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Implications of long waves in harbor management: The Gijón port case study

Daniel González-Marco[a,*], Joan Pau Sierra[a], Obdulia Fernández de Ybarra[a,b], Agustín Sánchez-Arcilla[a]

[a] *Maritime Engineering Laboratory, Technical University of Catalonia, Barcelona 08034, Spain*
[b] *Europrincipia S.L., Cerdanyola del Vallés 08290, Spain*

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Abstract

The increase in maritime traffic means that ports have to continuously improve their efficiency. This involves reducing the inactivity caused by adverse climatic conditions. Adverse conditions that inconvenience port users include short and long waves. In this paper, the effect of long waves on port operations in Gijón harbor (Spain) is analyzed by means of a numerical model. Short wave propagation inside the harbor was compared with two different combinations of short and long waves. Taking into account the wave heights that limit operations, the periods of inactivity due to waves were computed for every dock. The results show that the harbor offers very good protection against wind (short) waves. Nevertheless, the port's inefficiency is significantly increased if long waves are present in the wave trains affecting the harbor. This illustrates the importance of taking into account long waves in port management. Finally, other limited effects of long waves in harbor environmental management issues are pointed out.

1. Introduction

Port operations are one of the most important "water-dependent" activities. Therefore, many Coastal Management Programs have specific policies for port development [1]. Although large urban ports are generally under pressure from a variety of stakeholders to integrate non-trade objectives into harbor planning and management [2], their main activity is to provide services to maritime traffic.

*Corresponding author. Tel.: +34 934015761; fax: +34 934011861.
E-mail address: daniel.gonzalez-marco@upc.edu (D. González-Marco).

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In recent decades, maritime traffic in Spain has increased significantly. In 1970, 145 million tons were moved in harbors managed by national authorities. This figure increased to 227 million tons in 1980, 338 million tons in 2000 and 382 million tons in 2003 [3].

This increase in maritime traffic means that ports have to continuously improve their facilities and services and optimize their infrastructure. Therefore, solutions are sought to minimize problems for users. In particular, ports aim to reduce the inactivity or the decrease in operation performance caused by adverse climatic conditions. Adverse conditions that inconvenience users and even halt operations include the wind, currents and short and long waves.

The climatic conditions which cause problems for port operations are different in every terminal, as handling procedures and types of equipment determine what ship movements are permissible. For example, ship movements are greatly restricted in the case of container operations so the range of admissible climatic conditions is limited. In contrast, operations involving tankers permit a much wider range of water and ship movements. As the use of containers continues to rise and transport costs continue to decline [4], the shelter provided by harbors needs to be improved in order to reduce problems and increase efficiency.

Previous studies [5] have analyzed the threats that earthquakes and tsunamis pose to port and harbor communities and assessed ports' vulnerability to these hazards. In addition, descriptions of how long waves are generated and how they penetrate harbors are frequent in the literature. However, studies that analyze the implications of long waves from the perspective of harbor management are rare. The aim of this paper is therefore to analyze such implications in a Spanish harbor: Gijón harbor.

2. Long waves

Long-period waves are water surface oscillations with periods that are longer than those of surface wind waves and shorter than those of the dominant tidal variations. Their periods are between 1 and 600 min, their amplitudes are normally less than 10 cm and they generally occur in coastal embayments and harbors [6]. These long-period waves may affect water circulation and exchange, cause moored ships to move, contribute to extremely low or high water levels, damage harbor facilities [7] and disturb port operations. The effects of long-period waves may be considerable if they coincide with harbor resonance. In particular, standing waves (seiches) are of concern to harbors because they present different resonant modes. One or two of these modes will predominate in a given harbor or embayment, depending on the geometry of the harbor and the forcing. Forcing normally takes the form of oscillations in the oceanic boundary condition or sudden changes in weather conditions [6].

It is customary to explain and analyze seiches forced by free long waves outside a harbor and subharmonics generated by wave–wave interaction within the harbor itself [8]. External sources include those due to free long waves generated by surf beats or refraction [9], tsunamis [10], excitation by internal waves [11,12] and meteorological forcings [13]. Non-linear mechanisms for generating low frequency forcing from incident short waves within a harbor have been described (see e.g. [14–16]). In addition Fabrikant [17] and Otta [8] describe the generation of long waves within harbors by coast-parallel currents.

Long waves that have periods of less than 5 min are usually forced by the set-down that accompanies groups of wind waves [18]. Wave groups occur in a random fashion at sea, based on the assumption that the sea can be represented as a sum of components with different periods and associated energy spectra. Wave groups can generate surface perturbations with a period of the order of minutes. Such perturbations have a considerable effect on large moored vessels, since the natural periods of horizontal oscillation of such vessels on their moorings are typically within the range of 30 s–2 min. Therefore, a significant resonant response of the vessel can be produced by relatively small-amplitude, long-period wave motions. In some cases, this can cause the moorings to part. This problem for vessels moored inside harbors can be exacerbated by long-period wave motions amplified by harbor resonance [14].

The spatial evolution of irregular surface gravity waves in intermediate and shallow waters is largely influenced by the non-linear transfer of energy between spectral components. This leads to the generation of free long waves. Therefore, relatively high levels of low-frequency energy in the nearshore area have been widely reported in the literature [19]. Theoretically, obliquely incident wave groups may transfer energy to free waves, thus satisfying the edge wave dispersion relation [20]. This resonant process can result in large amplitude waves being trapped on the shoreline. Longuet-Higgins and Stewart [21] used the concept of radiation stress to show the existence of a long-period forced wave associated with incident wave groups.

Previous experimental data [22,23] have also shown that the time variation of the breakpoint position, which occurs when incident waves are of varying amplitude, can generate waves at the group period (and its harmonics). This may be a significant source of long waves.

Irrespective of their origin, long waves pose a threat to port operations, especially when their periods are close to those of the natural oscillation of harbor basins.

3. Study area

Gijón harbor dates back to 1840. It is located in the Cantabrian Sea (43°34′N, 5°41′W, North Atlantic Spanish coast) within the Bay of Biscay (see Fig. 1, left). The port is built

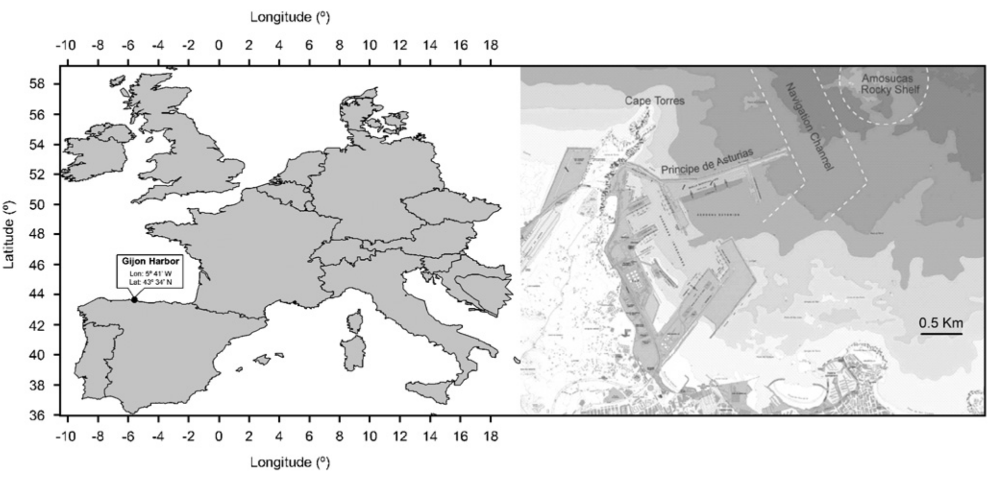

Fig. 1. Location of Gijón port and general harbor layout.

on reclaimed land in the sheltered area of the Peñas and Torres capes, which provide natural protection against NW storms, the most energetic in the Cantabrian Sea. Together with the Amosucas rocky shelf (1000 m NE of the harbor mouth, see Fig. 1, right), whose depth ranges from 30 to 15 m (at low tide), the port breakwater and Torres cape define the navigation channel that must be taken to access the port. This situation also acts as a concentration factor for the incoming waves.

