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COMPARISON OF SCR FIELD RESPONSE WITH ANALYTICAL PREDICTIONS

Yiannis Constantinides
Chevron
Houston, Texas, USA

Jen-hwa Chen
Chevron
Houston, Texas, USA

Lee Tran
2H Offshore
Houston, Texas, USA

Prahlad Enuganti
2H Offshore
Houston, Texas, USA

Mike Campbell
2H Offshore
Houston, Texas, USA

ABSTRACT

Design of deepwater risers involves the use of multiple conservative design parameters to account for the uncertainty in the understanding of the behavior of complex structures. As the oil industry moves into deeper and harsher waters, the design tolerances are getting stretched. Chevron has been monitoring the structural response of a deepwater Gulf of Mexico steel catenary riser (SCR) to improve the understanding of riser behavior and to evaluate the existing analysis and design methodologies against actual field measurements.

The following paper presents a selected set of results from benchmark of SCR response in storm conditions against analytical predictions, based on industry standard methodologies. The predictions are based on a finite element analysis (FEA) modeling of the riser structure with empirically formulated models for hydrodynamics and soil-structure interaction. Predicted riser response in terms of accelerations and stresses along the length are compared against field measurements showing good overall agreement.

INTRODUCTION

Chevron is successfully monitoring the structural response of one of the deepwater production risers in the Gulf of Mexico. In addition to riser monitoring, the vessel motions and metocean information is also monitored. Aside from integrity management, the goal of the monitoring systems is to provide field measurements to support research and development efforts. The current program focuses on understanding the basic mechanics of steel catenary riser (SCR) response and to validate the analysis methodology and assumptions used for design.

With exploration moving into deeper water, under challenging design conditions, there is a strong need to assess the existing design methodology and assumptions and potentially refine it. The standard analysis model for SCR design is based on simplified empirically derived models for soil-structure interaction and hydrodynamics, using a finite element analysis (FEA) riser model. These models were derived using either laboratory scale experiments or limited section field tests. There is limited validation against model scale experiments and none against full scale in field monitored data.

There is a history of research in this area, especially in the early development stages of the SCR concept. One of the first efforts that studied dynamic response of SCRs was the Highly Compliant Riser (HCR) Joint Industry Project [1]. The program included a series of model tests to understand SCR and other riser type response. The tests were conducted in a lake using a small scale diameter aluminum pipe, with a characteristic aspect ratio of a deepwater riser, using an idealized hard seafloor. Motions were applied at the top of the pipe to simulate vessel motions and the response was captured by a series of strain-gauges. The project combination of analysis and testing resulted in an initial understanding of SCR response in idealized conditions. A number of prediction tools, mostly finite element based, were benchmarked against the tests with various degrees of success.

Following the HCR work, the STRIDE joint industry project [2] conducted a full scale test program to investigate the effects of seabed riser interaction on SCR response and stresses. The tests were carried out at a tidal harbor with seabed properties similar to those of deepwater Gulf of Mexico. A short section of a near full scale steel pipe was tested, representing the touch-down section of an SCR. The tests provided a valuable understanding of SCR soil interaction and produced models to predict this response.

Previous programs collected valuable information in either model scale laboratory tests with ideal seafloor conditions or larger scale riser section with characteristic seafloor conditions. The current program closes the gap by obtaining actual SCR measurements, large scale in field conditions. This study is focused on the validation of analysis methodologies by comparing field measurements against software predictions. A parallel paper describes the analysis of field measurement to understand SCR response [6].

RISER AND MONITORING SYSTEM DESCRIPTION

Riser System

The monitored riser is an oil production SCR located deepwater Gulf of Mexico at a depth of 4000 ft. It consists of a 9.625" steel pipe with a 2" thermal insulation and VIV suppression strakes throughout the length of the riser.

Riser Monitoring System

The production SCR is instrumented with motion and strain measurement devices distributed between hang-off and touchdown zones. The motion measurement devices (INTEGRIpod) measure the riser acceleration in 3 directions and angular rates in 2 planes. The strain measurement devices (INTEGRIstick) measure bending strain in 2 planes. The location of all the sensors is shown in Figure 1. A total of 8 data channels of fully synchronized data are continuously collected from each monitoring device at a sampling frequency of 10 Hz. A more detailed description of the system can be found in [3].

