AGENDA

9:00  INTRODUCTIONS
      (Bob Bea)

9:15  PROJECT PLAN REVIEW AND UPDATE
      (Bob Bea)

10:00  BREAK

10:15  PROJECT PROGRESS AND STATUS
       (Mehrdad Mortazavi)

11:30  DISCUSSION

12:00  LUNCH

1:00   VERIFICATION CASE STUDIES
       (Ken Loch & Mehrdad Mortazavi)

2:30   A COMPARISON OF LEVELS 2, 3 AND 4 OF
       SCREENING (Peter Young)

3:00   DISCUSSION / BREAK

3:15   SOFTWARE DEMONSTRATION
       (Mehrdad Mortazavi)

3:45   PLANS FOR NEXT 6 MONTHS & MEETING

4:00   DISCUSSION

4:30   ADJOURN
PROJECT SPONSORS

Arco Exploration and Production Technology
California State Lands Commission
Exxon Production Research Company
Mobil Research and Development Company
Shell Oil Company
Unocal Corporation

&

U. S. Minerals Management Service

sponsoring associated projects:

"Verification of Screening Procedures"

&

"Dynamic Nonlinear Response In Severe Sea States"
COMPLEX
LINEAR & NONLINEAR ANALYTICAL MODELS

SIMPLIFIED
ULTIMATE LIMIT STATE ANALYTICAL MODELS

Field & Lab
Data & Experience

STATIC -
STRUCAD & USFOS
RSRs, $\mu$, $\alpha$

- Ken Loch
- Peter Young

DYNAMIC -
USFOS, FACTS
RSRd, $\mu$, $\alpha$

- Peter Young
- Charles Bowen

platform & caisson performance
in Hilda, Camille, Andrew and frame tests, caisson tests

- Mehrdad Mortazavi

DYNAMIC
LDOF
$F_v$

- Charles Bowen
- Peter Young

RSR = RSRs $F_v$

- Screening
- Parametric studies
- Reliability analyses
- Preliminary design
- Checking complex models
Screening Methodologies for Use in Platform Assessments and Requalifications

PROJECT OBJECTIVE

Further develop and verify qualitative and simplified quantitative screening methodologies for platform assessments so they can be used in practice

... and develop a reliable and easy to use tool to check the results of level 3 and 4 platform analyses!!

Level 1 - 'Scoring Factors'

Level 2 - 'Limit Equilibrium'
PROJECT SCOPE REVIEW

LEVEL 1
(If time available)

- Qualitative ranking factors and detailed assessment guidelines
- Verification / demonstration of applications

LEVEL 2

- Automated input for 4, 6, 8, and 12 leg geometries
- Storm loading algorithms (shallow water, 20th Edition procedures, loading effects)
- Element capacity modifications (joints, local wave forces, deck leg P-Δ, leg capacity, pile axial failure mode, biases)
- Damaged elements (holes, dents, cracks), and repaired elements (grouted)
- Reliability analysis
- Verification / demonstration of applications
PROGRESS SCHEDULE REVIEW

2 years

May 1993 - April 1994

- LEVEL 2 - 6, 8, 12 leg geometry (Completed)
- LEVEL 2 - Element capacity modifications (Completed)
- LEVEL 2 - Verification cases (Completed)
- LEVEL 2 - Loading modifications (Started)

May 1994 - April 1995

- LEVEL 1 - Ranking factors & assessment guidelines (If time available)
- LEVEL 2 - Damaged & repaired elements (Started)
- LEVEL 1 & 2 Verification cases & documentation (Started)
- LEVEL 2 - Reliability analysis (Started)
- Project final report & software documentation
DELIVERABLES

#1 - (Level 1 and) Level 2 PC code (source, IBM 486)
    theory, user, and applications manuals

#2 - Engineering reports
    background, approaches, analytical procedures, verifications

#3 - Project meetings (every 6 months)
    meeting notes - project progress
PLATFORM REASSESSMENT & REQUALIFICATION

PROCESS

Select Platform For Assessment & Requalification

Perform Condition Survey According to API Guidelines and Evaluate Results

Propose Inspection, Maintenance & Repair (IMR) Program

ASSESS RSR

LEVEL 1 Scoring Factors

LEVEL 2 Limit Equilibrium

LEVEL 3 Modified Elastic

LEVEL 4 Nonlinear

Implement IMR Program & Record Results

Evaluate Fitness For Purpose

Yes

No, Decommission

No, Revise IMR

RSR = \frac{Ru}{Sr}

Ru = Rus F \nu
LEVEL 2
RSR 'SIMPLIFIED ANALYSES'

USER INPUT

STORM LOADING SHEAR PROFILES

PLATFORM SHEAR RESISTANCE PROFILES

PLATFORM LATERAL LOAD CAPACITIES

FRAGILITY CURVES

LOAD UNCERTAINTIES

CAPACITY UNCERTAINTIES

ENVIRONMENTAL

STRUCTURAL

FOUNDATION

WIND

WAVE

CURRENT

DECK

JACKET

PILES

STATIC

DYNAMIC

+20.0 m

+10.6

+3.1

0 MSL

-73.0 m
PROJECT PROGRESS & STATUS

- A Review of Past Developments
- Improved Axial Compression Capacity Formulation
- Bending Moment Resistance of Jacket Legs
- Damged and Repaired Members
- Simplified Probabilistic Failure Analysis
STORM LOADINGS

![Graph showing total force and forces due to waves and wind as a function of expected maximum wave height.]

