Moored ship problems in the Port of Cadiz.
Analysis of wave and long wave action
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Abstract

Several ro-ro and ferry vessels have suffered problems while moored in the Port of Cadiz during the last months. Large amplitude motions and breakage of mooring lines produce a serious decrease in the efficiency of load transfer or can even impede it, while safety is seriously threatened.

The Port and Coastal Research Center of CEDEX developed a project study aimed to define the problem, describe the reasons which cause it and propose solutions. Wave measurements, observation of ship motions, numerical wave propagation models, as well as wave and moored ship physical models have been applied to accomplish these objectives.

This paper will concentrate in the application of the physical model to define the wave and long wave conditions close to and inside the port, as well as the moored ship response in different situations.

Introduction

The Port of Cadiz is located in the South of Spain, close to the Strait of Gibraltar. It is subject to rather serious West wave storms from the Atlantic, as well as heavy winds from the East. The tidal range goes up to 3.90 m.

There are three main areas in the port: Zona Franca Basin, Cabezuela Quay and Commercial Basin, located more to the West. Most of the traffic is composed of liquid and solid bulk, transferred in Cabezuela Quay, but general cargo, containers and passengers are quite relevant as well. Therefore, ro-ro and ferry ships are the most frequent vessels in the Commercial Basin. There is also a rather active fishing harbour inside the basin.
The access channel and most of the basin were dredged to -13 m in 1991 in order to permit the access of larger ships. The original depth was 11 m. Few months later, a new marina called Port America was built close to the head of the West Breakwater. In 1992, the new ferry "Juan J. Sister" came into service for the Cadiz-Canary Islands line, with a weekly trip around the year. This was a quite larger ship (length, beam and depth) than those operating up to that moment.

Since 1992, several problems have been reported in the ro-ro and ferry berths, consisting in large amplitude motions and breakage of mooring lines. These phenomena have produced serious decreases in the efficiency of load transfer and delays in trip schedules. The fishing harbour and the marinas have also suffered the effects of long wave oscillations under the action of West waves, even quite moderate. As a consequence, a general opinion has grown among citizens and users against safety conditions and economy of the port.

**General scheme of the study**

CEDEX was asked by the Port Authority to develop a project study analyzing the situation. The aims of the work were, first of all, to define the problem, and then try to find the reasons which produce it. Finally, the Port and Coastal Research Center should propose solutions and test them.

A complete set of technical tools and procedures was applied in order to accomplish these objectives. These included wave measurements for several months, both inside and outside the port; observation and report of ship motions; wave climate analysis; numerical models for wave propagation and long wave response; and physical models for wave and long wave propagation and moored ship behaviour.
This paper will concentrate on the physical model tests and results, especially dealing with ships. Nevertheless, a huge amount of information was obtained and analyzed, providing helpful data to the Port Authority.

**Physical model wave propagation tests**

A 1:125 scale model of the channel and main basin was built in order to reproduce the approximation of waves and long waves towards the port. Typical West wave storms ($T_p=13$ s and $T_p=15$ s with $H_s$ varying between 2 and 3 m) were produced in the model.
Wave height was then measured in the channel, the basin entrance and along the quays by means of resistive probes.

**Long wave tests**

15 significant points were selected to define the long wave response of the port. The model was excited with a flat wave spectrum ("coloured noise") sweeping multiple frequencies in the range from 20 to 300 seconds.

Transfer functions were then computed for each point, showing the amplification coefficients from the external long wave energy to the local vertical response in each basin corner. Of course, amplifications only occurred in specific frequencies, depending on the geometry of the basin. The magnitude of the amplification varied also with the port layout.

![Figure 5. Amplification factor for long waves in Juan J. Sister berth (Present layout).](image)

**Test plan**

Several different port layouts were tested, in order to detect the exact reason of the high wave disturbance and long period oscillations. There was some discussion whether the changes in the port structures had affected the response of the basins or difficult situations were due to specially severe wave storms. Five port layouts were tested:

- **Former situation:** Before dredging the channel and the main basin.
- **Present situation:** After dredging the channel and basin (-13 m) and building Port America marina.
- **New breakwater:** A 350 m long structure, located to the west.
- **Modified channel:** An alternative solution, including an additional dredging in the west end of the port.
- **Combined solution:** This was a combination of breakwater and a smaller dredging.
Moored ship tests

The analysis of moored ship behaviour concentrated on "Juan J. Sister", a 5000 DWT ferry connecting Cadiz and the Canary Islands, but some conclusions are also valid for ro-ro ships. The analysis included several phases:
- **Collection of data**: Fenders and mooring lines, mooring geometry, loading-unloading schedule, etc.
- **Report of incidences**: A form (ship identification, mooring scheme and weather conditions) was filled by port personnel whenever problems occurred in the berth, for further analysis.
- **Mooring layout analysis**: Computation of elasticity and response characteristics of ships. Evaluation of dynamic conditions of the moored ship.
- **Model tests**: Measurement of motion amplitudes and forces on mooring lines and fenders. Comparison of different mooring systems and port layouts.