Due to its geographic location, the port of Gijón has become a link between the Iberian Peninsula and northern and southern Europe. In 2004, the trade volume was about 2958 million euros. The total traffic amounted to over 19 million tons, which was mainly made up of dry bulk (see Fig. 2). This trade volume has turned Gijón harbor into the leading port for dry bulk traffic within the Spanish harbor system.

The Gijón Port Authority started a development plan in the 1990s, which will eventually double the land and water surfaces and consequently enhance economic activities. Economic growth and harbor expansion have made it necessary to introduce a real-time management system for harbor operations and navigation traffic [24].

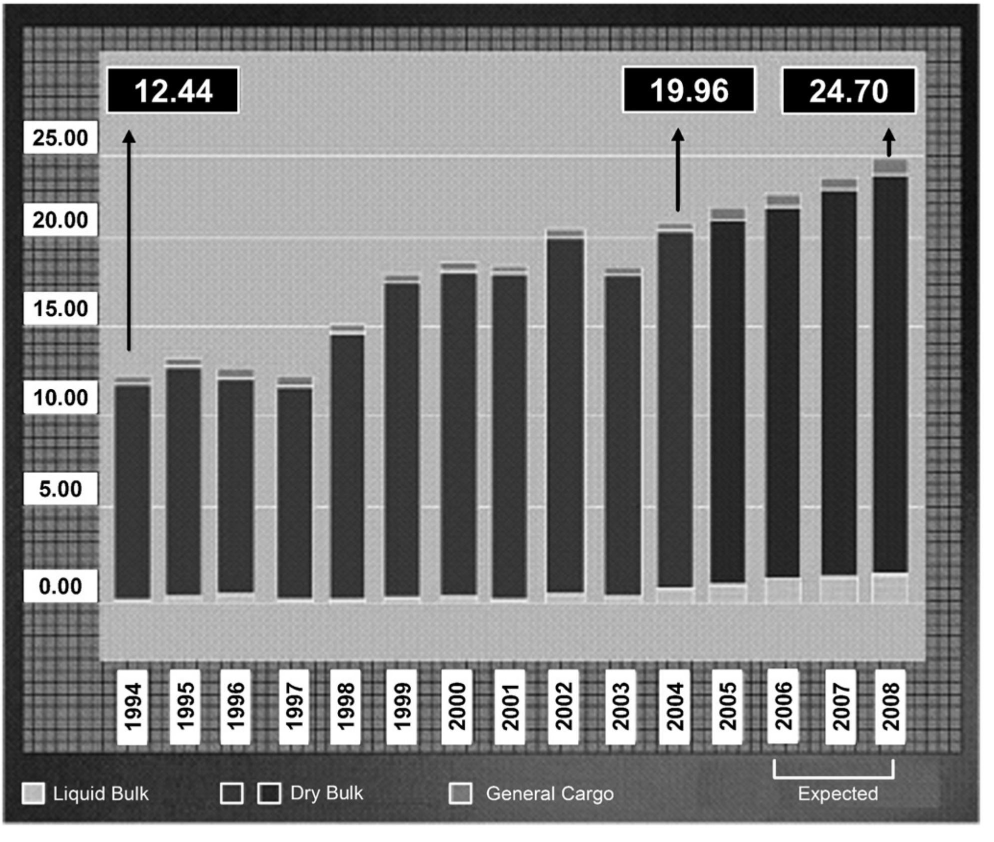

Fig. 2. Yearly traffic volume in Gijón port (adapted from [3]).

3.1. Bathymetric characteristics

As mentioned above, the area surrounding Gijón harbor has a complex topobathymetric configuration. This is mainly dominated by the Peñas and Torres capes and the Amosucas rocky shelf. These orographic features provide natural protection against wave storms, which come mainly from the fourth quadrant, and modify the incoming waves by diffraction and refraction. The inner harbor bathymetry shows depths from 20 to 5 m (at low tide, see Fig. 3). These depths permit large bulk carriers to access the port's facilities.

3.2. Wind climate

The wind climate off Gijón harbor was obtained from a multiparametric buoy deployed at a depth of 380 m in front of the Peñas cape [25]. It shows that the wind regime is dominated by two main components: E-ENE and W-WSW. The average percentage of calms (<1 m/s) recorded over 8 years (1997–2004) was 5.46%. Winds from the first and fourth quadrants can generate waves which produce harbor agitation. The other wind components blow from the land and do not generate waves which affect the harbor.

Winds from the E-ENE are weak and appear mainly during the summer, usually in conjunction with a synoptic situation of high pressures, which is an indicator of fine

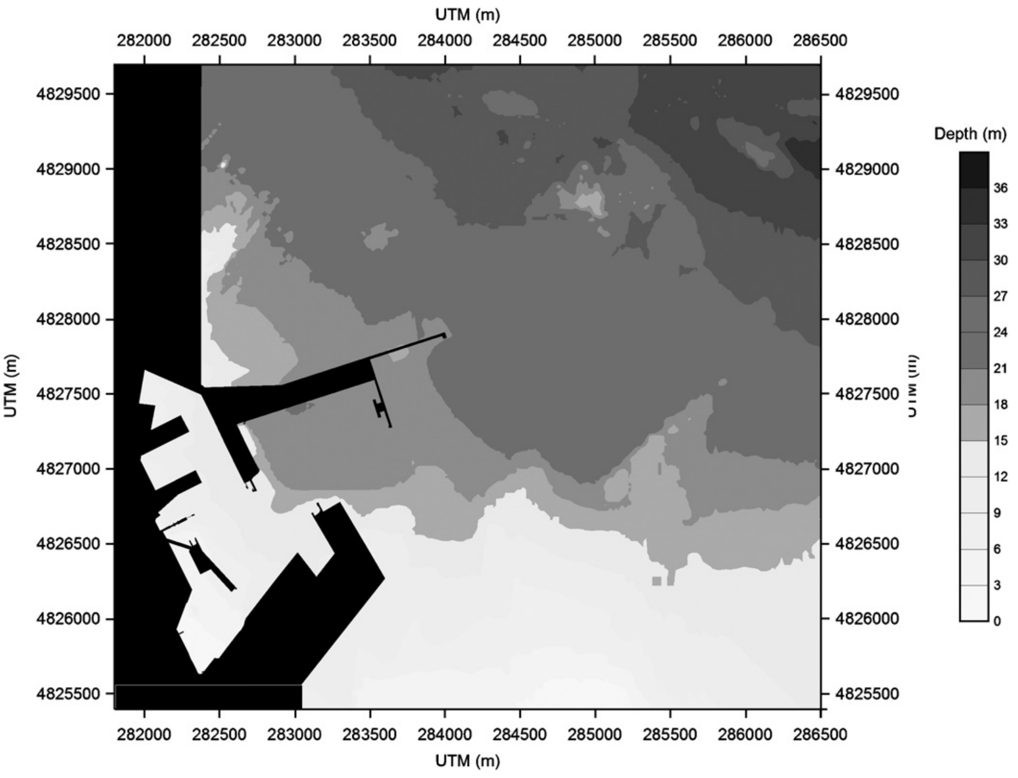

Fig. 3. Bathymetry of Gijón harbor (data supplied by Gijon Harbor Authority).

weather. However, winds from the W-WSW are stronger and dominant in the winter. During a classic storm scenario, the law of wind rotation is quite clear and direct: the wind starts to blow from the SW-W and then turns to the NW. This generates rough sea, which can bring harbor operations to a halt. The peak of the storm occurs when the winds turn to the N.