![Diagram illustrating near-surface wave force, wave force without surface effects, storm surge + tide, mean water level, jacket, and sea floor.]
PLATFORM CAPACITIES

DECK LEGS

JACKET

FOUNDATION
IMPROVED AXIAL CAPACITY FORMULATION
ORIGINALLY PROPOSED APPROACH

EQUILIBRIUM AT COLLAPSE

\[ P_v - 2 \frac{P_v^2}{\pi^2} \cos^{-1} \left( \frac{M_w + P_v \frac{\Delta}{M_r}}{1 - \frac{P_v}{P_E}} \right) = 0 \]

\[ P_E = \frac{\pi^2 \frac{EA}{(Kl/r)^2}} \]

\[ \Delta = \Delta_0 + \frac{5}{384} \frac{wl^4}{EI} \]

\[ M_w = \frac{wl^2}{10} \]
IMPROVED AXIAL CAPACITY FORMULATION
USFOS APPROACH

Non-linear material

Non-linear geometry

-plastic hinge

$v_e'' + \frac{P}{EJ}v_e' = 0$ (Elastic)
IMPROVED AXIAL CAPACITY FORMULATION
IMPROVED SIMPLIFIED APPROACH

\[ M_{xx} + \frac{P}{EI} M = -w - 8 P \frac{\Delta_0}{l^2} \]

\[ \xi = \frac{x}{l}, \quad \epsilon = l \sqrt{\frac{P}{EI}} \]

\[ M_{\xi\xi} + \epsilon^2 M = -w l^2 - 8 P \Delta_0 \]

\[ M(\xi) = \frac{\sin \epsilon (1-\xi)}{\sin \epsilon} M(\xi = 0) + \frac{\sin \epsilon \xi}{\sin \epsilon} M(\xi = 1) + \frac{1}{\epsilon} \left( \frac{\cos \epsilon (0.5 - \xi)}{\cos \frac{\epsilon}{2}} - 1 \right) \left( w l^2 + 8 P \Delta_0 \right) \]
IMPROVED AXIAL CAPACITY FORMULATION
IMPROVED SIMPLIFIED APPROACH

EQUILIBRIUM AT COLLAPSE

\[ M(\xi = 0.5) = -M(\xi = 0) = -M(\xi = 1) = M_U \]

\[ M_U = \left( \frac{1}{1 + 2 \frac{\sin 0.5 \varepsilon}{\sin \varepsilon}} \right) \left( \frac{1}{\varepsilon} \right) \left( \frac{1}{\cos \frac{\varepsilon}{2}} - 1 \right) (w l^2 + 8 P_U \Delta_\varphi) \]

\[ \frac{M_U}{M_p} - \cos \left( \frac{\pi P_U}{2 P_p} \right) = 0 \]
$w = 0$

$P_v = P_{cr}^{(API)}$

**INITIAL OUT-OF-STRAIGHTNESS**

$$\Delta \theta = \frac{M_p \cos \left( \frac{\pi P_{cr}}{2 P_p} \right)}{\left( \frac{1}{1 + \frac{2 \sin 0.5 \varepsilon}{\sin \varepsilon}} \right) \frac{1}{\varepsilon^2} \left( \frac{1}{\cos \frac{\varepsilon}{2}} - 1 \right) (8 P_{cr})}$$
IMPROVED AXIAL CAPACITY FORMULATION
VERIFICATION CASES

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<th>K</th>
<th>Delta0/L</th>
<th>M</th>
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<th>Pu/Pusfos</th>
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(api)
IMPROVED AXIAL CAPACITY FORMULATION
VERIFICATION CASES

END-ON

Pu / Pu_{stos} vs. K

- SCREEN
- USFOS
IMPROVED AXIAL CAPACITY FORMULATION
VERIFICATION CASES

BROADSIDE

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<tr>
<th>METHOD</th>
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IMPROVED AXIAL CAPACITY FORMULATION
VERIFICATION CASES

BROADSIDE

\[
\frac{P_u}{P_{ustos}} \quad K
\]

- SCREEN
- USFOS
VIRTUAL WORK

\[ W^{(e)} = W^{(i)} \]

\[ P_u = P_{BH} + \frac{2(M_J + M_K)}{H_{BAY}} \]

ORIGINAL APPROACH

\[ M_J = M_K = 0 \]

\[ P_u = P_{BH} \]
IMPROVED JACKET CAPACITY FORMULATION
IMPROVED APPROACH

MOMENT DISTRIBUTION IN A JACKET LEG

\[ M_0 = \frac{P_D h_D^2}{2EI} + \frac{P_D h_D}{CR} \leq M_P \]

\[ M_1 = M_0 - P_D h_D \leq M_P \]

FOR EQUAL SPANS, CONSTANT MOMENT OF INERTIA AND LIMITING CASE OF RIGID SUPPORTS:

\[ |M_2| \leq 0.286 |M_1| \]
DAMAGED AND REPAIRED MEMBERS

OBJECTIVE:

TO DEVELOP SIMPLIFIED METHODS TO EVALUATE THE EFFECTS OF MEMBER DAMAGE AND REPAIR ON PLATFORM RESPONSE TO EXTREME LOADINGS

DAMAGE CLASSIFICATION:

- DENTS
- GLOBAL BENDING
- CORROSION
- FATIGUE CRACKED JOINTS
DAMAGED AND REPAIRED MEMBERS
DENTS AND GLOBAL BENDING

Analytical methods

- **Beam-column Analysis** (Ellinas 1984, Chen 1987, Ricles et al. 1992, Loh 1993)

- **Numerical Integration Methods** (Kim 1992, Duan 1993)

