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A REVIEW CONCERNING THE ROGUE WAVES AND THEIR IMPACT ON NAVIGATION CONDITIONS

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ABSTRACT

This work presents a review of data from the literature related to abnormal waves, also known as rogue waves or freak waves, due to their destructive effects on ships, on marine structures and activities. There are considered abnormal waves, the waves with the height exceeding at least twice the significant wave height for a given sea state.

The most recent researches have shown that extreme waves with crest to trough heights of 20 m until 30 m occur more frequently nowadays. These types of waves suddenly strike the ship, making the situation particularly dangerous during the storm conditions if the ship is in a head sea and suddenly goes into an abnormal roll.

Therefore, it is imposed that the current design criteria to generally consider the significant wave heights of 20 m till 30 m. Also, the dynamic forces of the waves impact should be included in the structural analysis of the ship.

Keywords: rogue waves, marine environment, significant wave height, diffractive focusing, navigation conditions

1. INTRODUCTION

The seas and oceans are usually characterized by a corrugated surface, hard to describe, which consists of waves with different characteristics and moving in different directions. Two types of waves usually characterize the sea surface: wind waves and swell waves [28], [29].

Wind waves are formed under wind action that puts added pressure on the water surface. Simultaneously with this pressure, the air masses friction occurs, that are moving by the water particles that are removed from the balance position and determined to execute a rotational movement, describing closed trajectories. This movement of the water particles represents the propagation of an energy state without a proper translation. Initially, it forms small folds (capillary waves), which, after the wind termination, amortization due to superficial tension. If the wind intensifies and acts for a longer time, the waves sizes increase and they are transformed into gravitational waves. When the wind stops beating, leaving just the water under its own weight influence and of the inertial forces, or they remove from the generation area, the waves get a regular shape, turning into the swell waves or wind waves.

The waves are defined by a series of elements as: λ - wave length, h_w - wave height, T - wave period, c - celerity, $\omega = 2\pi/T$ - pulsation wave, $k=2\pi/\lambda$ - wave number [17].

The characteristic elements of the waves depend on the wind intensity, the extent of the maritime area in which acts the wind, the water depth and so on.

Generally, the waves propagate in distinct groups that succeed at approximately equal intervals and between, the sea seems less hectic. The waves from each group have different heights and speeds of propagation. For this reason, the interference phenomenon occurs, causing a progressive increase in height. It was observed that the ninth or tenth wave within a group is taller and more dangerous than the others.

Among the waves formed at the sea surface, the so called rogue waves are very high. With respect to such waves, there are two options: the classical rogue waves and extreme abnormal waves.

The classical extreme waves are defined by modelling the surface process as a stationary and homogeneous slightly non-Gaussian random field. Their probability of occurrence is rare, with a value of 10^{-4} [15]. A lot of them do not pose a real threat to navigation.

The abnormal waves differ from the "classical" huge waves. These are gravitational surface waves whose height is much higher than that expected for the sea state.

For the navigation, the rogue waves represent a frightening and often life-threatening phenomenon [12], [13], [14].

In recent decades, these type of waves, often described as 'walls of water', 'appearing from nowhere', have received considerable attention, both in the scientific community and also in shipping and offshore industries [5].

So, the first rogue wave phenomenon has been discussed in scientific literature by Draper (1964), while Mallory (1974) has provided initial information on the large and abnormal waves in the Agulhas current off the southeast coast of South Africa [8], [24].

On the 1st of January 1995, it was recorded the best-known and reliable recording of a rogue wave at the Draupner platform in the North Sea.

There are many reasons why these wave phenomena may occur.

Often, the extreme events can be explained by the presence of the ocean currents (e.g. Agulhas current) or bottom topography that may cause focusing of wave energy in a small area [22]. On the other hand, it is believed that in the open ocean – away from non-uniform currents or bathymetry –, these waves can be produced by nonlinear self modulation of a slowly varying wave train [18].

This paper briefly presents the rogue wave phenomenon and its implications on the shipping and offshore platforms.

2. ROGUE WAVES

The rogue waves are particular waves, very dangerous, with the profile of a singular wave that has very high crest or trough away with a very high local slope [23].

