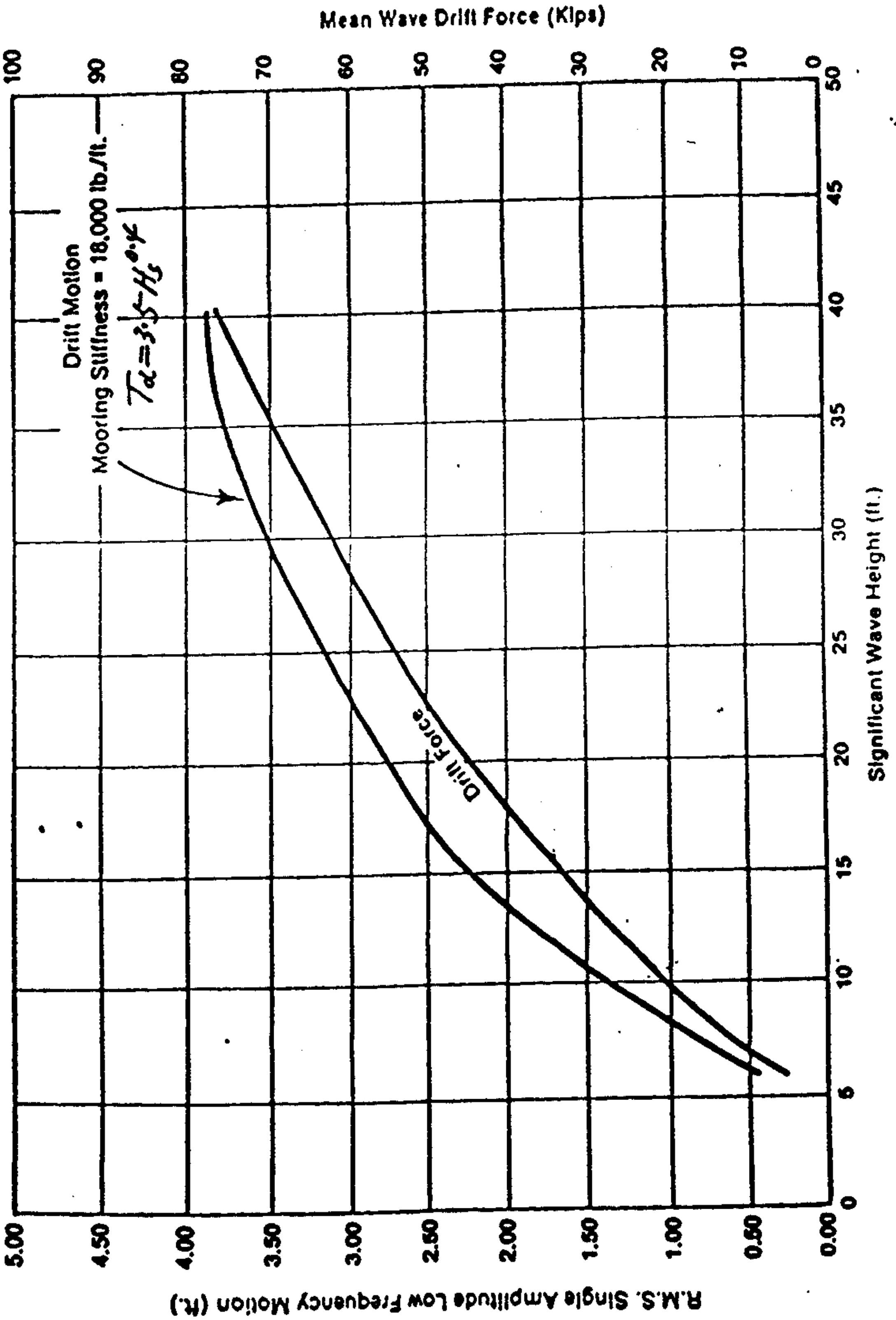


Fig. 3a. Wave Drift Force and Motion for Semisubmersibles (Beam Seas)

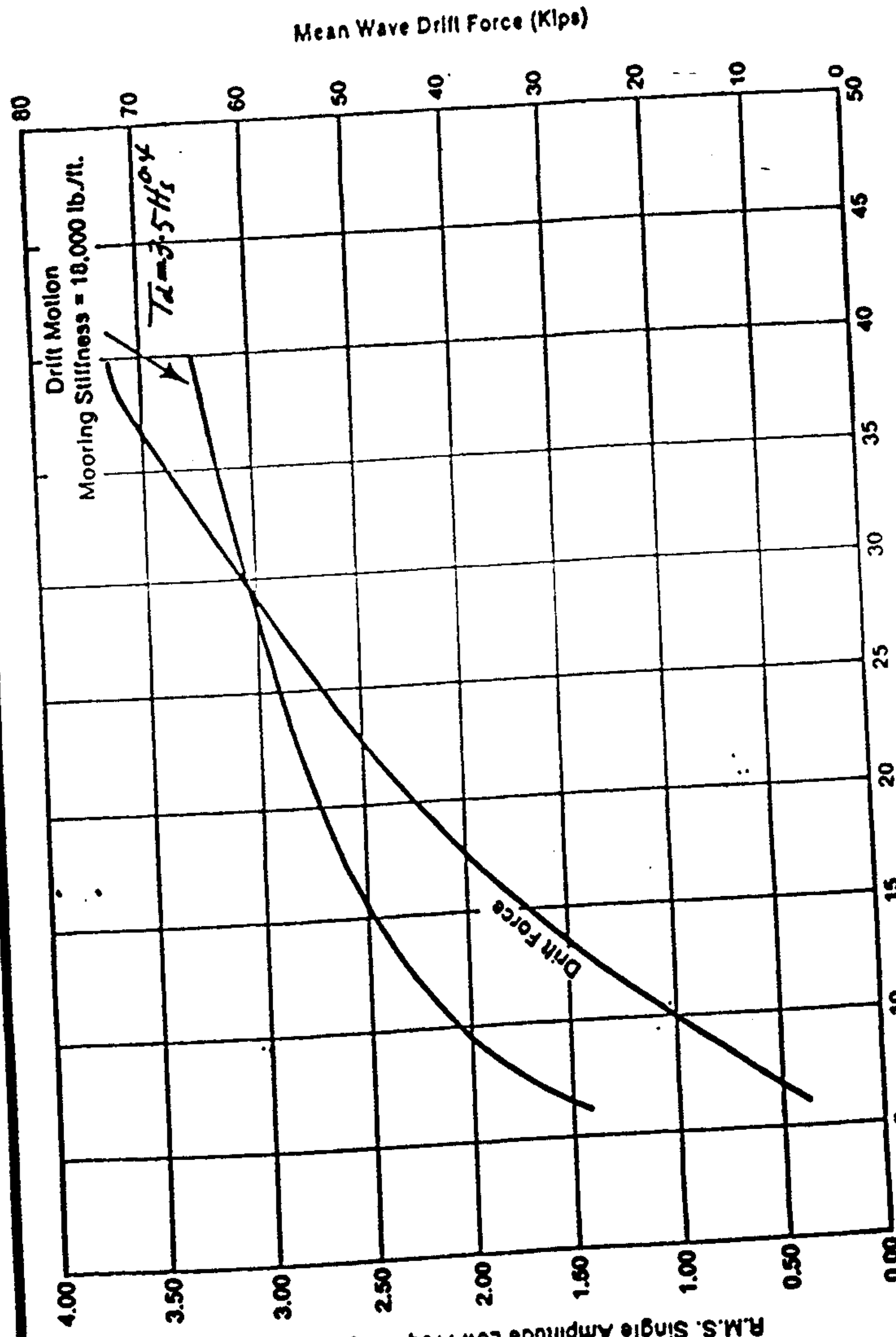


Fig. 3b. Wave Drift Force and Motion for Semisubmersibles (Bow Seas)

5.0. Mooring Analysis

5.1 Extreme Response Analysis

Generally, the mooring system of a semi-submersible is as shown in Figure 5.1. Permanent mooring systems should be designed for two primary considerations: system overloading and fatigue. For mobile moorings, only analysis for extreme response is required.

Extreme responses normally govern the design of the FPS mooring. They include vessel offset, mooring line tension, anchor load, and suspended line length. The environmental effects can be divided into three categories:

- Steady state forces including current force, mean wind and mean wave drift forces.
- Low frequency vessel motions due to wind and waves.
- Wave frequency vessel motions.

The responses of a mooring system to mean forces are predicted by static catenary equations. Generally speaking, the responses to low frequency motions can also be predicted by the same method because of the long periods of these motions. The responses to wave frequency vessel motions are usually predicted by one of the following two methods:

(1) Quasi-State Analysis

In this approach, the dynamic wave loads are taken into account by statically offsetting the vessel by an appropriately defined wave included motion. Vessel failead motions and dynamic effects associated with mass, damping and fluid acceleration are neglected. Research in mooring line dynamics has shown that the reliability of the mooring designs based on this method can vary widely depending on the vessel type, water depth and line configuration. Therefore, the quasi-static method is not recommended for the final design of a permanent mooring. However, because of its simplicity, this method can be used for temporary moorings and preliminary studies of permanent moorings with higher factors of safety.

(2) Dynamic Analysis

Dynamic analysis accounts for the time varying effects due to mass, damping, and fluid acceleration. In this approach, the time-varying fairlead motions are calculated from the vessel's surge, sway, heave, pitch, roll and yaw motions. Generally it is sufficient to account for only the vertical and horizontal fairlead motions in the plane of the mooring line. Dynamic models are used to predict mooring line responses to the fairlead motions. Several dynamic analysis techniques are available. The distinguishing feature among various dynamic analysis techniques is the degree to which non-linearity are treated. There are four primary nonlinear effects which can have an important influence on mooring line behavior:

- Nonlinear Stretching Behavior of the Line

The strain or tangential strength of the line is a function of the tension magnitude. Nonlinear behavior of this type typically occurs only in synthetic materials such as nylon. Chain and wire rope can be regarded as linear. In many cases the non linearity can be ignored and a linearized behavior assumed using a representative tangent or secant modules.

- Changes in Geometry

The geometric non linearity is associated with large changes in shape of the mooring line.

- Fluid Loading

The Merinos equation is most frequently used to represent fluid loading effects on mooring lines. The drag force on the line is proportional to the square of the relative velocity(between the fluid and the line), hence is nonlinear.

- Bottom effects

In most mooring designs, a considerable portion of the line is in contact with the seafloor. The interaction between the line and the seafloor is usually considered t be a frictional process and is hence nonlinear. In addition, the length of grounded line constantly changes, causing an interaction between this non linearity and the geometric non linearity.

Two methods, frequency domain and time domain analyses, are commonly used for predicting dynamic mooring loads. In the time domain method, all of the nonlinear effects can be modeled. The elastic stretch is mathematically modeled, the full Merinos equation is included, the position of the mooring line is updated at each time step and the bottom interaction is included using a frictional model. The general analysis implies the recalculation of each mass term, dampening term, stiffness term and load at each time step. Hence the computation can become complex and time consuming.

The frequency domain method, on the other hand, is always linear as the linear principle of superposition is used. Hence, all nonlinearities must be eliminated, either by direct linearlization or by an iterative linearlization.

- Line Stretching

The line stretching relationship must be linearized and a definite value of the modules assumed at each point. The modules can not be a function of line tension but can vary along the line. This is usually not a bad assumption even in the case of synthetic material and, in most cases, a suitable linearlization can be achieved.

- Geometry change

In the frequency domain method it is assumed that the dynamic displacements are small perturbations about a static position. The static shape is fixed and all geometric quantities are computed based on this position. The mass, added mass, stiffness, etc. are computed only once. Changes in catenary shape due to the dynamic motion contribution are generally not severe. Hence, a linearlization about the position under mean load is generally acceptable.

- Fluid Loads

The nonlinear term in the Merinos equation must be linearized. The quadratic relationship in the relative velocity must be replaced by an equivalent linear relationship. The linearlization should take into account the frequency content of the line motion spectrum.

- Bottom Effects

The frictional behavior between the grounded line and the seafloor can not be represented exactly in the frequency domain. Only the "average" or equivalent behavior of the line can be postulated and included. This simplification should be adjusted to the analysis objective.

5.2 Quasi-Static and Dynamic Analysis

The procedure outlined below is recommended for the analysis of extreme response using a quasi-static or dynamic approach. The calculated response in accordance with this procedure should satisfy the design criteria.

The analysis is normally performed with the following computer programs:

1) Hydrodynamic Motion Analysis programs
These programs are used to determine wave frequency and low frequency vessel motions.

2) Static Mooring Analysis program
This program is used to analyze mooring line response to steady state environmental forces and low frequency motions.

3) Dynamic Mooring Analysis program
This program is used to analyze mooring line response to wave frequency motions.

The recommended analysis procedure is described below:

a) Determine wind and current velocities, and significant wave heights and periods, for both the maximum design, and operating conditions in accordance with guidelines.

b. Determine the mooring pattern, characteristics of chain and wire rope to be deployed, and initial tension.

c. Determine the steady state environmental forces acting on the hull.

d. Determine the vessel's mean offset due to the steady state environmental forces using the static mooring analysis program.

e. Determine the low frequency motions. Since calculation of low frequency motions requires the knowledge of the mooring stiffness, the mooring stiffness at the mean offset should be determined first using a static mooring analysis computer program.

f. Determine the significant and maximum single amplitude wave frequency vessel motions using a hydrodynamic motion analysis program.

g. Determine the vessel's maximum offset, suspended line length, quasi-static tension, and anchor load.

h. Determine the maximum line tension and anchor load. A frequency domain or time domain dynamic mooring analysis program should be used.

i. Compare the maximum vessel offset and suspended line length from step g and maximum line tension and anchor load from step g or h. If the criteria are not met, modify the mooring design and repeat the analysis.

5.3 Mooring Analysis in MODUSIM

In MODUSIM, it is assumed that the total expected lateral capacity of the mooring system is $\overline{R_u}$. There are two modes of mooring system failure. One is that all the mooring lines are broken, the MODU will be in free floating condition. The other is that the horizontal hurricane load is larger than the total anchor holding force and some of the mooring lines are not broken so that the MODU will be in dragging condition.

$\overline{R_{u1}}$, denotes failure mode one (Free floating);
$\overline{R_{u2}}$, denotes failure mode two (Anchors dragging).

These failure modes are defined by the MODUSIM users.

For mooring analysis in MODUSIM, users can use the following simplified formula which can be determined from the regression analysis to determine the maximum line tension of MODU in different environmental condition:

1. Determine Mean Environmental Force.

2. Determine Mean Offset.

$$\text{Mean.Offset} = A * F_{mean} + B \tag{5.1}$$

3. Determine Dynamic Offset.

$$\text{Dyn.Offset} = C * H_s^2 + D * H_s + E \tag{5.2}$$

4. Determine Total Offset.

$$\text{Total.Offset} = \text{Mean.Offset} + \text{Dyn.Offset} \tag{5.3}$$

5. Determine Maximum Line Tension

$$\text{Tension} = F * \text{Tot.Offset}^2 + G * \text{Tot.Offset} + H \tag{5.4}$$

Parameters A, B, C, D, E, F, G, H are determined from regression analysis by users

If the information of parameters are not available, it is recommended to use the assumption that if the environmental force is larger than the mooring capacity, the mooring system will fail.

5.4 Water Depth Factor

The algorithm is specific for one rig type at a given water depth and mooring system. The maximum line tension calculated from the processes presented above is a function of vessel type, mooring system, mean offset wave height and water depth. Changes in any of these makes the constants in the algorithm change. The influence of these different variables can cause havoc when trying to create a simple algorithm. For example, a given dynamic offset may increase tensions significantly in shallow water and have no impact in deep water. With a large mean offset, a small dynamic offset can cause a large increase in tensions. The variables are highly non-linear and difficult to predict.

When determining a safe location to stack a MODU, one of the criteria is adequate water depth. To have the best possible chance for survival in a hurricane, this may be interpreted as choosing a location with the optimal water depth for the mooring system. Research shows that as a rig is moved into shallow water, the capacity of the mooring system decreases. This reflects an increase in mooring system stiffness as water depth decreases, and for a stiffer system, a given vessel offset will produce larger tensions.

A simple way to solve this problem is to introduce a "water depth correction factor" to modify the calculated forces. The forces are calculated as before and then multiplied by a "water depth correction factor". The resulting force could then be used to determine the approximate total tension. Based on the mooring system performance curves from Noble Denton, a regression analysis has been performed and the water depth correction factor can be defined as (See Figure 5.2):

5.4 Water Depth Factor

The algorithm is specific for one rig type at a given water depth and mooring system. The maximum line tension calculated from the processes presented above is a function of vessel type, mooring system, mean offset wave height and water depth. Changes in any of these makes the constants in the algorithm change. The influence of these different variables can cause havoc when trying to create a simple algorithm. For example, a given dynamic offset may increase tensions significantly in shallow water and have no impact in deep water. With a large mean offset, a small dynamic offset can cause a large increase in tensions. The variables are highly non-linear and difficult to predict.

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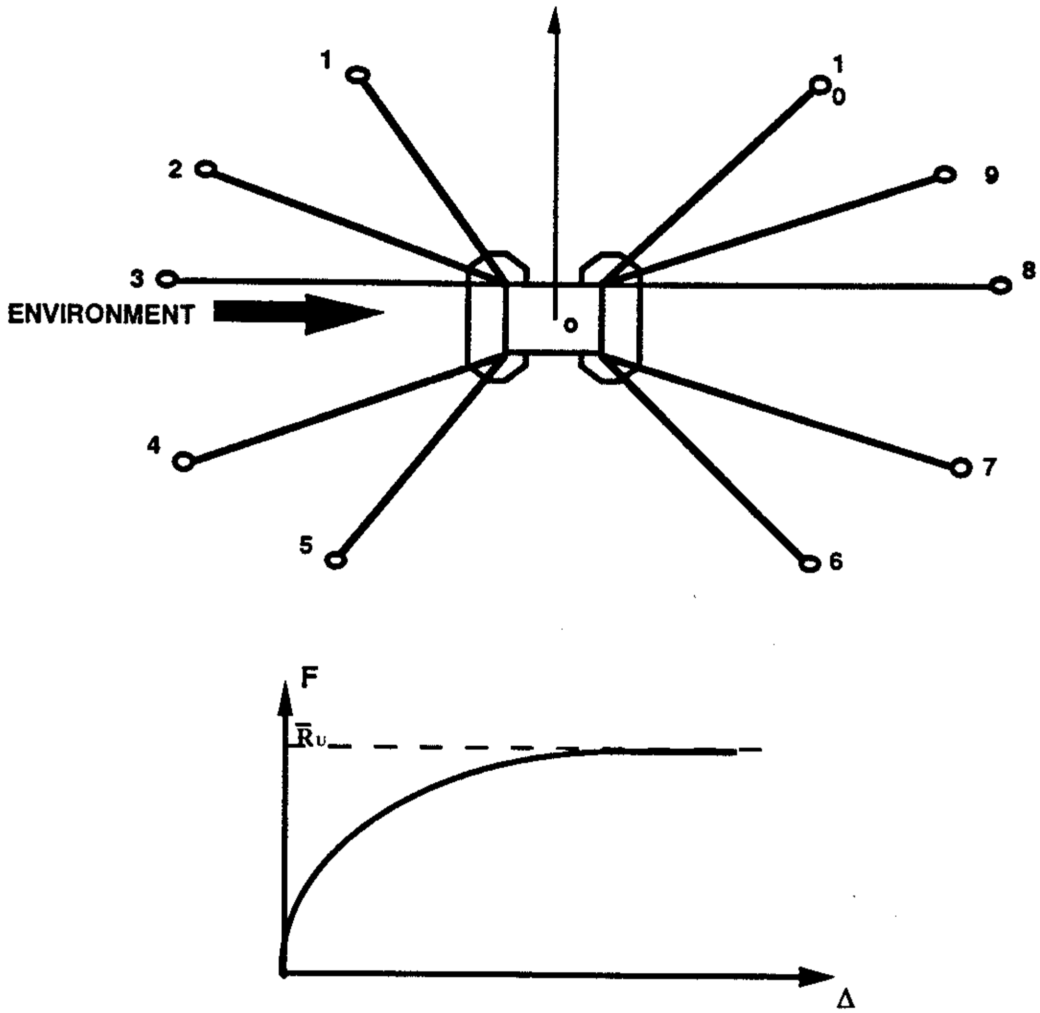
$$\text{Water Depth Factor} = 0.056 * \left(\frac{\text{Water Depth}}{250}\right)^2 - 0.45 * \left(\frac{\text{Water Depth}}{250}\right) + 1.89 \qquad (5.8)$$

where the unit of Water Depth is feet.



Mooring
Capacity

Fig. 5.1. Mooring System Configuration

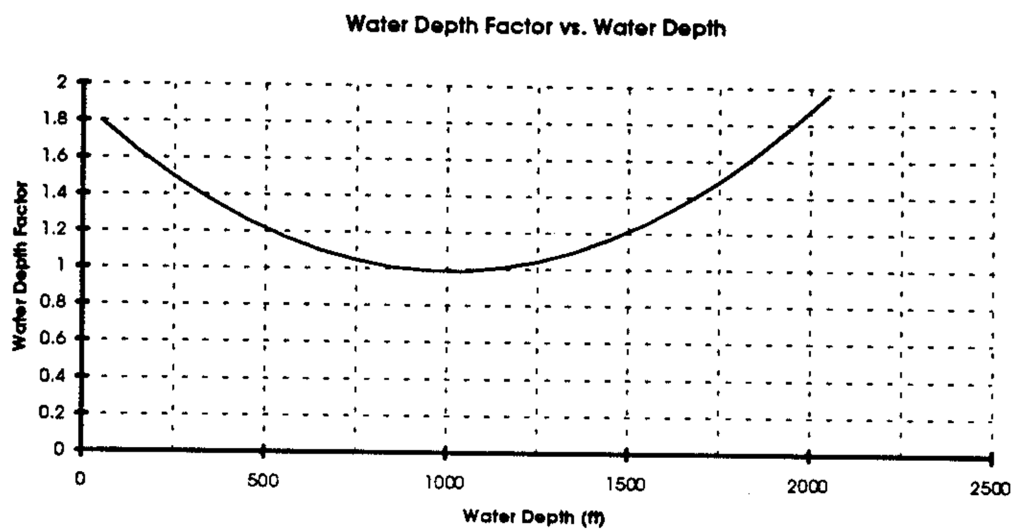


Figure 5.2. Water Depth Factor vs. Water Depth

6.0. MODU Moving Modeling

6.1 MODU Moving Modes

There are two moving modes associated with the depth of the water and the draft of the MODU. They are defined as:

$T < d + \Delta d$	case A:	MODU Floating
$\Delta d + d < T < \Delta d + d + \eta_{max}$	case B:	MODU Skipping
$T > \Delta d + d + \eta_{max}$	case C:	MODU STOP

where,

T = draft of the MODU

d = depth of the water

η_{max} = maximum wave height

Δd = surge of sea surface

6.2. MODU Moving Distance Modeling

6.2.1 Case A: MODU Floating

a) Free Floating Condition

During a short period of time (Δt), the MODU is assumed to move with a steady velocity. We assume that the total hurricane horizontal steady force is equal to the hydrodynamic force. (See Fig. 4.1)

$$F_{Hsteady} = F_{wave} + F_{wind}$$

$$= F_{Hydro} = [C_D A_P \rho / 2][V_{MODU} - V_{Current}]^2 \qquad (6.1)$$

where

$C_D = 0.7$

A_P =Projected Area

ρ =64 lb/ft^3

F_{Wind} =Steady wind force

F_{Wave} =Mean wave drift force

So:

$$V_{MODU} = \sqrt{\frac{F_{Wind} + F_{Wave}}{C_D A_p \rho / 2}} + V_{Current} \qquad (6.2)$$

and,

$$\Delta_{move} = V_{MODU} \Delta t \tag{6.3}$$

where,

Δt = hurricane simulation time period   case A-- MODU Floating

b) Dragging Condition

Here, we also assume the MODU moves with a steady velocity, so the total hurricane horizontal steady force minus anchor dragging force is equal to the hydrodynamic force.

$$F_{Hsteady} = F_{wave} + F_{wind} - F_{Anchor}$$

$$= F_{Hydro} = [C_D A_P \rho / 2][V_{MODU} - V_{Current}]^2 \tag{6.4}$$

where,

$C_D = 0.7$

A_P = Projected Area

ρ = 64 lb/ft^3

F_{Wind} = Steady wind force

F_{Wave} = Mean wave drift force

So

$$V'_{MODU} = \sqrt{\frac{F_{Wind} + F_{Wave} - F_{Drag}}{C_D A_p \rho / 2}} + V_{Current} \tag{6.5}$$

and,

$$\Delta_{move} = V'_{MODU} \Delta t \tag{6.6}$$

Here, the dynamic anchor drag force is assumed as,

$$F_{dynamic} = \varepsilon F_{static} \tag{6.7}$$

where,

$\bar{\varepsilon} = 0.5, \qquad V_{\varepsilon} = 30\%.$

t = hurricane time period case A--MODU Floating

6.2.2 Case B: MODU Skipping

When the MODU moves in skipping mode, during a wave period, the MODU will move when $T < \Delta d + d + \eta_{max}$, and it will stop when $T > \Delta d + d + \eta$. Since wave period is usually short, we can not assume the MODU moves with a steady velocity now. A moving differential equation needs to be solved:

$$F_{Wave} + F_{Wind} + [C_D A_p \rho / 2](V_{Current} - V_{MODU})^2 = M \dot{V}_{MODU} \tag{6.8}$$

$$\Delta_{move} = \frac{1}{2} \cdot \dot{V}_{MODU} \cdot \Delta t^2 \tag{6.9}$$

6.3. MODU Collision Modeling

The surrounding structures are assumed to be located within several large target circles with radius R_i from 0.5 to 5 nm. Collision happens when the MODU runs into one of these circles and collides with structures within the circle. From the simulation, the MODU's moving route is determined. If the distance between the moving route and the center of the circle is less than R_s, the MODU has encountered the circle. To determine whether or not the MODU collides with structures within the circle, a pre-prepared simulation was performed.

During the simulation, the MODU is assumed to moving at a straight line within the circle before collision happens. The direction in which the MODU runs into is assumed uniformly distributed from $0^0 - 180^0$. Target structures are also assumed uniformly distributed within the circle. With a given circle radius and the number of structures within the circle, the distance between these structures and the MODU route is determined. The collision happens if one of these distance is less than safety distance, say 100m. With a given R_i and N, the process is repeated many times to get the probability of collision on the condition of MODU runs into the circle. For different R_i and N, the simulation results are presented in Figure. 6.1.

Based on the results from the simulation, the following observations can be made:

1. $R \leq 2$nm, the collision probability increases rapidly from 30% to 80% when N increases from 10 to 30. When N is larger than 40, the collision probability is very high and does not change much when N increases.

2. $R \geq 3$ nm, the collision probability increases slowly with N.

3. In both cases, the collision probability increases rapidly at first, then slow down when N is large enough.

4. From the Fig.6.1, we found, for most general circle (radius R=2.4nm and number of structures within the circle N=40), the collision probability is approximately 60%.

6.4. Modeling of Holding after the Collision

During hurricane Andrew, the Zane Barns collided with several platforms after breaking loose from its location. From past experience, we know that the MODU drift direction may change after the first collision, or may remain at the collision location for hours before it starts to drift again. The MODUSIM user can define whether or not holding happens and how long it is held after collision happens. Figure 6.2 shows that the MODU's moving route changes a lot if it is held for two hours after the first collision.