- **Non-linear Finite Element Method** (FEM)
DAMAGED AND REPAIRED MEMBERS
Ellinas' Approach

\[ \sigma_{pd} = \sigma_y \frac{D}{l} \left[ \frac{16}{9} \delta_d^2 + \left( \frac{t}{D} \right)^2 - \frac{4}{3} \delta_d \right] \]

\[ \delta_d = \frac{d_d}{D} \]

\[ \lambda_d = \frac{L}{r_d} - 0.2\pi \sqrt{\frac{E}{\sigma_y}} \]

\[ \frac{1}{\sigma_c} \sigma_{ud}^2 - \left[ 1 + \alpha \lambda_d + \frac{A_e e_d}{Z_d} + \frac{f_y}{\sigma_c} \right] \sigma_{ud} + f_y + \sigma_{pd} \frac{A_d e_d}{Z_d} = 0 \]
DAMAGED AND REPAIRED MEMBERS
Loh's Unity Check Equations

Dent-Section Capacities and Properties

\[
\frac{P_{st}}{P_*} = \frac{A_{st}}{A_*} = \exp\left(-0.08 \frac{dd}{t}\right) \geq 0.45, \quad \frac{M_{st}}{M_*} = \frac{I_{st}}{I_*} = \exp\left(-0.06 \frac{dd}{t}\right) \geq 0.55
\]

Strength Check

\[
UC = \frac{P}{P_{st}} + \sqrt{\left(\frac{M - M_{ud}}{M u_d}\right)^a + \left(\frac{M_*}{M_u}\right)^2} \leq 1.0
\]

\[
UC = \frac{P}{P_{st}} + \sqrt{\left(\frac{M + M_u}{M u_d}\right)^2 + \left(\frac{M_*}{M_u}\right)^2} \leq 1.0
\]

Stability Check

\[
UC = \frac{P}{P_{crd}} + \sqrt{\left(\frac{M - \left(1 - \frac{P}{P_{Ed}}\right) M_{ud}}{M u_d}\right)^a + \left(\frac{M_*}{\left(1 - \frac{P}{P_E}\right) M_u}\right)^2} \leq 1.0
\]

\[
UC = \frac{P}{P_{crd}} + \sqrt{\left(\frac{M + \left(1 - \frac{P}{P_{Ed}}\right) M_{ud}}{M u_d}\right)^2 + \left(\frac{M_*}{\left(1 - \frac{P}{P_E}\right) M_u}\right)^2} \leq 1.0
\]

\[
\frac{P_{crd}}{P_{crd 0}} + \frac{P_{crd} \Delta Y}{\left(1 - \frac{P_{crd}}{P_{Ed}}\right) M_{ud}} = 1.0
\]
DAMAGED AND REPAIRED MEMBERS
Sensitivity Analysis of Ellinas' vs Loh's Formulation

\[ P / P_{cr} \]

\[ \text{DELTA} / L \]

\[ dd / D = 0 \]

ELLINAS

LOH

\[ Delta / L = 0 \]

ELLINAS

LOH

\[ dd / D \]
DAMAGED AND REPAIRED MEMBERS
A Comparison Between Experimental and Predicted Capacities

\[
\text{\[\text{Diagram}\]}
\]

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<tr>
<th>TEST</th>
<th>D (IN)</th>
<th>t (IN)</th>
<th>L (IN)</th>
<th>Sy (KSI)</th>
<th>E (KSI)</th>
<th>(\text{dd/D} (%))</th>
<th>(\text{delta/L} (%))</th>
<th>e/\lambda (%)</th>
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<th>(\text{delta/L} (%))</th>
<th>e/\lambda (%)</th>
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<th>BCDENT (KN)</th>
<th>LOH (KN)</th>
<th>ELLINAS (KN)</th>
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31
DAMAGED AND REPAIRED MEMBERS
A Comparison Between Experimental and Predicted Capacities

![Graph showing comparison of Pu/Ptest for BCDENT, LOH, ELLINAS, and RICLES]
DAMAGED AND REPAIRED MEMBERS
Sensitivity Analyses and Conclusions

- The residual strength decreases significantly as the dent depth increases.

- Column strength is more sensitive to local denting damage when slenderness parameter $\lambda$ is small.

- For a given dent depth, the analyses show a decrease in residual strength for members with higher D/t ratio.

- There is negligible conservatism in assuming a mid-length dent location for any practical dent within the middle-half section of a member's effective length.

- Lateral loadings, such as those caused by wave forces, can significantly affect dented brace capacity.

- Ricles (1993): DENTA (developed by Taby 1988), Loh's interaction equation, numerical integration based on M-P-$\Phi$ relationships, and the non-linear FEM are able to predict the residual capacity of the test members reasonably well.
PROBABILISTIC FAILURE ANALYSIS
Objective and Background

Objective:

To develop a reliability based level 2 screening procedure to identify critical platforms and their potential failure modes.