3.3. Mean water level

The tidal regime in the Bay of Biscay is semi-diurnal. There are two clearly defined high tides and two low tides every day. Fig. 4 shows the main tidal parameters, which were obtained by analyzing sea-level time series collected with a tidal gauge in Gijón harbor during the period 1996–2003 [26].

3.4. Wave climate

The information regarding the mean and extreme wave climate was taken from three wave buoys deployed in the area surrounding Gijón harbor. Two of the buoys (Gijón 1 [27] and Gijón 2 [28] buoys) were placed in intermediate waters and one (the Peñas buoy [29]) was situated in deep waters (see Table 1). Only the Peñas buoy was directional. Therefore, the information on wave direction refers strictly to this buoy.

The mean wave regime is directly related to operational harbor conditions. In intermediate waters, the mean significant wave height H_s (defined as four times the sea-surface standard deviation) was between 1 and 2 m 40–45% of the time, with associated peak periods T_p of 10–12 s. The H_s which was exceeded 12 hours per year was 5.7 m.

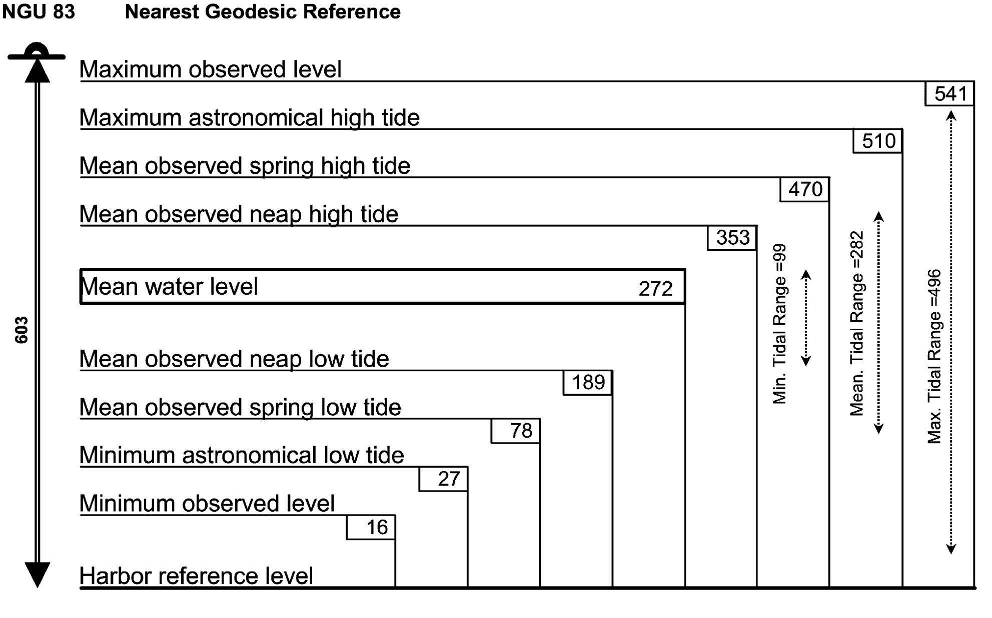

Fig. 4. Tidal levels in Gijón harbor (data extracted from [26]).

Table 1
Characteristics of buoy data (data extracted from [27–29])

Buoy	Coordinates	Depth (m)	Analyzed period (years)
Gijón 1	003°08.58′W	23	1981–2003 (mean)
	43°34.02′N		1981–2004 (extreme)
Gijón 2	005°40.02′W	43	1994–2003 (mean)
	43°36.72′N		1994–2002 (extreme)
Peñas	006°10.2′W	382	1997–2003 (mean)
	43°44.4′N		1997–2004 (extreme)

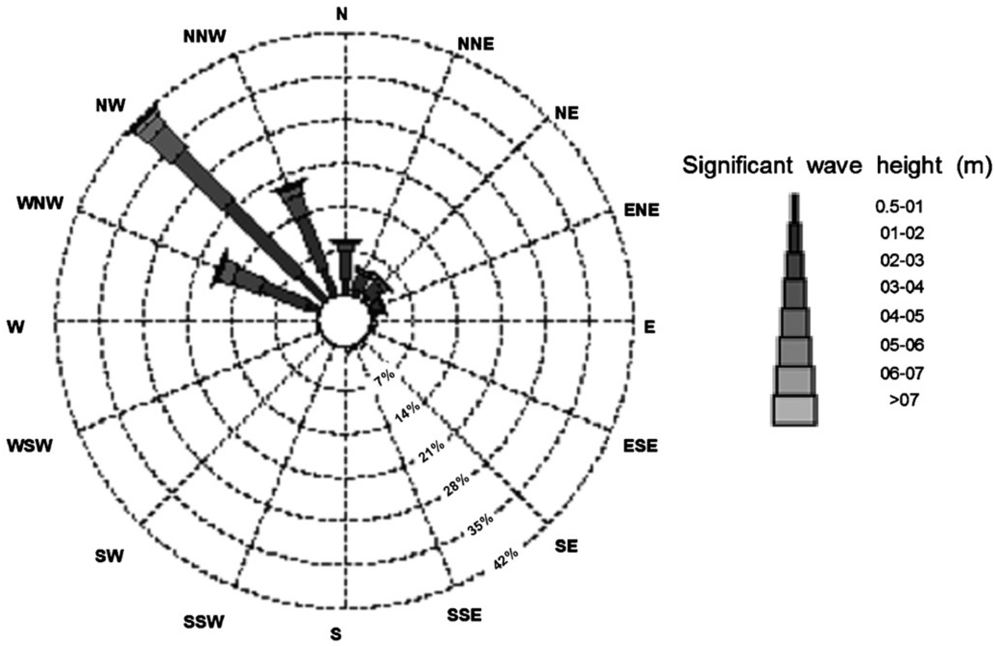

Fig. 5. Directional distribution of waves at the Peñas buoy (data extracted from [29]).

The deep water, directional Peñas buoy showed that waves come from the fourth quadrant about 79% of the time (see Fig. 5).

The directional mean wave climate in deep waters was obtained by fitting the wave data of the Peñas buoy (taken during the period 1997–2002) to a Weibull distribution for each directional sector, as illustrated in Table 2.

The extreme wave climate for the study area was obtained following the peak-over-threshold (POT) methodology. Table 3 compiles relevant extreme wave information for deep waters taken from the Peñas buoy during the period 1998–2004 [30], calculated using the Weibull distribution. Table 4 provides the same information for intermediate waters taken from Gijón 1 buoy during the period 1981–2002 [31], which was also calculated using the Weibull distribution.

Table 2
Mean directional wave climate (Peñas buoy, data extracted from [29])

Sector	Frequency (%)	90.0%	95.0%	97.0%	99.5%
N	8.58	2.6 m	3.0 m	3.4 m	4.4 m
NNE	4.51	2.3 m	2.6 m	2.9 m	3.6 m
NE	4.62	2.3 m	2.7 m	3.0 m	3.7 m
ENE	2.46	2.1 m	2.3 m	2.5 m	2.9 m
WNW	17.74	3.3 m	3.8 m	4.2 m	5.3 m
NW	41.90	3.8 m	4.5 m	4.8 m	6.2 m
NNW	19.54	3.0 m	3.6 m	3.9 m	5.1 m

Table 3
Extreme wave climate in deep waters (Peñas buoy, data extracted from [30])

Return period (years)	20	50	225	475
Central estimation of H_s (m)	10.77	11.62	12.93	13.55
Upper band 90% H_s (m)	12.71	13.94	15.89	16.83
Expected value of T_p (s)	14.61	14.89	15.29	15.48
Probability to be exceeded in 20 years	0.64	0.33	0.09	0.04
Probability to be exceeded in 50 years	0.92	0.64	0.20	0.10

Table 4
Extreme wave climate in intermediate waters (Gijón buoy 1, data extracted from [31])