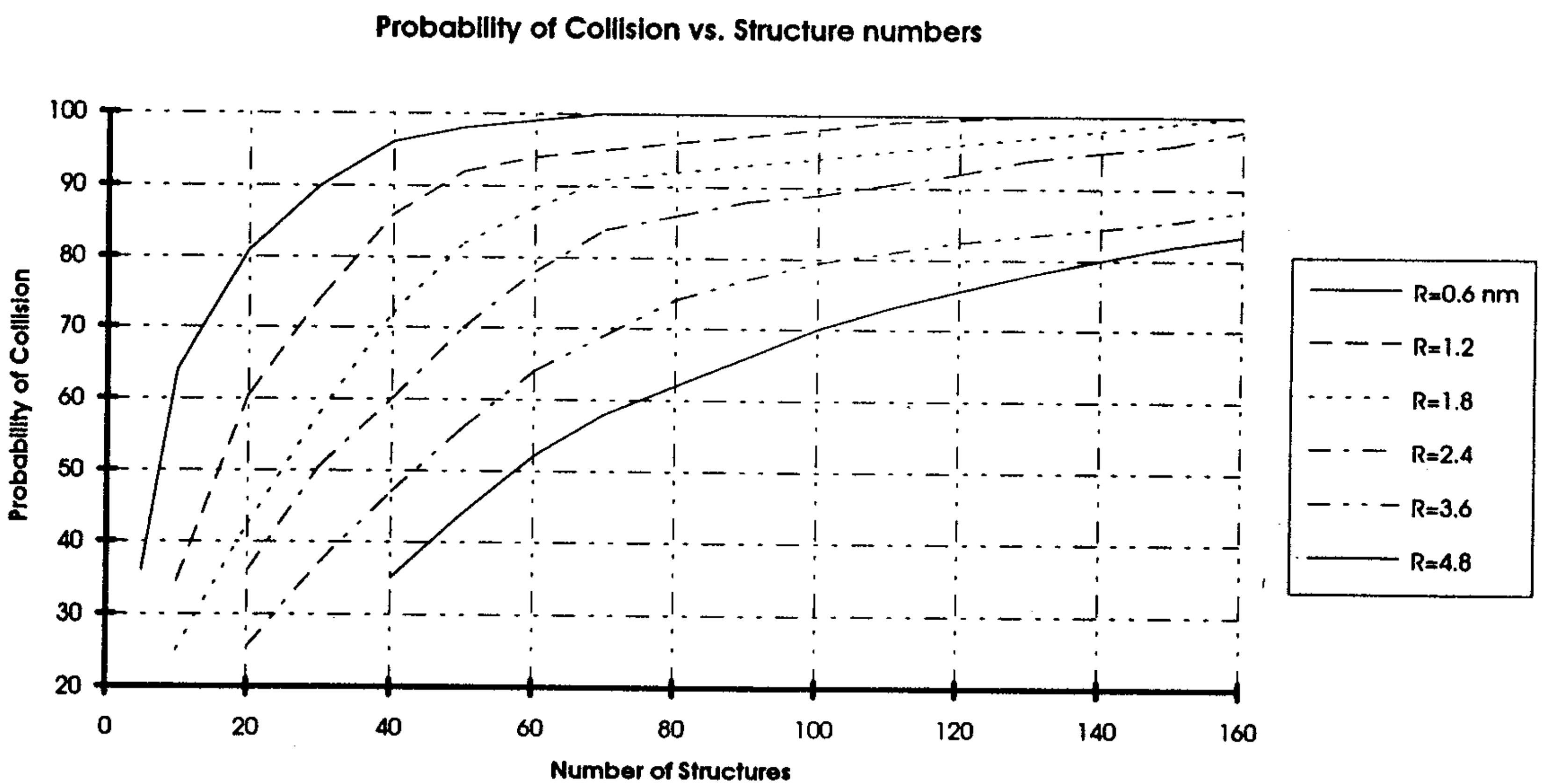
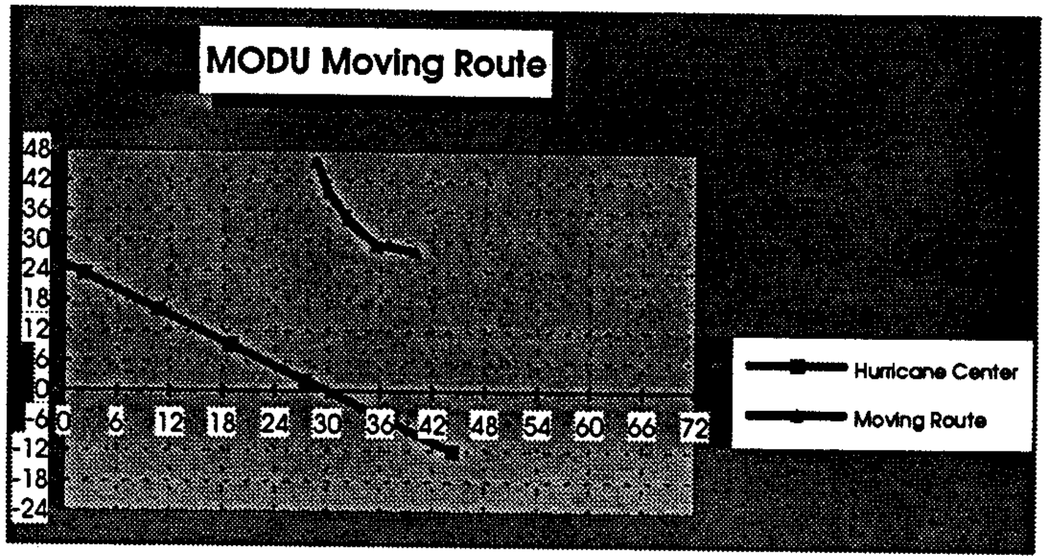
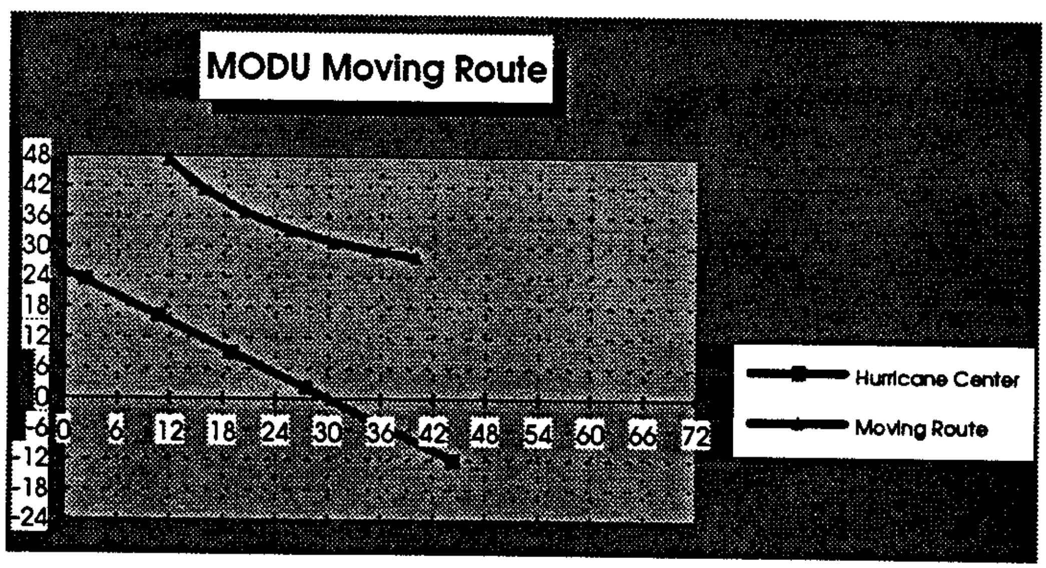


Figure 6.1 Collision Probability vs. Structure Density within Given Target Circles

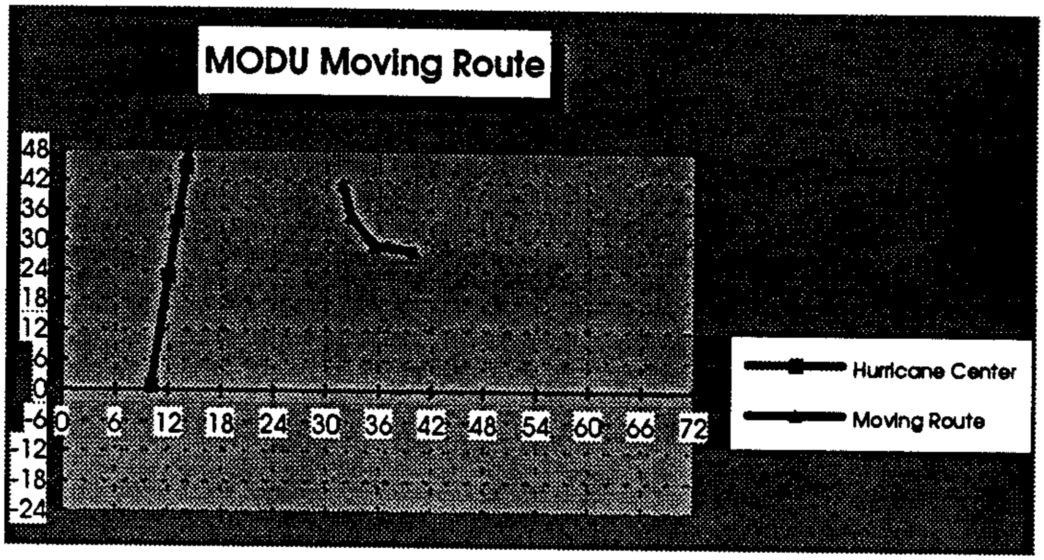


Holding for 2 hours at the First Collision

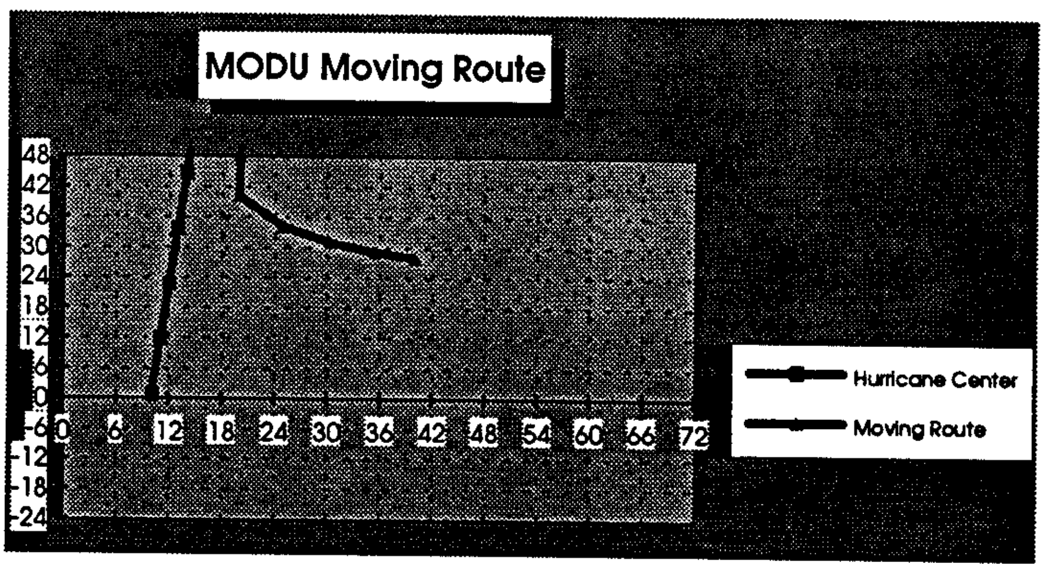


No Holding

Figure 6.2 Modeling of Holding



Holding for 2 Hours at First Collision



No Holding

7.0. Monte-Carlo Simulation

7.1 Introduction

Simulation is a technique for conducting experiments in a laboratory or on a digital computer in order to model the behavior of a system. Monte-Carlo simulation is usually used for problems involving random variables of known or assumed probability distributions. Using statistical sampling techniques, a set of values of the random variables are generated in accordance with the corresponding probability distributions. These values are used to obtain a "sample" solution. By repeating the process and generating several sets of sample data, many sample solutions can be determined. Statistical analysis of the sample solutions is then performed.

The MODU's moving in a hurricane is a very complicated process. The environmental force and the MODU moving direction are time-dependent variables. The process can be modeled by direct computer simulations using the probability models for the hurricane parameters, the MODU's approximate to the site, and the number of hurricanes.

The simulation procedure can be summarized as follows:

1) Select a reference frame in which the site is located.(See Fig.7.1);

2) Generate the number, n, of hurricanes which occur during the period of consideration, i.e., 1 years, within the reference frame using a Poisson distribution with an occurrence statistics at the location, i.e., γ_h;

3) Generate a sets of random variables $X, \Delta P, R, \varphi, V_H$ according to the distribution and joint distribution functions given in Section 2.3;

4) For each set of the parameters generated in 3), calculated the wind, wave and current force time histories at the site according to the parameter models. If the MODU mooring system is failure, then determine the MODU moving route time history during the hurricane;

5) Check if the distance between large facilities and the MODU moving route is smaller than the safety distance;

6) Repeat steps 2-5 N times(trials) and record the number of trials in which the collision happens, say c, the relative frequency c/N for large N is the estimate of the probability that the MODU will collide with large facilities in 1 years.

The detailed procedure is illustrated in Fig.7.2 , Fig.7.3 and later Sections.

7.2. Detailed Computer Simulation Approach

1) Select a reference frame in which the site is located.(See Fig.7.1)

A reference is selected in which the MODU is located. The X-axis is chosen as parallel to the coastal line, and Y-axis is chosen as perpendicular to the coastal line. The user determined information includes:

a) Original point of the reference (longitude and latitude);

b) The width of the reference frame (Xmax-Xmin);

c) The distance from X-axis to coastal line;

d) The water depth at the site of MODU's location.

Based on such information, x and y coordinates of the MODU in the reference frame are determined.

X and Y coordinates and radius of large facility circles are determined by users either, and the corresponding collision probabilities can be found out from Figure 6.1.

2) Generate the number, n, of hurricanes which occur during the period of consideration, i.e., 1 years, within the reference frame using a Poisson distribution with an occurrence statistics at the location, i.e., .γ_h

For example, if the reference frame is chosen at area C, with width 100 nm, we know the occurrence rates at a point in region C is 0.00163/year-nm, so the occurrence rate within the reference frame is 0.163/year.

3) Generate a sets of random variables $X, \Delta P, R, \varphi, V_H$ according to the distribution and joint distribution functions given in Section 2.3.

4) For each set of the parameters generated in 3), calculated the wind, wave and current force time histories at the site according to the parameter models. If the MODU mooring system is failure, then determine the MODU moving route time history during the hurricane.

As in Fig.7.1, the hurricane is assumed to be a storm traveling along a straight line with a given translation speed and direction or in curve condition, a straight line during different Δt step. And the changes in the storm parameters over the life of the storm are not considered.

The coordinate of the hurricane center is:

$$X_H = X_0 + V_H t \cos\varphi \tag{7.1}$$

$$Y_H = V_H t \sin\varphi \tag{7.2}$$

The coordinate of the mooring MODU and large facilities are (X_M, Y_M) and (X_{F_i}, Y_{F_i}) , (i=1, to n, where n is the number of large facilities around the MODU).

where,	X_0	:	Uniform distribution
	φ	:	Triangular distribution
	$V_H, R, \Delta P$	:	Jointly log normal distribution

The distance between MODU and hurricane center is :

$$r = \sqrt{(X_H - X_M)^2 + (Y_H - Y_M)^2} \tag{7.3}$$

The environmental force acting on the MODU:

a) Wind force: The wind force acting on the MODU is calculated using the procedure given in section 4.1. The direction of the wind force γ_{Wind}, (polar angle in degree) is given by (refer to Fig. 7.1 for definition of γ, β, α, and θ):

$$\gamma_{Wind} = \beta_{Wind} + \varphi + 90^0 \tag{7.4}$$

where:

$$\beta_{Wind} = \theta + \alpha + 90^0 \tag{7.5}$$

$$\theta = 90^0 - \varphi + arctg\frac{Y_H - Y_M}{X_H - X_M} \qquad X_H < X_M \tag{7.6}$$

$$\theta = 270^0 - \varphi + arctg\frac{Y_H - Y_M}{X_H - X_M} \qquad X_H > X_M \tag{7.7}$$

$$\alpha = 22 + 10\cos\theta \tag{7.8}$$

b) Wave force:The wave force is calculated using the procedure given in section 4.3. The direction of the wave force γ_{Wave}, (polar angle in degree), is given by:

$$\gamma_{Wave} = \beta_{Waves} + \varphi - 90^0 \tag{7.9}$$

where:

$$\beta_{Wave} = \theta + \alpha + a(\frac{r}{R})^b - 90^0 \tag{7.10}$$

$$a = 144 + 39\cos\theta - 25\sin\theta - 15\cos 2\theta \tag{7.11}$$

$$b=-0.08 \tag{7.12}$$

Here α, θ are the same as in wind force.

c) Current Force: The current force is calculated using the procedure given in section 4.2. Here we assume the direction of the current force is the same as that of the wave force.

Then, as shown in Fig.7.4, the total environmental forces acting on the MODU is:

$$\bar{F}_{Total} = \bar{F}_{Wave} + \bar{F}_{Windl} + \bar{F}_{Current} = \bar{F}_1 + \bar{F}_2 \quad (7.13)$$

$$|F_{Total}| = F_1^2 + F_2^2 + 2F_1F_2\cos(\gamma_1 - \gamma_2) \quad (7.14)$$

where F_1, F_2 denotes wind and wave forces . The direction, γ_{Total} (polar angle in degree) is:

$$\gamma_{Total} = \gamma_1 + \arccos\left(\frac{F_{Total}^2 + F_1^2 - F_2^2}{2F_{Total}F_1}\right) \quad (7.15)$$

During the hurricane time history, in each short time period, i.e., 1 hour, we check whether the environmental force will exceed the MODU mooring capacity. If the mooring system is failure, then the MODU will move in the direction the same as the direction of the total environmental force, with velocity V_M, where V_M is calculated using the procedure given in section 6.2.

After Δt, i.e., 1 hour, the hurricane center and the MODU will move to a new place. The new position of hurricane center and the MODU are:

$$X_H' = X_H + V_H \Delta t \cos\varphi \quad (7.16)$$

$$Y_H' = Y_H + V_H \Delta t \sin\varphi \tag{7.17}$$

and,

$$X_M' = X_M + V_M \Delta t \cos\gamma_{Total} \tag{7.18}$$

$$Y_M' = Y_M + V_M \Delta t \sin\gamma_{Total} \tag{7.19}$$

The above procedure is repeated until the MODU collides with large facilities or the MODU stops.

5) Check if the distance between large facilities and the MODU moving route is smaller than the safety distance.

The MODU runs into the circle when the distance between the center of the circle and the MODU moving route, say d, is less then R_{Safe}, where d is given by the following procedure:

The linear equation of the MODU moving route during one short time period Δt is:

$$Y - Y_M = tg(\gamma_{Total})(X - X_M) \tag{7.20}$$

So,

$$tg(\gamma_{Total})X - Y + Y_M - X_M tg(\gamma_{Total}) = 0 \tag{7.21}$$

We let,

$$A = tg(\gamma_{Total})$$

$$B = -1$$

$$C = Y_M - X_M tg(\gamma_{Total})$$

Then, we have,

$$d = \frac{\left| AX_{F_i} + BY_{F_i} + C \right|}{\sqrt{A^2 + B^2}} \tag{7.22}$$

where, $X_M \le X_{F_i} \le X'_M$ and $Y_M \le Y_{F_i} \le Y'_M$ are the coordinates of large facilities.

6) Repeat steps 2-5 N times(trials) and record the number of trials in which the collision happens, say c, the relative frequency $\frac{\sum C_i P_i}{N}$ for large N is the estimate of the probability that the MODU will collide with large facilities in 1 years.

During the simulation, record the number of trials in which the MODU runs into each circle, C_i, thus for large N, the estimate of the probability of collision is:

$$P(\text{runs into circle}) = \frac{\sum C_i}{N} \tag{7.23}$$

$$P(\text{collides with structure}) = \frac{\sum C_i P_i}{N} \tag{7.24}$$

$$P(\text{collide with given target circle}) = \frac{C_i}{N} \tag{7.25}$$

$$P(\text{collide with structure within certain circle}) = \frac{C_i P_i}{N} \tag{7.26}$$

where,

N = number of trials;

C_i = number of trials in which the MODU runs into the given target area;

P_i = probability of collision with structures within the given target circle i, with given radius of circle(R_i) and number of structures within the circle(N_i), P_i can be found out in Fig.6.1.

7.3. Sample Size and Variance Reduction Techniques

7.3.1 Sample size

The simulated data according to Monto-Carlo method should be treated as a sample of experimental observation, and therefore, is subjected to sampling error. The simulation can be modeled as a binomial process. Let Y denote the number of collisions on the N trials, then $\overline{P_c} = \frac{Y}{N}$ is the unbiased estimation of probability of collision (P_c), which has mean P_c, variance $\frac{P_c(1-P_c)}{N}$. The standard error of the estimation is:

$$SE(\overline{P_c}) = \frac{\overline{P_c}(1-\overline{P_c})}{N} \tag{7.27}$$

The coefficient of variation of the probability based on simulation is:

$$COV = \frac{\sqrt{\frac{\overline{P_c}(1-\overline{P_c})}{N}}}{\overline{P_c}} = \sqrt{\frac{1-\overline{P_c}}{N\overline{P_c}}} \tag{7.28}$$

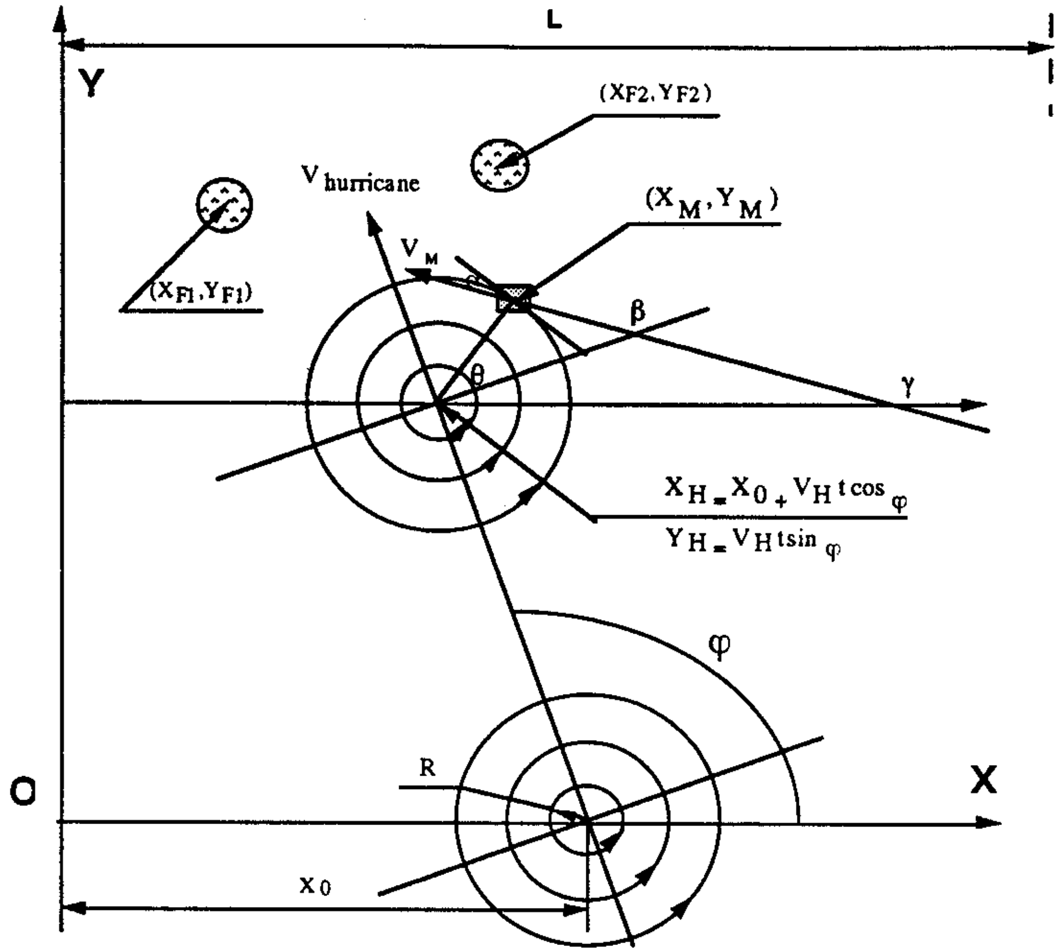
It is seen that the C.O.V. is dependent on the number of simulations N and the probability of collision, P_C. Therefore, since the estimated probability P_C is small which is usually the case, N should be large enough to decrease the error. For example, for N=3000, the coefficient of variation is approximately 10% at P_C=0.03.

7.3.2 Variance Reduction Techniques

Statisticians and practitioners have developed several techniques for drawing random samples. The Latin Hyper cube sampling is used in the program. It recreates the input distribution through sampling in fewer iterations when compared with the Monte Carlo method, especially if the input distribution is highly skewed or has some outcomes of low probability.

The key to Latin Hyper cube sampling is stratification of the input probability distributions. Stratification divides the cumulative curve into equal intervals on the cumulative probability scale(0 to 1.0). A sample is then randomly taken from each interval or " stratification" of the input distribution. Sampling is forced to represent values in each interval, and thus, is forced to recreate the input probability distribution.

The technique being used during Latin Hyper cube sampling is "sampling without replacement". The number of stratification of the cumulative distribution is equal to the number of iterations performed. For example, for 100 iterations, 100 stratification are made to the cumulative distribution. A sample is taken from each stratification. However, once a sample is taken from a stratification, this stratification is not sampled from again--its value is already represented in the sampled set. For sampling within a given stratification, the program chooses a stratification for sampling then randomly chooses value from within the selected stratification.