Background:

\[ P_f|H = 1 - \Phi \left( \frac{\ln \left( \frac{R_u}{S|H} \right)}{\sqrt{\sigma_{lnR}^2 + \sigma_{lnS}^2 - 2\rho \sigma_{lnR} \sigma_{lnS}}} \right) \]

![Graph showing probability of failure conditional on expected maximum wave height.](image)
PROBABILISTIC FAILURE ANALYSIS
FOSM Based Component and System Reliability

\[ M = \ln R - \ln S \]

\[ U = \frac{(M - \mu_M)}{\sigma_M} \]

\[ P_f = \text{CDF}(U) \]

assuming lognormal distribution for loads and capacities the exact reliability index can be given as:

\[ \beta = \frac{\mu_M}{\sigma_M} \]

\[ \mu_M = \ln \left( \frac{\mu_R}{\mu_S} \sqrt{\frac{1 + V_S^2}{1 + V_R^2}} \right) \]

\[ \sigma_M^2 = \ln(1 + V_R^2) + \ln(1 + V_S^2) - 2 \ln(1 + \rho_{RS} V_R V_S) \]

\[ P_f = \Phi(-\beta) \]

Series System:

\[ \max P_{fi} < P_{fs} < \sum_i P_{fi} \]
PROBABILISTIC FAILURE ANALYSIS
Uncertainty in Loading

WAVE LOADING:

\[ S_H = K_H H^\alpha \]

Drag force dominated structure:

\[ S_H = K_d K_u H^2 \]

Professor Bea:

<table>
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<th>( \sigma_{lnx} )</th>
<th>BIAS (( B_x ))</th>
<th>( \sigma_{lnBx} )</th>
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<td>( K_d )</td>
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PROBABILISTIC FAILURE ANALYSIS
Uncertainty in Component Capacities

**Deck Capacity:**

\[
\mu_{RD} = \mu_{Mcr} \cos[(\pi Q / 2n \mu_{Pcrl})](2n - QL^2/6EI)/L
\]

\[
\sigma_{RD} = \left[ \sigma^2_{Mcr}(\delta_{RD}/\delta_{Mcr})^2 + \sigma^2_{Pcrl}(\delta_{RD}/\delta_{Pcrl})^2 + 2\sigma_{Mcr}\sigma_{Pcrl}\right. \\
\left. (\delta_{RD}/\delta_{Mcr})(\delta_{RD}/\delta_{Pcrl}) \right]^{1/2}
\]

where

\[
\delta_{RD}/\delta_{Mcr} = \cos[(\pi Q / 2n \mu_{Pcrl})](2n - QL^2/6EI)/L
\]

\[
\delta_{RD}/\delta_{Pcrl} = (\pi Q \mu_{Mcr} / 2n (\mu_{Pcrl})^2) \sin[(\pi Q / 2n \mu_{Pcrl})] \\
(2n - QL^2/6EI)/L
\]

\[V_{Mcr} = 0.106, \quad V_{Pcrl} = 0.117\]

- \(V_{Mcr}\), \(V_{Pcrl}\) are reported to be constant over the entire range of practical values of \(E_t/fyD\) and \(D/t\) respectively.
PROBABILISTIC FAILURE ANALYSIS
Uncertainty in Component Capacities

Jacket Bay Capacity:

\[ \mu_{Rji} = \Sigma \alpha_i \mu_{Ri} + \mu_{RL} \]

\[ \sigma_{Rji} = [ \Sigma (\alpha_i \sigma_{Ri})^2 + \Sigma \alpha_i \alpha_j \sigma_{Ri} \sigma_{Rj} + (B_{FL} \sigma_{RL})^2 ]^{1/2} \]

\[ R_i = f(\lambda) \]

\[ \lambda = (1/\pi) (f_y/E)^{0.5} (KL/r) \]

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<th>1.0</th>
<th>1.2</th>
<th>1.4</th>
</tr>
</thead>
<tbody>
<tr>
<td>( V_{Ri} )</td>
<td>0.099</td>
<td>0.100</td>
<td>0.106</td>
<td>0.119</td>
<td>0.150</td>
<td>0.212</td>
</tr>
</tbody>
</table>
PROBABILISTIC FAILURE ANALYSIS
Uncertainty in Component Capacities

Foundation Capacity:

Axial capacity:

\[ \mu_{RFa} = \mu_q A_P + \mu_f A_S \]

<table>
<thead>
<tr>
<th>Axial Pile Capacity in</th>
<th>Bias</th>
<th>C.O.V.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sand</td>
<td>0.9</td>
<td>0.47 - 0.56</td>
</tr>
<tr>
<td>Clay</td>
<td>1.3 - 3.7</td>
<td>0.32 - 0.53</td>
</tr>
</tbody>
</table>

Lateral capacity in clay:

\[ \mu_{RFI} = \frac{1}{2} [ -27 D^2 \mu_{Su} + (27 D^2 \mu_{Su})^2 + 144 \mu_{Su} D (\mu_{fy} - Q/nA) Z]^{0.5} + \mu_{RL} \]

Lateral capacity in sand:

\[ \mu_{RFI} = 2.382 (\mu_{fy} - Q/A_P) Z^{2/3} (\mu_{y} D \tan^2(45 + \mu\phi/2))^{1/3} + \mu_{RL} \]

<table>
<thead>
<tr>
<th>Lateral Capacity in</th>
<th>Bias</th>
<th>C.O.V.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Clay</td>
<td>0.92</td>
<td>0.20</td>
</tr>
<tr>
<td>Sand</td>
<td>0.81</td>
<td>0.21</td>
</tr>
</tbody>
</table>
# Probabilistic Failure Analysis