The rogue waves are recognized when they occur, but there is no single definition of such waves. They are not necessarily the biggest waves on the sea. For forming the rogue waves, without a generally accepted theory, it admits several possible mechanisms: the presence of the strong currents, especially where sea currents have an opposite direction to the travel direction of the waves, or in the coastal waters due to the concentration of refraction or diffraction, most likely, through natural processes or randomly in smaller waves by absorbing the energy from them etc. The rogue waves occur relatively infrequent and they have a short lifespan.

The most common rogue wave is defined by the ratio of the wave height and the significant wave height exceeding certain limits. In a pragmatic approach, a freak wave is a wave with wave height zero-down cross that exceeds 2 times the significant wave height ($H/H_s > 2$), repeatedly, and, thus, they can be considered to be abnormal events [9], [10]. In mathematical terms, this is [16]:

$$H_{max} > 2 \text{ x } H_s \text{ or } C_{max} > 1.25 \text{ } H_s$$

where H_{max} denotes the zero-crossing wave height, C_{max} is the crest height, and H_S is the significant wave height, defined as four times the standard deviation of the surface, typically calculated from a 20-minute measurement of the surface elevation.

The rogue waves are also known as strange waves, huge waves, killer waves, extreme waves and they are not necessarily the biggest waves on the sea. They are very well localized in space and in time and are more common on the high seas. Some of the extreme waves occur suddenly and they persist for a very short period of time, even less of a wave period. As a result, the lifetime of the events with extremely high wave varies from a few seconds to tens of characteristic wave period [10].

The extreme waves are typically characterized by high levels of speed, but higher speeds do not necessarily correspond to the rogue waves, and so, the abnormal waves can be characterized by a moderate speed of the fluid [33].

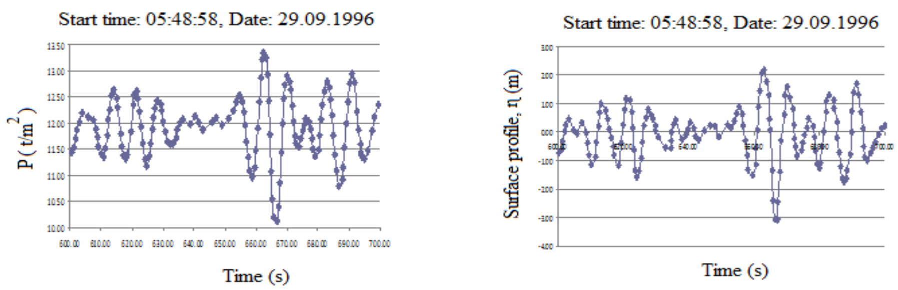
The presence of the rogue waves is currently considered a natural phenomenon of the oceans. A long time, the evidences of their presence lacked, although the sailors report them and the damages produced to the ships suggested their existence. The rogue waves were quoted in the media as a probable cause of the unexplained disappearance of many ocean-going vessels. One of the cases where there is evidence that might indicate an incident of rogue wave is the loss of the cargo ship MS Munich in 1978. There is other evidence when such waves hit the passenger ships [7], container ship, tankers, fishing vessels and marine and coastal structures, sometimes with catastrophic consequences. It is believed that more than 22 transport ships have been lost due to rogue waves between 1969 and 1994 [21].

In the years 1995-1996, the wave measurements made in Filyos in the south-western region of the Black Sea, offshore from Turkey, where 7949 records were obtained, revealed the presence of the rogue waves in 206 of 217 done recordings. In 28 recordings, in which Hs is greater than 1.0 m, the ratio H/Hs ranged between 2.34

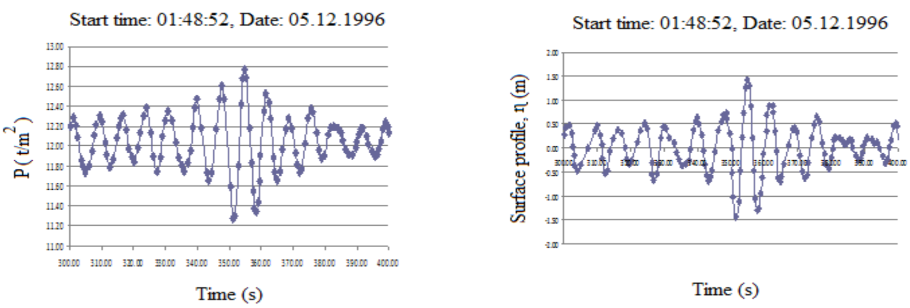
and 2; for the ratio of 2.34, the rogue wave was of 2.69 m and Hs of 1.14 m. The biggest observed rogue wave was of 5.27 m with Hs = 2.58 m and the ratio H/Hs = 2.04. The points of the surface profile of the highest rogue wave and the highest values for H/Hs recorded are shown in Figure 1 [1].