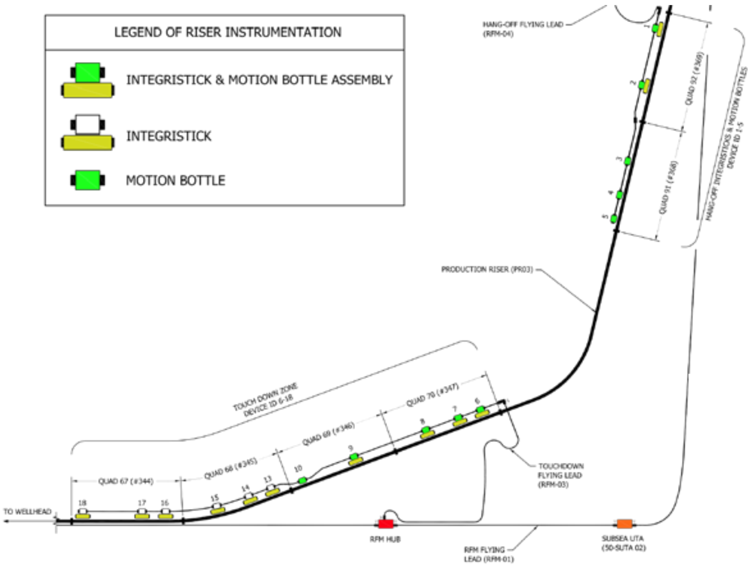

Figure 1: Monitoring system description and device location.

Figure 2: Monitoring device located at SCR touch down zone.

Environmental and Facilities Monitoring System (EFMS)

The production facility where the SCR is located is equipped with a continuous vessel monitoring system. The system monitors the high order vessel motion through a 6DOF accelerometer based instrumentation and the low order motions through a GPS. In addition to the vessel motions the system also monitors wind, wave and current.

DATA PROCESSING AND ANALYSIS METHODOLOGY

The primary objective of this study is to benchmark the riser response predicted by riser design software against field measured riser response. The ideal methodology to benchmark riser design software is to drive the riser FEA model with measured vessel 6dof motions and compare predictions of riser response along the length against field measurements. However, following a benchmarking feasibility assessment, it has been determined that for seastates studied in this work, there isn't sufficient signal to noise ratio in the vessel 6DOF measurements to reliably drive the riser model. A further discussion on this matter can be found in [4]. The riser benchmarking was thus performed using riser motions derived from the topmost hang-off monitoring device (device 1) located 130ft from the riser attachment point, to drive the FEA model and obtain predictions of riser response along the length.

The goal is to obtain a level of confidence in the software predictions and calculate the bias between measurements and analysis predictions. The software benchmarking activity is broken down into the following steps:

- Convert riser accelerations and angular rates measured in the local monitoring device coordinate system into riser accelerations in the global coordinate system. The global riser accelerations at device 1 locations are transformed to obtain riser displacements in the global coordinate system. The derived riser motions at device 1 location are wave frequency motions used to drive the riser FEA model and determine riser response along length;
- Analyze the measured riser strain readings and transform them into the global riser plane;
- Drive the FEA model using the wave frequency and vessel motions from the riser top device in conjunction with vessel offset and low frequency motions;
- Compare measured riser accelerations at device locations against FEA predictions at corresponding locations;

- Compare measured riser stresses along length at monitoring device location against FEA predictions at corresponding locations;
- Perform benchmarking on a variety of events and assemble the results for statistical analysis to determine bias and partial safety factors.

Due to the small values of current speed observed in the benchmark events no current was included in the simulations. The wave loading on the riser was also assumed small and was not modeled. The riser hang-off starts around 600ft below the surface where the wave load is very small as it diminishes exponentially with depth.

Derivation of Riser Motions in Global Coordinate System from Accelerometer Measurements

The SCR has 10 motion measurement stations distributed along its length: 5 at the Hang-off zone and 5 at the touch down zone (TDZ). The acceleration measurement station assembly at each location is installed such that the motion bottle is at 12 degrees offset from top dead center of the SCR and the strain measurement station is aligned with the top dead center of the riser. Here, top dead center is defined as the topmost point along the riser circumference.

It is observed that the riser torsionally rotates from the initial position and continues to rotate during each production start-up and shut-down operation. Therefore, the angle of each monitoring station axis is calculated based on mean acceleration measurements at each monitoring station and accounted for in the coordinate system transformation.