**Example Application**

<table>
<thead>
<tr>
<th>s</th>
<th>$\bar{H}_m$ (feet)</th>
<th>$\sigma_{H_m}$ (feet)</th>
<th>Type</th>
<th>$P_{AR2}$</th>
<th>$P_{AR1}$</th>
<th>$P_{Largest}$</th>
<th>$P_{Largest}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.11</td>
<td>34.0</td>
<td>11.4</td>
<td>Lognormal</td>
<td>34.5</td>
<td>11.7</td>
<td>28.9</td>
<td>3.49</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>END-ON LOADING</th>
<th>SHEAR (KIPS)</th>
<th>RESIST. BIAS</th>
<th>C.O.V.</th>
<th>FORM</th>
<th>SORR</th>
<th>FORM</th>
<th>SORR</th>
</tr>
</thead>
<tbody>
<tr>
<td>DECK LEGS</td>
<td>120</td>
<td>0.83</td>
<td>1.03</td>
<td>0.11</td>
<td>4.10</td>
<td>0.11</td>
<td>4.10</td>
</tr>
</tbody>
</table>

| JACKET | BAY1 | 404 | 0.83 | 1.03 | 0.10 | 3.28 | 2.39 |
| BAY2 | 409 | 0.83 | 1.03 | 0.10 | 3.28 | 2.39 |
| BAY3 | 494 | 0.83 | 1.03 | 0.10 | 3.28 | 2.39 |
| BAY4 | 515 | 0.83 | 1.03 | 0.10 | 3.28 | 2.39 |

| FOUNDATION | LATERAL | 520 | 0.83 | 1.03 | 0.10 | 3.28 | 2.39 |
| AXIAL | 855 | 0.83 | 1.03 | 0.10 | 3.28 | 2.39 |

| Upper Bound | 0.056 | 1.59 |
| Lower Bound | 0.038 | 1.78 |

$P_t$ = 0.038

40
PROBABILISTIC FAILURE ANALYSIS
Summary and Conclusions

- A simplified procedure is presented to perform structural reliability analysis of conventional, steel jacket, offshore platforms, which can be used in the process of reassessment and requalification of older platforms.

- The analysis is based on a first order second moment approach.

- It is assumed that the loads and capacities are lognormally distributed.

- The results from the simplified FOSM analysis are in good agreement with those gained from more sophisticated first order and second order reliability methods (FORM and SORM).
PROBABILISTIC FAILURE ANALYSIS
Future Work

- Considering correlations between load and resistance
- Including the uncertainty associated with joint capacities
- Integrating the reliability analysis procedure in "ULSLEA"
Verification of Screening Methodologies for Use in Gulf of Mexico Platform Requalifications

Kenneth J. Loch
Project Objectives

- To further develop and verify the viability of Level 2 screening methods
- To utilize hurricane Andrew platform survival and failure experiences to help verify Level 4 non-linear analyses
Project Scope
Jan. 94 - Dec. 94

- Amoco ST 161A
- PMB Benchmark
- Chevron ST 151H
- Chevron ST 151K
- Report
Verification Case Study Status

- Amoco ST 161A - completed
- PMB Benchmark - completed
- Kerr McGee ST 34-2,3 - completed
- Kerr McGee ST 34-4 - completed
- Chevron ST 151H - data available
- Chevron 151K - data available
- Shell SP 62 - data available
- Shell SS 274 - data available
- Phillips SMI 76B - data available
- Phillips NCI - A - data available
- others (Mobil, Unocal, Exxon)
General Description

- Eight leg drilling and production platform
- Designed by McDermott using 25-year Glenn storm (H=55 ft.)
- Installed in 118 ft of water in 1964
- Broadside and end-on framing battered at 1:8
- Cellar and main decks at +34 ft and +47 ft respectively
Platform Details

- No joint cans (0.5 in. jacket leg thickness)
- Gusset plates used for leg K-joints
- $F_y = 43$ ksi or 58 ksi
- 36 in. piles penetrate 165 ft of soft to stiff clay and 25 ft of dense sand
- Vertical braces range in size from 14 in. in the fourth (upper) bay to 20 in. in the first bay
Platform History

◆ 1972: First risk analysis performed
◆ 1973: Pile-leg annulus grouted as a result of assessment
◆ 1974: Hurricane Carmen
  • eye passed within 10 miles of platform
  • hindcast 58 ft wave, SE, no damage
◆ 1988: Risk analysis, all eight conductors removed, bottom deck cleared
Platform History Continued

- 1992: Hurricane Andrew
  - eye passed within 8 miles of platform
  - 60-64 ft waves, ESE
  - yielding in +10 ft K-joints, no grout
- 1992: Risk analysis and retrofits
  - 10% more load would cause collapse
  - conductor removal reduces loads by 20%
  - +10 ft K-joints grouted
Level 4 Analysis

- Static pushover analysis
- Utilized Amoco's 1992 USFOS model
- WAJAC generated hydrodynamic loads
- Broadside and end-on analyzed separately to match Level 2 approach
USFOS Model

- Only major structural members modeled
- Grouted pile/leg member used leg diameter (39 in.) and double the leg thickness (1.0 in.)
- Initial imperfection based on Chen’s buckling curve for critical braces
- PMB PAR program developed non-linear springs, but T-Z and Q-Z modeled as equivalent linear springs
- Rigid joints assumed due to grout
Isometric
Broadside Elevation
End-on Elevation
Loading Information

- Assumed marine growth = 1.5 in.
- $Cd = 1.2$
- $Cm = 1.2$
- $w_{kf} = 0.88$
- Broadside loading
  - $H = 64$ ft, $T = 13.3$ sec.
  - In-line current = 31 in/sec, $cbf = 0.80$
- End-on loading
  - $H = 72$ ft, $T = 14.6$ sec
  - In-line current = 2.6 in/sec, $cbf = 0.70$
Loading Profiles

ST 161A Broadside Shear Profile

ST 161A End-On Shear Profile

Amoco ST 161A
Broadside Force-Displacement History

Maximum base shear = 3,861 kips
Broadside Failure Progression
Broadside Critical Brace Axial Force History

Values normalized by plastic capacity
Broadside Critical Brace P-M Interaction

Values normalized by plastic capacity
End-on Force-Displacement History

Maximum base shear = 3,905 kips
End-on Failure Progression
End-on Critical Brace Axial Force History

