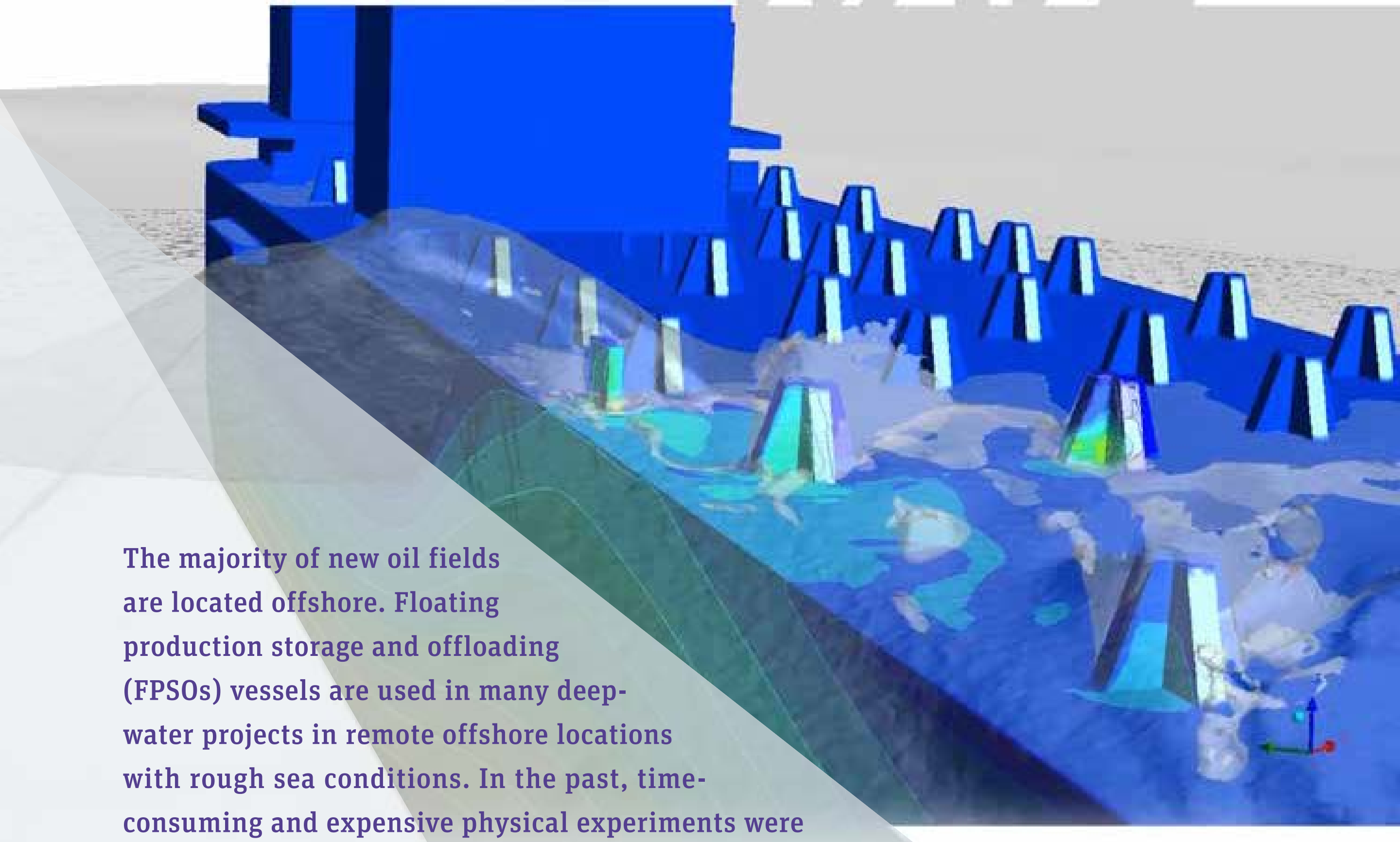
RIDE THE WAVE



The majority of new oil fields are located offshore. Floating production storage and offloading (FPSOs) vessels are used in many deep-water projects in remote offshore locations with rough sea conditions. In the past, time-consuming and expensive physical experiments were the only alternatives to ensure that vessels could withstand the highest possible sea states without damage. Petrobras uses ANSYS simulation to reduce the number of experiments required and obtain more detailed loading data.

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The pre-salt layer is a geological formation on the continental shelves that was laid down before a salt layer accumulated above it during the breakup of the Gondwana supercontinent into the continents we know today. Discoveries in the pre-salt layer in the past few decades on the Brazilian continental shelf are estimated at 50 billion barrels of oil, four times greater than Brazil's previous reserves. These reserves present an enormous drilling challenge because they lie under up to 3,000 meters of seawater, 2,000 meters of rock and 2,000 meters of salt. And, because they lie in deep water up to hundreds of kilometers off the coastline where difficult weather and sea conditions are often experienced, bringing oil and gas to the surface presents special challenges for FPSO vessels used to receive these hydrocarbons from the wells, then process, store and offload them into a tanker or pipeline.