Main results

Wave penetration

Wave disturbance in the basin became quite worse after dredging the channel and building Port America. The increase in wave height varied of course in different areas, but values 25% to 50% worse appeared in most of the quays. Some areas even doubled the local wave height.

The reason seems to be a very special phenomenon: As West waves progress from deep water towards the channel, the effect of refraction (difference in depth between the channel and the natural bottom around) becomes very remarkable. Waves travelling in the edges of the channel tend to turn away from the center of the fairway and change their height as well. The result is that in the Western side of the channel, the waves turn almost 90 degrees to the South, and at the same time there is a large concentration of energy in that area. The old West breakwater, as an evidence of this, has suffered quite a significant damage in the last years. This propagation process occurred already with the -11 m channel, but the effect was not so serious.

Waves reach the West breakwater head with large amplitude, travelling in an direction oblique enough to permit them enter the basin. Afterwards they can reflect in the many vertical quays and reach almost any point of the port. Part of the energy could be damped through diffraction behind the breakwater, but that was only before Port America was built. Now, the expansion area does not exist any more, so the situation becomes even worse.

Therefore, it seems that the changes in the channel geometry and the port layout are actually to blame for a serious deterioration of wave conditions in the basin.
Analysis of the solutions proposed

The first alternative consisted of a 350 m breakwater built west of the present breakwater. The aim was to reduce wave energy exactly in the area where it concentrates, and prevent it from travelling inside the basin. It showed to be very effective, with results very similar to the former port conditions.

The second alternative was based in the fact that waves changed their direction travelling along the west edge of the channel. Therefore, if the channel edge was moved more to the West, we could perhaps prevent the waves coming so directly inside the port. The cost of this solution was comparable to that of the breakwater, but it was not so effective.

Finally, a combination of dredging and building a breakwater in the west corner was not so good and more expensive. On the other hand, it would allow for an eventual extension of the port in the future.

Moored ship behaviour

The mooring scheme used for "Juan J. Sister" looked rather inefficient, because of several reasons:

- Loose or low tension lines
- Large vertical line angles
- Mixed fiber and steel lines
- High asymmetry in all directions

The behaviour of such a moored ship in a basin with large wave disturbance and long wave amplification was evidently quite negative. This is specially serious in the case of a ship subject to very strict motion limitations: For the sake of safety of the vehicles coming through the ramp, surge motions should not be more than 30-50 cm, sway should stay below 30-40 cm and yaw should be less than 2 degrees. At the same time, maximum roll motions should be limited to 2 degrees and heave amplitude should be lower than 50 cm, in order to keep passengers safe in the footbridges and prevent damage to the footbridges themselves.

The results of the model tests were as bad as expected: In the present situation, surge and sway were the critical motions, showing high amplitudes even for low wave heights. The mooring conditions could be improved increasing pretension in the lines (3 t), or even better, using constant tension devices.

![Figure 6. Berth downtime index for different solutions.](Image)
Nevertheless, downtime index would be in the order of 7 to 10 difficult situations per year.

In the next set of tests, the mooring geometry was kept constant while the port layout changed. The effect of the breakwater was very significant, and the ship experienced motion amplitudes half of those measured in the present state. The result was that downtime became much lower (4-6 unpleasant situations per year), and similar to the reference value before the channel was dredged. The second alternative was not that profitable, and produced a downtime index of 6-8. The combination of breakwater and dredging was similar to the first one, both in motion amplitudes and corresponding downtime (4-5 per year).

**Changes in mooring configuration**

The Port Authority asked for a temporary solution to be applied until the final solution was decided and built. The mooring configuration should be optimized for the present situation of the port in order to reduce the critical motions to a minimum.

Four mooring variants were defined and tested, trying to correct the mistakes found in the previous phase of the analysis: Wire was limited to spring lines, while polipropilene was used in bow and stern lines and breast lines. A more symmetric and balanced mooring system was used without increasing the number of lines very much. Three additional bollards were installed in order to permit longer lines, especially for breast and stern lines. Higher pretension (6 t instead of 3 t) was also tested.

The results were quite satisfactory. Motion amplitudes became much lower (up to 65% reduction in surge), so downtime was significantly reduced (7-10 expected problem situations per year could be decreased to 4-5). The mooring variants involved only small changes (modification of the mooring layout and installation of three new bollards) with a negligible cost compared to the consequences of excessive ship motions.
Conclusions and recommendations

Any significant alteration of the geometry of a port (new layout, new structures, dredging, etc.) should be thoroughly analyzed in advance by means of numerical or physical models to prevent unexpected problems affecting port efficiency and safety.

In this case, the solutions to an irremediable modification of the channel had two objectives:

- **Temporary solution**: Optimization of the mooring scheme in order to reduce ship motions to a minimum under wave and long wave action, including the use of exceptional lines or bollards. This is a short term arrangement, applicable until a decision about definitive solutions is taken and the final structures are ready to work.

- **Final solution**: The tests performed gave useful indications about the final conditions for the moored ships after the new breakwater is built or the additional dredging is carried out.