$V_H, X_0, \varphi, R, \Delta P$	Random variables
X_0	Uniform distribution
φ	Triangle distribution
$V_H, R, \Delta P$	Jointly lognorminal

Fig. 7.1 Monte-Carlo Simulation Reference

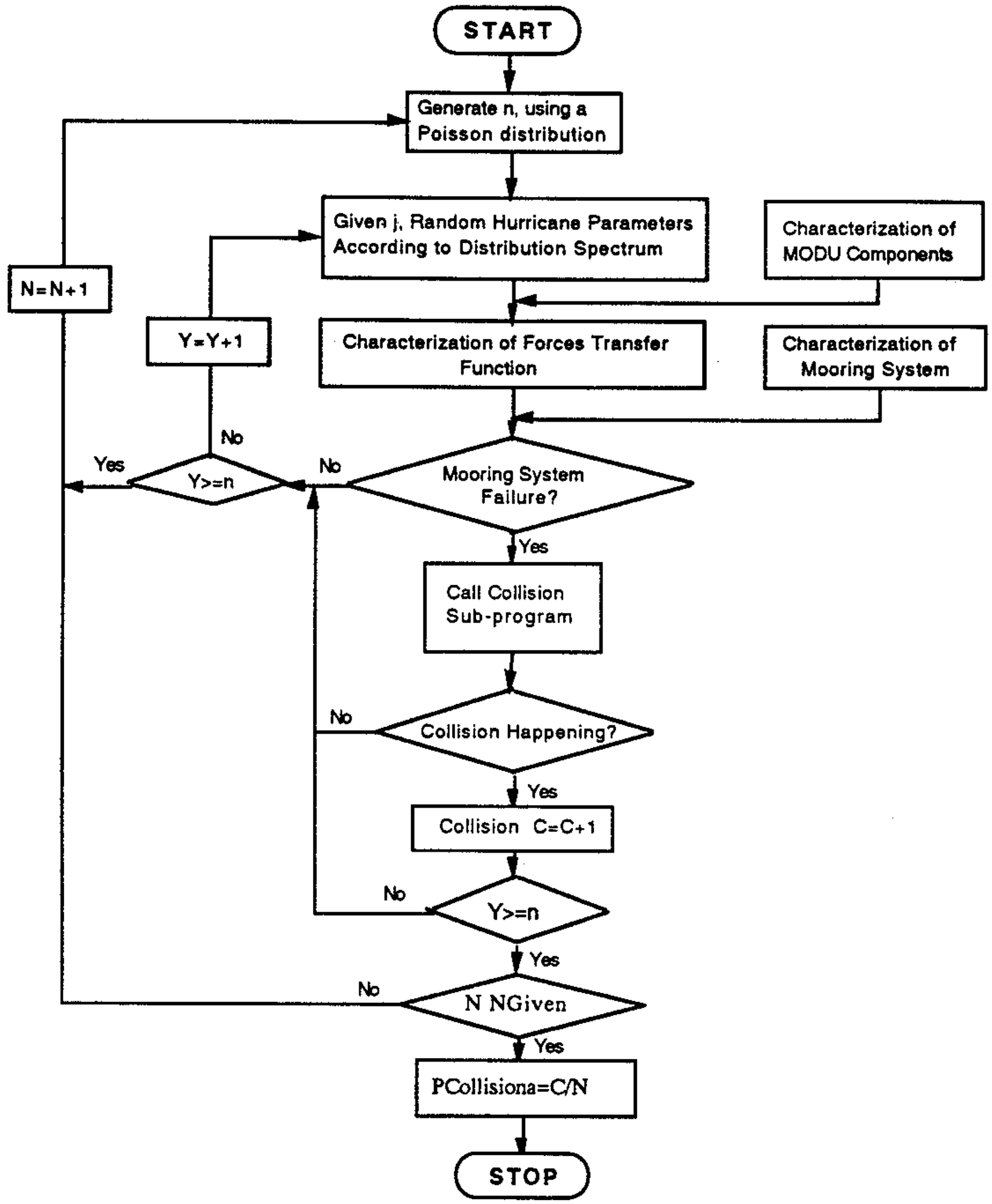


Fig. 7.2 Monte-Carlo Simulation Procedure

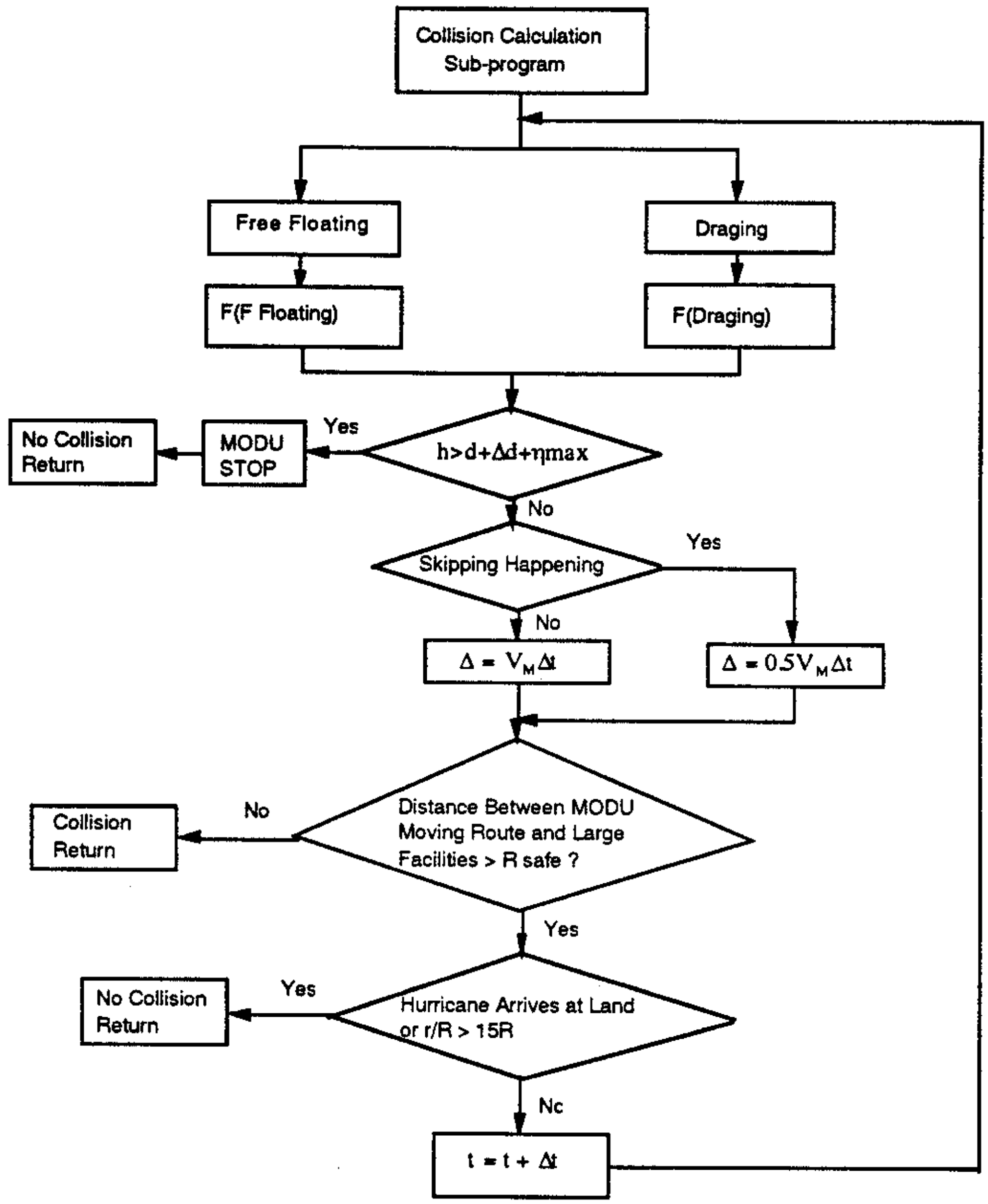


Fig. 7.3 Monte-Carlo Simulation Procedure

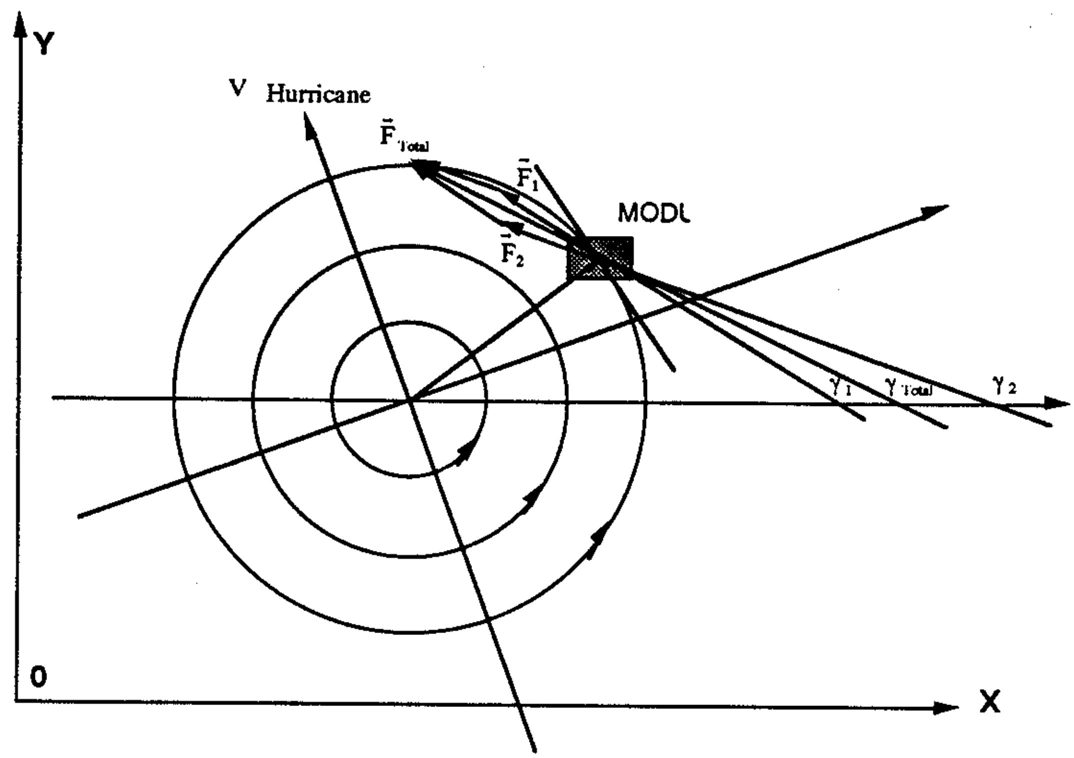


Fig. 7.4 Environmental Force Configuration

8.0. Parametric and Case Studies

8.1 Introduction

The simulation program MODUSIM developed during this research has four major functions:

#1. Given MODU's location, estimate the probability of mooring system failure and probability of collision with surrounding structures after mooring failure;

#2. Given MODU's location and possible coming hurricanes, predict hurricanes coming routes, estimate the probability of mooring failure and probability of collision, calculate the time to system failure;

#3. Given a known hurricane's track, straight line or curve, simulate whether the mooring system will break and also the MODU's moving route after mooring failure;

#4. Given an incoming hurricane, simulates hurricane tracks based on Markov model assumption and calculates the histogram of the environmental conditions, ex., wind speed, wave height and current velocity.

For parametric and sensitivity study, function #1 of MODUSIM was used. The MODU "Zane Barnes", which moved very significant distance during hurricane Andrew in 1992 was used as an example in the parametric and sensitivity study.

In order to have confidence in the estimate of the collision probability, the sample size required, N, should be of the order of at least 100 times the reciprocal of the collision probability. For the range of probability level of interest in this study, i.e., 1%<P<6%, the required sample size(i.e., number of simulations) is of the order of 2000 to 10000.

8.2 Simulation Setting and MODU's Parameters

The principal dimensions of "Zane Barnes" are summarized in Appendix 1. Prior to hurricane Andrew, the Zane Barnes was located at La-Grand Isle Block 87 with 200 ft depth of water in the Gulf of Mexico. (Longitude $90^0 5'$, Latitude $28^0 40'$). The shoaling coefficient k is 0.97. The storm track of "Andrew" and storm parameters are presented in Fig. 8.1 and Fig. 8.2. As the hurricane loading on the MODU is large enough to break the mooring system only when r/R is less than 10, we chose the hurricane parameters during this period as the average of time step 5 and 6 (Fig. 8.2). $\Delta P = 82mb$, $V_F = 11knots$ and $R = 15nm$. The hurricane track direction is 140 degrees. The reference frame is selected as in Fig. 8.3. The original point is longitude $90^0 30'$ and latitude $28^0 25'$. The simulation began when r/R was 10, ended when the hurricane center reached land or the MODU stopped.

Several different simulation settings were used in the parametric and sensitivity study:

1. The hurricane tracks are assumed to be either straight line or curve;

2. Either Airy wave theory or Stokes 5th wave theory is used to calculate the environmental force on the MODU;

3. The MODU is assumed to be either in free floating or in dragging condition after the mooring system fail;

4. The MODU has different mooring capacity and is located in different places.

8.3 Analysis of the Parametric Study Results

Several simulations with different combinations of tracks and wave theory assumptions have been performed. The results are summarized in Table 8.1 to 8.5. The results include different combinations of assumptions and the probability of mooring system failure and the probability of collision, in detail, the probability of collision with the first 5 largest target structures are also presented.

Table 8.1 and 8.2 presents a comparison of the results from different assumptions of hurricane tracks (curved and straight) and wave theory (Airy and Stokes) used to calculate the environmental loads. The results shows that the simulation setting 2, "Straight line" assumption and Stokes theory, has the largest probability of collision while Setting 3, "Curve" assumption and Airy theory, has the least probability of collision. The results from Setting 1 and 4 are very close. This may imply that "Straight line" assumption and Stokes theory may increase the probability of collision while "Curve" assumption and Airy theory may decrease the probability of collision. And their influence on the probability of collision are close. It can be seen that, the combination of the "Curve" assumption and Stokes theory is a reasonable model.

Table 8.1 are the results from the assumption of MODU in free floating condition while Table 8.2 are the results from the assumption of MODU in dragging condition. From the results, it can be seen that in large structure density area, the probability of collision may decrease greatly if anchors are designed to drag prior to any mooring line breaking since in this case the MODU will not move far. However, if the rig is to be located near subsea structures that could be damaged by a dragging anchor, the operator may use pile anchors or oversized drag anchors to cause the mooring lines to break first.

Table 8.1

MODU NAME					Zane Barnes					
Mooring System										
Mean (Kts):		3500			Number of Mooring Lines:				8	
STD :		1000			Number of Breaking Lines:				8	
Simulation Setting 1 :										
Track Type:		Line			Simulation Number:				3000	
Wave Theory:		Airy			Time Step:				1 Hour	
Simulation Result										
Num	**XM**	**YM**	**Dep.**	**P1%**	**P2%**	**P3%**	**P4%**	**P5%**	**Pm**	**Pc**
1	40	28	170	1.9	0	0.02	1.8	0.8	8.7%	3.96%
Simulation Setting 2:										
Track Type:		Line			Simulation Number:				3000	
Wave Theory:		Stokes			Time Step:				1 Hour	
Simulation Result										
Num	**XM**	**YM**	**Dep.**	**P1%**	**P2%**	**P3%**	**P4%**	**P5%**	**Pm**	**Pc**
1	40	28	170	1.18	0	0	2.64	0.42	10.03%	4.26%
Simulation Setting 3:										
Track Type:		Curve			Simulation Number:				3000	
Wave Theory:		Airy			Time Step:				1 Hour	
Simulation Result										
Num	**XM**	**YM**	**Dep.**	**P1%**	**P2%**	**P3%**	**P4%**	**P5%**	**Pm**	**Pc**
1	40	28	170	0.92	0.14	0.02	0.12	0.06	3.3%	1.42%
Simulation Setting 4:										
Track Type:		Curve			Simulation Number:				3000	
Wave Theory:		Stokes			Time Step:				1 Hour	
Simulation Result										
Num	**XM**	**YM**	**Dep.**	**P1%**	**P2%**	**P3%**	**P4%**	**P5%**	**Pm**	**Pc**
1	40	28	170	1.58	0.2	0	0.42	0.08	5.3%	2.34%

Table 8.2

MODU NAME			Zane Barnes							
Mooring System										
Mean (Kts):		3500		Number of Mooring Lines:				8		
STD :		1000		Number of Breaking Lines:				6		
Simulation Setting 1 :										
Track Type:		Line		Simulation Number:				3000		
Wave Theory:		Airy		Time Step:				1 Hour		
Simulation Result										
Num	**XM**	**YM**	**Dep.**	**P1%**	**P2%**	**P3%**	**P4%**	**P5%**	**Pm**	**Pc**
1	40	28	170	2.34	0.04	0	0.36	0	8.67%	2.78%
Simulation Setting 2:										
Track Type:		Line		Simulation Number:				3000		
Wave Theory:		Stokes		Time Step:				1 Hour		
Simulation Result										
Num	**XM**	**YM**	**Dep.**	**P1%**	**P2%**	**P3%**	**P4%**	**P5%**	**Pm**	**Pc**
1	40	28	170	2.24	0.02	0	0.5	0	10.02%	2.8%
Simulation Setting 3:										
Track Type:		Curve		Simulation Number:				3000		
Wave Theory:		Airy		Time Step:				1 Hour		
Simulation Result										
Num	**XM**	**YM**	**Dep.**	**P1%**	**P2%**	**P3%**	**P4%**	**P5%**	**Pm**	**Pc**
1	40	28	170	1	0.06	0.02	0.08	0	3.26%	1.16%
Simulation Setting 4:										
Track Type:		Curve		Simulation Number:				3000		
Wave Theory:		Stokes		Time Step:				1 Hour		
Simulation Result										
Num	**XM**	**YM**	**Dep.**	**P1%**	**P2%**	**P3%**	**P4%**	**P5%**	**Pm**	**Pc**
1	40	28	170	1.6	0	0	0.02	0	6.5%	1.62%

Table 8.3 summarize the results from different assumed mooring capacities given a curved storm track and Stokes theory to calculate wave kinematics. The mean value of the mooring capacity was changed from the normal value of 3500 kips up and down 30%. The collision probability remains almost the same. The mooring strength is not important to the collision probability. It is found that anything intense more than about a one year hurricane storm will cause breakaways. The difference in mooring strength only results in different MODU moving route. In high structure density areas, it seems that mooring strength is not important to the collision probability. However, when the surrounding structures are far from the MODU, this difference may change the probability of collision a lot. In this case, it is still useful to test the various mooring systems for different mooring strength.

Table 8.4 and 8.5 summarize results from different MODU locations. User input the best preferred MODU sitting place and the acceptable radius of sitting area. The program automatically calculates the collision probability at eight orientations within the acceptable area. (Fig. 8.4). These can give the user a suggestion on where to locate the MODU to have the least risk to surrounding facilities in hurricanes.

The results show that the collision probability is very sensitive to the location of the large target structures around the MODU. The target structures in this study are all located to the North-West of the MODU (Fig. 8.3). It is obviously that locations 1, 2, 7, 8 have the largest collision probability while location 4 has the least collision probability. In the area where the target structures are not located regular like here, it would be very difficult to determine where to site the MODU to have the least risk. In this case, the simulation program would be of great help.

Table 8.3.

MODU NAME					Zane Barnes					
Simulation Setting :										
Track Type:			Curve		Simulation Number:				3000	
Wave Theory:			Stokes		Time Step:				1 Hour	
Mooring System 1:										
Mean (Kts):			2500		Number of Mooring Lines:				8	
STD :			750		Number of Breaking Lines:				8	
Simulation Result										
Num	**XM**	**YM**	**Dep.**	**P1%**	**P2%**	**P3%**	**P4%**	**P5%**	**Pm**	**Pc**
1	40	28	170	2.1	0.08	0	1.04	0.1	8.2%	3.5%
Mooring System 2:										
Mean (Kts):			3500		Number of Mooring Lines:				8	
STD :			1000		Number of Breaking Lines:				8	
Simulation Result										
Num	**XM**	**YM**	**Dep.**	**P1%**	**P2%**	**P3%**	**P4%**	**P5%**	**Pm**	**Pc**
1	40	28	170	0.64	0.06	0	2.3	0.48	10.2%	3.82%
Mooring System 3:										
Mean (Kts):			4500		Number of Mooring Lines:				8	
STD :			1300		Number of Breaking Lines:				8	
Simulation Result										
Num	**XM**	**YM**	**Dep.**	**P1%**	**P2%**	**P3%**	**P4%**	**P5%**	**Pm**	**Pc**
1	40	28	170	1.74	0.1	0	0.4	0.04	5%	2.36%
Mooring System 4:										
Mean (Kts):			2500		Number of Mooring Lines:				8	
STD :			750		Number of Breaking Lines:				6	
Simulation Result										
Num	**XM**	**YM**	**Dep.**	**P1%**	**P2%**	**P3%**	**P4%**	**P5%**	**Pm**	**Pc**
1	40	28	170	2.14	0.02	0	0.06	0	8.3%	2.22%
Mooring System 5:										
Mean (Kts):			3500		Number of Mooring Lines:				8	
STD :			1000		Number of Breaking Lines:				6	
Simulation Result										
Num	**XM**	**YM**	**Dep.**	**P1%**	**P2%**	**P3%**	**P4%**	**P5%**	**Pm**	**Pc**
1	40	28	170	1.28	0	0	0.06	0	6.3%	1.34%
Mooring System 6:										
Mean (Kts):			4500		Number of Mooring Lines:				8	
STD :			1300		Number of Breaking Lines:				6	
Simulation Result										
Num	**XM**	**YM**	**Dep.**	**P1%**	**P2%**	**P3%**	**P4%**	**P5%**	**Pm**	**Pc**
1	40	28	170	0.84	0.02	0	0	0	4.5%	0.86%

Also, it can be seen that the probability of mooring failure is very close in different locations, while the collision probabilities are different. These may also imply that once hurricane comes, the mooring system will fail. The difference in sitting location only results in different MODU moving routes, and different collision probabilities.

The study shows that should a MODU mooring failure occur, collision with a platform was likely. This may due to the high density of platforms within the area. However, a series of simulations was conducted varying the location of MODU, so the distance from the MODU to the closest target circles. The result of these simulations show that the most likely collision target circle around the MODU is Target 1 and 4, those which is located at north-west to the MODU. So a MODU should be moored as far as possible from the north-west target circles in this case. For example, if Zane Barnes were moored at (47,20) instead of (33,35) which is about 20 NM to the south-east, the probability of collision will be one half of before (Table 8.4).

Table 8.4

MODU NAME		Zane Barnes	
Mooring System			
Mean (Kts):	3500	Number of Mooring Lines:	8
STD :	1000	Number of Breaking Lines:	8
Simulation Setting:			
Track Type:	Curve	Simulation Number:	2000
Wave Theory:	Stokes	Time Step:	1 Hour

Simulation Result

Num	XM	YM	Dep.	P1%	P2%	P3%	P4%	P5%	Pm	Pc
1	40	38	99	0.39	1.23	0	0.27	0.09	7.05%	2.91%
2	47.07	35.07	120	0.3	0.48	0.78	0.09	0.03	5.95%	2.4%
3	50	28	17	0.72	0.21	0.57	0.27	0.12	6.95%	2.16%
4	47.07	20.9	220	0.69	0.03	0.09	0.6	0.24	5.75%	***1.83%***
5	40	18	240	0.15	0	0	0.87	0.81	6.55%	2.22%
6	32.9	20.9	220	0.06	0	0	0.81	1.05	6.2%	2.31%
7	30	28	170	0	0	0	3.3	0	5.5%	3.3%
8	32.9	35.07	120	0	3.3	0	0.03	0	6.2%	***3.51%***
9	40	28	170	2.01	0.09	0	0.48	0.03	***5.65%***	2.67%

Table 8.5

MODU NAME						Zane Barnes				
Mooring System										
Mean (Kts):		3500				Number of Mooring Lines:			8	
STD :		1000				Number of Breaking Lines:			6	
Simulation Setting:										
Track Type:		Curve				Simulation Number:			3000	
Wave Theory:		Stokes				Time Step:			1 Hour	
Simulation Result										
Num	**XM**	**YM**	**Dep.**	**P1%**	**P2%**	**P3%**	**P4%**	**P5%**	**Pm**	**Pc**
1	40	38	99	0.12	0.18	0	0	0	6.6%	0.36%
2	47.07	35.07	120	0	0	0.24	0	0	5.7%	0.36%
3	50	28	170	0.06	0	0.48	0	0	5.7%	0.54%
4	47.07	20.9	220	0.06	0.06	0	0	0	*5.7%*	*0.12%*
5	40	18	240	0	0	0	0.12	0.06	4.9%	0.24%
6	32.9	20.9	220	0	0	0	0.9	0.12	7%	1.2%
7	30	28	170	0	0	0	3.42	0	6.3%	*3.42%*
8	32.9	35.07	120	0	2.94	0	0	0	6.3%	2.94%
9	40	28	170	1.14	0	0	0	0	6.1%	1.14%

8.5 Case Studies

Thorough verification studies on MODU "Zane Barnes" have been performed. The characteristics of the MODU are summarized in Appendix A. The case study includes all the functions of MODUSIM.

8.5.1 Function #1

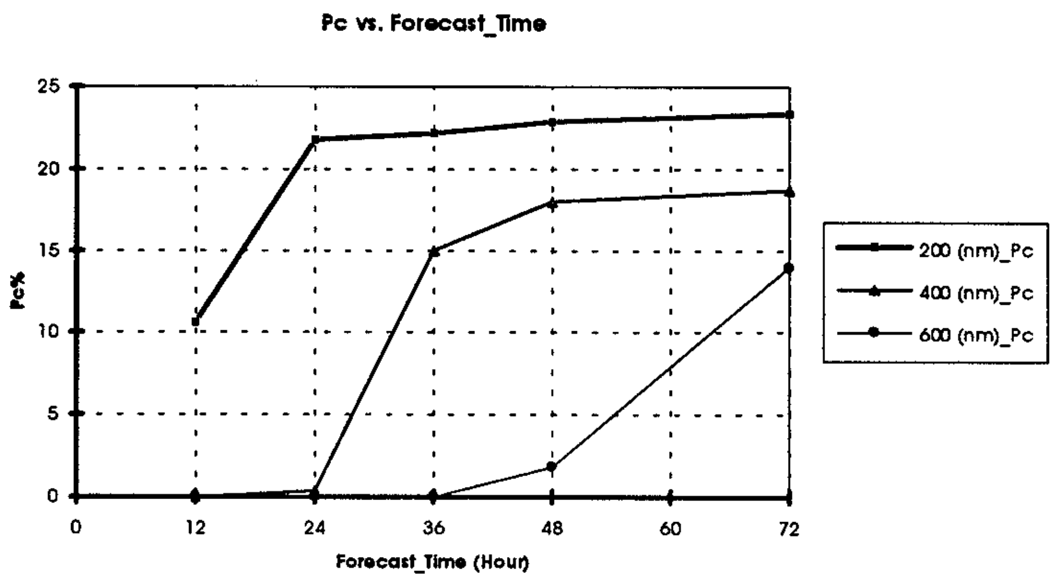
The MODU's location and system configuration are the same as in the parametric studies. The mean mooring capacity is 3500 kips and it is assumed that the MODU is in the free floating condition after the mooring lines break. Based on the curved track assumption and with Stoke's 5th theory used to determine the wave kinematics, the probability of mooring system failure is 5.3% and the probability of collision with the surrounding structures is 2.34%.

8.5.2 Function #2

Given the incoming hurricane with the data from Andrew, at the different distance between the hurricane center and Zane Barnes, the probability of collision at different forecast times has been determined. The results are summarized in Table 8.6 and Figure 8.5.