As the riser motions at each location are dynamic with several degrees of freedom and no initial frame of reference, a methodology is derived to obtain riser motions in the global frame of reference. The key features of the coordinate transformation methodology in measured accelerations are:

- Initial angles of each measurement station's inclination and rotation are calculated from mean values of X, Y, and Z accelerometer measurements;
- Acceleration measurements at each monitoring station location are filtered to reduce noise:
    - High pass filter at 0.013Hz (75 seconds period) on all accelerometers and angular rate sensors;
    - Low pass filter at 1Hz (1 second period)
- Obtain transformation matrix that rotates the coordinate system from one time step to the next using angular rates.

The coordinate transformation removes the contamination of the accelerometer dynamic measurement by the gravity component also referred as g-contamination. As the sensor inclination (*θ)* changes, the static gravity component projection *g*cos(θ)* changes contaminating the measurements with a false dynamic contribution. G-contamination is removed from the motion time trace via step-wise extrinsic rotations using Euler angles at different time steps using the following equation described in detail in [5]:

$$\begin{Bmatrix} Surge \\ Sway \\ Heave \end{Bmatrix}^{@\,t_n} = \begin{bmatrix} \cos\theta\cos\alpha & -\cos\theta\sin\alpha & \sin\theta \\ \sin\alpha & \cos\alpha & 0 \\ -\sin\theta\cos\alpha & \sin\theta\sin\alpha & \cos\theta \end{bmatrix} \begin{bmatrix} a_{11} & a_{12} & a_{13} \\ a_{21} & a_{22} & a_{23} \\ a_{31} & a_{32} & a_{33} \end{bmatrix}^{@\,t_1} \Box \begin{bmatrix} a_{11} & a_{12} & a_{13} \\ a_{21} & a_{22} & a_{23} \\ a_{31} & a_{32} & a_{33} \end{bmatrix}^{@\,t_n} \begin{Bmatrix} X \\ Y \\ Z \end{Bmatrix}^{@\,t_n}$$

The global coordinate system is referred to as surge, sway and heave axis with X,Y,Z being the measured accelerations or motions and α,θ the measured angles corresponding to rotations about X and Y axis. The new matrix a_{ij} is solved and updated at each time step with the readings rotated back into the global coordinate system. All accelerations are double integrated to obtain displacements. Detailed description of the methodology, formulation and procedure is presented in Li et al. [5].

The accelerometer-derived motions are subsequently combined with the low order offset motions from the vessels monitoring system to drive the riser analysis model. The SCR top offset and low frequency motions are important as they affect the location of the touch down point (TDP) and since the accelerometers don't capture these motions, the GPS measurements are used to add these effects.

Riser Stresses from strain measurements

The torsional orientation of the strain measurement stations is accounted for and the strains are transformed into SCR in-plane and out-of-plane components. In this study we present only comparisons with the in-plane components, being more important for design. The strains are converted to stresses and appropriate filtering is applied similar to the accelerometers.

Riser analysis model and methodology

The objective of this study is to evaluate the analysis methodologies typically used for SCR design. The methodology and model used is consistent with the design model that is typical to what is used in the industry. The riser dynamics are modeled using the FEA software FLEXCOM. The structural dynamics are modeled using a second order FEA formulation with the hydrodynamics modeled through the Morrison equation. Soil-riser dynamics are modeled using linear springs and a friction force. These quantities are obtained using site-specific geotechnical information that is processed and transformed into these linear and simplified values although the soil response is much more complex. The FEA model consists of 661 elements using a timestep of 0.1 seconds yielding adequate spatial and temporal numerical convergence. The last node of the FEA model is placed at the location of the top measurement device that provides the motion boundary conditions from field measurements.

Benchmark cases

The benchmark cases presented in this study consisted of periods with the highest measured riser response which correlated to the highest observed seastates in 2009. After careful screening, 36 30 minute cases were identified, corresponding to wave intensities up to the equivalent of a 10-yr winter storm for the Gulf of Mexico. These are often referred to as fatigue seastates as fatigue is dominated by their frequent occurrence and are important riser fatigue damage contributors.

BENCHMARK OF RISER ACCELERATIONS AGAINST ANALYSIS PREDICTIONS

The FEA riser model is driven using riser hang-off motions calculated at the device 1 location using methodology listed in the previous section. The analysis predictions of riser accelerations at other riser monitoring system locations are compared against corresponding device measurements.

The analysis predicted riser accelerations at hang-off device 3 location are compared against device 3 measurements in the heave, surge and sway axis, as shown in Figure 3. The predicted and measured heave accelerations correlate extremely well with measurements in both amplitude and phase. The surge and sway analysis accelerations are comparable in amplitude but the phasing is not entirely consistent throughout the time trace. The heave acceleration spectra at device 3 also shows a good correlation between measurements and analysis predictions, as shown in Figure 4.