Return period (years)	20	50	225	475
Central estimation of H_s (m)	7.22	7.68	8.39	8.72
Upper band 90% H_s (m)	7.85	8.47	9.46	9.94
Expected value of T_p (s)	17.33	17.66	18.14	18.36
Probability to be exceeded in 20 years	0.64	0.33	0.09	0.04
Probability to be exceeded in 50 years	0.92	0.64	0.20	0.10

3.5. Long waves in Gijón harbor mouth

Lara et al. [32] developed an analytical procedure which relates wind (short) and long waves at the Gijón harbor mouth. This procedure was based on field measurements in the area surrounding Gijón harbor. From the records of a pressure sensor placed in front of the harbor mouth, information on gravity and infragravity waves was obtained using spectral analysis. After taking swell events from the total number of registers, empirical formulations (Eqs. (1) and (2)) were fitted to obtain integrated spectrum parameters for long waves, according to a JONSWAP spectrum. Thus,

$$H_s^* = 0.0068 \cdot H_s^{1.402} T_p^{0.667}, \tag{1}$$

$$T_p^* = 8.03 \cdot T_p, \tag{2}$$

where H_s^* is the significant wave height of long waves and T_p^* is the peak period of long waves.

Thus, using a JONSWAP spectrum, the associated long wave at the Gijón harbor mouth can be obtained in terms of its integrated spectrum parameters. With this methodology, Lara et al. [32] reached several conclusions about the presence of long waves at the Gijón harbor mouth:

- The long waves are within the range of 60–400 s.
- The maximum energy band for infragravity waves is in the interval 130–200 s for storm events.
- An energy concentration appears in the 75–90 s band (its occurrence is not related to storm events).

3.6. Real-time management system for Gijón harbor

Gijón harbor has developed a real-time management system for navigation traffic, harbor operations and harbor expansion works. This system is based on a combination of real-time wave measurements and wave forecasting simulations [24]. The system has three main steps (see Fig. 6): (i) wave data measurements in intermediate waters; (ii) wave forecasting 48 h in advance using two-third-generation wave models, WAM [33] and SWAN [34]; and (iii) real-time and short-term forecasting calculations of navigation channel and harbor agitation conditions, based on an elliptic mild-slope propagation model. The system enables the harbor authority to establish:

- Real-time and forecast calculations of grounding probability during a ship's passage through the navigation channel.

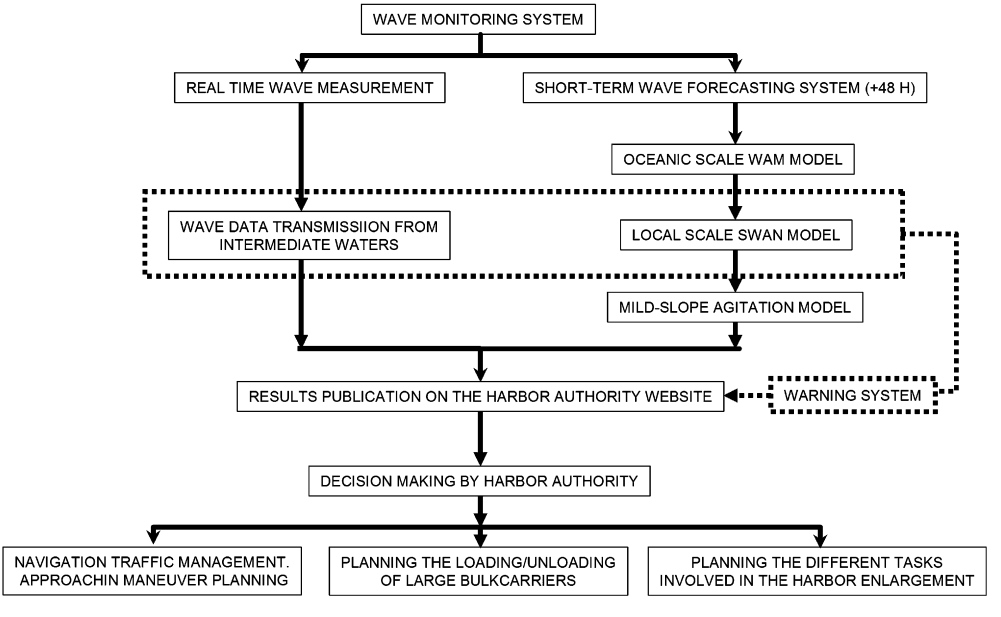

Fig. 6. Scheme of the Gijón harbor wave monitoring system.

- A plan for the loading/unloading operations of large bulk carriers in solid bulk facilities.
- A plan of the building work to be carried out to expand the port, in accordance with wave conditions.

The main limitations of this system are as follows:

- The wave simulation model only works with regular (or monochromatic [35]) waves and does not allow for irregular wave propagation.
- The system cannot simulate wind and long-wave propagation simultaneously; therefore, it is not able to reproduce the combined effect of the two wave types.

4. Material and methods

In order to analyze the significance of the aforementioned limitations, an exercise was carried out using a Boussinesq-type numerical model. This model allows the simultaneous propagation of long waves and irregular wind waves.

Boussinesq-type models [36] were originally developed to simulate the propagation of long waves. Various modifications were subsequently introduced [37–40] that enabled this type of model to solve wind-wave propagation and low-frequency motion. Mutual interactions between wind and long waves are inherent in these models. Therefore, they enable the non-linear processes involved in the propagation, shoaling, breaking and run-up of irregular wave trains to be studied [19]. Madsen et al. [41] used a Boussinesq-type numerical model and found good agreement with experimental data for long-wave generation and propagation in the nearshore area. Smallman and Cooper [42] applied a 2DH Boussinesq model to reproduce set-down propagation inside harbors. Similarly, Bingham [43] used a Boussinesq model to predict the induced short- and long-wave motion of a restrained floating body in restricted water. In addition to phase-solving models, Nadaoka and Raveenthiran [44] developed a phase-averaged Boussinesq model to describe wave groups and the accompanying long-wave evolution. Karambas and Koutitas [19] employed a Boussinesq model to simulate low-frequency waves induced by short-wave groups. They calculated the resonant response of harbors to bound waves generated by short-wave groups. They then compared the results with the experimental data available in the literature. There was good agreement between the calculations and the experimental data.

In the present paper, a 2DH Boussinesq-type numerical model is used to reproduce wind- and long-wave penetration into Gijón harbor. The possible resonance in different basins is analyzed, as are the implications for harbor management. The model is described in [37].

The model runs were carried out with irregular wind waves that had a significant wave height of 1 m, a peak period of 10 s and a direction from NW. Thus, the agitation coefficient is the wave height obtained from the simulation since this coefficient is the ratio between the wave height at a particular point in the harbor and the wave height outside the harbor. Long waves have been assumed to be monochromatic. In simulations with both types of waves, linear superposition was considered.