Table 8.6 Simulation Result of Forecast Probability

Distance	200 nm		400 nm		600 nm	
Hour\Type	Pa_Moor	Pa_Coll	Pa_Moor	Pa_Coll	Pa_Moor	Pa_Coll
12	18.4	10.6	0	0	0	0
24	55	21.8	0.8	0.36	0	0
36	56	22.2	21.8	15	0	0
48	57.6	22.9	40	18	4.2	1.8
72	60	23.4	43.4	18.7	30	14



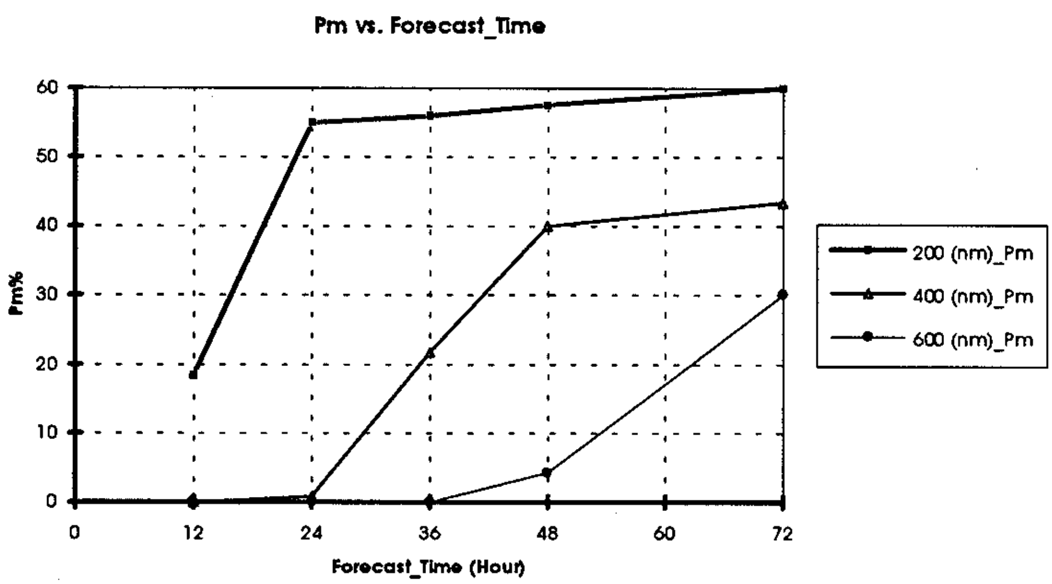


Figure 8.5 Probability of Failure vs. Forecast Time

It can be seen from the results that when the hurricane is 600 nm away, the MODU is safe in the following 48 hours and the probability of collision (Pc) increases rapidly after 48 hours. When the hurricane is 400 nm away, the MODU is safe in the following 24 hours and Pc increases rapidly between the 24 to 36 hours, then Pc stays at high level after that. When the hurricane is 200 nm away, the Pc always stays at high level. The same thing happens to the probability of mooring failure. (Fig. 8.5)

8.5.3 Function #3

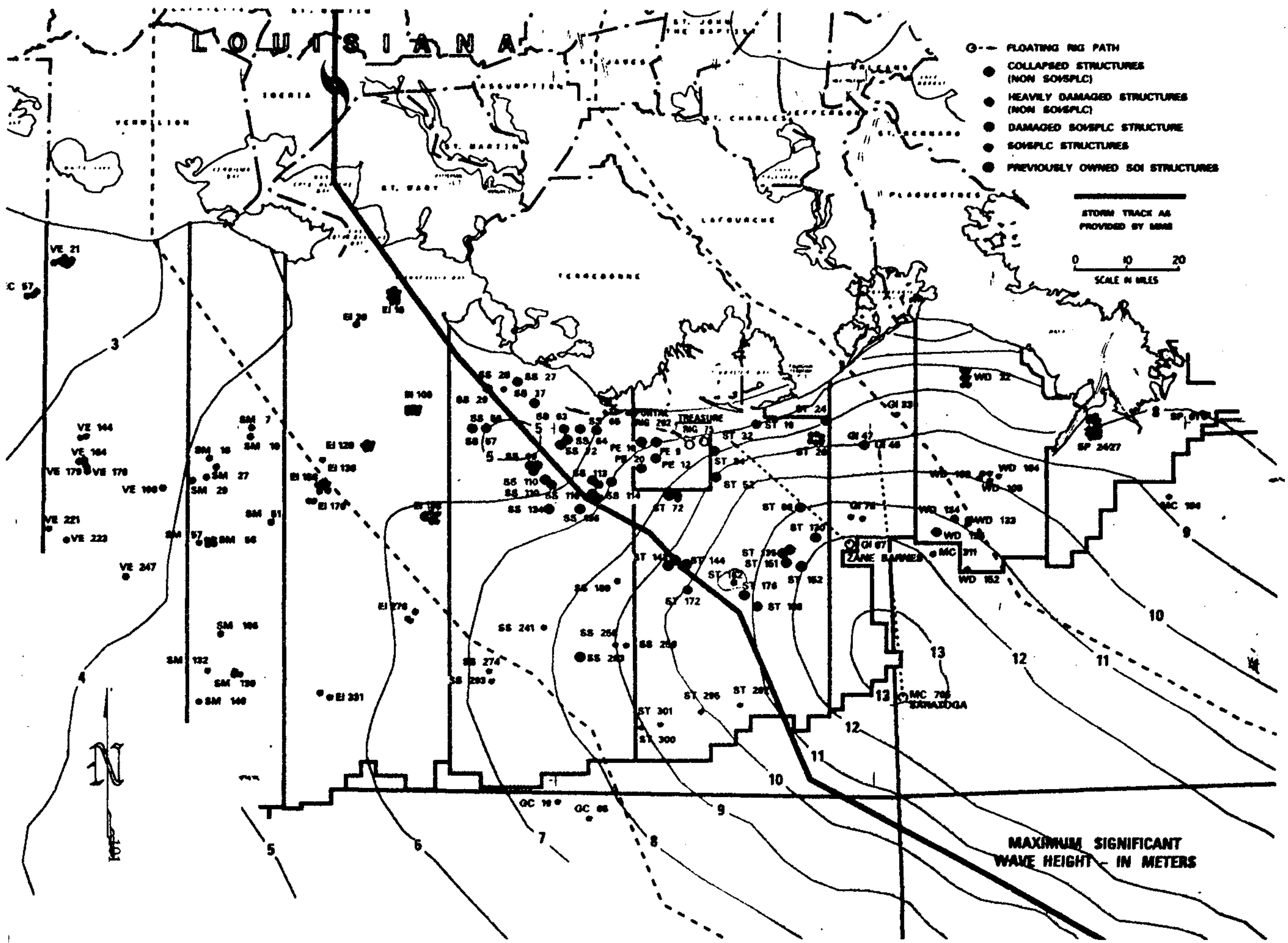
To verify Function #3, the Zane Barnes was driven to northwest for about 30 nm, stopped at South Timbalier (Block 32) in a water depth of 45 ft. It was in free floating at first and in skipping when the water depth was less than the draft. Different values of mooring capacity were assumed in the simulation. The results are in Figure 8.6.

The mean mooring capacity in Fig. 8.6a is 3500kips, 4500kips in Fig. 8.6b and 5500kips in Fig. 8.6c. In Fig. 8.6d, the MODU was held for an hour during each collision, and the result from this assumption is the closest to the real route. This may imply that the mooring capacity of Zane Barnes is around 4500kips and it was held for about an hour at each collision during its travel.

Another three MODUs from Gulf of Mexico are also utilized to verify MODUSIM. Zapata Saratoga, which moved from Miss Canyon 705 to Grand Isle 47 during Andrew, is simulated in free floating condition. Treasure 75, which was ballast on bottom and moved 4 miles from South Pelto 7, and Ocean Now Era, which was moved 800 ft from Grand Isle 103, are simulated in dragging condition with two mooring lines dragging. (See Figure 8.7 and Figure 8.8). It is found that results from MODUSIM agrees very well with the real route.

8.5.4 Function #4

For use of Function #4, detailed application can be found in Chapter 9.2, Preliminary Study of Environmental Forecast in Hurricanes.



MAXIMUM SIGNIFICANT WAVE HEIGHT - IN METERS

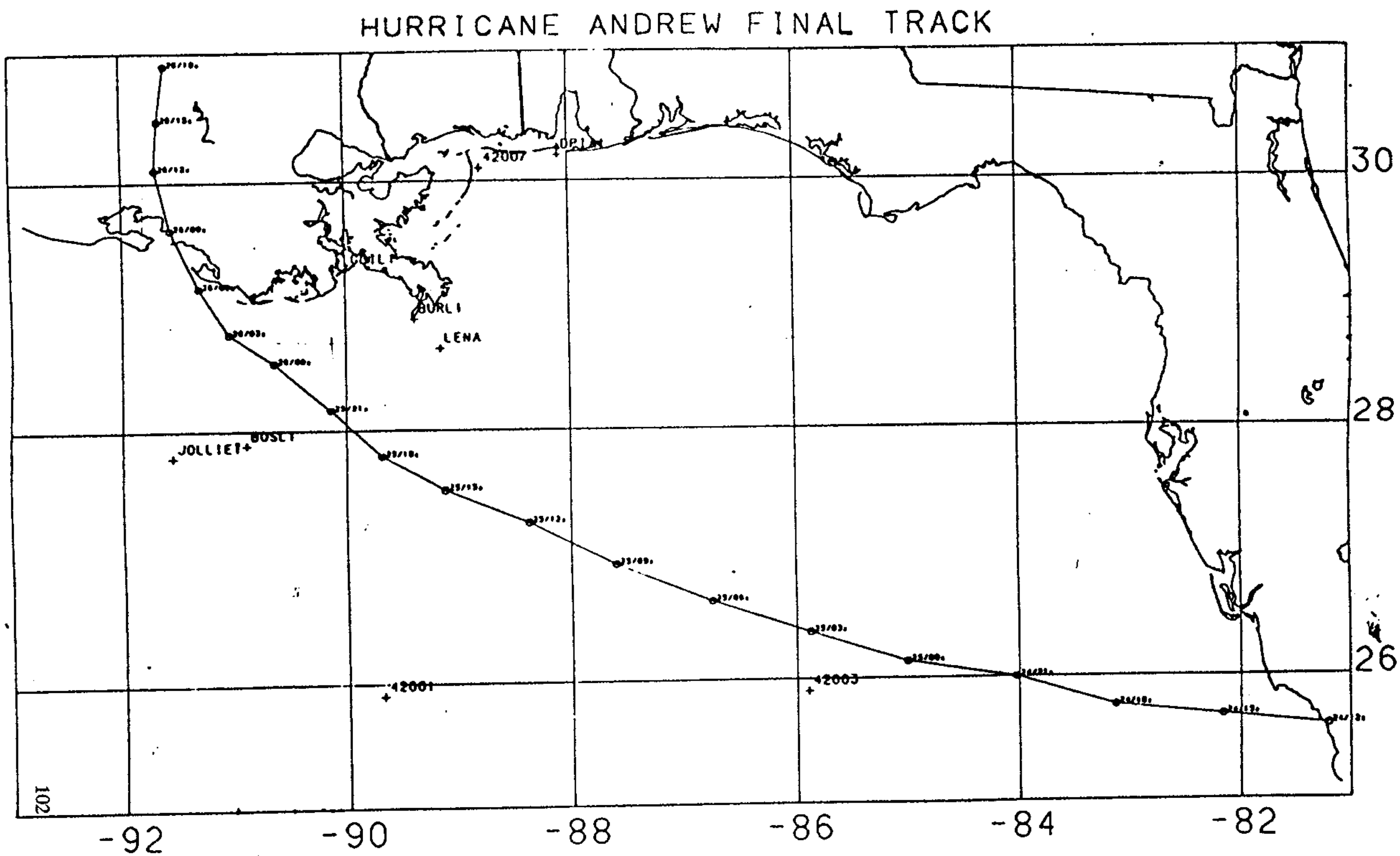


Figure 8.1 Storm Track for Hurricane Andrew

1. Storm parameters and track used for numerical model simulation of boundary layer wind field

Tropical Cyclone Input Data Project ANDREW JIP
Storm # 9208 Name ANDREW Duration of Hindcast 60 hours

SNAP 1 EYELAT = 26 ., DIREC = 280 ., SPEED = 13 ., EYPRES = 947.,
RADIUS = 9 ., PFAR =1016 ., SGW = 7 ., AN1 = 120.,

SNAP 2 EYELAT = 26 ., DIREC = 280 ., SPEED = 13 ., EYPRES = 943.,
RADIUS = 9 ., PFAR =1016 ., SGW = 7 ., AN1 = 120.,

SNAP 3 EYELAT = 27 ., DIREC = 295 ., SPEED = 13 ., EYPRES = 948.,
RADIUS = 12 ., PFAR =1016 ., SGW = 8 ., AN1 = 125.,

SNAP 4 EYELAT = 28 ., DIREC = 295 ., SPEED = 13 ., EYPRES = 944.,
RADIUS = 15 ., PFAR =1016 ., SGW = 9 ., AN1 = 125.,

SNAP 5 EYELAT = 28 ., DIREC = 305 ., SPEED = 11 ., EYPRES = 932.,
RADIUS = 15 ., PFAR =1016 ., SGW = 11 ., AN1 = 125.,

SNAP 6 EYELAT = 29 ., DIREC = 320 ., SPEED = 10 ., EYPRES = 936.,
RADIUS = 15 ., PFAR =1016 ., SGW = 9 ., AN1 = 140.,

SNAP 7 EYELAT = 30 ., DIREC = 340 ., SPEED = 9 ., EYPRES = 958.,
RADIUS = 15 ., PFAR =1016 ., SGW = 8 ., AN1 = 155.,

SNAP 8 EYELAT = 30 ., DIREC = 355 ., SPEED = 9 ., EYPRES = 973.,
RADIUS = 15 ., PFAR =1016 ., SGW = 8 ., AN1 = 160.,

SNAP 9 EYELAT = 30 ., DIREC = 5 ., SPEED = 8 ., EYPRES = 982.,
RADIUS = 15 ., PFAR =1016 ., SGW = 8 ., AN1 = 170.,

SNAP 10 EYELAT = 31 ., DIREC = 5 ., SPEED = 8 ., EYPRES = 990.,
RADIUS = 16 ., PFAR =1016 ., SGW = 8 ., AN1 = 175 ,

Storm Track Table

STEP	LAT	LONG	SNAP	ROT	(YMDH)
[illegible]	25 36	-81 12	1	0	92082412
[illegible]	25 41	-82 10		0	2415
[illegible]	25 46	-83 09	1	0	2418
[illegible]	26 00	-84 03		0	2421
[illegible]	26 08	-85 02	2	0	2500
[illegible]	26 23	-85 54		0	2503
[illegible]	26 38	-86 47		0	2506
[illegible]	26 56	-87 38	3	0	2509
[illegible]	27 16	-88 24		0	2512
[illegible]	27 31	-89 08	4	0	2515
[illegible]	27 47	-89 42	5	0	2518
[illegible]	28 10	-90 09	5	0	2521
[illegible]	28 33	-90 39		0	2600
[illegible]	28 47	-91 03	6	0	2603
[illegible]	29 09	-91 19		0	2606
[illegible]	29 37	-91 34	7	0	2609
[illegible]	30 06	-91 42	8	0	2612
[illegible]	30 29	-91 40	9	0	2615
[illegible]	30 54	-91 36	10	0	102618

Figure 8.2 Storm Parameters for Hurricane Andrew

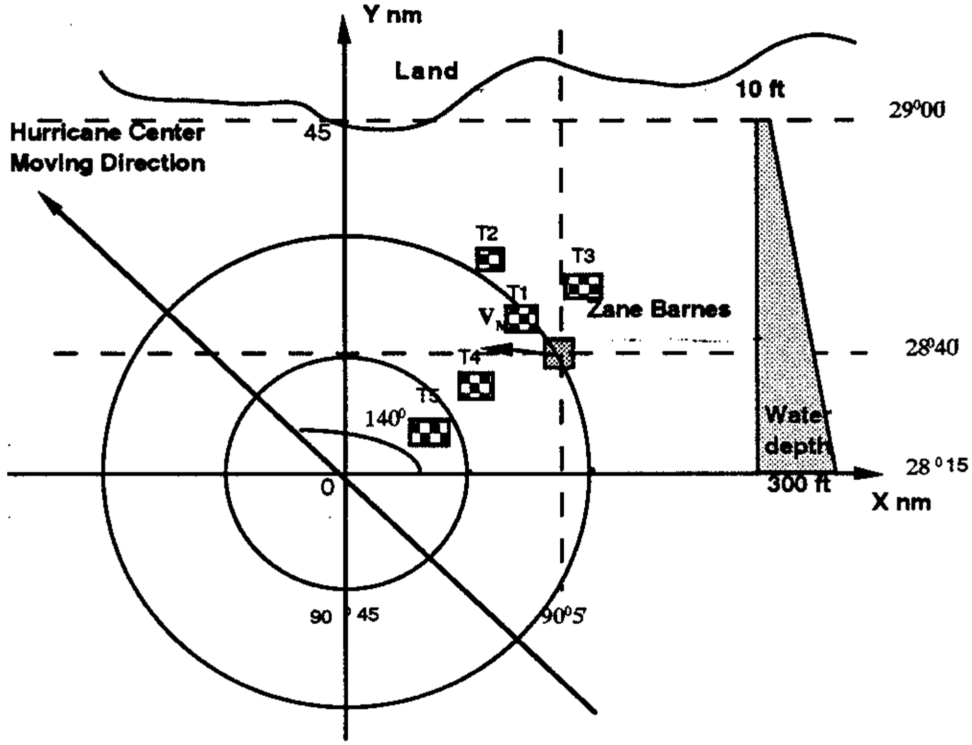


Fig. 8.3 Reference Frame in Andrew

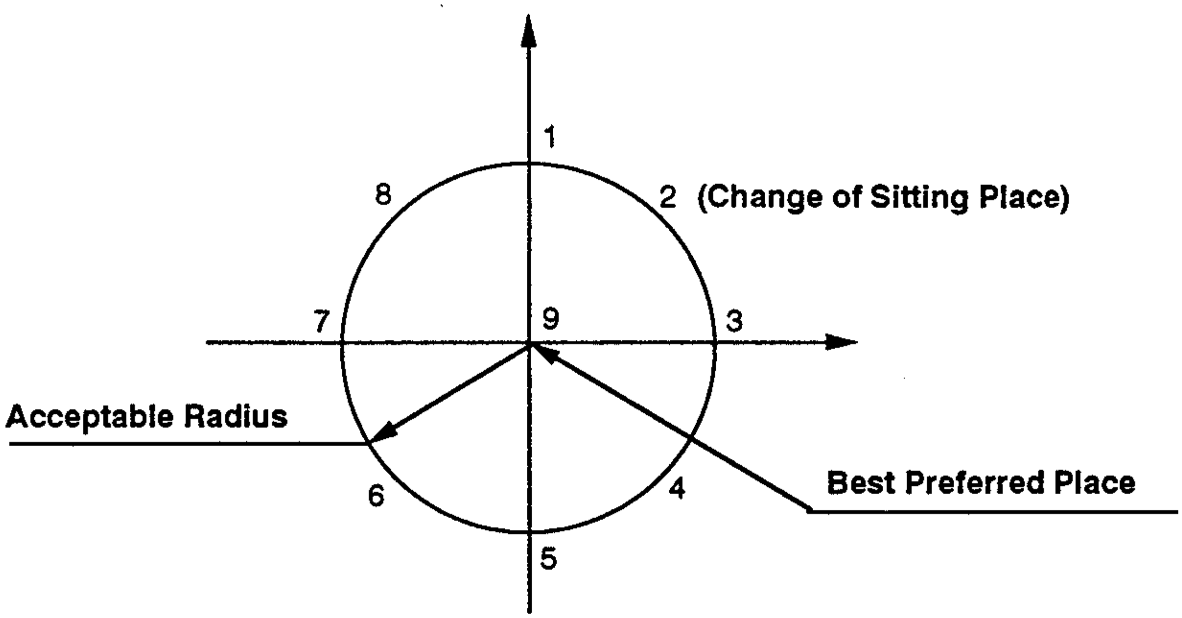
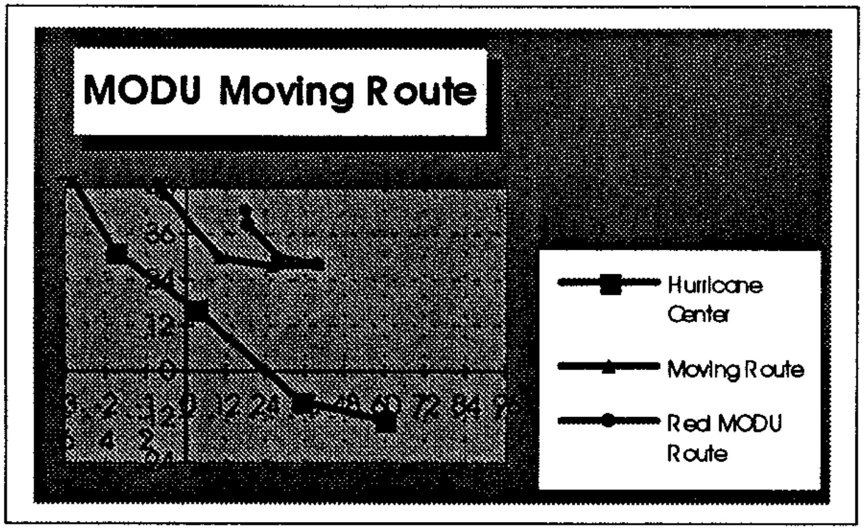
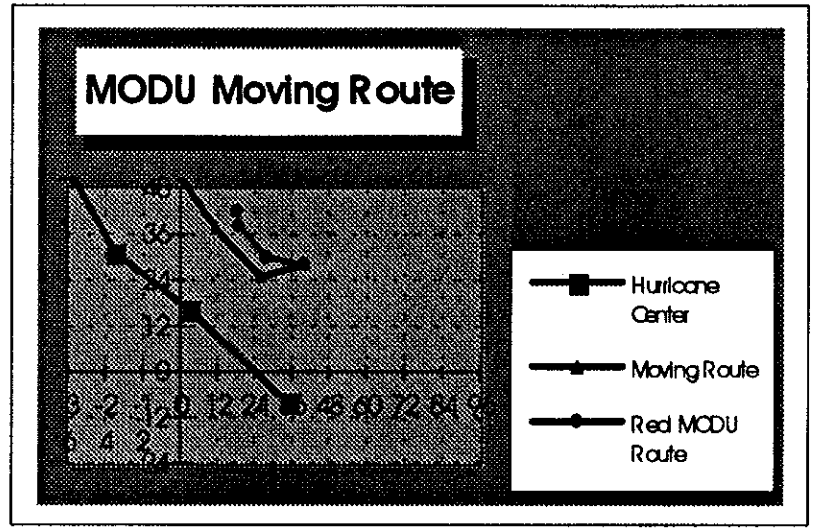


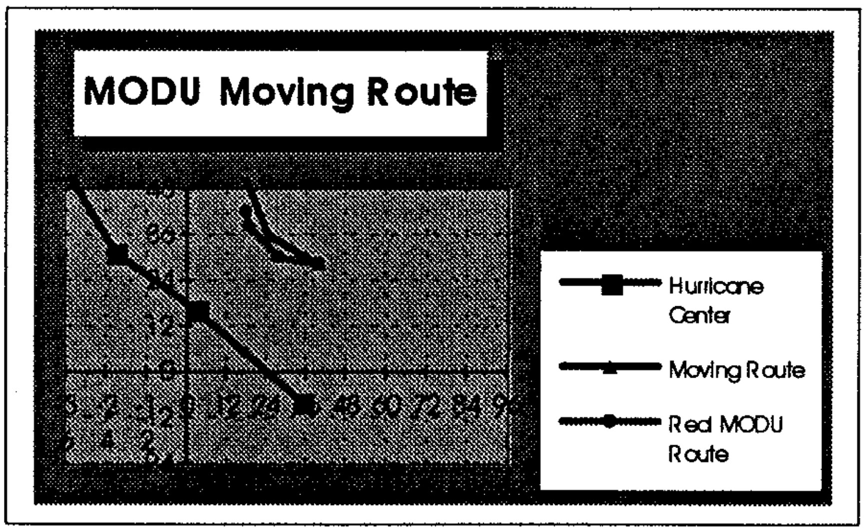
Figure 8.4 Changing of MODU's Siting Place