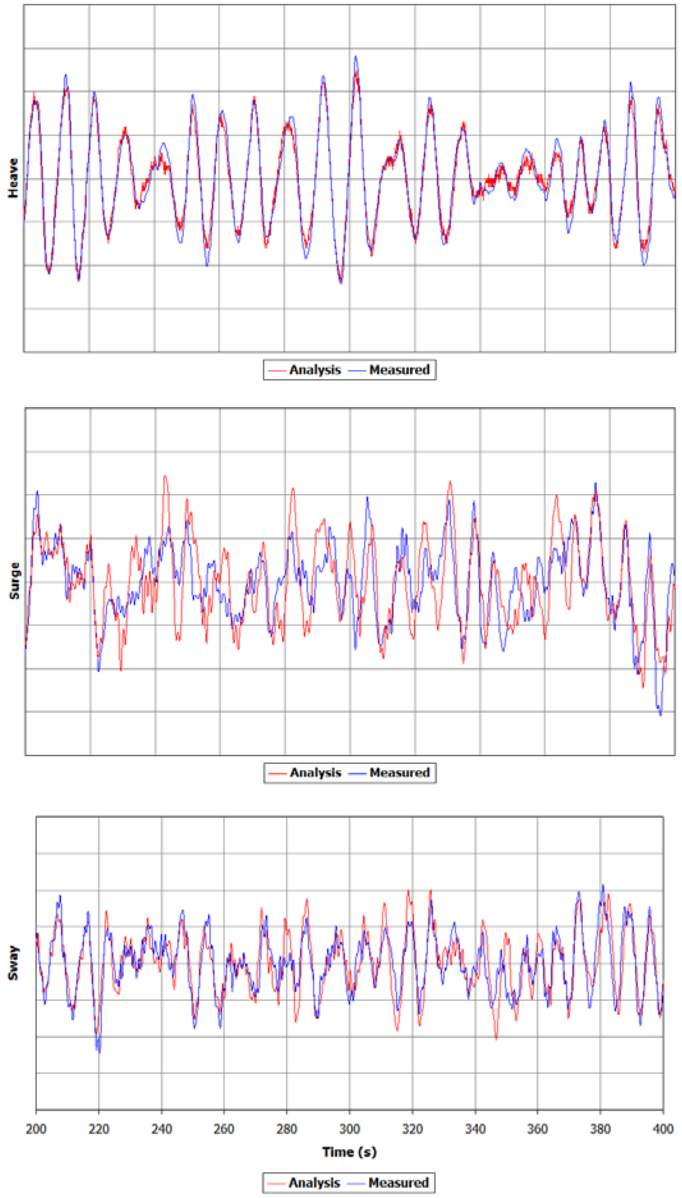

Figure 3: Riser acceleration comparison of measurements against analysis predictions at hang-off device 3 location.

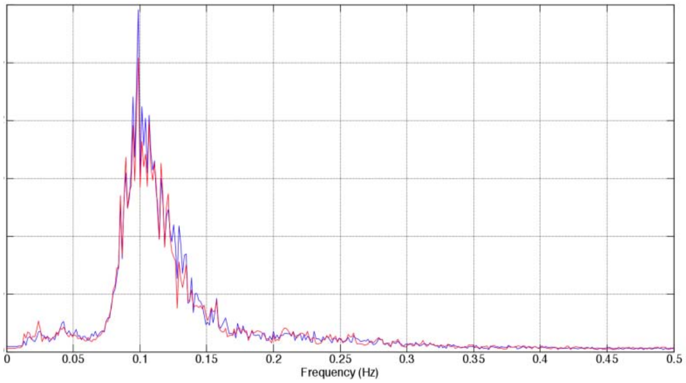

Figure 4: Heave acceleration comparison of hang-off device 3. Measurements illustrated with blue lines and analysis with red.

Riser TDZ accelerations are also analyzed during the same period to benchmark riser design software at the TDZ. The measured and predicted accelerations show a good correlation in both the heave and resultant accelerations, as shown in Figure 5 for the resultant values.