Values normalized by plastic capacity
End-on Critical Brace P-M Interaction

Values normalized by plastic capacity
Comparison with Actual Platform Performance

◆ ST 161A survived 60-64 ft waves 15° off broadside during Andrew
◆ USFOS model predicts first member failure at 91% of load from 64 ft broadside wave
◆ Deck loads are very significant and hence loading is very sensitive to wave height and surge
◆ Imperfection and member orientation combination is realistic but conservative

◆ Conclusion: USFOS model would predict survival during likely Andrew loading
VERIFICATION CASE STUDIES
Level 2 Results (AMOCO'S ST161A)

BROADSIDE LOADING

\[ \text{H} = 64 \text{ ft}; \quad \text{T} = 13.3 \text{ sec}; \quad \text{U}_c = 2.6 \text{ ft/sec} \]

<table>
<thead>
<tr>
<th></th>
<th>Level 4 (SESAM)</th>
<th>Level 2 (ULSLEA)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Base shear (kips)</td>
<td>4,252</td>
<td>4,428</td>
</tr>
<tr>
<td>Jacket Load (kips)</td>
<td>2,510</td>
<td>2,586</td>
</tr>
</tbody>
</table>

BROADSIDE LOADING

![Graph showing storm shear capacity and platform elevation](image-url)

**STORM SHEAR / PLATFORM SHEAR CAPACITY (KIPS)**
VERIFICATION CASE STUDIES
Level 2 Results (AMOCO'S ST161A)

BROADSIDE LOADING

<table>
<thead>
<tr>
<th></th>
<th>Level 4 (USFOS)</th>
<th>Level 2 (ULSLEA)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Base shear at collapse (kips)</td>
<td>3,861</td>
<td>3,670</td>
</tr>
</tbody>
</table>

BROADSIDE LOADING

STORM SHEAR / PLATFORM SHEAR CAPACITY (KIPS)
VERIFICATION CASE STUDIES
Level 2 Results (AMOCO'S ST161A)

END-ON LOADING

$H = 72 \text{ ft}; \ T = 14.6 \text{ sec}; \ U_c = 0 \text{ ft/sec}$

<table>
<thead>
<tr>
<th></th>
<th>Level 4 (SESAM)</th>
<th>Level 2 (ULSLEA)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Base shear (kips)</td>
<td>3,487</td>
<td>3,814</td>
</tr>
<tr>
<td>Jacket Load (kips)</td>
<td>2,252</td>
<td>2,579</td>
</tr>
</tbody>
</table>

END-ON LOADING

![Graph showing storm shear, SWL, and mudline capacities](image-url)
VERIFICATION CASE STUDIES
Level 2 Results (AMOCO'S ST161A)

END-ON LOADING

<table>
<thead>
<tr>
<th></th>
<th>Level 4 (USFOS)</th>
<th>Level 2 (ULSLEA)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Base shear at collapse</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(kips)</td>
<td>3,905</td>
<td>3,128</td>
</tr>
</tbody>
</table>

END-ON LOADING

STORM SHEAR / PLATFORM SHEAR CAPACITY (KIPS)
PMB Benchmark Platform
General Description

◆ Four leg platform in Ship Shoal area
◆ Installed in 157 ft of water in 1970
◆ Broadside and end-on framing battered at 1:11
◆ Decks located at +33 ft, +43 ft, +56 ft and +71.5 ft
◆ Three 30 in. and one 48 in. conductors are located in northern half of platform
◆ Boatlandings on east and south sides
Platform Details

- Jacket is identical for both primary orthogonal directions
- Legs thickened at joint, 1.25 in. vs. 0.5 in.
- $F_y = 43$ ksi all members
- 36 in. piles penetrate 355 ft of soft to stiff clay and 28 ft of silty sand (at -197 ft)
- Vertical braces range in size from 16 in. in the seventh (upper) bay to 20 in. in the first bay
Level 4 Analysis

- Static pushover analysis
- WAJAC generated hydrodynamic loads
- Rigid and flexible foundation assumptions both analyzed
USFOS Model

- Only major structural members modeled
- Pile/leg annulus ungrouted, thus, jacket joints slaved transversely to pile members. Piles, jacket and deck legs rigidly connected at top
- Initial imperfection based on Chen’s buckling curve for critical braces
- Non-linear soil springs developed using API guidelines (static)
- Rigid joints assumed due to thickened sections
Orientation

True North

Platform North

45°

X

Y

30 ft on center

30 ft on center

PMB Benchmark
Isometric
Side Elevation
Loading Information

- Assumed marine growth = 1.5 in.
- Cd = 1.2
- Cm = 1.2
- wkf = 0.88
- Broadside loading
  - $H = 67 \text{ ft, } T = 14.3 \text{ sec.}$
  - In-line current = 37 in/sec, cbf = 0.80
Force-Displacement History

Maximum base shear = 1,673 kips

PMB Benchmark
Failure Progression

1

2

3

PMB Benchmark
Compression T-Z and Q-Z Soil Spring Force History
Fixed Base Force-Displacement History
(Dynamic Pile Capacity Case)

Maximum base shear = 3,440 kips
Fixed Base Failure Progression

1  2  3

4  5  6

PMB Benchmark
Fixed Base Critical Brace Axial Force History

Values normalized by plastic capacity

PMB Benchmark
Fixed Base Critical Brace
P-M Interaction

Values normalized by plastic capacity

PMB Benchmark
Research Plans for Next Three Months

- Analyze and document Chevron ST 151H and Chevron ST 151K
- Investigate sensitivity of Level 4 analysis results to input parameters:
  - $F_y$
  - vertical deck forces
  - soil spring assumptions (cyclic, static and dynamic)
- Document benefits and pitfalls of Level 4 analyses based on research experience
- Write final report
VERIFICATION CASE STUDIES
Level 2 Results (Benchmark Structure)

\[ H = 67 \text{ ft}; \quad T = 14.3 \text{ sec}; \quad U_c = 3.1 \text{ ft/sec} \]