Table 5
Significant wave heights limiting operations according to vessel type

Type of vessel	H_s (m)
Tanker <30,000 DWT	1.5
Tanker: 30,000–200,000 DWT	2.0
Tanker >200,000 DWT	2.5
Bulk carrier (loading)	1.5
Bulk carrier (unloading)	1.0
LNG, LPG <60,000 m^3	1.2
LNG, LPG >60,000 m^3	1.5
General cargo	1.0
Container ship	0.5
Ro-ro	0.5
Cruise	0.5

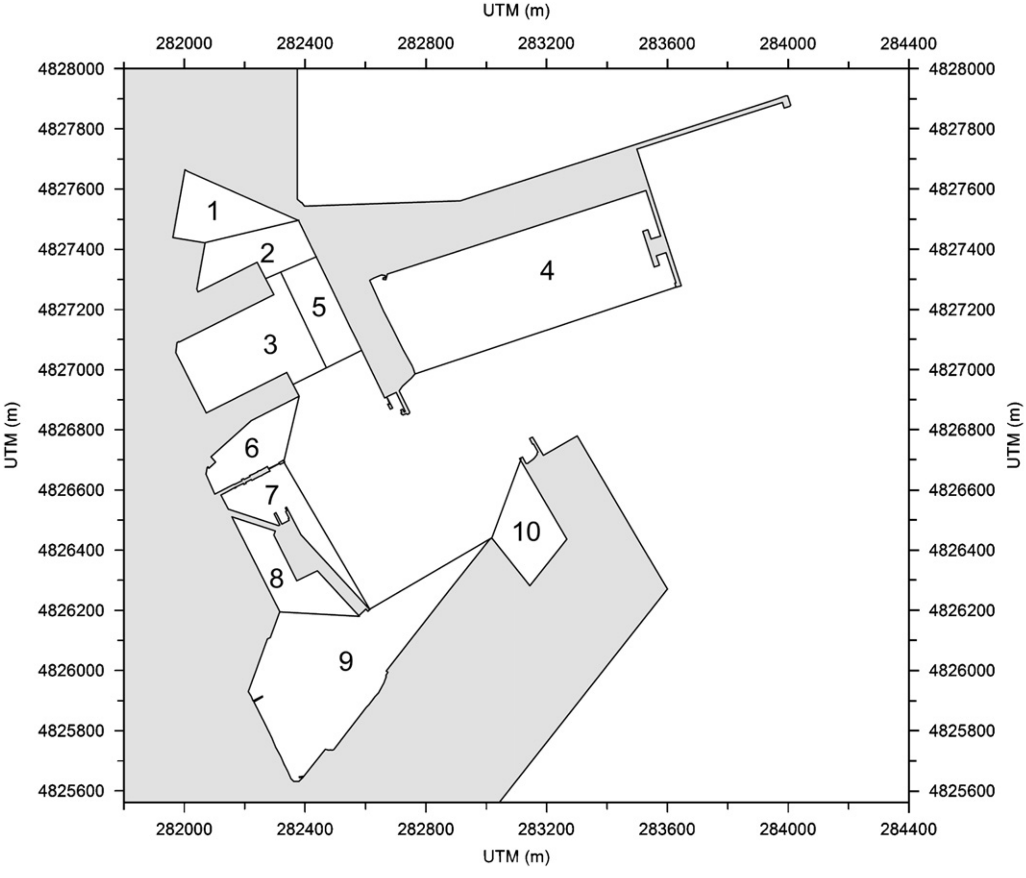

Fig. 7. Basins or sectors of Gijón port considered in the analysis.

The limiting conditions of operation for the different basins were taken from [45]. Table 5 shows the maximum wave heights with which operations can proceed, as a function of the type of vessel and operation.

Fig. 7 illustrates the different sectors or basins of the port of Gijón that will be further analyzed. Different port operations are carried out in each sector. If the results of the numerical model and the port operations and values included in Table 5 are taken into account, the percentage of time that wave heights exceed operation limits can be determined for the different basins and operations.

5. Results and discussion

Fig. 8 presents the results of the numerical model for wind waves. The agitation coefficients show that the harbor responds well to the prevailing waves. Waves from the NW (including WNW and NNW) are present 79% of the time. These waves are diffracted in the main breakwater. Consequently, wave heights inside Gijón port are greatly reduced. For most of the operation areas, the agitation coefficient is less than 0.2 or slightly above this value. This implies that a wave height of 1 m outside the harbor is transformed into a wave height of about 0.2 m inside it.

Table 6 summarizes the results depicted in Fig. 8. column 1 indicates the area studied (see Fig. 7); column 2 the type of operation carried out in the area; column 3 the wave

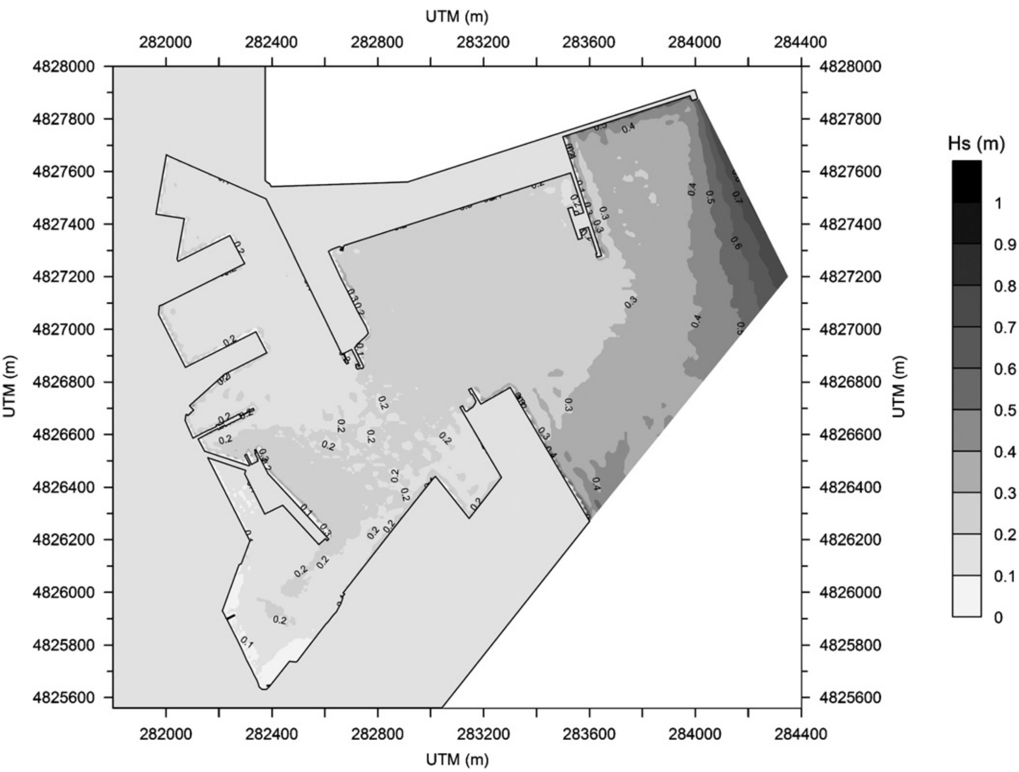

Fig. 8. Results of the numerical model for wind-wave propagation inside Gijón harbor.

Table 6
Probability that operations would have to be stopped due to wind waves for the various docks in Gijón port

Area	Operation	H_{lim} (m)	K_a	$H_{s0}/\geqslant H_{lim}$ (m)	$F(H_{s0})$	% $H_s \geqslant H_{lim}$
1	Dry bulk					
	Loading	1.0	0.16	6.25	0.9998	<0.1
	Unloading	1.5	0.16	9.38	1.0000	<0.1
2	General cargo	1.0	0.16	6.25	0.9998	<0.1
3	General cargo	1.0	0.17	5.88	0.9996	<0.1
	Dry bulk					
	Loading	1.0	0.17	5.88	0.9996	<0.1
	Unloading	1.5	0.17	8.82	1.0000	<0.1
4	Dry bulk					
	Loading	1.0	0.23	4.35	0.9937	0.5
	Unloading	1.5	0.23	6.52	0.9999	<0.1
5	Dry bulk					
	Loading	1.0	0.15	6.67	0.9999	<0.1
	Unloading	1.5	0.15	10.00	1.0000	<0.1
	LNG–LPG					
	$<60{,}000\,m^3$	1.2	0.15	8.00	1.0000	<0.1
	$>60{,}000\,m^3$	1.5	0.15	10.00	1.0000	<0.1
6	Dry bulk					
	Loading	1.0	0.18	5.56	0.9993	<0.1
	Unloading	1.5	0.18	8.33	1.0000	<0.1
	Oil products					
	<30,000 TPM	1.5	0.18	8.33	1.0000	<0.1
	30,000–200,000 TPM	2.0	0.18	11.11	1.0000	<0.1
7	Oil products					
	<30,000 TPM	1.5	0.23	6.52	0.9999	<0.1
	30,000–200,000 TPM	2.0	0.23	8.70	1.0000	<0.1
8	Fishing	1.0	0.11	9.09	1.0000	<0.1
9	Oil products					
	<30,000 TPM	1.5	0.17	8.82	1.0000	<0.1
	30,000–200,000 TPM	2.0	0.17	11.76	1.0000	<0.1
	General cargo	1.0	0.17	5.88	1.0000	<0.1
10	Dry bulk					
	Loading	1.0	0.19	5.26	0.9988	<0.1
	Unloading	1.5	0.19	7.89	1.0000	<0.1
	Ro-ro	0.5	0.19	2.63	0.9109	7.0