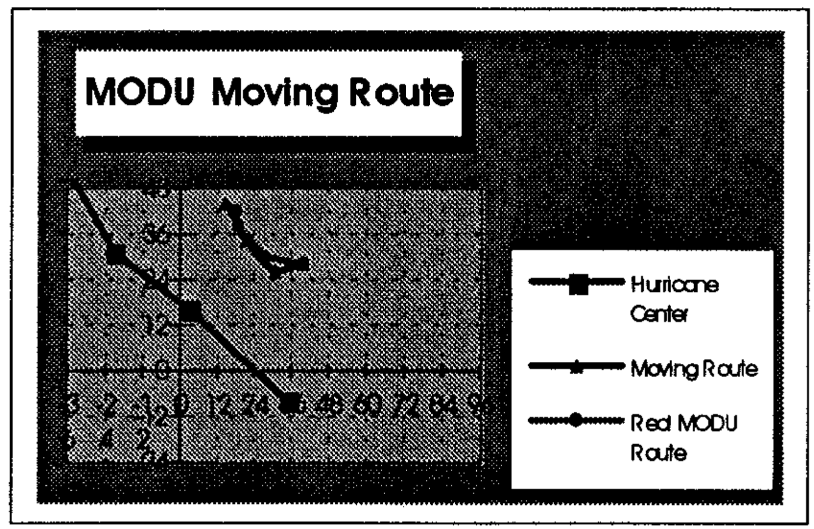
a. Mooring Capacity 3500kips



b. Mooring Capacity 4500kips

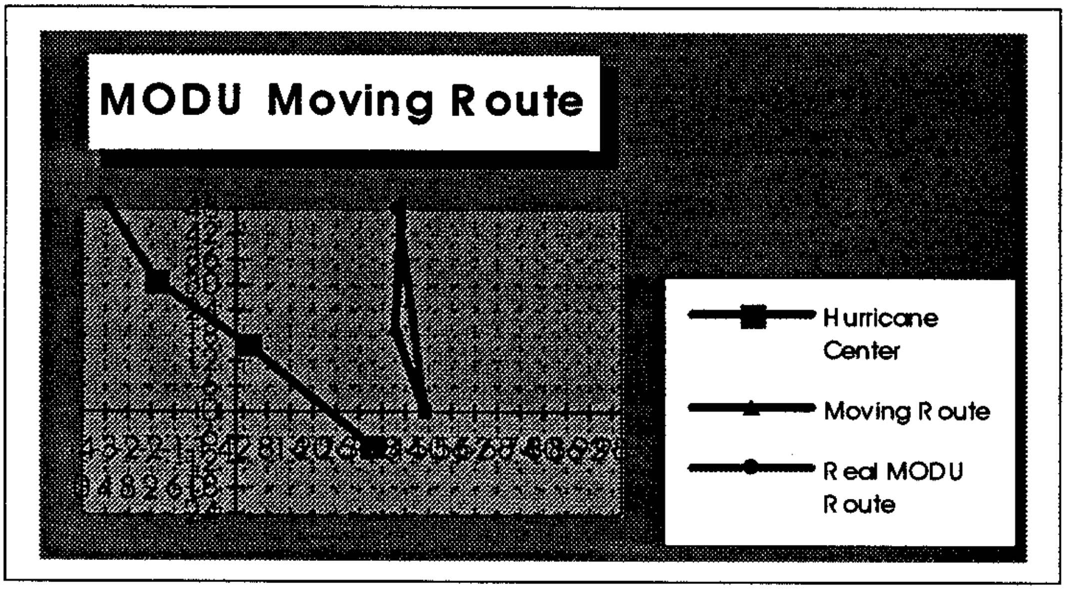


c. Mooring Capacity 5500kips

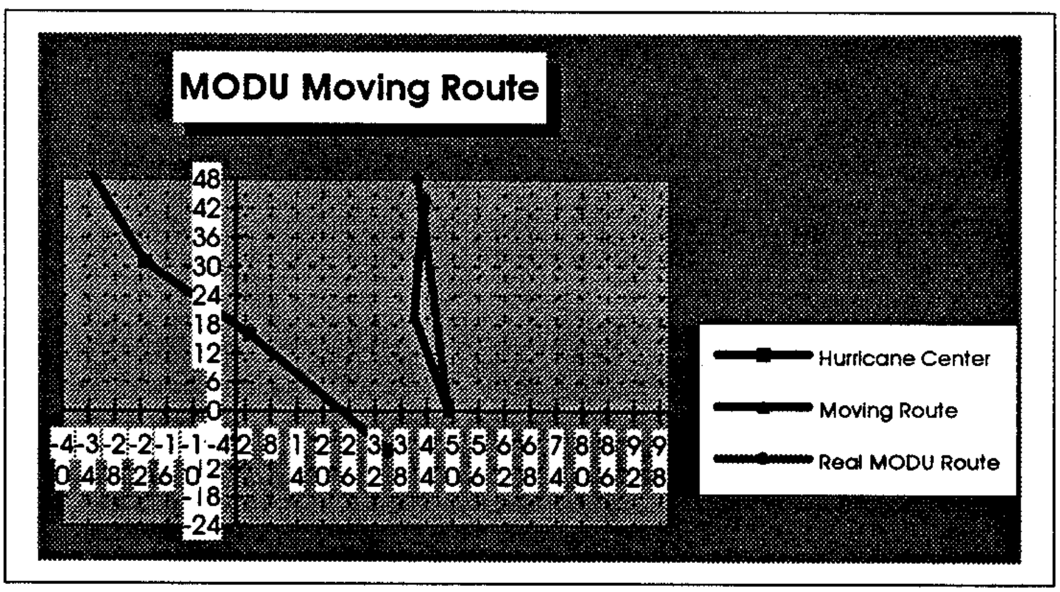


d. Mooring Capacity 4500kips, Holding 1h each Collision

Figure 8.6 Simulated Moving Route of Zane Barnes in Hurricane Andrew

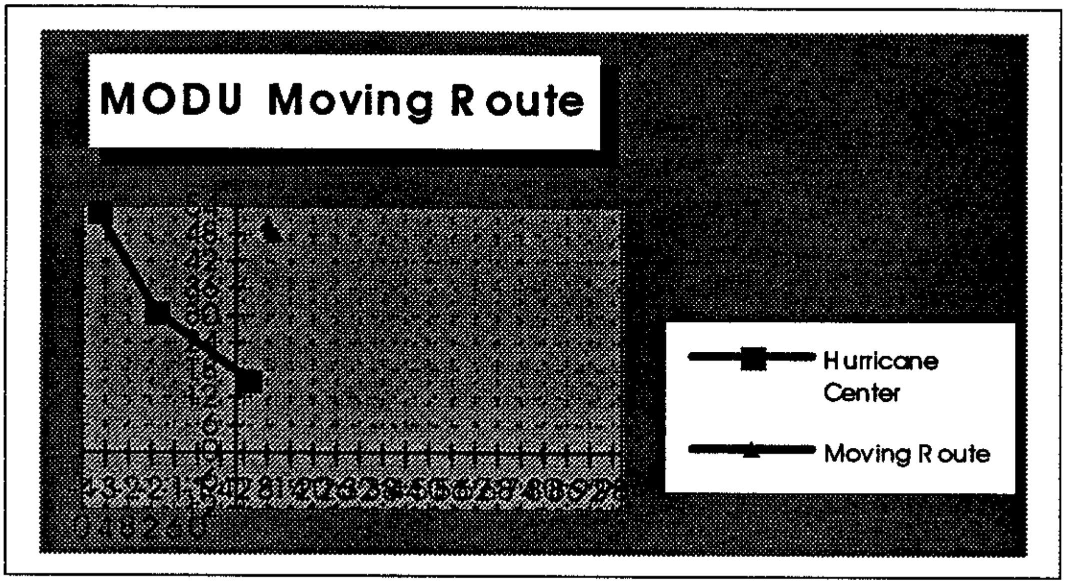


a. Mooring Capacity 4000kips

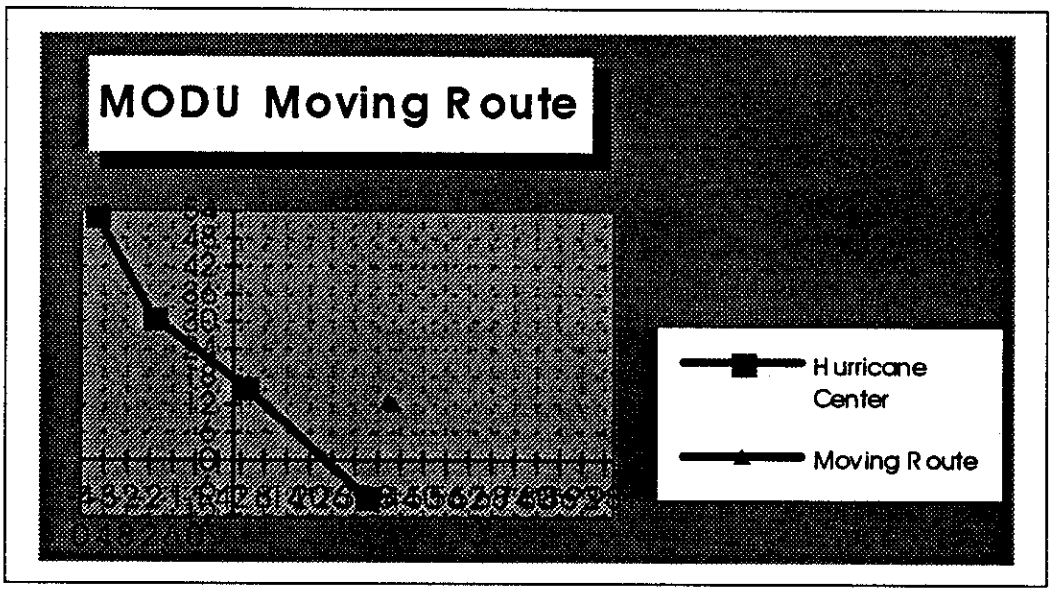


Mooring Capacity 4000kips, Holding 1h Each Collision

Figure 8.7 Simulated Moving Route of Zapata Saratoga in Hurricane Andrew



a. Treasure 75, Ballast on Bottom, Moved 4 miles from South Pelto 7



b. Ocean Now Era, Mooring Capacity 3000kips,
Moved 800 ft from Grand Isle 103

Figure 8.8 Simulated Moving Route of Treasure 75 and Ocean Now Era in Hurricane Andrew

9.0. Additional Studies

9.1 Simulate the Movement of Bottom Founded Platforms

9.1.1. Modeling of Jack-up

The analytical and simulation model has been expanded to include analysis of the movements of bottom-founded MODUs (jack-up).

The jack-up rig used in this research is a realistic amalgamation of several different existing deep water jack-up rigs. Properties such as flexural stiffness of the legs, overall dimensions and hull weights were averaged to yield an average harsh environment jack-up rig.

The rig has three independent square lattice truss legs supported at the sea floor by large spud cans. The principal properties of this average rig are summarized in Table 9.1. The centerline to centerline dimension between chords (vertical leg posts) is 39.6 ft. Each of the four chords has a cross sectional area of steel equal to 1.59 ft^2.

The structure is idealized as a planar assemblage of individual elements. The single degree of freedom model is idealized as consisting of three elements. The first element represents the two aft legs of the unit. The second element represents the hull, and the third element represents the fore leg. The element representing the 2 aft legs has twice the area, stiffness and moment capacity of the single fore leg listed in Table 9.1. The hull was assumed to have 5 times the stiffness of the legs.

Each node of the structure can have three degrees of freedom, translation in the horizontal and vertical, and rotation. The nodes can be controlled so as to have a zero displacements or rotations relative to the ground, or two nodes can be constrained to have identical displacements. The single

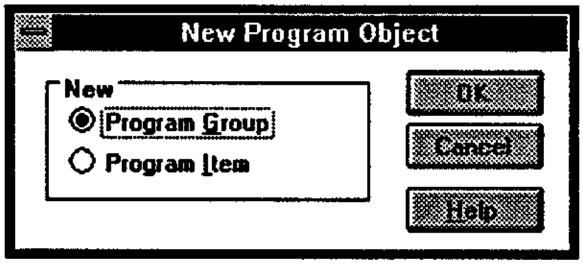


Figure A1.1: Select 'Program Group' for the MODUSIM program.

Next the following window will appear. Fill in the Description and Group File as indicated. Then select OK.

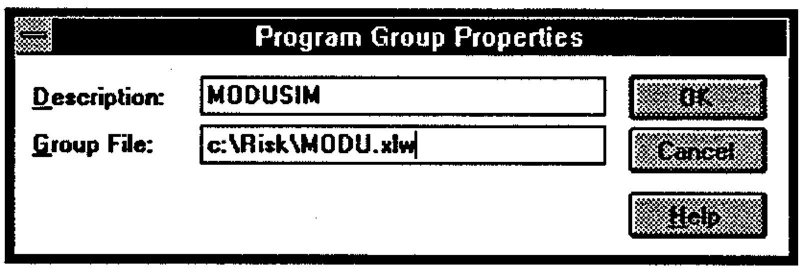


Figure A1.2: Specify the group name and the filename and path.

Notice that a new program group **MODUSIM** has been created in your Microsoft Windows. Now you can double click the icon to start MODUSIM.

A2. Input Data

A2.1 Introduction

After double clicking the **MODUSIM** icon, the main window will pop up like the following Figure 2.1. The menu bar can be changed to general Excel 4.0 menu bar by "Ctrl+M" and back to MODUSIM by "Ctrl+A". Those users who are not familiar with windows operation are recommended to following the step-by-step directions in this chapter. Here, for example, let's say we have a MODU named "Zane Barnes".

Figure A2.1 MODUSIM is popped up.

There are principally two ways of data input in the program:

a) by stepping through the input menu and defining the necessary parameters or

b) by opening an input file that has been originally created by stepping through the input menu and subsequently saved.

There are three commands under the **File** menu. **Open Input File** command allows to open the saved simulation input and result file. **Save Input As** command allows to save the current simulation setting and simulation result.

SIMULATION RESULT

MODU NAME:		ZANE BARNES			
LOCATION:		MOORING CAPACITY		FAILURE MODE	
X	Y	MEAN	STD.	NOM	NOB
50	28.1	3500	1000	8	6
Probability of collision:			0.0114		
Target 1	Target 2	Target 3	Target 4	Target 5	Mooring
0.0048	0.0006	0.0048	0.0006	0	0.09

Figure A2.2 Saved Simulation Result

Click **Exit** to quit the application.

Warning: All the current simulation setting and results will be lost if you leave the program. Save the simulation setting and results if necessary.

The data that needs to be defined by the user is subdivided into five principle categories:

- General MODU Information
- Mooring System Information
- Simulation Setting Data
- Execute the Program
- General Jackup Information

A2.2 General MODU Information

There are five commands under **Input** Menu to input the required information.

MODUINF command allows to input the MODU's general information. The dialogue box 'MODU INFORMATION' will pop up when **MODUINF** command is selected.

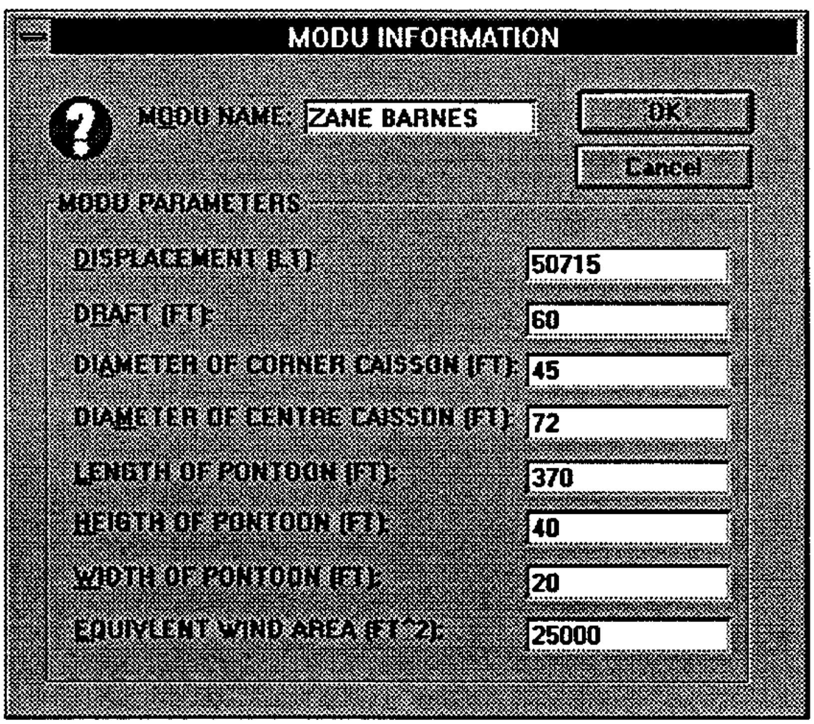


Figure A2.3 Input MODU General Information

To input the information, you can click on the certain box with mouse or type 'ALT' + 'Underline letter'. For example, to input **DISPLACEMENT**, type **ALT+D** When you finished, click **OK**, or you can click **Cancel** to cancel the dialogue.

MODULOC command allows to input coordinates of MODU's initial location. When **MODULOC** command is selected, the dialogue box 'MODU LOCATION' will pop up.

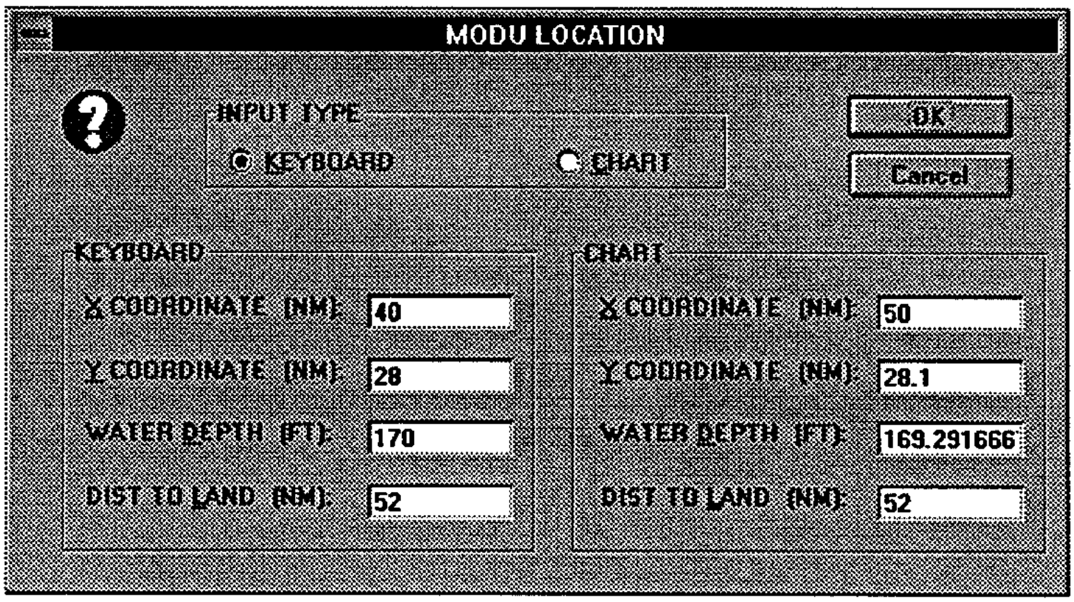


Figure A2.4 Input MODU Initial Location

In the group of **Input Type**, if **Keyboard** is selected, the information will be input from keyboard to the box in the group of **keyboard**. The input information includes X, Y coordinates, water depth of MODU location and the distance from X-axis to coast. If **Chart** is selected, next command **LOCHART** need to be selected to input information from chart. It is recommended that **Keyboard** function is used to input the initial location and **Chart** function is used to change the location of MODU.

If **Chart** was selected in the **MODULOC** command, **LOCHART** command need to be selected, and the chart 'MODU Moving Route' will pop up. To change the location of the MODU, click on the MODU while hold down **CTRL**, then drag MODU to wherever you want it to be sited.

LARGE FACILITY INFO command allows to set up the simulation for probability of collision within target circles. 'LARGE FACILITY INFORMATION' dialogue box will pop up when it is selected.

Number of Platforms: Structure number within the target circle.
Radius of Circle: Radius of target circle
Radius of safe Distance: The safety distance between the MODU and structures.

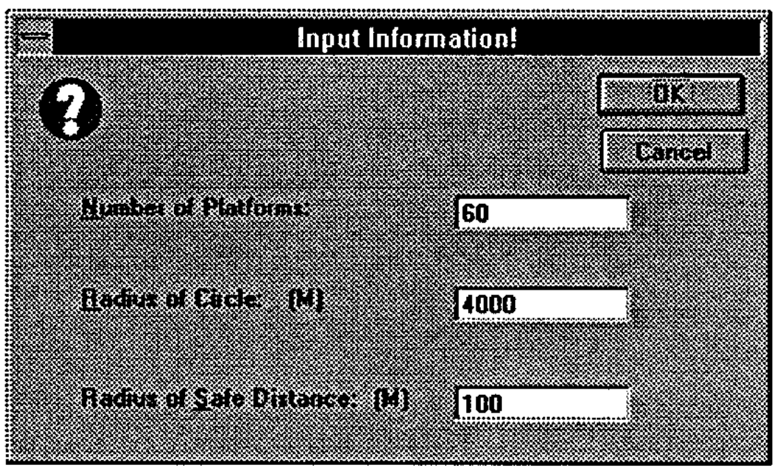


Figure A2.5 Input Target Circle Information

Note here, the location of target circles is determined by the user from file [MODU.xlw]modu.xls. You can choose as many as 5 target circles.

CALCU PROB command allows to begin the simulation of collision within the target circle. When the simulation is completed, a dialogue box will pop up the calculation result. A pre-calculated curve about the probability of collision within the target circle with R=0.6 to 4.8 NM is presented in Figure 6.1. For a target circle with given radius and number of structures, the probability of collision can be found from the curve.

A2.3 Mooring Capacity Information

Mooring Command under **Input** menu allows to input mooring system information. The dialogue box 'Mooring System' will pop up when **Mooring** command is selected.

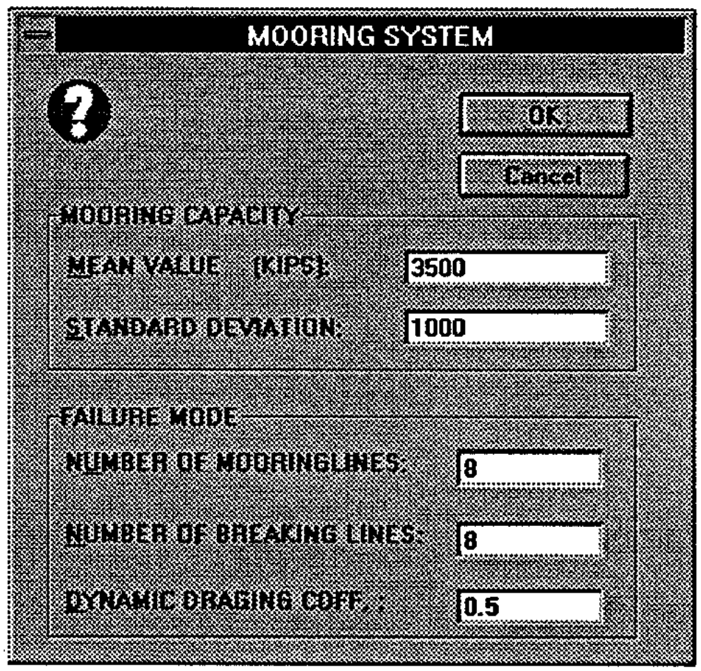


Figure A2.6 Input Mooring System Information

In the group of **MOORING CAPACITY**, input the mean value and standard deviation of mooring strength; in the group of **FAILURE MODE**, input the total number of mooring lines, number of broken lines while failure and the dynamic dragging coefficient of anchor while they are dragging in the bottom of the sea.

A2.3 Simulation Setting Data

There are five commands under the **Simuset** menu to define the required data:

SIMUTYPE command allows to set up the simulation. The dialogue box 'SIMULATION TYPE' will pop up when **SIMUTYPE** is selected.

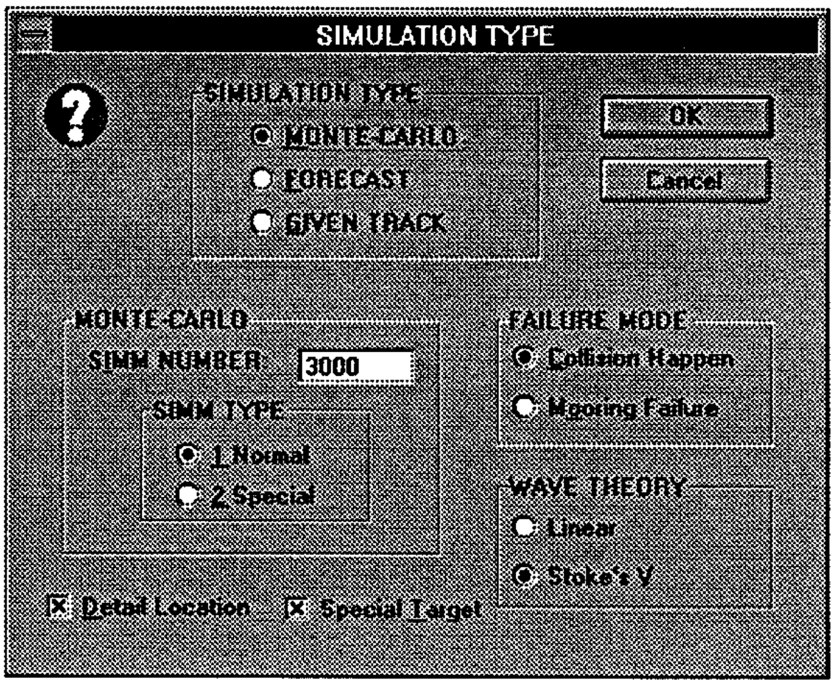


Figure A2.7 Set Up the Simulation

Following are the selected combinations to get the specific MODUSIM functions mentioned in Chapter 8.

Function A:	**Monte-Carlo+Normal;**
Function B:	**Forecast+Normal;**
Function C:	**Given Track;**
Function D:	**Forecast+Normal.**

Click **Collision Happen** to define failure mode as collision happens. Click **Mooring Failure** to define failure mode as mooring lines break. Select wave theory as **Linear** or **Stoke's** 5th theory. Check **Detail Location** to include the MODU information within target circles. Check **Special Target** to calculate the probability of collision within a given target.

If **Forecast** is selected, the given hurricane parameters should be input in the following 'Hurricane Parameter' dialogue box. Check **Straight Line** or **Curve** to determine the type of hurricane tracks in the simulation. Select forecast time type for Function B.

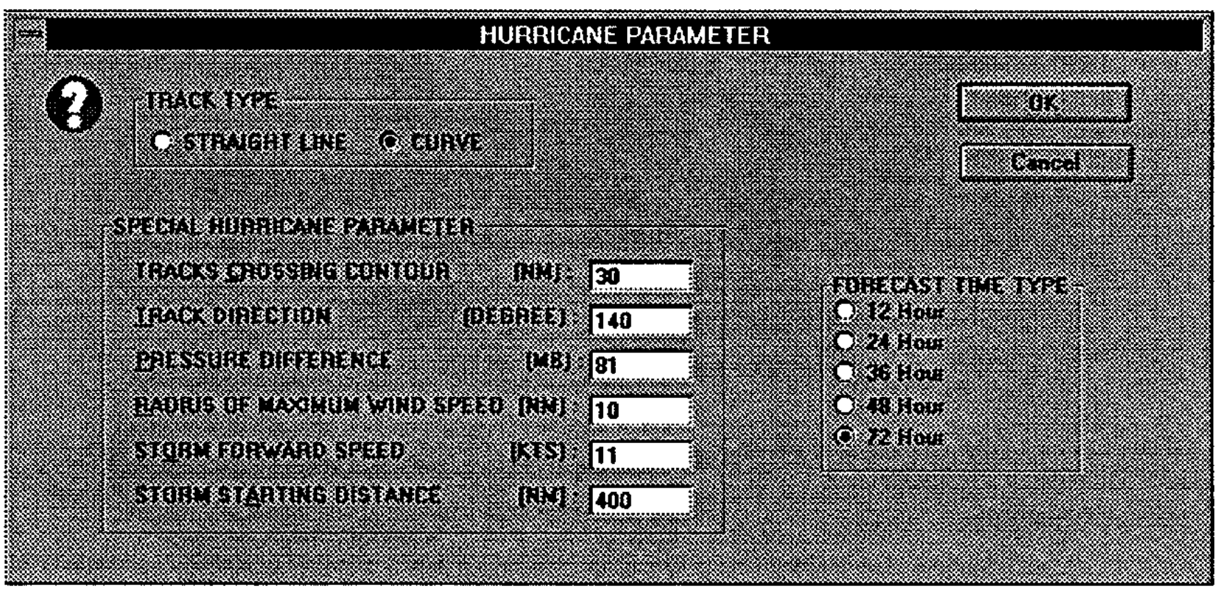


Figure A2.8 Input Hurricane Parameter

If **Forecast** is selected, the following 'Env. Data Simulation Setting' dialogue box will pop up after the 'Hurricane Parameter' dialogue box. Select **Env.Forecast** to perform environmental condition forecast as stated in Chapter 9.2.

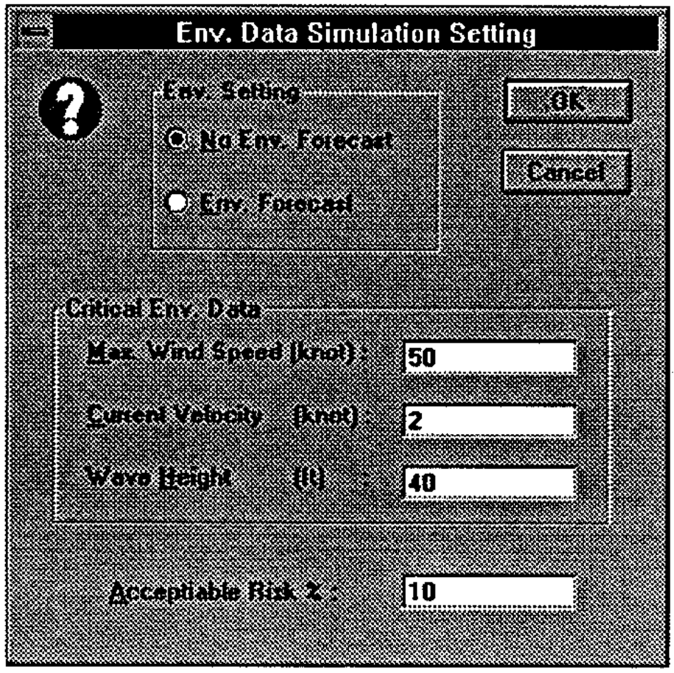


Figure A2.9 Environmental Simulation Setting

If **Given Track** is selected, the 'Given Hurricane Track' dialogue box will pop up after the 'Simulation Type' dialogue box. Input the general hurricane information in the group of **Hurricane Parameter**. There are at most eight points that can be input to describe the hurricane track. **DT** is the time step between the adjacent points.