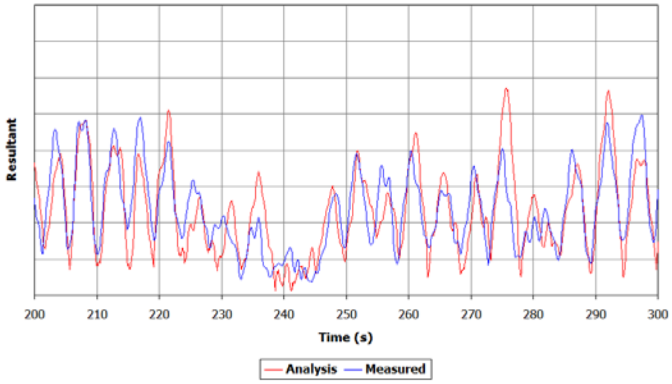

Figure 5: Resultant riser acceleration at TDZ device 8 with analysis prediction.

The resultant accelerations from analysis are compared against measured riser accelerations for all devices over all 36 benchmark periods in Figure 6. It is observed that at the hang-off, analysis predictions are either equal to the field measurements or slightly conservative, but at the TDZ, the analysis predictions are consistently more conservative than measurements.

Benchmarking of riser design software shows analysis to be conservative in predicting riser accelerations along length with an overall bias of 1.2 against field measurements.

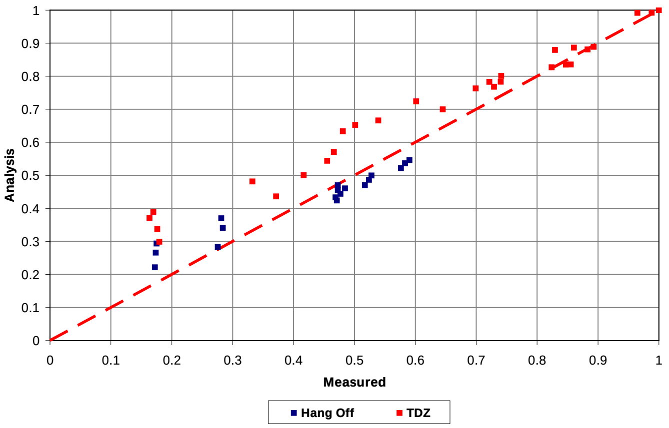

Figure 6: Resultant riser accelerations from measurements compared against analysis

BENCHMARK OF RISER STRESSES AGAINST ANALYSIS PREDICTIONS

As part of the benchmarking of riser design software, analysis predicted riser stresses are compared against field measurements at corresponding locations. As the riser stresses at TDZ vary significantly over short distances, it is critical to determine the location of the monitoring station with respect to the TDP for accurate benchmarking. This was accomplished through analysis of the riser ROV inspection videos. A zone where the touchdown point is located was identified and the range of locations was included in the analysis. The results presented in this paper are for the nominal position from ROV inspection but the results of the entire range are equally important to assess the bounds of the analysis prediction and factors of safety.

The stress time trace comparisons of analysis against field measurements at the TDP locations have a very good correlation in amplitude of response and phasing. The wave frequency filtered device 15 stresses from both field measurements and analysis results in an excellent correlation, as shown Figure 7. The remainder of stress comparisons for benchmarking are conducted in only the wave frequency range.

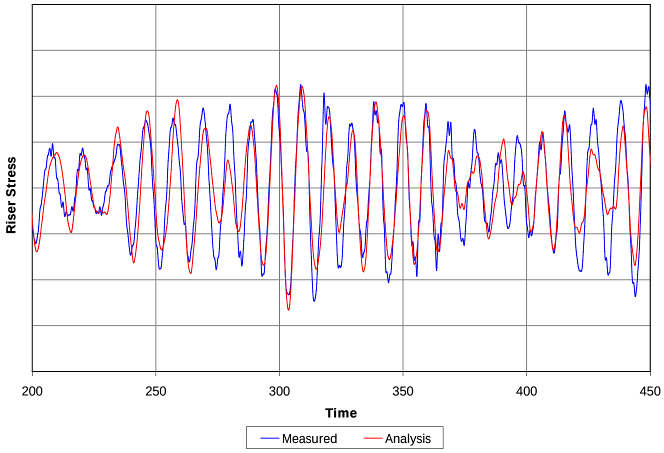

Figure 7: Stress comparison at TDP device 15 with analysis prediction

Good correlation in wave frequency response is observed in the spectras of all TDZ devices, as shown in Figure 8 for device 15. Hence excellent correlation is observed between measurements and analysis predictions for both riser accelerations and stresses.