<table>
<thead>
<tr>
<th></th>
<th>Level 4 (SESAM)</th>
<th>Level 2 (ULSLEA)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Base shear (kips)</td>
<td>2,656</td>
<td>3,055</td>
</tr>
<tr>
<td>Jacket Load (kips)</td>
<td>2,279</td>
<td>2,678</td>
</tr>
</tbody>
</table>

END-ON LOADING

STORM SHEAR / PLATFORM SHEAR CAPACITY (KIPS)
VERIFICATION CASE STUDIES
Level 2 Results (Benchmark Structure)

<table>
<thead>
<tr>
<th></th>
<th>Level 4 (USFOS)</th>
<th>Level 2 (ULSLEA)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Base shear at collapse</td>
<td>3,440</td>
<td>3,212</td>
</tr>
<tr>
<td>with fixed base (kips)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

END-ON LOADING

STORM SHEAR / PLATFORM SHEAR CAPACITY (KIPS)
VERIFICATION CASE STUDIES
Level 2 Results (Benchmark Structure)

AXIAL PILE CAPACITY

END-ON LOADING   BROADSIDE LOADING

RSR

- COMPRESSION
- TENSION

0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1.0
<table>
<thead>
<tr>
<th>Case #</th>
<th>Configuration</th>
<th>Wave Direction</th>
<th>Level 2 Analysis</th>
<th>Level 4 Analysis</th>
<th>Ratio USFOS/SCREEN</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Failure Mode</td>
<td>Base Shear (kips)</td>
<td>Failure Mode</td>
</tr>
<tr>
<td>1</td>
<td>8 leg double battered</td>
<td>End-on</td>
<td>1st jacket bay</td>
<td>2,860 (2,700)</td>
<td>1st jacket bay</td>
</tr>
<tr>
<td></td>
<td>K-braced</td>
<td>Broadside</td>
<td>2nd jacket bay</td>
<td>2,900</td>
<td>2nd jacket bay</td>
</tr>
<tr>
<td>2</td>
<td>8 leg double battered</td>
<td>End-on</td>
<td>1st jacket bay</td>
<td>3,128</td>
<td>1st jacket bay</td>
</tr>
<tr>
<td></td>
<td>K-braced</td>
<td>Broadside</td>
<td>1st jacket bay</td>
<td>3,670</td>
<td>1st jacket bay</td>
</tr>
<tr>
<td>3</td>
<td>4 leg double battered</td>
<td>End-on</td>
<td>4th, 5th and 6th</td>
<td>3,212</td>
<td>5th and 6th jacket bays</td>
</tr>
<tr>
<td></td>
<td>K-braced</td>
<td></td>
<td>Foundation</td>
<td>1,955 (1,740)</td>
<td>Foundation</td>
</tr>
</tbody>
</table>

* Including the shear in jacket legs
** Including the platform selfweight
Peter Young
Graduate Student Researcher

and

Professor Robert Bea

Department of Civil Engineering
University of California at Berkeley

7th October 1994
OBJECTIVE

Given two roughly identical wellhead protectors subjected to Hurricane Andrew storm shears, determine ability to predict the observed performance of the two structures:

- Wellheads Protector 2 and 3 (WP2/3) collapsed

- Wellhead Protector 4 (WP4) suffered no significant damage.
THREE APPROACHES TO DETERMINE RESPONSE

- Linear Elastic Analysis Using StruCAD*3D
  - Piles fixed $\approx 5$ pile diameters below mudline
  - Approximate linear springs at mudline
  - Nonlinear soil-structure interaction along length of the piles

- Ultimate Limit State Limit Equilibrium Analysis (ULSLEA)

- Nonlinear Static Pushover Analysis Using Usfos
  - Piles pinned at mudline
  - Nonlinear Winkler soil springs
STRUCTURAL CHARACTERISTICS

- Wellheads Protector 2 and 3 (WP2/3)
  - 52' mean water depth (MWL)
  - Oriented -45° from true north
  - 2 exterior well caissons (36"ø)

- Wellhead Protector 4 (WP4)
  - 49' MWL
  - Oriented parallel to true north
  - 1 interior well caisson (36"ø)
3D ISOMETRIC OF WP2/3
SOIL CHARACTERISTICS

- Upper Layer of Weak Clays (to depth of 64')
  Shear Strengths = 0.31-0.50 ksf

- Intermediate Layer of Clays (64' to 172')
  Shear Strengths = 0.5-1.5 ksf

- Underlying Layer of Stiff Sands (below 172')
  Shear Strength = 2.0 ksf
WIND, WAVE AND CURRENT CHARACTERISTICS

- ABS wind profile with maximum velocity of 98 knots

- 40' maximum wave height
  - 9.5 second wave period
  - Stream Function 9th Order wave theory

- Constant 6 ft/sec current over water depth

- $C_d = 1.2$ accounts for marine growth

- Maximum Surge and Tide of 3'
BS BASE STORM SHEAR VS. DISTANCE TO ORIGIN

![Graph showing storm shear vs. distance to origin with curves for WP2/3 and WP4.](image)
3D DEFLECTED ISO OF WP2/3
Broadside Loading
3D DEFLECTED ISO OF WP2/3
End On Loading
3D DEFLECTED ISO OF WP4
Broadside Loading
3D DEFLECTED ISO OF WP4
End On Loading
WP2/3 ANALYSES