height limit, H_{lim}, for the type of operation carried out in the area; column 4 the average agitation coefficient, K_a, in the area; column 5 (obtained by dividing column 3 by column 4) indicates the wave height outside the harbor that leads to the operation limit in this dock being exceeded; column 6 indicates the probability that the value in column 5 will not be exceeded (taking into account the wave climate described above); and column 7 describes the probability (as a percentage) that operations will have to be stopped due to waves (in this case wind waves) in a specific area. This last value was obtained by subtracting the value in column 6 from 1 and multiplying the result by 0.79 (the frequency of occurrence of waves with a NW component, including WNW and NNW, since waves with other directions hardly affect the harbor, see Fig. 5).

An analysis of Table 6 shows that Gijón port offers excellent shelter against wind waves. This enables port operations to proceed most of the time. According to the numerical model results, in most of the docks the probability of waves exceeding the operation limit is less than 0.1%. In Area 4 only (see Fig. 7), the loading of dry bulks is liable to be stopped 0.5% of the time (which is very reasonable). In Area 10, ro-ro operations may be hindered 7% of the time (due to the low limit of 0.5 m fixed for these operations).

Once Gijón harbor's good response to wind-wave attack had been verified, the implications of long waves were analyzed. Two different cases were studied. In the first, the characteristics of the superimposed long wave were taken from [32]. From Eqs. (1) and (2), a long wave with a period of 80.3 s and a wave height of 0.03 m were obtained and linearly superimposed onto the same wind wave used in the previous run. As mentioned before, this period is in the range of infragravity waves (75–90 s) observed in Gijón harbor that are unrelated to storm events. The simulation results are presented in Fig. 9.

A simple overview of these results shows a considerable increase in wave agitation in the harbor. While the agitation coefficients in the previous run were around 0.2, in this case they ranged between 0.4 and 0.5 for the entire harbor. The results for this case are presented in Table 7 (which follows the same format as Table 6).

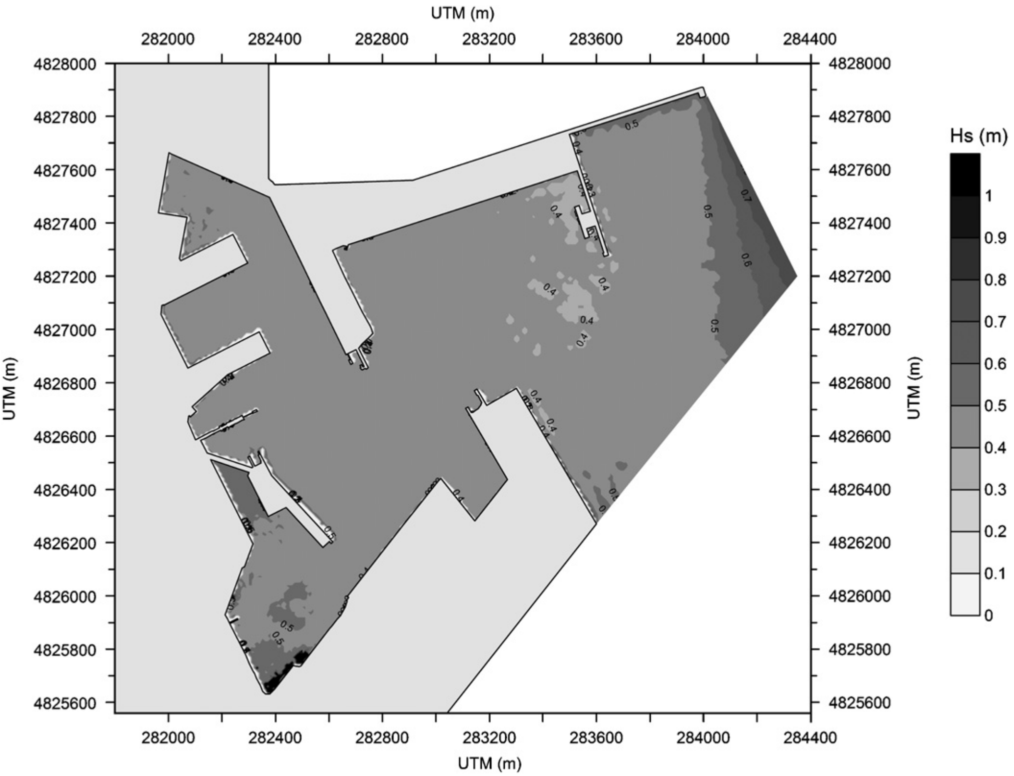

Fig. 9. Results of the numerical model for wind waves plus a long wave with $H_s^* = 0.03$ m and $T_p^* = 80.3$ s.

Table 7
Probability that operations would have to be stopped due to a combination of wind waves and a long wave with $H_s^* = 0.03$ m and $T_p^* = 80.3$ s for the various docks in Gijón port

Area	Activity	H_{lim} (m)	K_a	$H_{s0}/\geqslant H_{lim}$ (m)	$F(H_{s0})$	% $H_s \geqslant H_{lim}$
1	Dry bulk					
	Loading	1.0	0.48	2.08	0.8172	14.4
	Unloading	1.5	0.48	3.13	0.9560	3.5
2	General cargo	1.0	0.48	2.08	0.8172	14.4
3	General cargo	1.0	0.47	2.13	0.8271	13.7
	Dry bulk					
	Loading	1.0	0.47	2.13	0.8271	13.7
	Unloading	1.5	0.47	3.19	0.9601	3.2
4	Dry bulk					
	Loading	1.0	0.41	2.44	0.8844	9.1
	Unloading	1.5	0.41	3.66	0.9806	1.5
5	Dry bulk					
	Loading	1.0	0.46	2.17	0.8369	12.9
	Unloading	1.5	0.46	3.26	0.9641	2.8
	LNG–LPG					
	$<60{,}000\,m^3$	1.2	0.46	2.61	0.9081	7.3
	$>60{,}000\,m^3$	1.5	0.46	3.26	0.9641	2.8
6	Dry bulk					
	Loading	1.0	0.44	2.27	0.8562	11.4
	Unloading	1.5	0.44	3.41	0.9713	2.3
	Oil products					
	<30,000 TPM	1.5	0.44	3.41	0.9713	2.3
	30,000–200,000 TPM	2.0	0.44	4.55	0.9955	0.4
7	Oil products					
	<30,000 TPM	1.5	0.47	3.19	0.9601	3.2
	30,000–200,000 TPM	2.0	0.47	4.26	0.9927	0.6
8	Fishing	1.0	0.47	2.13	0.8271	13.7
9	Oil products					
	<30,000 TPM	1.5	0.49	3.06	0.9516	3.8
	30,000–200,000 TPM	2.0	0.49	4.08	0.9902	0.8
	General cargo	1.0	0.49	2.04	0.8074	15.2
10	Dry bulk					
	Loading	1.0	0.43	2.33	0.8658	10.6
	Unloading	1.5	0.43	3.49	0.9746	2.0
	Ro-ro	0.5	0.43	1.16	0.4925	40.1

An analysis of Table 7 reveals how the presence of a small long wave (with a wave height of only 3 cm) in the wave train significantly increases wave agitation in the harbor. When only short waves were present in the wave train, the agitation coefficients ranged from 0.11 to 0.23. When a long wave was superimposed, the agitation coefficients oscillated between 0.41 and 0.49. If these long waves were constantly present in the wave trains approaching Gijón harbor, the time in which operations would have to be stopped would increase considerably. Thus, dry bulk unloading operations could not be carried out between 1.5% and 2.8% of the time (depending on the dock) and dry bulk loading would not be feasible between 9.1% and 12.9% of the time. Small oil carriers would have to stop operations between 2.3% and 3.2% of the time. Larger carriers would have to halt operations between 0.4% and 0.6% of the time. LNG ships would not be able to operate 2.8% (large ships) and 7.3% (small ships) of the time; in the case of fishing ships, this figure would be 13.7%. Finally, general cargos would not be able to operate between 13.7% and 15.2% of the time and the ro-ro terminal would not be in service 40.1% of the time.