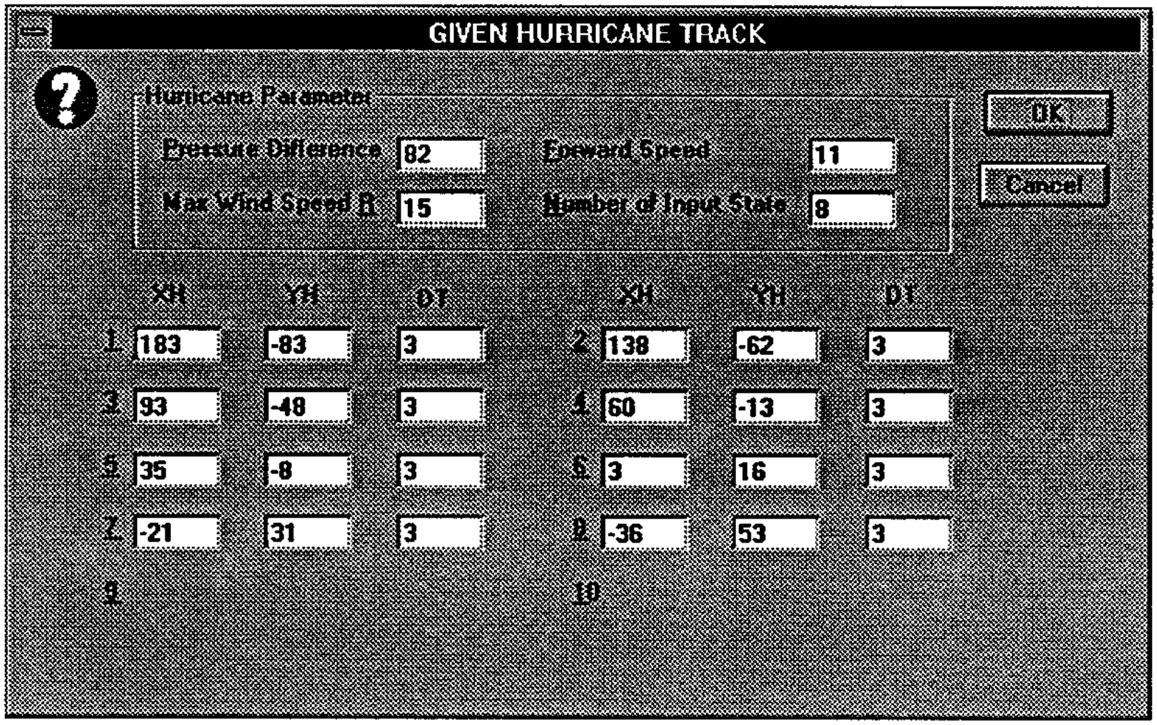


Figure A2.10 Given Hurricane Track Information

SIMUPARA command allows to input calculation coefficients. The dialogue box 'SIMULATION PARAMETERS' will pop up when it is selected. Input the wind, wave and current force coefficients in **FORCE PARAMETERS**, Select the type of current velocity distribution in **CURRENT TYPE,** Select the time step between the re-calculation of environmental forces in **TIME STEP**.

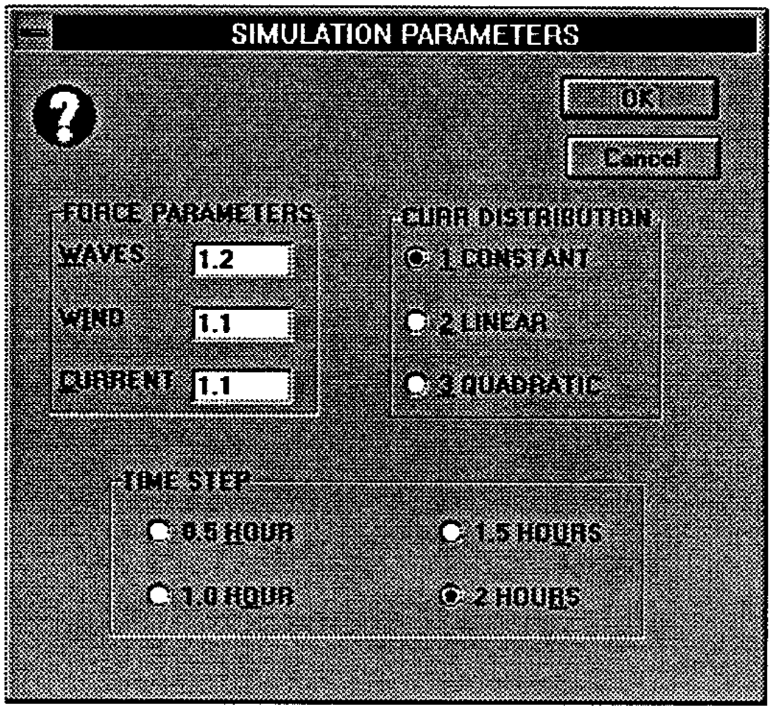


Figure A2.11 Input Calculation Coefficients

RAND PARA command allows to input probability distributions of random parameters. The dialogue box 'RANDOM PARAMETER' will pop up when **RAND PARA** command is selected.

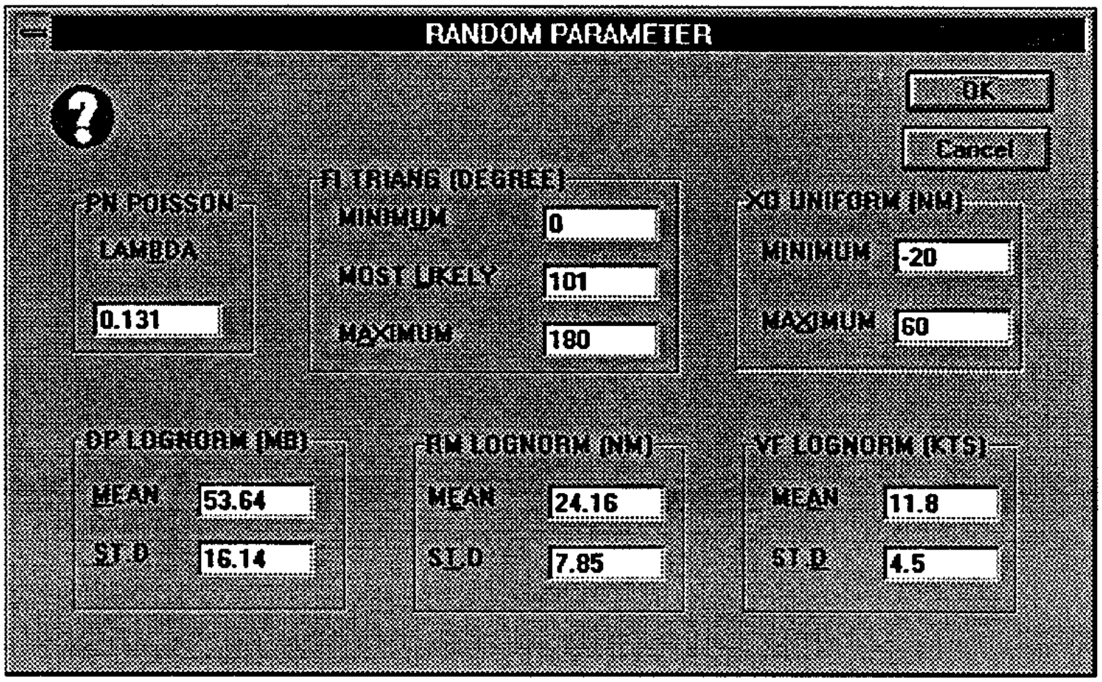


Figure A2.12 Input Random Parameter Information

Note here, Lamta is the hurricane occurrence rate at a point in the selected reference per year per nautical mile.

PARA CORRELATE command allows to input correlation among random parameters. The dialogue box 'PARAMETER CORRELATION' will pop up when it is selected.

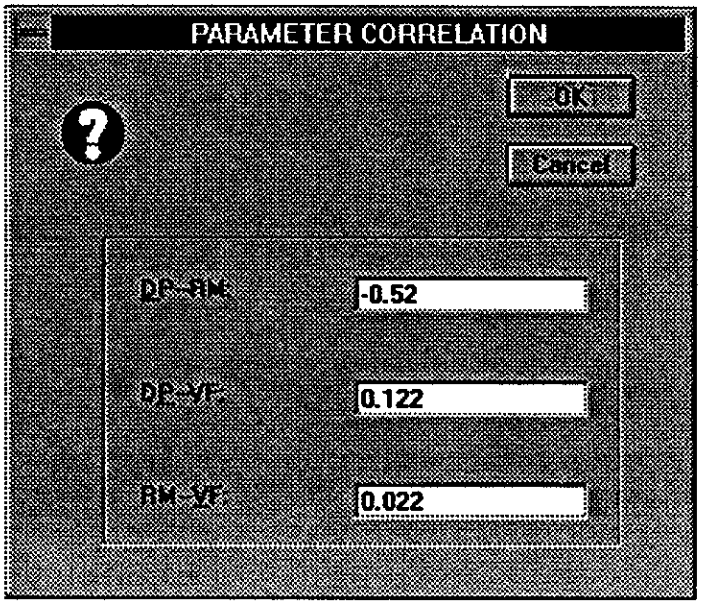


Figure A2.13 Input Correlation Coefficients among Random Parameters

Markov Modeling command allows to input the definition of states in Markov chain model and the transition probability matrix.

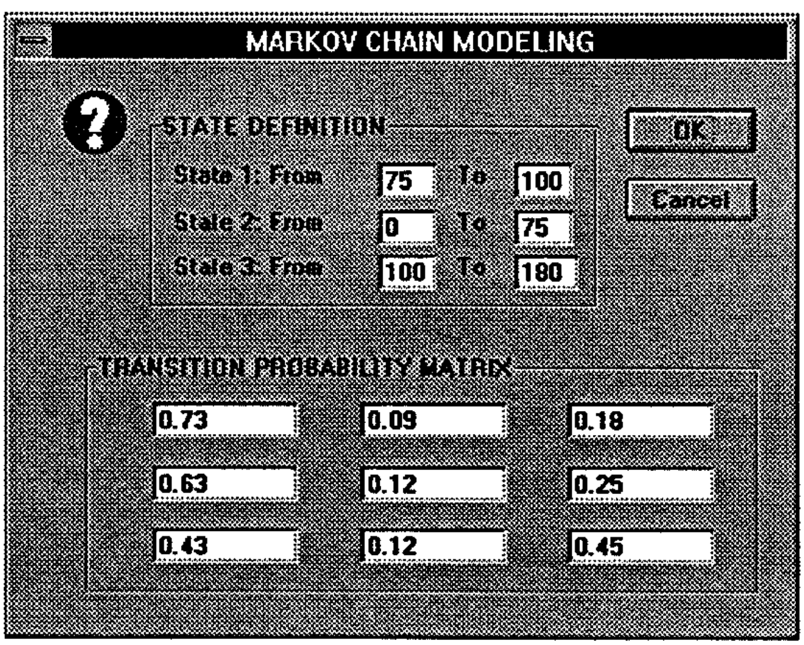


Figure A2.14 Input Markov Model Setting

A2.4 Execute the Program

There three commands under **RUN** menu;

RESET command allows to reset the program before each simulation.

RUN command is clicked to begin the simulation. Before click **RUN**, you should set up @RISK simulation parameters. The recommended @RISK simulation settings is as in Figure 2.12. After the simulation is completed, a dialogue box will pop up.

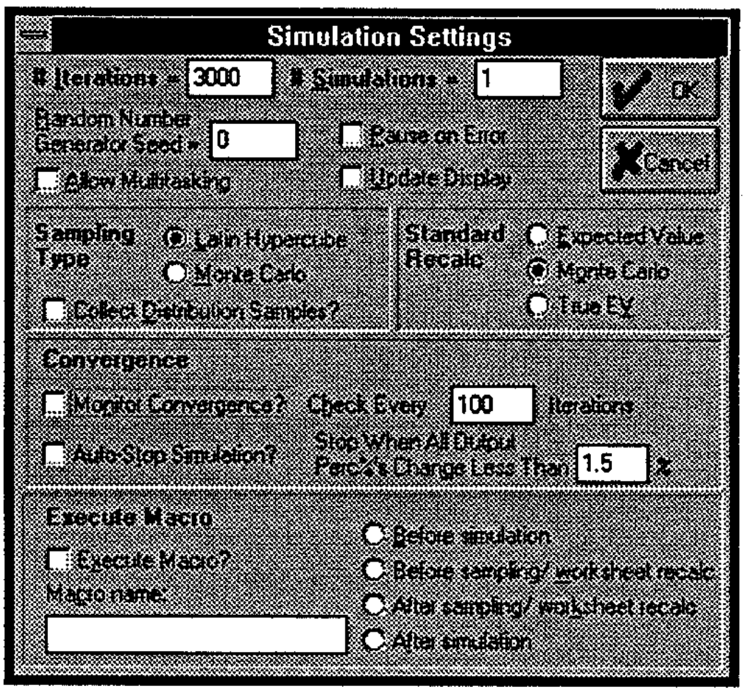


Figure 2.15 @Risk Simulation Setting

Strategy command allows to do strategy simulation to determine the best place to site the MODU within the acceptable area.

A2.5 General Jackup Information

The MODUSIM has been updated to simulate the movement of bottom founded MODUs. There are three command under the **Jackup** menu.

Jackup Type command allows to determine the MODU type, foundation type and failure mode.

Jackup Info allows to input the general information of the jack-up.

Capacity allows to input the foundation capacity and leg capacity.

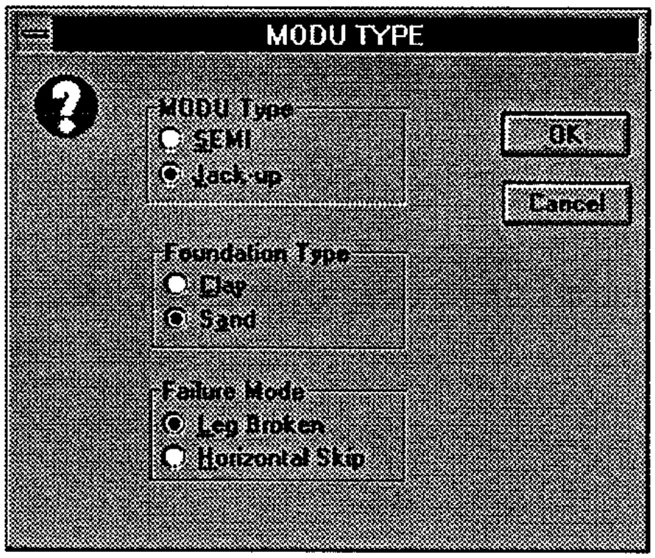


Figure A2.16 Input Jackup Type Information

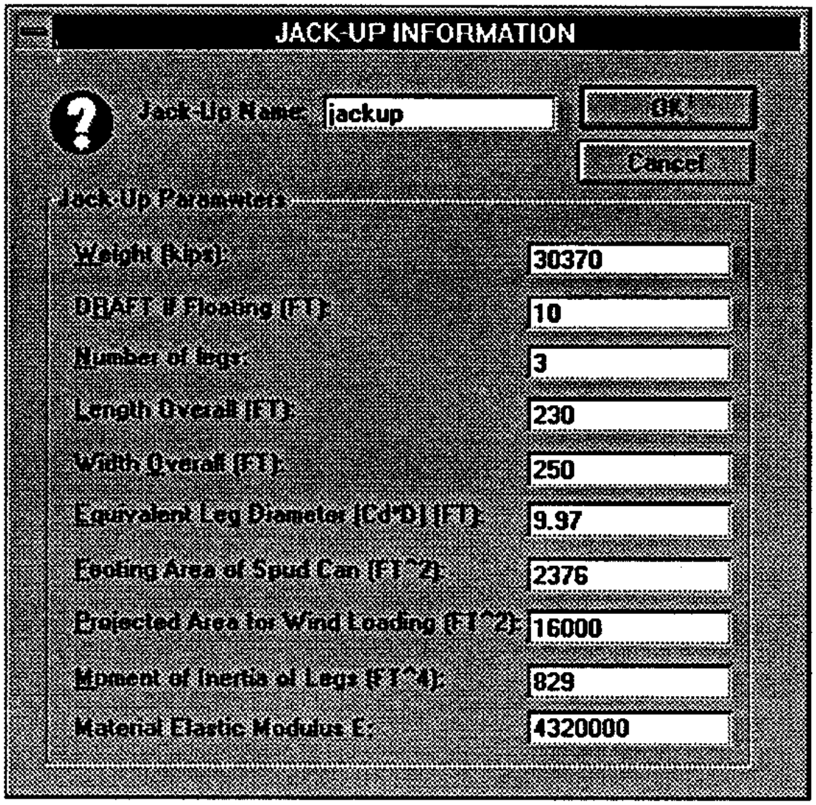


Figure A2.17 Input General Jackup Information

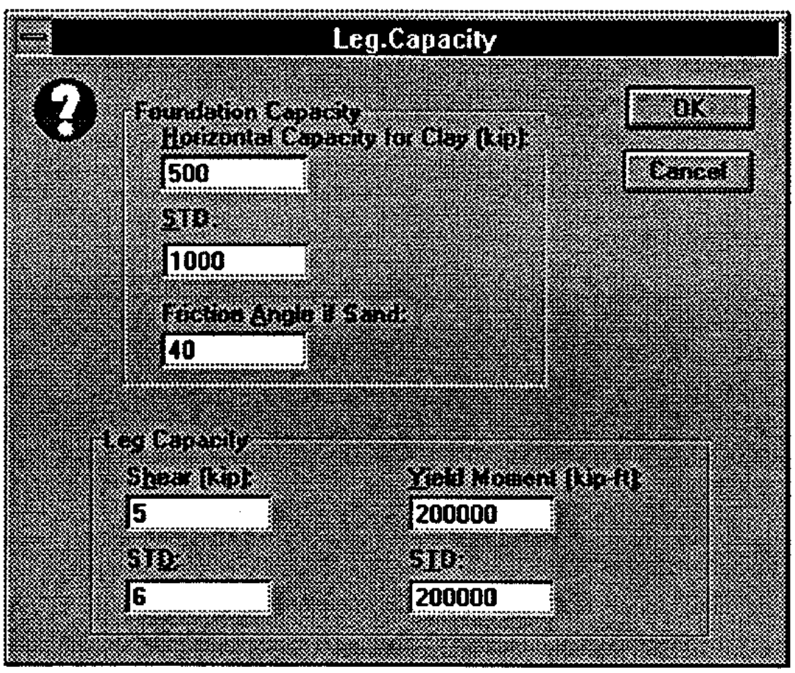


Figure A2.18 Input Jackup Capacity Information

A3. Output

The output of MODUSIM can be in numerical and graphical format.

Click **RESULT** command for simulation result.

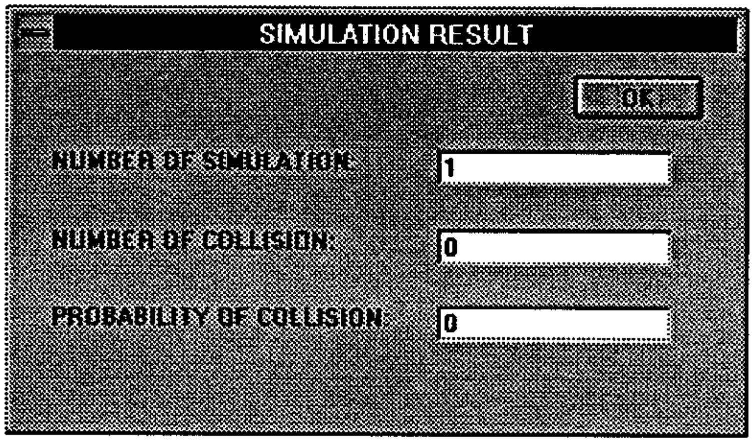


Figure A2.19 Simulation Result

Click **RESUTAR** for output of special target collision probability.

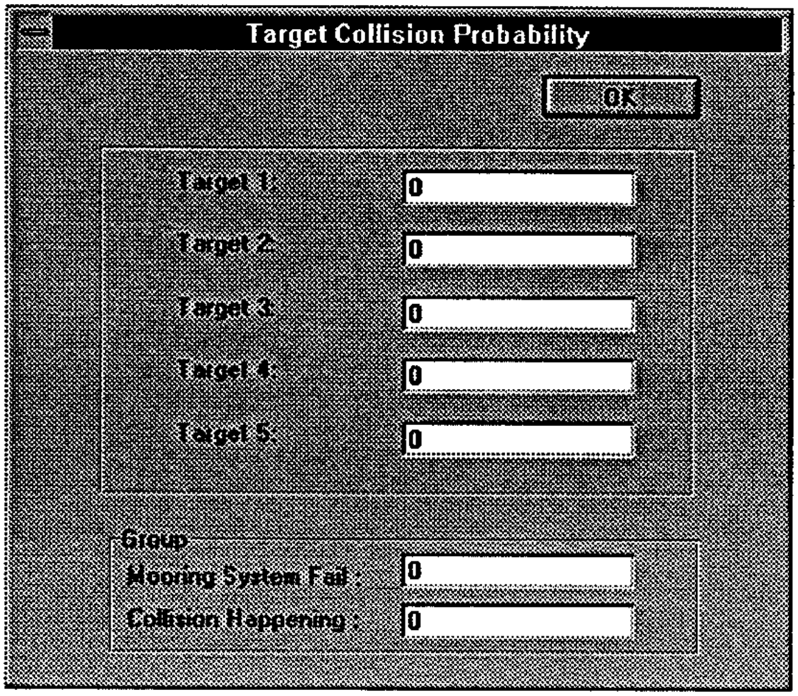


Figure A2.20 Simulation Result for Target Circles

Click **Summary** command for the simulation result from Strategy function.

Click **Env.Result** to get the result from the simulation of the environmental conditions.

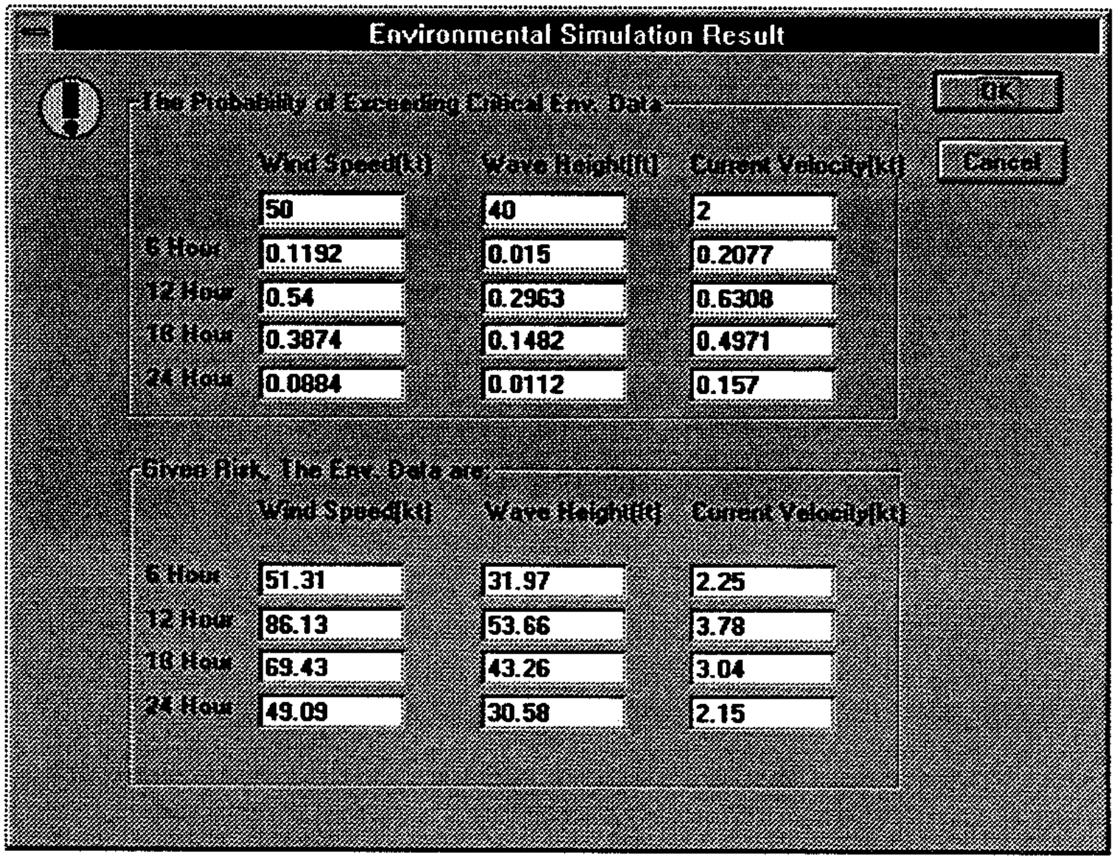


Figure A2.21 Environmental Condition Simulation Result

Click **Histogram** command to get the histograms of environmental condition. The following 'Type of Histogram' dialogue box will pop up. Select different forecast time and different forecast type of hurricanes.

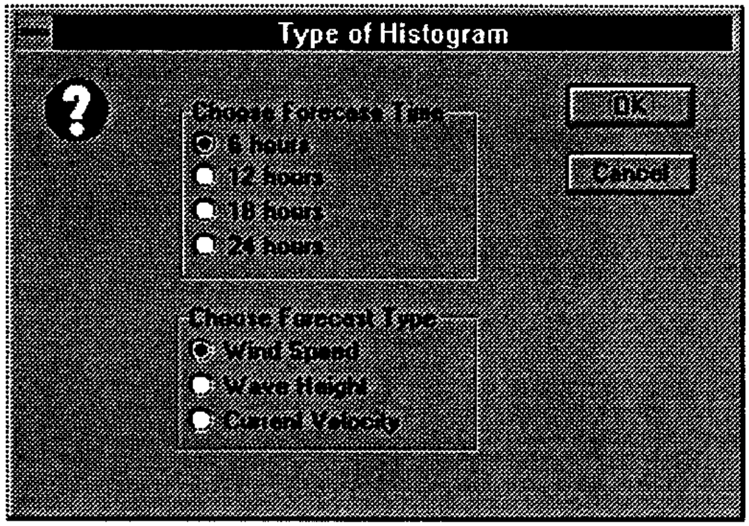


Figure A2.22 Type of Histogram

Click **Return** command to return to the welcome screen.

In case of simulation the MODU's movement during a given hurricane, click **ROUTE** command to get the MODU's moving route during hurricanes.

During the simulation of a given track, a dialogue box 'COLLISION HAPPENING' will pop up whenever a collision happens. Click **STOP HERE** to stop the simulation. Click **NO REPORT** to skip the 'COLLISION HAPPENING!' dialogue box after the following collision. Click **HOLDING** and input **HOLDING TIME** to make the MODU stop at the collision place for a while.

If **Update Screen** is clicked, the MODU route and hurricane track will not be updated each step on the screen. This will make the simulation faster.