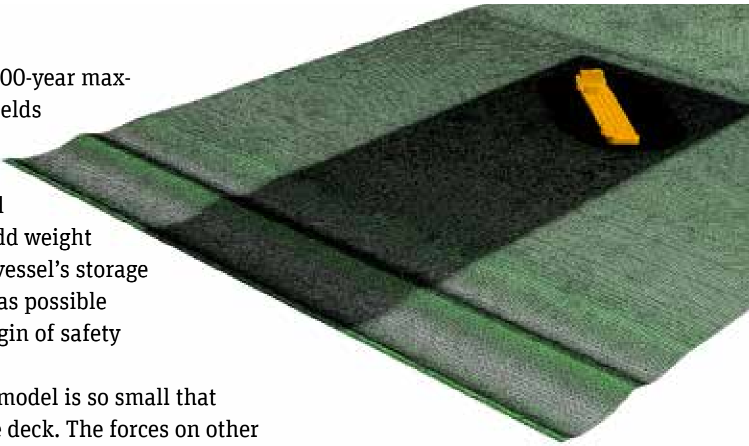
The worst-case scenario, called green water, occurs when unbroken waves roll over the deck of the FPSO. Green water is not a threat to the integrity of the vessel, but can damage critical equipment on its surface, such as control valves, cable trays, fire protection equipment, and the like. In the worst case, this may halt production for expensive repairs to be performed. The company could lose revenues of hundreds of thousands of dollars per day. Currently, oil companies primarily use scale-model experiments to evaluate loading under green-water conditions, but this approach is limited by the complexity of monitoring loads in very congested topside areas in model scale experiments. It is difficult to predict in advance where the highest loads will be imparted, so sensors are often not in the right positions. Petrobras has overcome these challenges by employing ANSYS Fluent computational fluid dynamics (CFD) software to predict forces on deck structures with a much higher level of resolution than can be achieved with physical testing.

> **"*ANSYS CFD software* predicts forces on deck structures with a much higher level of resolution than can be achieved with *physical testing*."**

DECK STRUCTURE DESIGN CHALLENGES

FPSO deck structures must be designed to withstand a 100-year maximum significant wave height of 12 meters in pre-salt fields gearing up for production, compared to 9 meters or less in post-salt fields. This upgrade may require the addition of features such as structural barriers and local reinforcements to on-deck equipment. These features add weight to the structure, which increase its cost and reduce the vessel's storage capacity. The goal is to quantify the loads as accurately as possible so that structures can be designed with a sufficient margin of safety but not overdesigned.

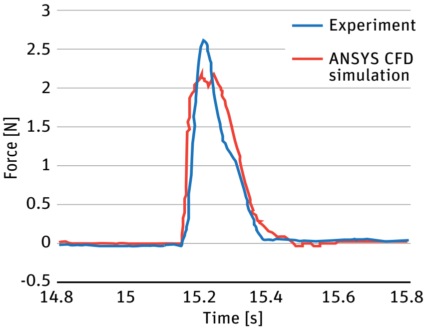
A problem with scale-model experiments is that the model is so small that only a few force measurements can be performed on the deck. The forces on other structures must be estimated, and these estimates must be high to account for uncertainty. Scale-model experiments also take about three months to plan and run, and are very expensive. One-dimensional hydraulic codes are sometimes applied to this problem, but since they don't account for the geometry of the structures, they also can only provide estimates of the relevant loading.



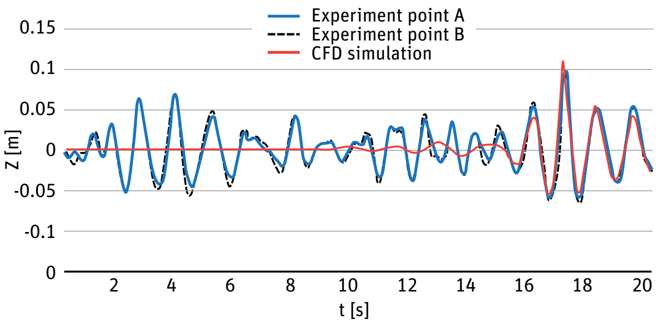
^ CFD mesh with refined area shown in black

SIMULATING GREEN-WATER LOADING

Petrobras engineers recently set out to apply ANSYS CFD to this problem, starting with a simulation of a scale-model experiment so that the simulation results could easily be validated. The model test condition was carefully chosen to intensify the green-water effects; it does not represent a true operational configuration. In the physical experiment,