The analysis of the records showed that the recorded distribution of the wave surface profile that contains rogue waves deviates from the Gauss distribution with a negative asymmetry between -0.01 and -0.4.

Also, although it was found out that the likelihood of the rogue waves is over-predicted by the Rayleigh distribution, the larger ratio Hs/RMS indicates the fact that the distribution of the wave height may be represented by Rayleigh model.



(a) Extreme wave height=5.27 m, Hs=2.57 m, AI=2.04



(b) Extreme wave height=2.69 m, Hs=1.14 m, AI=2.34

Fig. 1 The pressure and the surface profile of the highest rogue wave recorded in September 29 1996 (a) and the highest value H/Hs registered on 5 December 1996 (b) (results processed from [1]) where $AI=H_{extreme}/H_S >2$ is the abnormality index

In the majority of cases, the characteristics of the rogue waves and their likelihood of occurrence appear to be consistent with the random wave theory of second order. There are exceptions, but it is unclear whether they are measurement or statistical errors, or the waves are produced by physical mechanisms that are not covered by the model [9].

The scientific confirmation of the presence of rogue waves occurred in January 1995, when it was reported such a wave at the Draupner platform in the North Sea, whom it caused damage. The wave presence was proven by satellite images.

Figure 2 shows two examples of rogue waves: in the Gorm area and Draupner platform in the North Sea.

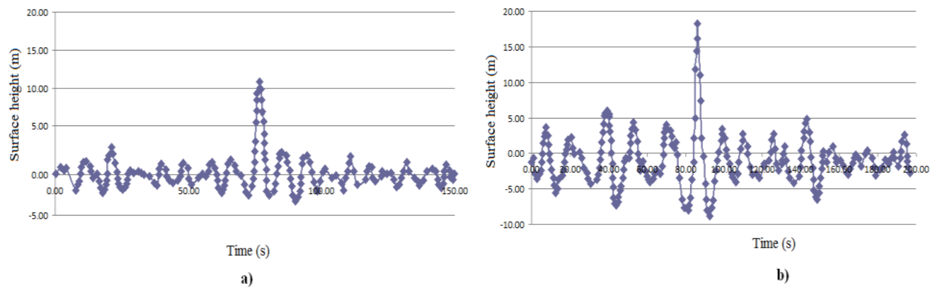


Fig. 2 Rogue waves. a) Gorm area, b) Draupner platform (results processed from [9])

A rogue wave was recorded in the in Gorm area from the North Sea on 17 November 1984. The wave that stands out has a crest height of 11 m that exceeds the significant wave height of 5 m with a factor of 2.2. The rogue wave against the Draupner platform in the North Sea was recorded on 1 January 1995, at 15:20. The crest height was about 18.5 m and a height greater than the significant wave height of 11.8 m with a factor of 1.54 [9].

The studying of the rogue waves by the scientific community began more intense since 2000 through research programs, meetings and workshops. In 2004, the scientists using radar images from the European Space Agency for three weeks, observed ten huge waves, each 25 m or greater [10].

One of the major problems regarding the rogue waves is the investigation of their effect on the structural response and the understanding of their generation mechanism.

Buchner and Bunnik investigated the effect of rogue waves on floating structures for deep water, focusing on numerical prediction of the response of the platform to extreme waves [2]. Clauss, Hennig, Cramer and Brink [3] and Clauss, Schmittner and Klein [4] conducted numerical and experimental tests to accurately reproduce a predefined recording of rogue waves in a wave pool and they investigated their effect on the structural and wave response.