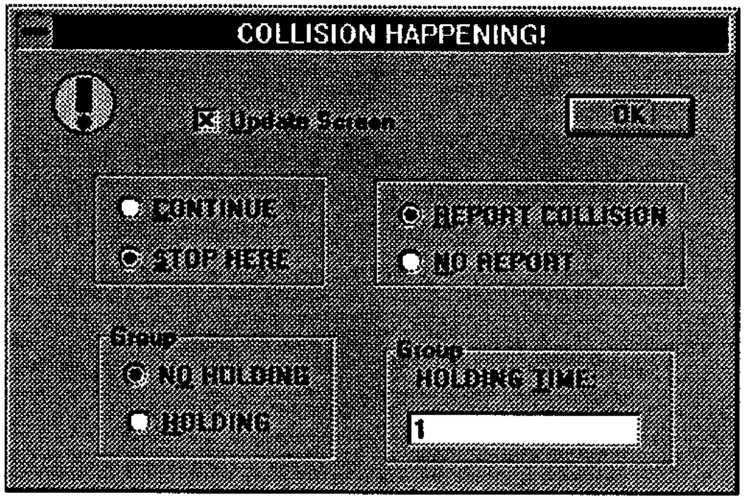
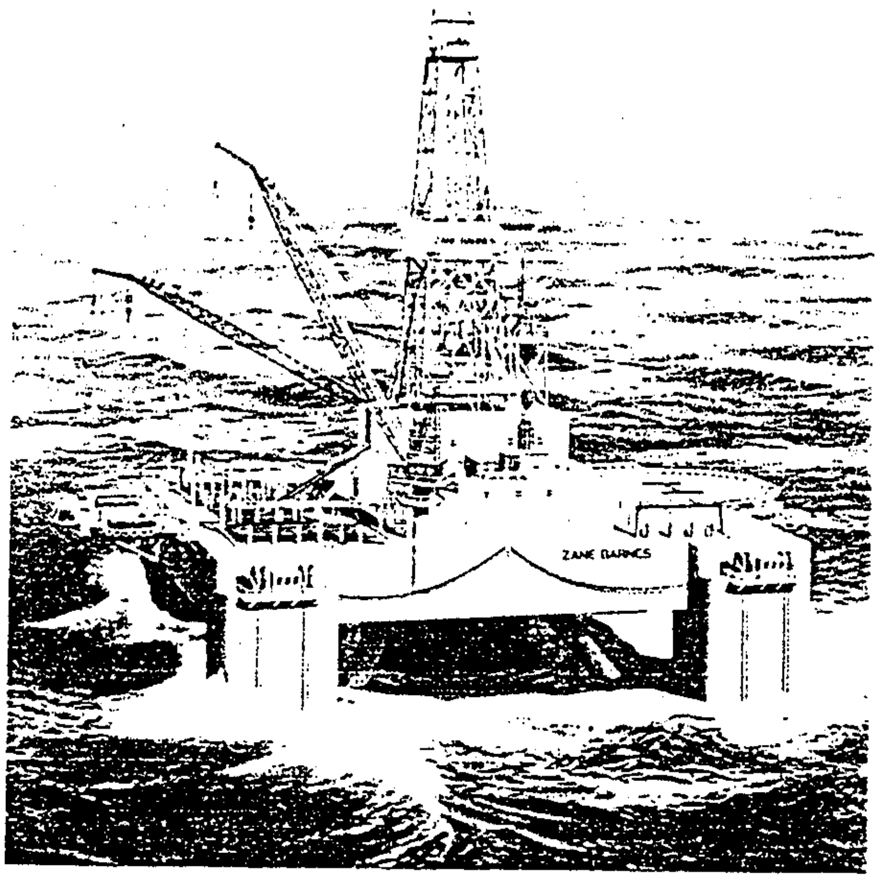


Figure A2.23 Collision Happening Dialogue Box

GENERAL	
Name	Zane Barnes
Owner	Reading & Bates Drilling Company
Manager	Reading & Bates Drilling Company
Year/yard built	1986, by Ishikawajima-Harima Heavy Industries Co. Ltd., Aichi, Japan
Design	Friede & Goldman L-1020 Trendsetter, propulsion assisted semisubmersible

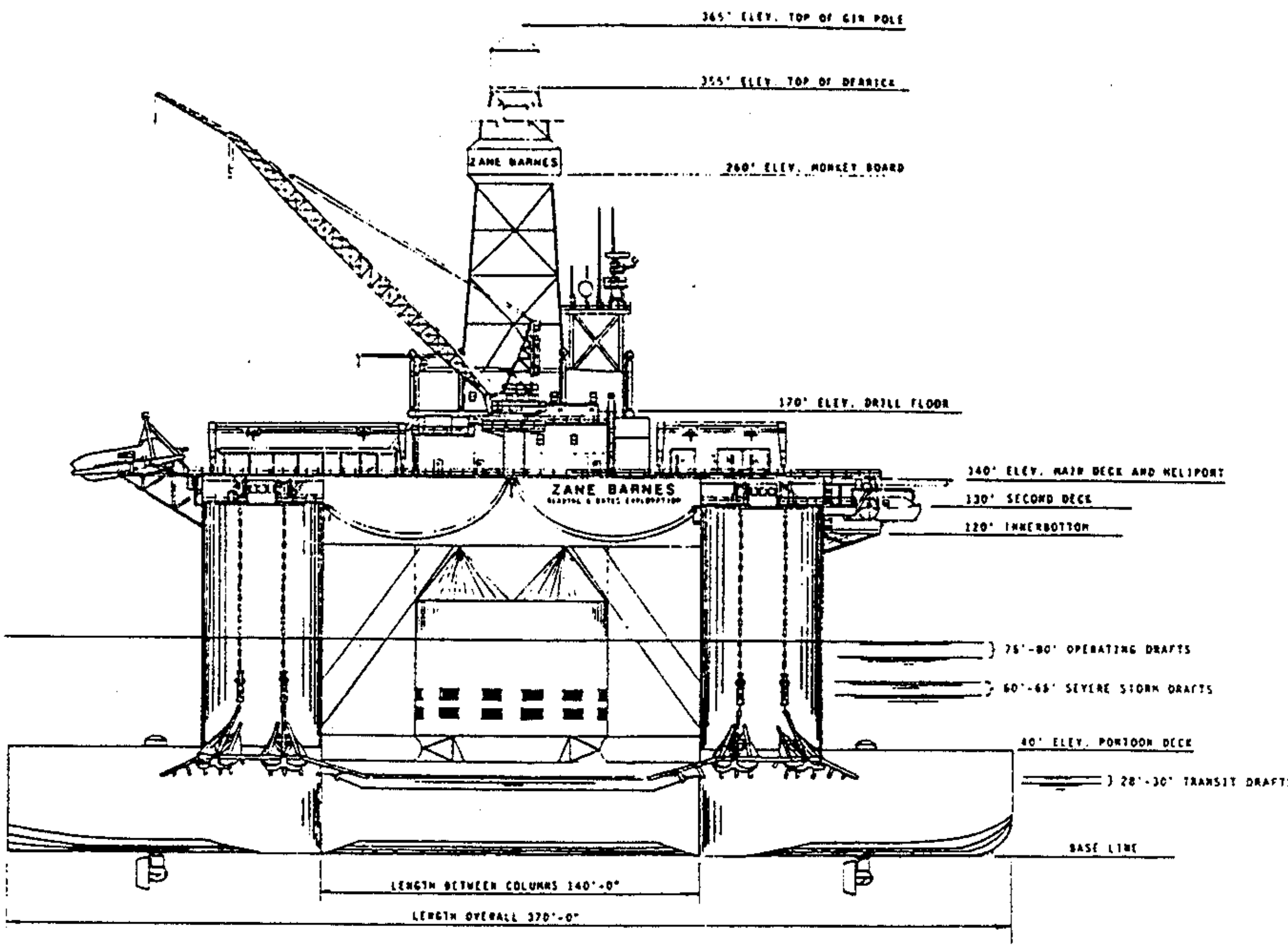


REGULATORY	
Registration	U.S.A.
Classification	ABS
Approvals	US Coast Guard; UK DOE; IMO; NMD; CCG

PRINCIPLE DIMENSIONS	
Length overall	370 ft.
Width overall	255 ft. (excl. anchor racks)
Height to main deck	140 ft.
Deck area	Approx. 50,625 ft² (upper hull dimensions 225 ft x 225 ft x 25 ft deep; open deck space (excl. heliport) 15,000 ft²
Moon pool	28 ft diameter at top, 38 ft diameter at bottom
Columns	4 x corner caissons, 45 ft across flats; transverse spacing 180 ft c-c; longitudinal spacing 185 ft c-c; centre caisson 72 ft diameter
Pontoons	2 x 370 ft at 45 ft beam amidships x 60 ft beam at ends x 30 ft deep amidships x 40 ft deep at ends

POWER/PROPULSION	
Main power plant	2 x Wärtsila 12V32; 2 x Wärtsila 8R32
Generators	2 x Stromberg HSPTL-15-855; 2 xStromberg HSPTL-15-855
Power distribution	Stromberg 6.9 KV medium voltage system with Ross-Hill SCR system
Emergency power	Wärtsila LR32D diesel generator set, 1480 KW
Propulsion	2 x 5500 hp azimuth thrusters, variable pitch/speed; provision for DP with two additional 5500 hp azimuth thrusters
Towing requirements	Varies with location

DRAFT/DISPLACEMENT	
Operating draft	75-80 ft.; air gap 35-40 ft.
Transit draft	28-30 ft.; air gap 85-87 ft.
Survival draft	60-65 ft.; air gap 50-55 ft.
Operating displacement	50,715-52,311 LT
Transit displacement	29,376-31,434 LT



ELEVATION

OPERATING PARAMETERS

Maximum water depth	5000 ft.
Maximum drilling depth	30,000 ft.
Transit speed	Excess of 8 knots
Survival criteria	Maximum survival storm with 5000 LT variable deck load; wind, 1 min. mean, 100 knots; current nil; 60 ft significant wave height, 110 ft maximum; average period 12.9 seconds
Drilling capability	Maximum drilling with 5000 LT variable deck load; wind, 1 min. mean, 60 knots; surface current 3 knots; current at 1500 ft WD, 1 knot; significant wave height 30 ft, maximum 60 ft; average period 9.7 seconds
Design temperature	-20 deg C

CAPACITIES

Variable deck load	Minimum variable deck & column load 5000 LT (drilling/storm/transit)
Substructure loads	Setback 500,000 lbs; rotary 1,600,000 lbs; riser tensioner load 2,000,000 lbs; max. design load 4,100,000 lbs
Tubulars in pipe racks	12,500 ft^2 with 30-ton gantry crane service
Liquid mud	4000 bbls
Bulk mud & cement	29,000 ft^3
Sack materials	10,000 sacks
Drilling water	21,000 bbls in lower hulls
Potable water	100 bbls in upper hull; 3400 bbls in caissons
Fuel oil	1100 bbls in upper hull; 37,350 bbls in lower hulls
Chain/anchors	Chain lockers sized for 4000 ft of chain
Other	Cellar deck storage 3450 ft^2; lube oil 600 bbls; JP-5 42 bbls; liquid additive tanks 95 bbls; seawater ballast 48,900 bbls in caissons, 151,400 bbls in lower hulls; clean mud oil 8500 bbls

DRILLING EQUIPMENT

Derrick	185 ft high, 40 ft x 40 ft base, static hook load 2,000,00 lbs
Drawworks	3000 hp
Rotary	49½"
Top drive	Provision for top drive system
Pipe handling system	Mechanical pipe ramp handling system located on the aft deck; upper and lower racker arms; iron roughneck
Motion compensator	Western Gear, 600,000 lbs capacity; capacity latched or rod fully extended 1,600,000 lbs; 25 ft stroke
Riser tensioners	6 x dual tensioners, total 1,200,000 lbs x 50 ft stroke; provision for two additional tensioners
Guideline tensioners	Guidelineless BOP system
Cementing unit	Halliburton SKF-4 Twin HT-400

degree of freedom model, shown in Figure 9.1. constrains the nodes at the foundation (nodes 1 and 4) to have zero displacements in the horizontal, vertical and rotational directions (i.e. fixed end conditions). The nodes representing the leg-hull connection (nodes 2 and 3) are constrained to have identical horizontal displacements, zero vertical displacements and zero relational displacements. By constraining nodes 2 and 3 to have identical displacements, the only motion possible is in the X direction shown in Figure 9.1.

The mass was distributed equally among the three legs. Since the element between nodes 1 and 2 represents the two aft legs of the unit, 2/3 of the rig is located at node 2. The remaining 1/3 of the rig mass is located at node 3.

The static wave forces were computed at one second intervals using Morison's equation with a drag coefficient (C_D) equal to 0.7 and inertia coefficient (C_M) equal to 1.2. The wave forces were computed using linear wave theory or Stoke's 5th theory. Current velocities were included in computing the hydrodynamic forces on the jack-up rig. The result of this process is a time history of the static wave forces acting on the jack-up at one second intervals.

The direction of approach of the waves was assumed to be orthogonal to a line between the two aft legs of the rig (parallel to the longitudinal centerline). This was done in order to induce the maximum loading in the single fore leg.

The yield moment of the leg section was computed assuming a linear stress distribution across the leg section. The yield moment was defined as the moment which resulted in the tension edge of the section reaching yield stress (36 ksi), as shown for the yield moment in Figure 9.2. The plastic moment was computed assuming the chord sections were fully yielded and the stress distribution was as shown for the plastic moment in Figure 9.2.

9.1.2 Foundation Capacities

The capacity of the foundation is determined by its ability to withstand the vertical and horizontal loads transmitted to it by the jack-up unit. The vertical capacity is developed by the shear strength of the soil beneath the footing. The horizontal capacity is developed by the combination of sliding resistance and developed passive pressure of the soil as the footing applies increasing horizontal stresses to the soil.

The horizontal sliding resistance is the summation of the frictional resistance and the mobilized passive pressure of the soil as the footing reacts against it. The frictional resistance H can be computed using Eq. 9.1, assuming undrained soil conditions. In computing the sliding resistance, the mean value of the remolded shear strength of the soil was used (S_u). The resulting sliding resistance of the foundations are for typical Gulf of Mexico soil conditions, sliding resistance ranges between 2590 kips and 1295 kips. The range in the sliding resistance is due to the potential variation in the effective area of the footing due to spud can rotations. As was computed in the bearing capacity analysis the effective area of the foundation (A) can be approximately 50% of the static area.

$$H = S_U A \tag{9.1}$$

Passive pressure is the pressure that is developed by soils to resist movement when a load is applied to the soil mass. The fundamentals of bearing capacity discussed above are based on the development of passive pressure to resist the vertical loads. The mobilized passive pressure to resist the horizontal loads can be estimated using Eq. 9.2.

$$\overline{\sigma_p} = K_p \overline{\sigma_v} + 2c\sqrt{K_p} \tag{9.2}$$

The coefficient of passive pressure K_p is defined in Eq. 9.3.

$$K_p = Tan^2(45 + \phi / 2) \tag{9.3}$$

For clays with the angle of internal friction (ϕ) equal to zero, K_p is equal to 1.0. The value of the cohesion (c) (c and S_U are used interchangeably) is that of the initial shear strength of the soils, 0.5 ksf for the Gulf of Mexico. The resulting maximum passive pressures that could be developed by this foundation is 4.2 ksf for the Gulf of Mexico locations. The project area of the spud can is 412.5 ft^2. The resulting load capacities per spud can are 1730 kips for the Gulf of Mexico location (Table 9.2).

Table 9.2 Foundation Capacities of GOM

	Median Value	Standard Deviation
Moment	662071 (kip-ft)	0.106
Axial Load	41409 (kip)	0.117
Horizontal	3391 (kip)	0.40

9.1.3. Failure Modes of Jack-up

There are four principal failure mechanisms due to environmental loading on the jack-up: horizontal displacements, bearing capacities, overturning and leg failure. The occurrence of any one of these failure modes would render the jack-up unserviceable. Based on this, the jack-up system can be modeled as a system of elements in series, in which the probability of failure of the entire system is the probability of failure of the most likely to fail element.

Overturning has been traditionally computed as the point at which the vertical reaction at the seafloor on the weather side leg is equal to zero. Typically, no consideration has been given to the transient nature of the wave loading. The duration of loads which are capable of causing the rig to overturn is relatively short, and the instant this load is removed, the rig returns to equilibrium. Realistically overturning can only occur if the center of gravity of the rig is pushed beyond the line of action of the vertical reaction of the leeward footing. This of course assumes that the rig will not suffer a bearing failure or a collapse of the leeward leg. The overturning failure is more an indication of the potential of inducing a failure into the system due to other components picking up the additional load and exceeding their capacity. Also, the effects of the vertical capacities are not important due to the effects of pre-loading on the foundation. During pre-loading, the soil beneath the footing is consolidated under loads higher than those experienced during operations, hence as long as the vertical loads on the foundation remain below the pre-load no significant further consolidation should occur. The intent of pre-loading the foundation is to replicate the expected maximum loading the foundation would experience during an extreme event. There will be however, a small amount of settlement of the foundation due to further or secondary consolidation of the soils beneath the footings, however this occurs over a long period of time and is not a storm response.

As the preliminary nature of the study in this area, the evaluation of the rig will concentrate on the horizontal foundation failure modes and leg failure in the study.

a. Leg Failure

The ultimate shear that can be resisted by a leg is obtained based on bending moment capacities of the leg. The interaction of bending moment and axial force (**M-P**) is taken into account. The maximum bending moment and axial force that can be developed in a leg is limited by local buckling of leg cross-sections.

The vertical dead loads of the decks are assumed to be equally shared between the deck legs. The vertical live loads in the legs caused by the lateral overturning forces are computed and summed to define the axial loading in each leg.

Due to relatively large axial loads (weight of the decks and topside facilities) and large relative displacements (deck bay drift) at collapse, $P-\Delta$ effect play a role in reducing the lateral shear capacity and hence is taken into account.

To derive a realistic estimate of $P-\Delta$ effect without leaving the framework of a simplified analysis, it is assumed that the deck is rigid. The analysis is done using the direct stiffness method, with the nodal displacements as unknowns. The equilibrium condition to be solved is given as:

$$P = K \bullet \Delta \tag{9.4}$$

where P is the lateral load and K is defined as:

$$K = \sum_{Legs} \frac{12EI}{h^3} \tag{9.5}$$

E=Elastic Modules

I=Moment of inertia about the axis of bending for the leg

h=height of the leg

b. Horizontal Displacement

During a wave period, if the total lateral force is larger than the foundation horizontal capacity, the Jack-Up will move forward and backward. In the shallow water condition, the forward wave force generally is larger than the backward wave force, the Jack-UP will move step by step along the wave propagate direction. Here for a simplified analysis, it is assumed that the MODU's moving time is quarter wave period forward. The moving distance during a wave period is defined as:

$$S_{wave\_period} = \frac{1}{2} \cdot a \cdot (\frac{T}{4})^2 \quad (9.6)$$

where a is the acceleration of the MODU and is defined as:

$$a = \frac{\sum F_{environment} - \sum F_{resistant}}{m_{MODU}} \quad (9.7)$$

9.1.4 Example of Martin 3 Jackup in Andrew

During hurricane Andrew, Jackup Martin 3 broke legs and moved from Ship shoal 263 to South Timballer. The result from MODUSIM (Figure 9.3) did not agree with the real route. We find from Figure 9.3 that if the MODU's legs were broken before Andrew reached the MODU's location, the MODU would always move to deep water by the environmental forces. Since the MODU moved to shallow water in fact, this may imply that the MODU's legs were broken after Andrew pasted the MODU's location. Because the maximum environmental forces happened when Andrew reached the MODU, MODUSIM would assume that the MODU's legs were broken at that time and so the resulting moving route would be different from the real one. From this point of view, the MODUSIM need to be improved to simulate such cases.

9.2 Preliminary Study of Environmental Forecasts in Hurricanes

Proper evaluation of a storm's early warning signals are important to safe and effective evacuation of platforms. Weather forecasting reliability of the tracks and intensities of severe storms has been improving. Forecasting is continually updating hypotheses and developments resulting in decreasing uncertainty levels over time. However, these uncertainties create a number of problems for decision makers.

As a result of these uncertainties, it is important to determine the criteria for platform evacuations and securing operations. Evacuation and securing criteria can be based upon a number of factors such as:

- wave heights,
- wind speeds,
- storm distance,
- storm direction,
- storm forward speed,
- type of MODU,
- capacity of unit and mooring to withstand extreme loading,
- availability of evacuation and securing vessels and helicopters,
- distance from the unit to shore,
- the number of personnel to evacuate.

The reliability of the warning systems are dependent upon the ability to forecast danger and to effectively response to it. For offshore operations, early warning signals come in the form of storm forecasting. Currently, there are two ways to get the storm forecasting. The first way is to get a forecast hurricane track from weather bureau whenever a hurricane comes. The error bound associated with this forecasting is very large indeed. For example, the error bound is up to 100 NM for 12 hour forecast, up to 300 NM for 24 hour forecast, up to 500 NM for 48 hour forecast. The other method is to use the Markov-chain model developed in this study. The advantage of the second method is that it is based on the statistical analysis and simulation so that it is easy to use and understand. Future work is needed to do to improve the Markov transmission matrix to reflect the other physical factors, ex., the hurricane coming season, detail place, etc..

With a given coming hurricane, the forecast track is simulated based on Markov model assumption. Simulation results are assumed as log-normally distributed. (Fig. 9.4 and Fig. 9.5).

Given a critical environmental condition level, the probability of exceeding the critical level at the MODU location can be determined. Given an acceptable risk level, ex., 10%, the acceptable environmental condition at different forecast time can be determined. (Fig. 9.6)

It can be seen from Figure 9.6, for given a critical environmental condition level with 40 kts. wind speed, 45 ft. wave height and 2 kts. current velocity, after 18 hours from now, the probability of exceeding the 40 kts. critical wind speed is 65.2%, 8.05% for wave height and 49.7% for current velocity. Or it also can be seen from the result, given an acceptable risk level, ex. 10%, the acceptable wind speed after 18 hours is 69.4 kts., 43.26 ft. for wave height and 3.04 kts. for current velocity.

Table 9.1 General Dimensions of Average Jack-up Rig

GENERAL DIMENSIONS AND CHARACTERISTICS OF AVERAGE JACK-UP RIG	
Length overall	230.0 ft
Width overall	250.0 ft
Depth of hull	33.0 ft
Length of spud legs	480.0 ft
Distance between centerlines of aft and fore legs (longitudinal)	160.0 ft
Distance between centerlines of aft legs (transverse)	190.0 ft
Diameter of spud can	55.0 ft
Footing area of spud can	2376 sq ft
Weight of hull	30,370 kips
Moment of inertia of legs	2487 ft^4
Rotational stiff. of jack housing and hull	$1.5*10^8$ k•ft/rad
Structural damping	2-5 %
Equivalent leg diameter (C_D * D)	9.97 ft
Projected area for wind loading	16000 sq ft
Flexural Stiffness of legs (EI/L)	$2.361x10^7$ kip•ft
Shear Area of Leg	3.5 sq ft
Yield Moment	$6.528x10^5$ kip•ft
Plastic Moment	$6.763x10^5$ kip•ft
Ultimate Moment	$7.433x10^5$ kip•ft
Yield axial load	$3.297x10^4$ kips
Ultimate axial load	$4.601x10^4$ kips
Balance Points for Axial Load - Moment Interaction Curve	
Yield axial load	$1.319x10^4$ kips
Yield moment	$5.288x10^5$ kip•ft
Ultimate axial load	$1.840x10^4$ kips
Ultimate moment	$6.026x10^5$ kip•ft

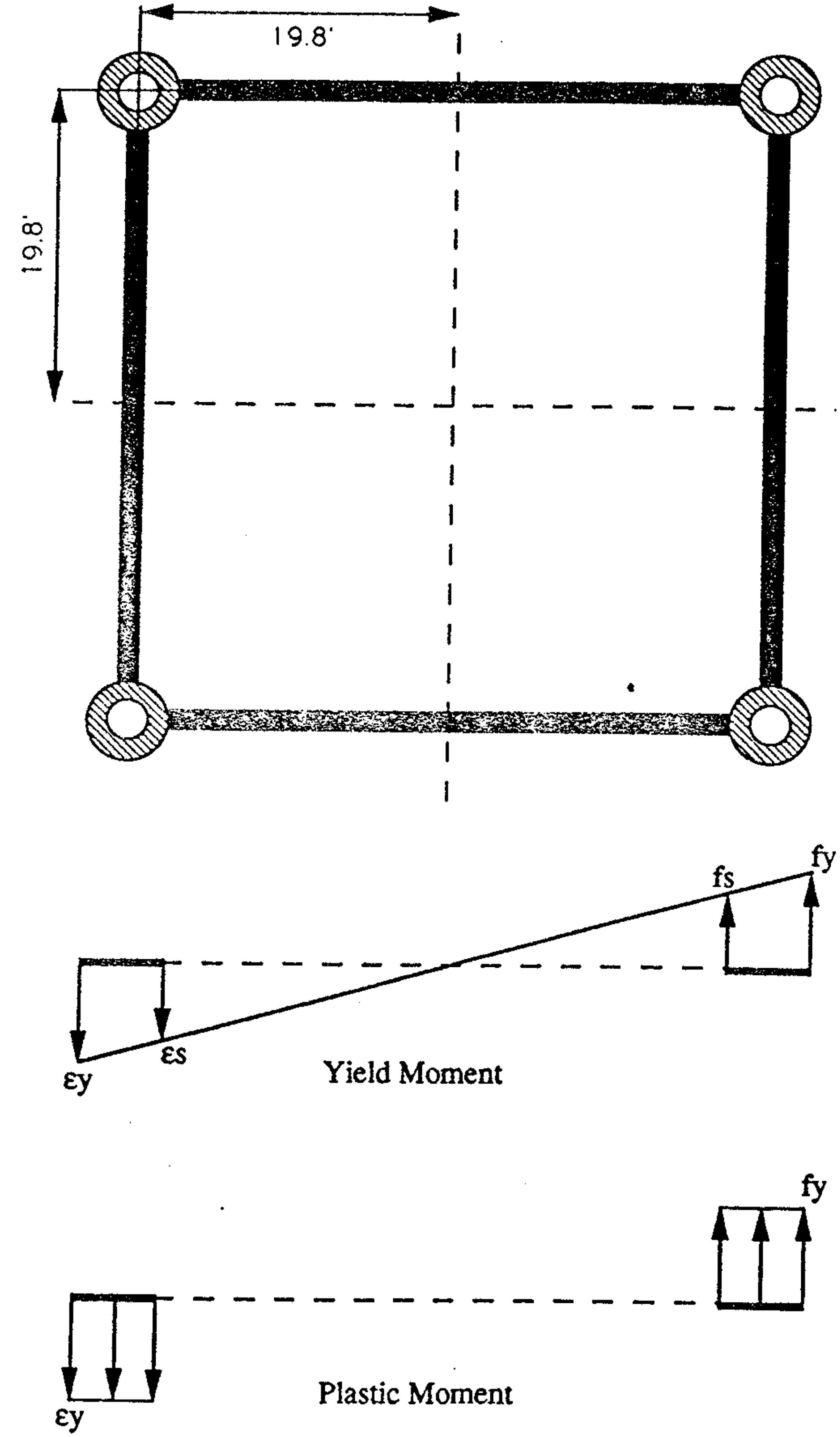


Figure 9.2 Definition of Yield Moment

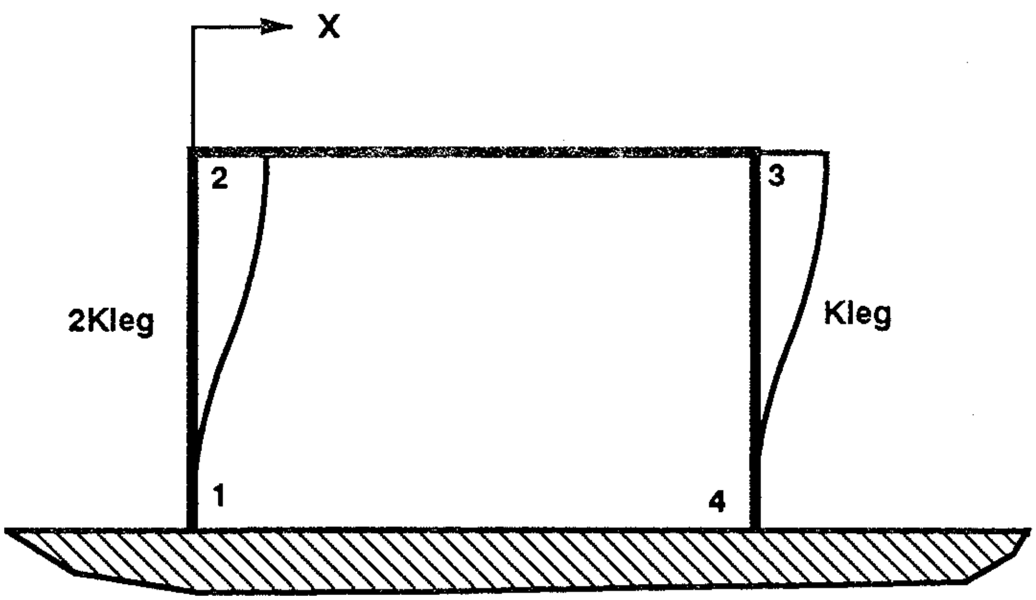
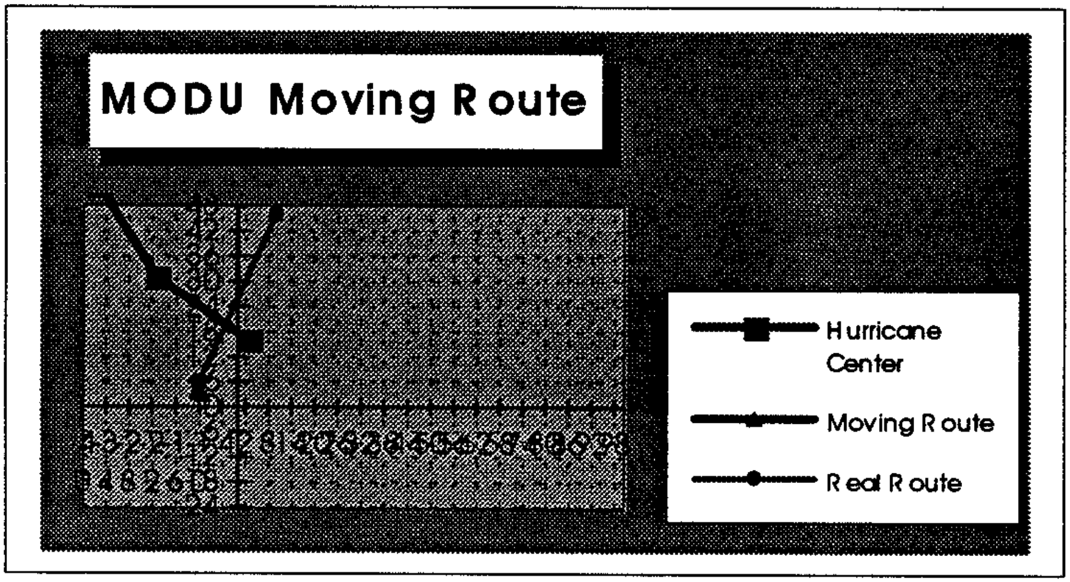
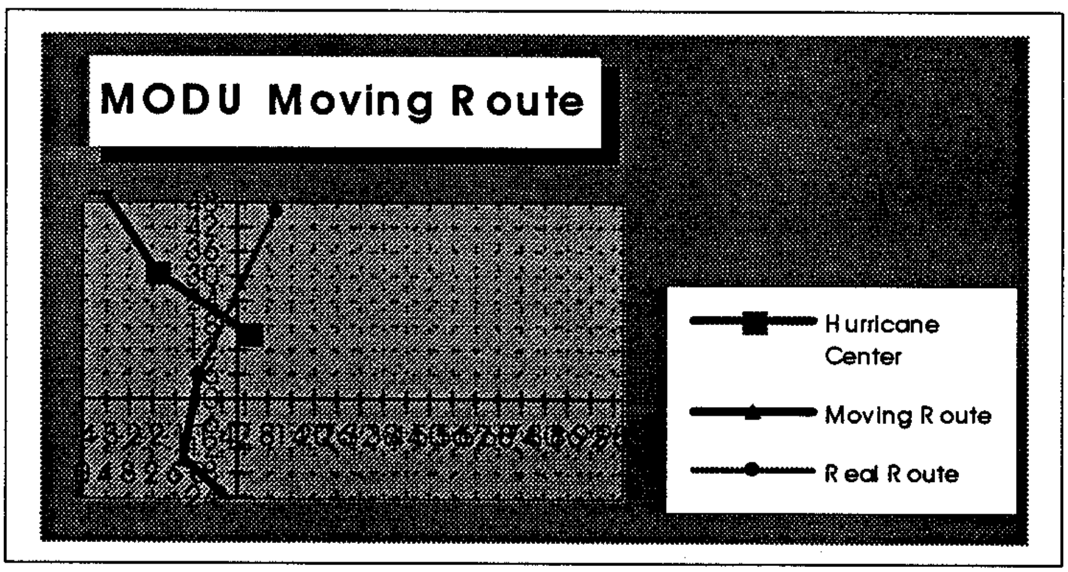