^ Validation of loading results



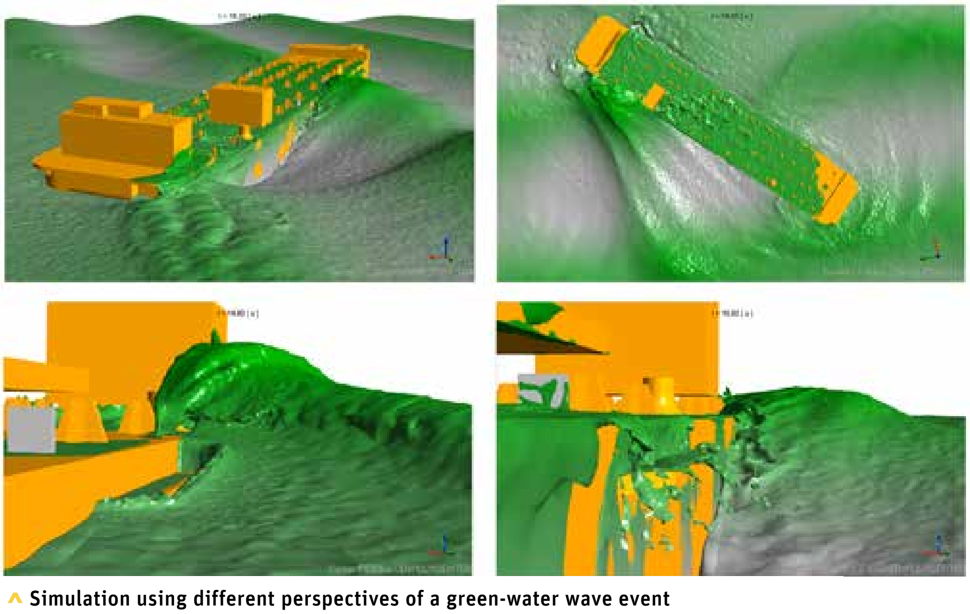
Validation of wave propagation results

loads were measured at six locations and water elevation at 38 locations. Petrobras engineers captured a time series of the wave from the experiment, selected the most critical part and wrote a MATLAB program that runs a fast Fourier transform to represent the irregular wave interest interval as a combination of linear wave components. They wrote a Fluent user subroutine to impose the wave combination as a boundary condition on the CFD simulation. Engineers imposed the movement of the vessel as measured in the lab on the CFD simulation as another boundary condition, using a dynamic mesh to accommodate vessel movement. They used the Fluent volume of fluid (VOF) model to track the interface between the surface of the water and the air. The shear stress transport (SST) turbulence model solved a turbulence/frequency-based model (k–ω) at the wall and k-ε in the bulk flow.

A mesh refinement study was performed for a 2-D model to select the appropriate mesh refinement for wave propagation. Prior wave impact studies were used to define the surrounding vessel mesh. This combination leads to a mesh of about 40 million cells. Petrobras engineers validated the simulation by comparing the simulation sea state to the experimental results. After an initial transient phase of up to 14 seconds, the simulation data matched the physical testing results.

> **“*Physical experiments* take about three months; *simulation* can be completed in 10 to 50 days.”**

Engineers synchronized video images from simulation animations and experimental data to qualitatively compare the location, time and intensity of wave breaking effects. Additionally, fluid forces from wave impact were measured in a few locations and compared with the simulation results. Simulation compared well with experimental data except in the hard-to-model breaking wave regions. Even in these cases, simulation values were higher than measured values, demonstrating that they could safely be used to design the deck structures.


Simulation using different perspectives of a green-water wave event

> **"The *simulation results* provided considerable information that cannot *be measured* with physical experiments."**

SIMULATION PROVIDES ADDITIONAL DATA

The simulation results provided considerable information that cannot be measured with physical experiments. For example, simulation determined loading at every point in the deck structures and hull. Also, simulation provided, for the first time, sufficient measurements to determine the physical mechanisms involved in wave interaction with the hull, especially the velocity field.

Simulation will not replace physical experiments, but will save time and money by reducing the number of experiments that are needed. Setting up and running a physical experiment takes about three months, but additional time is often needed due to test basin availability. Simulation can be completed in about 10 to 50 days depending on problem complexity. This time frame can be reduced in the future by harnessing additional computing resources. Most important, simulation has improved Petrobras' ability to ensure that FPSOs are able to withstand rough seas in lifting oil and gas in pre-salt deposits by providing more detailed loading predictions and other information that cannot be measured by physical testing. ∧

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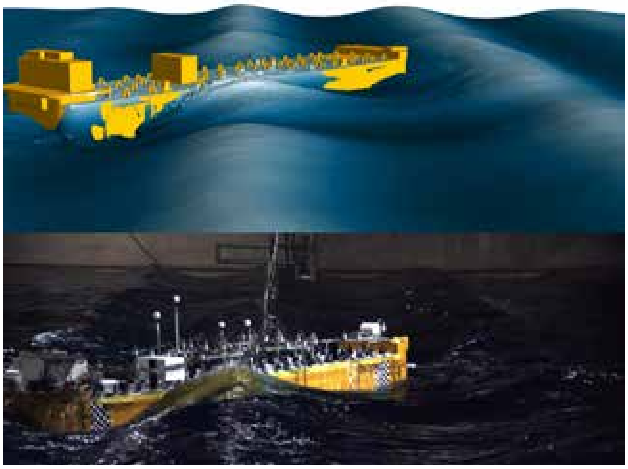

∧ Simulation provided a good match to experimental results.

Reference

Silva, D.F.C.; Esperança, P.T.T.; Coutinho, A.L.G.A. Green water loads on FPSOs exposed to beam and quartering seas, Part II: CFD simulations. *Ocean Engineering*, **2016**,

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