END-ON LOADING

BROADSIDE LOADING

STORM SHEAR / PLATFORM SHEAR CAPACITY (KIPS)
WP4 ANALYSES

END-ON LOADING

STORM SHEAR / PLATFORM SHEAR CAPACITY (KIPS)

BROADSIDE LOADING

STORM SHEAR / PLATFORM SHEAR CAPACITY (KIPS)
AXIAL PILE CAPACITIES

WP2/3

EO LOADING

BS LOADING

WP4

EO LOADING

BS LOADING
COMPARISON OF USFOS PINNED PILE ANALYSES

WP2/3 Global P-Δ

WP4 Global P-Δ
COMPARISON OF USFOS SOIL SPRING ANALYSES

WP2/3 Global P-Δ

WP4 Global P-Δ

Global Displacement (in)

Global Shear (kips)
# Comparison of Storm Shears from Three Analyses

<table>
<thead>
<tr>
<th>Analysis</th>
<th>WP2/3 EO</th>
<th>WP2/3 BS</th>
<th>WP4 EO</th>
<th>WP4 BS</th>
</tr>
</thead>
<tbody>
<tr>
<td>StruCad</td>
<td>1199</td>
<td>1299</td>
<td>1036</td>
<td>1088</td>
</tr>
<tr>
<td>ULS 1</td>
<td>1218</td>
<td>1322</td>
<td>1000</td>
<td>1110</td>
</tr>
<tr>
<td>ULS 2</td>
<td>1355</td>
<td>1474</td>
<td>1119</td>
<td>1244</td>
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<tr>
<td>Usfos</td>
<td>1141</td>
<td>1233</td>
<td>1036</td>
<td>1071</td>
</tr>
</tbody>
</table>

ULS 1 - ULSLEA with current mass transport
ULS 2 - ULSLEA without current mass transport
CAPACITY COMPARISON BETWEEN ULSLEA AND USFOS

Capacities

<table>
<thead>
<tr>
<th></th>
<th>WP2/3</th>
<th>WP4</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>EO</td>
<td>BS</td>
</tr>
<tr>
<td>Analysis</td>
<td>1320</td>
<td>1521</td>
</tr>
<tr>
<td>ULSLEA</td>
<td>919</td>
<td>1178</td>
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</tbody>
</table>

Reserve Strength Ratios

<table>
<thead>
<tr>
<th></th>
<th>WP2/3</th>
<th>WP4</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>EO</td>
<td>BS</td>
</tr>
<tr>
<td>Analysis</td>
<td>0.974</td>
<td>1.032</td>
</tr>
<tr>
<td>ULSLEA</td>
<td>0.806</td>
<td>0.955</td>
</tr>
</tbody>
</table>
### Dynamic Soil Spring Shear Capacities

<table>
<thead>
<tr>
<th>Loading</th>
<th>Wells 2 and 3</th>
<th></th>
<th>Well 4</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>LF</td>
<td>Shear</td>
<td>LF</td>
<td>Shear</td>
</tr>
<tr>
<td>EO</td>
<td>1.088</td>
<td>1242</td>
<td>1.205</td>
<td>1249</td>
</tr>
<tr>
<td>BS</td>
<td>1.289</td>
<td>1590</td>
<td>1.333</td>
<td>1427</td>
</tr>
</tbody>
</table>

### Andrew Storm Shear to Capacity Comparison

<table>
<thead>
<tr>
<th>Time</th>
<th>Storm</th>
<th>Below Capacity</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>R main</td>
</tr>
<tr>
<td>CDT</td>
<td>EO</td>
<td>1070</td>
</tr>
<tr>
<td></td>
<td>BS</td>
<td>194</td>
</tr>
<tr>
<td>WP2/3</td>
<td></td>
<td>1070</td>
</tr>
<tr>
<td>WP4</td>
<td>EO</td>
<td>392</td>
</tr>
<tr>
<td>WP4 Br</td>
<td>EO</td>
<td>430</td>
</tr>
</tbody>
</table>
CONCLUSIONS

- Pile Foundation Capacities of Primary Concern
  - Low stiffness and inherent lack of redundancy is not compensated by lateral soil resistance
  - Piles form soft-story failure mechanism
  - Caissons prevent full formation of mechanism and induce pile pullout

- Likely Failure of WP2/3 Due To:
  - Additional caisson stiffness induces pile pullout quicker
  - Principal storm wave loadings parallel to end on structural orientation

- Likely Survival of WP4 Due To:
  - Lower storm shears due to lower water depth and wave breaking
  - Principal storm wave loadings roughly between end on and broadside directions
• Analyze Shell SP62 Platform Using Usfos

• Analyze Phillips/Mobil/Unocal/Exxon Platforms Using Usfos

• Analyze Dynamic Response of Single Well Caissons to Hurricane Andrew

• Perform Parametric Analyses

• Document Results
PLANS FOR NEXT SIX MONTHS AND MEETING

- Finalizing the verification case studies
- Finalizing the work on Jacket-bays’ lower and upper-bound capacities
- Finalizing the damaged and repaired element algorithms (corrosion, holes, joint cracks) and integrating them in SCREEN
- Finalizing and integrating the reliability analysis procedures in SCREEN
- Further automating the input and developing a graphical input check for SCREEN
- Finalizing SCREEN (completion, calibration, and revision) based on the latest research developments and sponsors’ suggestions
- Next meeting proposed during April 1995