Figure 9.1 Jack up: Single Degree of Freedom Model



a. Foundation Horizontal Failure



b. Leg Broken

Figure 9.3 Example of Martin 3 Jackup in Andrew

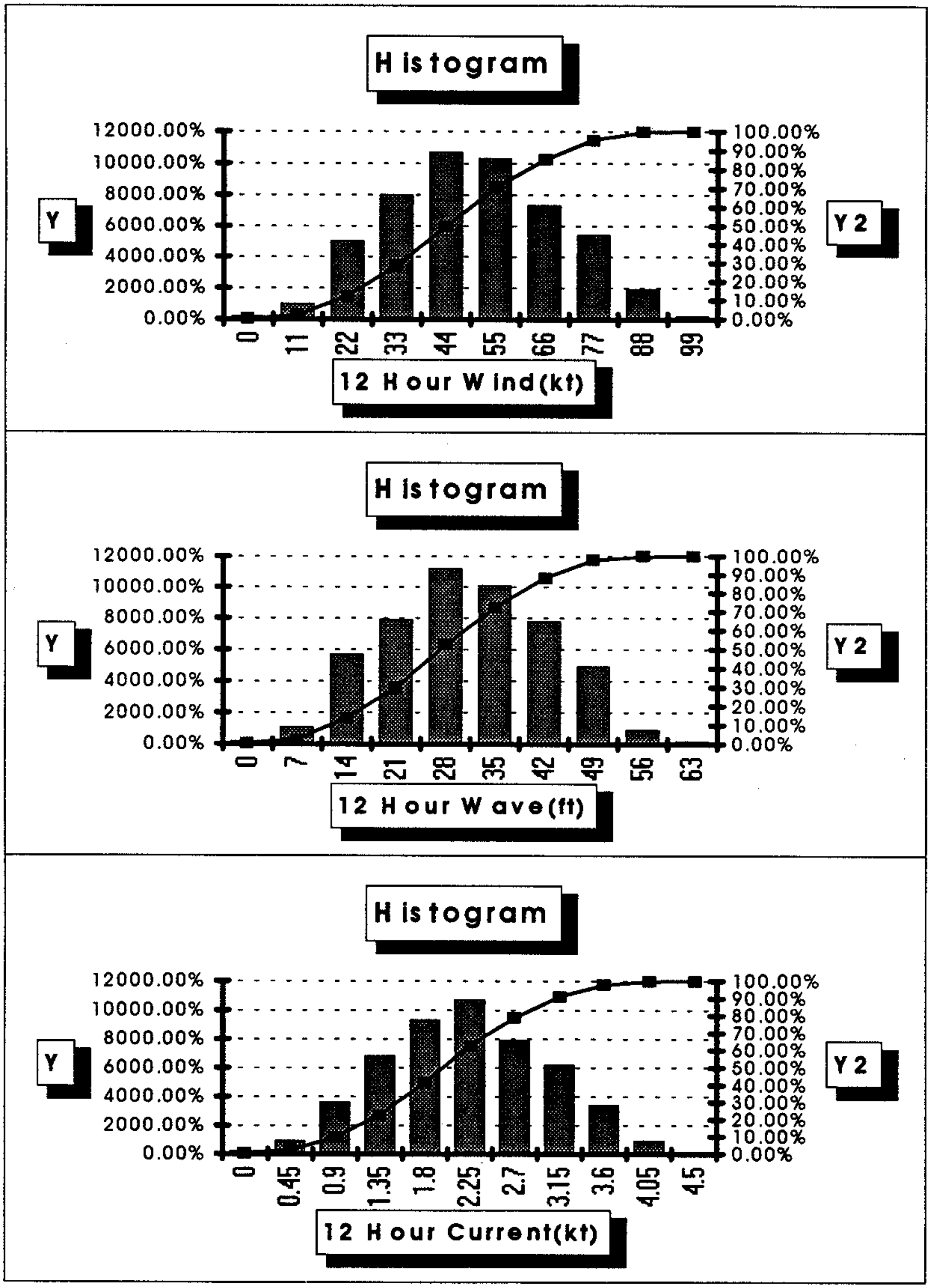
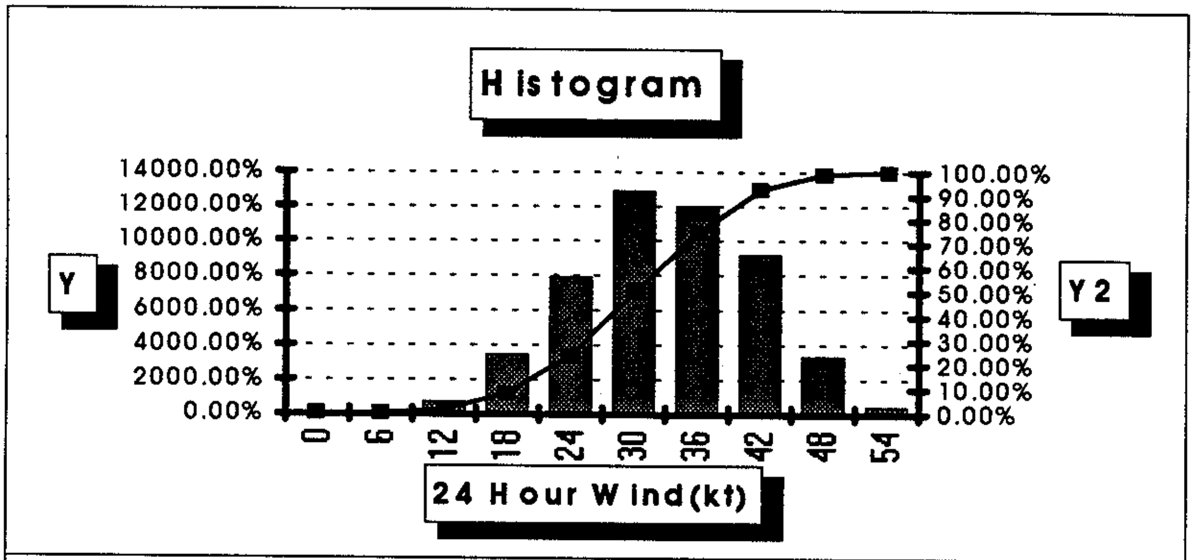
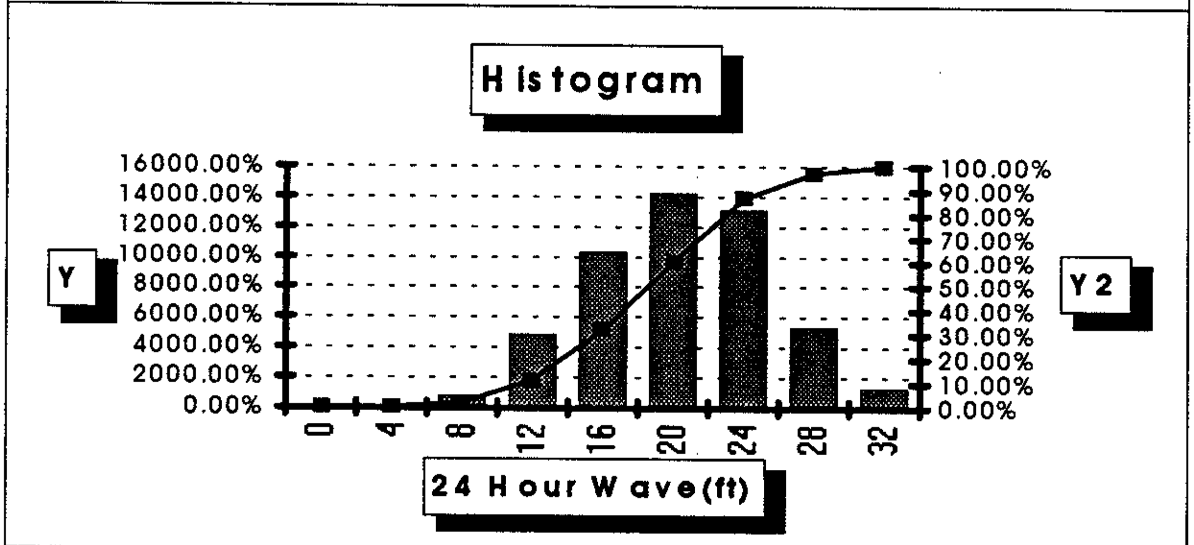
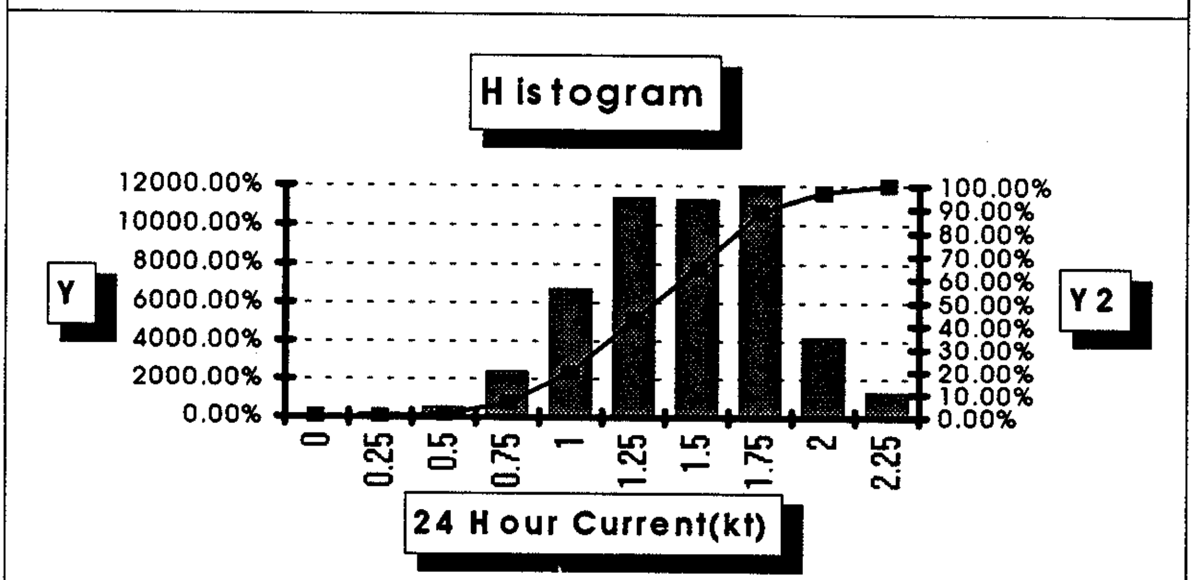


Figure 9.4 Histogram of Environmental Conditions in Hurricanes


Histogram
14000.00%
12000.00%
10000.00%
8000.00%
6000.00%
4000.00%
2000.00%
0.00%
Y
100.00%
90.00%
80.00%
70.00%
60.00%
50.00%
40.00%
30.00%
20.00%
10.00%
0.00%
Y2
0
6
12
18
24
30
36
42
48
54
24 Hour Wind(kt)


Histogram
16000.00%
14000.00%
12000.00%
10000.00%
8000.00%
6000.00%
4000.00%
2000.00%
0.00%
Y
100.00%
90.00%
80.00%
70.00%
60.00%
50.00%
40.00%
30.00%
20.00%
10.00%
0.00%
Y2
0
4
8
12
16
20
24
28
32
24 Hour Wave(ft)


Histogram
12000.00%
10000.00%
8000.00%
6000.00%
4000.00%
2000.00%
0.00%
Y
100.00%
90.00%
80.00%
70.00%
60.00%
50.00%
40.00%
30.00%
20.00%
10.00%
0.00%
Y2
0
0.25
0.5
0.75
1
1.25
1.5
1.75
2
2.25
24 Hour Current(kt)

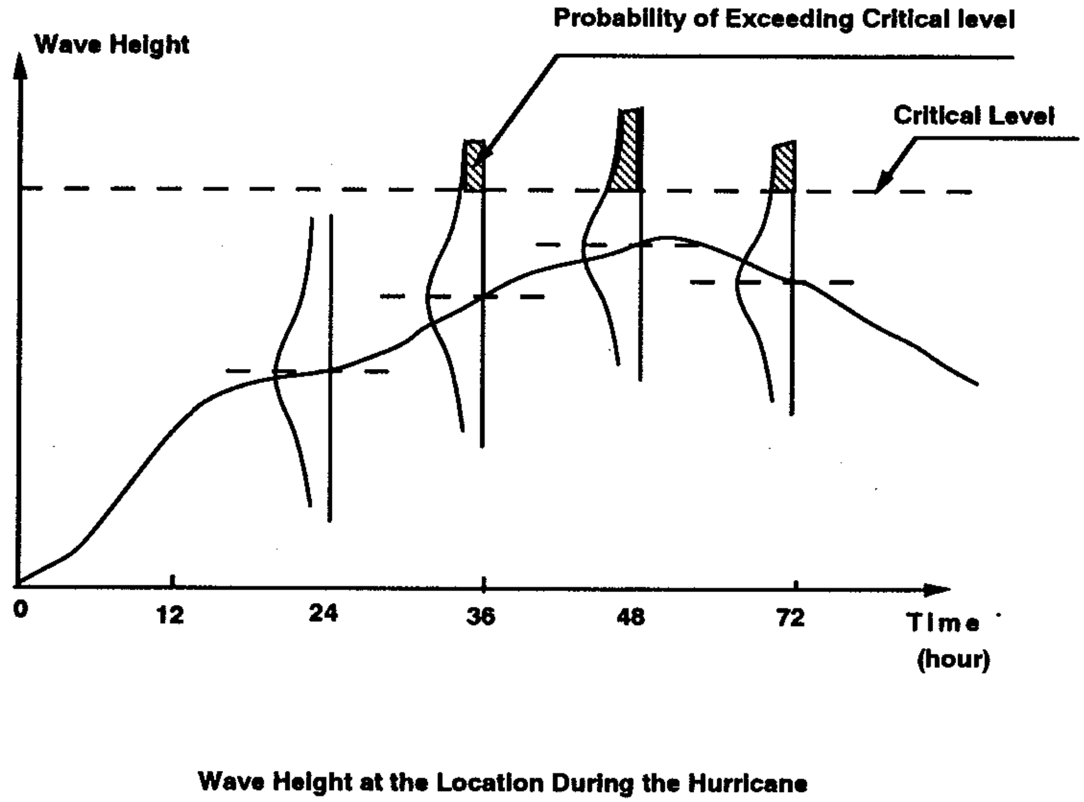


Figure 9.5 Wave Height at the Location During the Hurricane

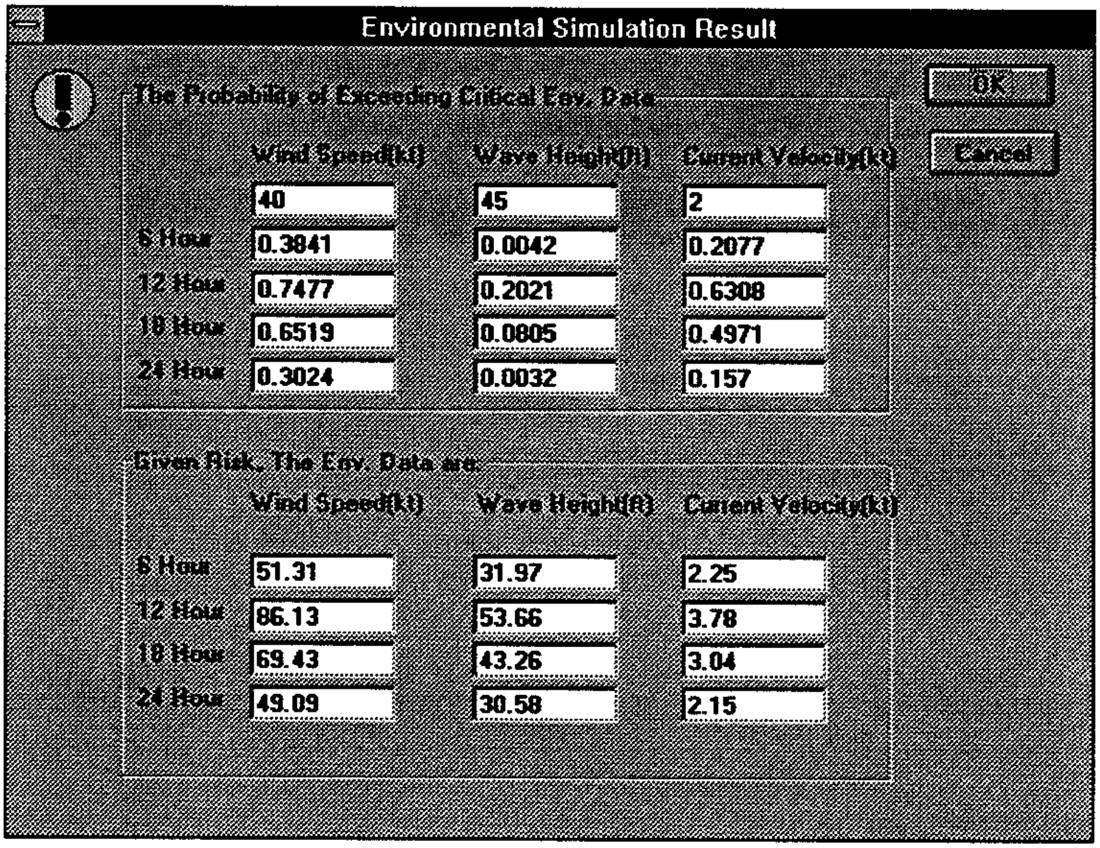


Figure 9.6. Environmental Simulation Result

10.0. Conclusion and Recommendation

A simulation model has been developed to predict the movements of MODUs in the Gulf of Mexico during hurricanes. A Monte-Carlo simulation model (MODUSIM) has been developed to enable prediction of the probability of collision between MODUs and surrounding large facilities. The variability of hurricane parameters and their correlation, the storm spatial geometry, shallow water shoaling effects, and modeling and parameter estimation uncertainties are considered. At last, the Zane Barnes, Zapata Saratoga and Treasure 75, which all moved a significant distance during hurricane Andrew, were used to verify the simulation model. The simulation results matched closely to the information on the performance of the semi-submersible MODUs during hurricane Andrew. Also, the probability of collision between a MODU and the surrounding structures has been determined.

Ways to Reduce the Collision Probability

From this study, it has been found that the best way to reduce collision probabilities is to design anchors to drag prior to any mooring line breaking. In this case, the MODU will not move far because of the large dynamic dragging force. However, if the rig is to be located near subsea structures that could be damaged by a dragging anchor, the operator may use pile anchors or oversized drag anchors to cause the mooring lines to break first.

Another effective way is to change the MODU's sitting location. using the MODUSIM, the best place with the least collision probability can be determined. For example, if Zane Barnes were moored at (47,20) instead of (33,35) which is about 20 NM to the south-east, the probability of collision will be one half of before (Table 8.4).

It seems that the mooring strength is not important to the collision probability. It has been found that a hurricane with an intensity greater than one year hurricane return period will cause breakaways. To reduce the collision probability in half, one needs to increase the mooring capacity by almost three times.

The recommended procedure to choose a best place to sitting MODUs is as follows:

1) Determine the large target structures in the area which are of interest;

2) determine the best preferred MODU sitting place and the acceptable radius of sitting area;

3) Using the MODUSIM function "Strategy", determine the best place to site the MODU within the acceptable area;

4) Change the mooring line failure mode (Free floating or Dragging) and mooring capacity with the MODU located at the best place to get the acceptable collision risk level.

Recommended Future Work

Potential research topics for further studies have been identified during the present research. These are listed and briefly discussed in the following:

• Perform Further Verification Studies

The verification studies performed during this research include 4 Gulf of Mexico MODUs. Although the results are extremely encouraging, additional studies on MODUs with different configurations would help increase the confidence in the MODUSIM.

• Further Refine Jack-up and Foundation Modeling

At present stage, MODUSIM includes a very simple procedure of modeling jack-up and foundation. The next step in refining the procedure would be to include more detail analysis of failure mechanics and soil foundation capacity. Refer to Reference [19].

• Develop Parametric Early Warning System Model for MODUs in Gulf of Mexico Hurricanes Conditions with the Information from MODUSIM

As discussed in Chapter 9.2, the reliability of the warning systems are dependent upon the ability to forecast danger and to effectively response to it. Future work still need to do to improve the Markov transmission matrix to reflect the other physical factors, ex., the season that hurricanes come, detail location of hurricanes, etc.. With a given incoming hurricane, the forecast track is simulated based on Markov model assumption. Simulation results are assumed as log-normally distributed.

• Develop Computer Based Evacuation Model

In order to examine evacuation procedures and decisions, it is important to develop models of these operations. An exhaustive model of securing and evacuation systems can be complex. These models should be simple enough to understand, yet detailed enough to include the important factors involved in the operation. For platform securing and evacuations, two PRA models are proposed. First is an event tree model distinguishing decisions and events at various states of the system. The second model uses influence diagrams allowing for greater flexibility in that decisions and variables are not totally ordered.

• Develop a Professional Version of MODUSIM

Based on a simultaneous development and verification/calibration approach, the present version of MODUSIM has been developed during the second year of this research. The program runs in

EXCEL4.0. It has the potential to be further developed and include additional features that enhance the speed and user-friendliness of the program. It seems that the most efficient way to do so would be to rewrite MODUSIM in Visual Basic using Excel 5.0.

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Appendix A MODUSIM

MODU Movement Simulation Program

User Manual

MODUSIM

MODU Movement Simulation Program

Table of Contents

A1. Introduction

A1.1 Introduction

MODUSIM is a computer simulation program developed for simulating the MODU's movement in hurricanes. It is based on simplified load, capacity and movement calculation procedures developed for the joint industry - Government sponsored research project called "***Securing Procedures for Mobile Drilling Units in the Gulf of Mexico Subject to Hurricanes***".

This research has been performed at the University of California at Berkeley, Department of Naval Architecture and Offshore Engineering by Research Assistant Jun Ying under supervision of Professor Robert Bea. The theoretical background of MODUSIM is documented in previous chapters of this report.

A1.2 Application Range of MODUSIM

MODUSIM can be applied to typical semi-submersible drilling units with generic geometry's and some special types of Jack-up platforms. The loading and mooring capacity has been calibrated to platforms located in 0 - 300 ft water depth. At this stage, MODUSIM is expected to give some reasonable results. For information on other limitations of the program, please refer to next sections of this appendix.

A1.3 Program Structure

The program is developed using Microsoft Excel Software. The following Excel files are bounded together under the workbook named MODU.xlw:

- Welcom1.xls
- MODUSIM.xlm

- modu.xls
- Stokev.xls
- Dbase.xls
- Coll.xlm
- Result.xls
- Route.xlc
- Histogram.xlc

A1.4 Installation

A1.4.1 Backup Disk

Before any installation begins, it is always a good practice to backup the program diskette in the back of the report. We assume you are already familiar with DOS commands or Windows operation. For example, in DOS you will need the DISKCOPY command to make backup copies of your program disk.

A1.4.2 System Requirements

To run MODUSIM 2.0, you must have a 386 or 486 based PC with 2MB RAM at least, MS DOS 5.0, Windows 3.0, EXCEL 4.0 and @RISK 3.0. A math co-processor chip is recommended for a 386 based PC, 486 based PCs come with one.

A1.4.3 Installation

To install MODUSIM 2.0, first copy all the files in the attached disk to your hard drive under the directory "c:\MODUSIM". Then you can open the file 'MODU.XLW' directly from EXCEL4.0 & @Risk3.0. Or you can specify the program group name, item name, and the path of MODUSIM to windows. Type WIN to execute Windows, select New from File menu in program Manager to add the program group. The following window will appear, select Program Group and then OK.