To sum up the previous results, if long waves with the characteristics described were constantly present in wave trains affecting Gijón port, some docks (dry bulk loading, general cargo and fishing) would have to halt operations for long intervals, others would no longer be operative (ro-ro) and the remainder would be out of service for longer (an increase from under 0.1% of the time to values around 3%).

The second long wave tested had a wave height of 0.20 m and a period of 200 s. It was also linearly superimposed onto the same wind-wave train as above. The period of this wave was selected as it is close to the natural oscillation period of some harbor basins. Therefore, it could generate resonant amplification. Moreover, this period is in the range of the infragravity waves observed in the area associated to storm events [32].

The results of the simulation are shown in Fig. 10. Wave heights greater than in both previous simulations can be seen. In particular, in Basins 1, 2, 3 and 6, there were

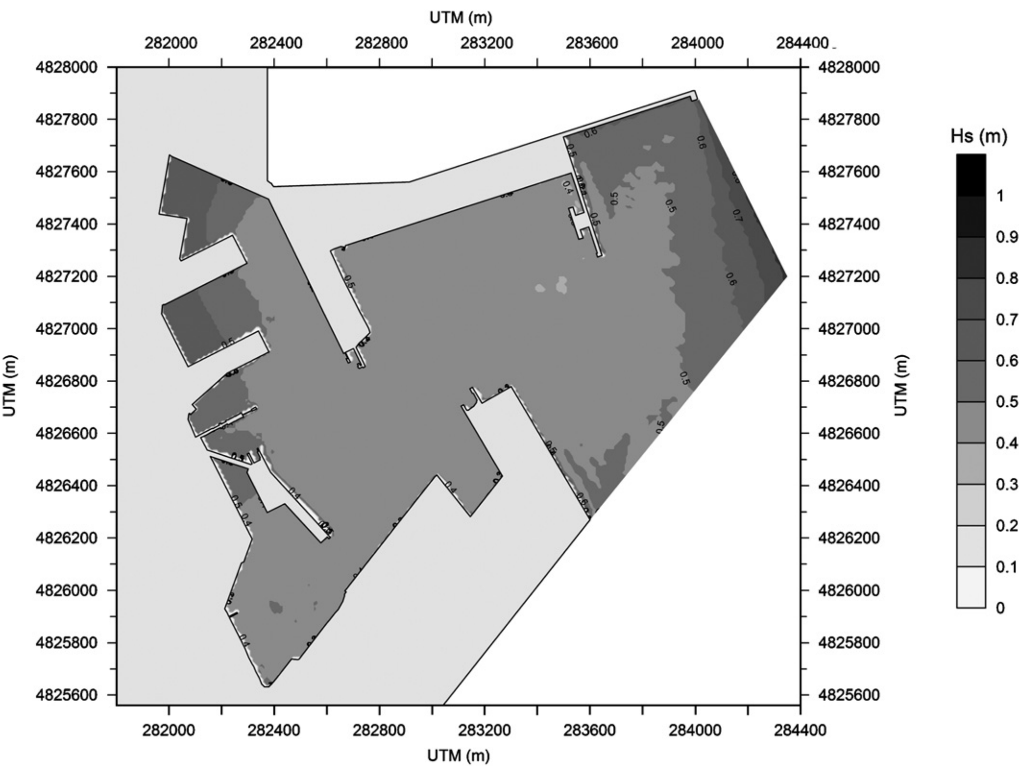

Fig. 10. Results of the numerical model for wind waves plus a long wave with $H_s^* = 0.20$ m and $T_p^* = 200$ s.

significant wave amplifications whose origin could be resonance. Table 8 shows the results for this case, in a similar way to Tables 6 and 7.

In this case, the agitation coefficients in the different areas ranged from 0.43 to 0.62, which are higher values than in the previous case. Thus, dry bulk unloading operations would have to be stopped between 2.0% and 9.4% of the time. Loading would be prevented between 10.6% and 25.1% of the time. The wider range of variation in this case

Table 8
Probability that operations would have to be stopped due to a combination of wind waves and a long wave with $H_s^* = 0.20$ m and $T_p^* = 200$ s for the various docks in Gijón port

Area	Activity	H_{lim} (m)	K_a	$H_{s0}/\geqslant H_{lim}$ (m)	$F(H_{s0})$	% $H_s \geqslant H_{lim}$
1	Dry bulk					
	Loading	1.0	0.62	1.61	0.6817	25.1
	Unloading	1.5	0.62	2.42	0.8814	9.4
2	General cargo	1.0	0.54	1.85	0.7580	19.1
3	General cargo	1.0	0.55	1.82	0.7482	19.9
	Dry bulk					
	Loading	1.0	0.55	1.82	0.7482	19.9
	Unloading	1.5	0.55	2.73	0.9220	6.2
4	Dry bulk					
	Loading	1.0	0.43	2.33	0.8658	10.6
	Unloading	1.5	0.43	3.49	0.9746	2.0
5	Dry bulk					
	Loading	1.0	0.46	2.17	0.8369	12.9
	Unloading	1.5	0.46	3.26	0.9641	2.8
	LNG–LPG					
	$<60{,}000\,m^3$	1.2	0.46	2.61	0.9081	7.3
	$>60{,}000\,m^3$	1.5	0.46	3.26	0.9641	2.8
6	Dry bulk					
	Loading	1.0	0.51	1.96	0.7876	16.8
	Unloading	1.5	0.51	2.94	0.9424	4.6
	Oil products					
	<30,000 TPM	1.5	0.51	2.94	0.9424	4.6
	30,000–200,000 TPM	2.0	0.51	3.92	0.9873	1.0
7	Oil products					
	<30,000 TPM	1.5	0.50	3.00	0.9471	4.2
	30,000–200,000 TPM	2.0	0.50	4.00	0.9888	0.9
8	Fishing	1.0	0.46	2.17	0.8369	12.9
9	Oil products					
	<30,000 TPM	1.5	0.47	3.19	0.9601	3.2
	30,000–200,000 TPM	2.0	0.47	4.26	0.9927	0.6
	General cargo	1.0	0.47	2.13	0.8271	13.7
10	Dry bulk					
	Loading	1.0	0.45	2.22	0.8466	12.1
	Unloading	1.5	0.45	3.33	0.9678	2.5
	Ro-ro	0.5	0.45	1.1	0.4671	42.1

is because of resonant amplifications in the basins. Therefore, the agitation coefficients increase considerably. This can be observed in Fig. 11, which compares the coefficients for the three cases. In the third case, small oil carriers' operations would not be possible between 3.2% and 4.6% of the time. The operations of larger carriers would have to be halted between 0.6% and 1% of the time. LNG ships would have to stop operations 2.8% (large ships) and 7.3% (small ships) of the time; in the case of fishing ships, this figure would be 12.9%. Finally, general cargos would not be able to operate between 13.7% and 19.9% of the time and the ro-ro terminal would not be in service 42.1% of the time.