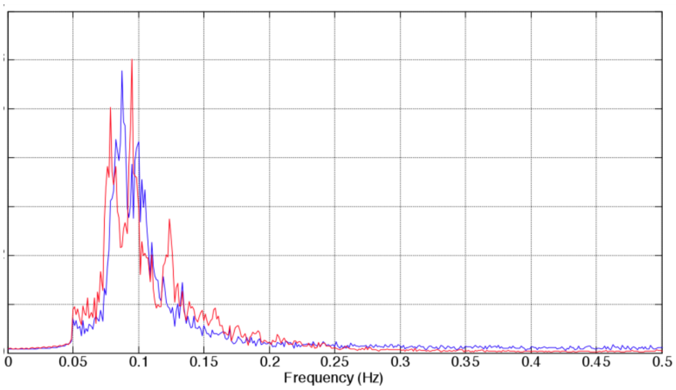

Figure 8: Stress spectrum comparison at TDP device 15 (blue) with analysis prediction (red).

The standard deviation of in-plane stress along the length of the riser is compared against measurements for various cases in Figure 9. It is observed that, for the majority of the 36 cases, the measurements are above the equality line indicating riser analysis is typically conservative in predicting riser stresses with an average bias of 1.2 for the nominal TDP location assumption. This is by using the design specific parameters without any calibration iterations.

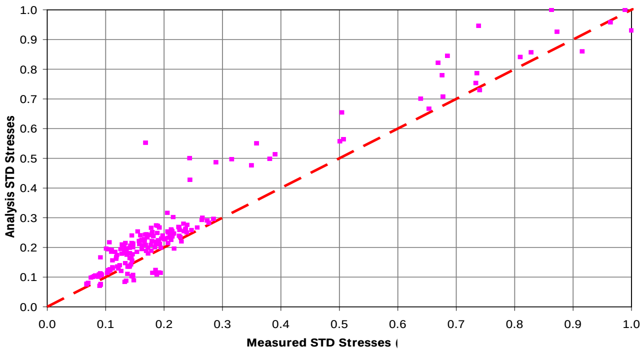

Figure 9: Comparison of normalized measured stresses with predicted along riser length for the 36 benchmark cases considered.

DISCUSION AND KEY FINDINGS

The key findings from benchmarking of riser design software are:

- Very good correlation is observed in riser accelerations between analysis predictions and field measurements, especially in heave direction. Discrepancies in surge sway phasing can be improved with refinements in the data analysis methodology.

- The resultant riser accelerations predicted by riser analysis are conservative with a bias of 1.2 when compared against measured riser response;

- Excellent correlation is observed between measured and analysis predicted riser stresses in wave frequency range;

- Riser analysis appears conservative in predicting riser stresses by a factor of 1.2 on average when compared against field measurements using the analysis methodology used in this study.

- Sensitivities and uncertainties in the analysis such as the range and location of the touchdown zone can alter the stress prediction bias. These bounds, not presented in this study, are essential to determine the bounds of prediction bias and factors of safety.

- The key factors that influence the prediction bias are the hydrodynamic coefficients (added mass and drag), the soil stiffness values and the corresponding empirical formulations used. This study suggests that the combination of these variables and models results in a conservative prediction rather than the individual values being conservative and appropriate. The paremeters used are standard for deepwater projects and no effort has been made to calibrate the models.

- The conclusions presented in this study are applicable to the range of vessel motions included in the study. For larger motions the soil-structure interaction can be different with the riser potentially pulling out of the trench instead of staying attached and embedded as the current understanding suggests.

CONCLUSIONS

The present study is an industry first effort to validate SCR analysis methodologies against field data focusing on wave loading and TDP response. A selected subset of the results from benchmark of SCR response in storm conditions against analytical predictions has been presented. The predictions of the FEA riser model with empirically formulated hydrodynamics and soil-structure models compare favorably against field measurements. Basic physics and response characteristics are captured adequately for design purposes. The predictions are on average conservative and suggest that the analysis methodology used is conservative. A proper reliability study accounting for key uncertainties and sensitivities is required to better quantify the prediction bias and determine the actual factors of safety. This is an important step forward in understanding SCR reliability and integrity management.

ACRONYMS

Steel Catenary Riser (SCR)
Finite Element Analysis (FEA)
Touch-down point (TDP)
Touch Down Zone (TDZ)
Riser Monitoring System (RMS)
Environmental and Facilities Monitoring System (EFMS)
Global Positioning System (GPS)
6 Degree of Freedom (6DOF)

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