3. THEORIES ON THE ROGUE WAVE FORMATION

So far, there is no generally accepted theory or explanation, regarding the formation of rogue waves, so we cannot clearly state which causes are the most frequent or if they vary from one place to another. It seems that there is still a consensus among the researchers that such waves occur in the presence of strong currents or in the coastal waters due to, in this case, most likely, the refraction or diffraction concentration, when the shape of the coast or the form of the seabed directs several small waves to meet in phase [9]. Their crest heights combine and form a rogue wave [10].

The areas with the highest risk appear to be those in which a marine current has an opposite direction to the main direction of the travel of the waves. Such an area is near Cape Agulhas in South Africa, where the warm Agulhas current has a south-westerly direction while the prevailing winds are from the west [10].

The rogue waves are formed in the open ocean, away from the strong currents or due to the topography. At present, the only viable admitted mechanism to generate such waves in the ocean is a modification of the Benjamin-Feir instability limit (BF) [9]. In this respect, in [17], it was studied the influence of the currents induced by the Danube River outflow in the coastal sector at the mouths of the Danube on the values of the Benjamin Feir index (BFI). This study was performed considering simulations with the SWAN model and the results show that the presences of the opposite currents substantially increase the BFI values and, consequently, the risks of occurrence of the freak waves in such marine areas.

The measurements in the Black Sea, carried out in 1996 and totalling 15,000 wave records, revealed the presence of a rogue wave H/Hs =3.9 (H=10.32 m; Hs=2.6 m). In order to understand the origin of the wave, the numerical simulation of the space wave movement was carried out. Thus, it could reveal the trajectories in moving of several groups of wave and the propagation paths of two solitary waves. Admitting that it is possible that when two solitary waves interact, the maximum amplitude of the field is equal to their sum, to rise up twice, respectively, when the solitary waves have equal amplitude, the researchers have concluded that, in this case only, the convergence of two solitary waves cannot explain the appearance of the rogue wave since the wave amplitude should not exceed 4.2 m in this case. Therefore, they believe that this process is characterized by an occurrence of a nonlinear interaction of a wave group with solitary waves and such a nonlinear interaction is accompanied by a linear amplitude summation, the concentration of the wave groups dispersion with small amplitude should play an important role in the rogue wave formation [21]. The mechanism of the nonlinear effects on the rogue wave formation admits that it is possible a rogue wave to be formed by nonlinear, random natural processes, from smaller waves. In this case, it is assumed that the rogue wave is formed by absorbing the energy from other waves. A model of this assumption is the nonlinear Schrödinger wave equation (NLS), in which a normal wave absorbs energy from the waves immediately before and after it, reducing them to the minor waves as compared to other waves.

In order to explain the formation of rogue waves, other mechanisms were proposed, too. One of these is that of the wind wave. In this case, it is recognized that, although it is unlikely that only the wind to generate a huge wave, the combined effect with other mechanisms could provide a full explanation of the phenomenon of the rogue wave. Since the wind transfers a part of its energy to the sea surface, an explanation related to the rogue wave occurrence would be for the case when very strong winds generate waves that meet strong opposite currents. This combination of two different energies transported in opposite directions can generate huge marine waves [10].

It is commonly accepted that the huge waves result by the random overlap in an underdeveloped sea (to the second degree) and they cannot be predicted from the wave spectrum, deterministically [9].

4. THE FORM AND FREQUENCY OF ROGUE WAVES

From the observations and the interviews with masters of vessels, the rogue ocean waves can be classified into tridimensional long crested waves and short-crested waves. The first type of rogue waves retains their shape as they travel over long distances and the second type seems to exist in a relatively short period of time. The wave with long crest is like the wave unstable train of Benjamin-Feir type, while the wave with short crest is like the linear wave focused on dispersion [33].

Besides the solitary waves, there were observed groups of such waves, too.

This paper points out the existence of three types of the rogue waves [10]:

- 'White walls' that are travelling along the ocean up to 10 km and may be generated by the encounter of wind sea systems with similar wave lengths, but different directions (cross seas) or by small scale disturbances inside storm areas;
- 'Three Sisters', representing groups of three waves that may receive energy from the atmosphere by extended squall lines travelling in the propagation direction of the group;
- ‘Singular Wave Tower‘caused by a huge storm that has up to four times the wave height of the storm and after a few seconds, it breaks.