The comparison of the three simulations (see Fig. 11) shows how long waves increase the agitation coefficient. Agitation coefficients from 0.11 to 0.23 are obtained when only wind waves move towards the harbor. If long waves with periods in the typically observed range [32] were always present in the wave trains affecting the harbor, these coefficients would increase at an approximate rate of between 2 and 4. If the wave trains always contained long waves with a period of 200 s, which is in the basin–resonance range and has also been associated with storm events [32], the agitation coefficients would be similar to the previous case. However, in some basins there would be an additional increase (between 12.5% and 29%) due to resonant amplifications.

Substantial variations in agitation conditions inside the harbor due to the presence of long waves show the significance of such waves to port operations. As the numerical results demonstrate, the presence of long waves increases oscillations in the water's free surface, making operations difficult for ships and increasing the inactivity time. Nevertheless, these waves are hardly taken into account in port design and are only considered when problems

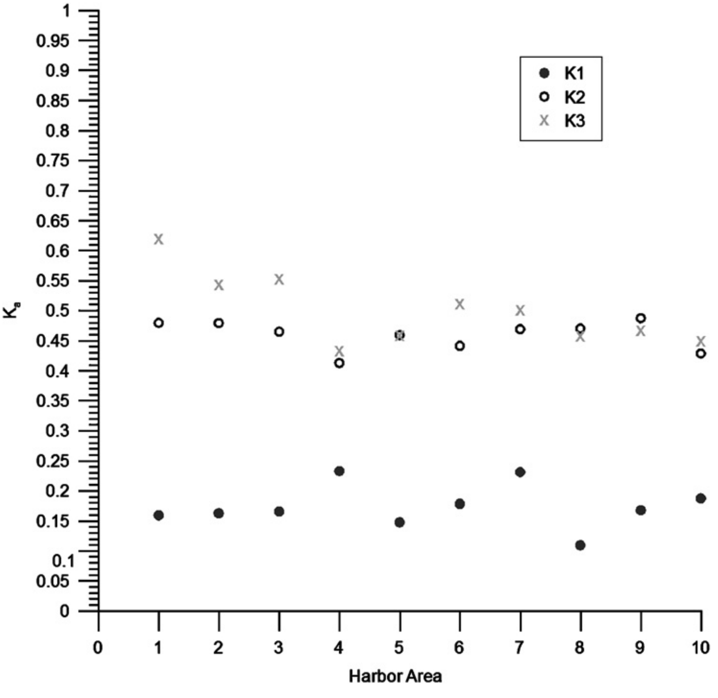

Fig. 11. Agitation coefficients obtained for wind waves (K1), wind waves plus a long wave with $T = 80.3$ s (K2) and wind waves plus a long wave with $T = 200$ s (K3).

appear. The results illustrate that it is essential to bear long waves in mind in port design and management to avoid problems such as an increase in port inactivity due to excess agitation inside the port.

6. Effects of long waves on environmental aspects of harbors

As has been shown, the main results focused on the effects of long waves on harbor operations, which is the most sensitive management issue arising from the presence of long waves in harbors. However, from an environmental point of view, there are other management issues that may be affected by the presence of long waves, but to a lesser extent: (i) sediment dynamics, (ii) ecosystems, (iii) water quality, and (iv) safety. A schematic overview of the limited effects of long waves on these environmental issues is presented below.

As mentioned above, in Gijón harbor the main effect of long waves is the increase in agitation coefficients, which significantly affects the operations and general dynamics of the harbor. Although this physical effect is considerable, the direct effects on sediment and ecosystems are very limited because the sediments in harbor environments are semi-cohesive (mud and clay, see e.g. [46]). For this reason, the initiation of motion and resuspension require agitation coefficients associated with waves that have a very large return period [46]. Moreover, since Gijón harbor is located in a rocky area, sediment contributions are small and irregular, which further limits the effects of long wave presence on these sediments. Regarding both pelagic and benthic communities, they are scarce in this type of environment (e.g. family mitilidae) and they are not affected by hydrodynamic variations such as those generated by long waves.

In terms of water quality, the presence of long waves that induce resonance amplifications, such as those found in Gijón harbor (see harbor areas 1, 2, 3 and 6 in Fig. 10), could generate standing waves (see e.g. [47]), which implies areas of no horizontal (anti-nodes) and no vertical (nodes) movement of the free surface. These scenarios tend to concentrate floating bodies/pollutants in the node region. As mentioned above, this feature may be important in Gijón harbor since it is the leading port for dry bulk in the Spanish harbor system. As can be seen in Fig. 2, about 85% of the total traffic corresponds to dry bulk, over 80% of which is coal. This coal could be transported to the water harbor domain by the wind and then concentrated on the nodes of the standing waves due to long wave induced resonance effects.

Finally, the last management issue that may be affected by long waves concerns the safety of navigating and moored vessels. The increase in harbor agitation due to long waves increases the likelihood of accidents due to vessels maneuvering into moorage or due to the lines of moored boats breaking. This may occur in particular in several areas of Gijón harbor: 1, 2, 3 and 6 (see Figs. 7 and 10). The worst consequences of such accidents would be in area 6, in which oil products are handled (see e.g. Table 8) and a limited oil spill could affect the harbor environment.

7. Summary and conclusions

A number of mechanisms generate long waves in the nearshore area and vicinity of harbors. In particular, meteorological forcing, wave groups, set-down and the non-linear transfer of energy between spectral components can generate this type of wave. This implies that long waves in wave trains moving towards harbors occur more often than is generally considered.

In Gijón harbor, the analysis of records from a pressure sensor placed in front of the harbor mouth showed that the presence of long waves is not an uncommon event. From this analysis, the maximum concentrations of energy for infragravitational waves were found in the bands of 130–200 s for storm events and 75–90 s under non-storm conditions.

Gijón harbor has developed a real-time management system for traffic navigation and harbor operations. This system is based on wave measurements and wave forecasting using numerical models. It enables the harbor authority to make decisions. However, its limitation is that the numerical modeling process is not able to reproduce the combined effect of wind and long waves.

To analyze the importance of long waves in port management, a study was carried out using a Boussinesq-type numerical model. This model allows long and irregular wind waves to be propagated simultaneously. The numerical model results showed that Gijón harbor offers a good shelter against wind waves, as only the ro-ro terminal would be exposed to waves exceeding the height threshold for its operation 7% of the time.

To analyze the effect of long waves, two different long waves were superimposed onto a wind-wave train. The first one had a period of 80.3 s and was obtained analytically from the expression which relates long wave characteristics to those of wind waves. This period is in the range of the infragravity waves that are observed in this area and are not related to storm events (75–90 s). The results showed how wave agitation increased at a rate of between 2 and 4 inside the harbor. Consequently, if these long waves were always present, operations would have to be stopped in many docks between 10% and 15% of the time, and they would no longer be possible in the ro-ro terminal.

The second long wave simulated (with the same wind-wave train) had a period of 200 s, which is in the range (130–200 s) of long waves observed for storm events. The period of this wave was selected as it is close to the natural oscillation period of some harbor basins. Therefore, it could generate resonant amplification. In the results of this simulation, wave heights that were greater than in both previous simulations were found in several basins. There were significant wave amplifications whose origin could be resonance.

Substantial variations in the agitation conditions inside the harbor due to the presence of long waves show the significance of such waves to port operations. Long waves increase the oscillations in the water's free surface, making operations difficult for ships and increasing the inactivity time. Therefore, it is essential to bear long waves in mind in port design and management.

As has been demonstrated, harbor operations are the management issue most affected by the presence of long waves in harbors. From an environmental point of view, four other issues (sediment dynamics, ecosystems, water quality and safety) have been pointed out that could potentially be affected by long waves. However, the effects of long waves on these four features proved to be limited in Gijón harbor.

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