As concerning the frequency of these waves, very few data are known. It is unanimously accepted that the rogue waves infrequently occur, without exactly specifying what is meant by "rare". Some wave measurements, carried out for five years in the South Atlantic Ocean, show that the appearance of waves of this type is more frequent than rare [23].

However, all the dominant concepts and many theoretical approaches about the rogue waves have been developed recognizing their rare occurrence [19].

The measurement results of the ocean processes show that the rogue waves appear less than the given prediction of the Rayleigh distribution.

In the waves measurements made in the Western part of the Black Sea in Turkey (Filyos), the likelihood of the rogue waves was of 0.00018, i.e. every 5,000 waves (217 rogue waves from 1232088 recorded waves) [1]; Didenkulova et al. [7] noticed from observations the appearance of the rogue waves every 4,000 waves, while, according to the Rayleigh distribution, [22] these waves would occur once at 3000 waves, pointing out a consideration that the appearance of rogue waves is over-predicted by the Rayleigh distribution.

However, Mori [27] considers that the rogue waves appear to occur with higher frequency than the Rayleigh distribution would show and he developed a modified approach based on a non-Gaussian process. He formulated a complex representation, which can be solved only numerically and expressed his results in an interesting correlation to the parameters $H_{1/3}$/RMS, corresponding to the Kurtosis index. To check their theory, Mori conducted a laboratory experiment in a tank with waves generated by the 2D spectrum Jonswap for deep water. He has showed that his theoretical results represent an improvement over the Rayleigh distribution regarding the likelihood of the rogue wave appearance and the laboratory results revealed more than their appearances.

The theoretical and experimental results and the observations of actual processes of the ocean have shown that the rogue waves are a real appearance and danger and of interest for the navigation.

5. CONSEQUENCES OF ABNORMAL WAVES ON NAVIGATION AND MARINE STRUCTURES

The existence of rogue waves has led to concerns regarding the impact of these waves on ships and offshore structures because this type of waves represents a danger for both ships and marine structures.

The characterization of the severity of a particular sea state that contains large random waves, some of them even breaking, is not possible using only the traditional parameters as height and period of the individual waves. The accidents due to the rogue waves have taken place even if there had been a quite unique exceeding of the critical threshold values for several parameters, simultaneously.

It was demonstrated that rogue waves have a significant impact on wave-induced bending moment (sagging and hogging), slamming and ship motions, such as heave, pitch and surge. Such waves may also significantly affect and even destroy the offshore wind farms [26], [27] or the wave energy farms operating in the coastal environment [6], [34], [35].

Results from several investigations were reported. For example, strip theory was one of them, but it was not able to capture the effects of rogue waves impact satisfactorily, while the CFD-based approach gave better predictions. The linear and second-order wave models are unable to capture very steep waves, such as rogue waves. Therefore, recently, an increase in the use of CFD tools has been noticed for the analysis of marine structures, which requires proper descriptions of very steep waves and the sea states in which they occur [26].

However, these investigations represent a significant step forward in analysing the impacts of rogue wave on ship structures.

In the last decades, there were a lot of ship accidents that were produced due to the rogue waves, which highlighted the necessity of a careful design and operation of marine structures and the need for being adapted to the climate change. Thus, a large number of commercial vessels, especially bulk carriers, have been lost in incidents involving extreme waves [11].

Therefore, it is very important for the marine safety to take into account the meteorological conditions (temperature, pressure and wind) and also the oceanographic conditions (waves, current) in the ship and offshore standards.

A review of the ship accident reports indicates a number of areas where ships may be vulnerable to rogue wave damage. Thus, for bulk carriers, the hatch covers and deck penetrations are extremely important. More than that, besides the static load of green water on hatch covers, they should be designed to withstand the dynamic load of the impact of the design wave breaking on the vessel.

In many cases of ships accidents due to the rogue waves, the wave smashed bridge windows and flooded instrument panels, disabling critical instruments and, in a number of cases, they caused a complete loss of power. An obvious solution is to strengthen bridge windows.

Also, the waves have ripped the lifeboats from their davits meaning that the safety systems must be especially rugged.

The dynamic force of wave impacts should be included in a dynamic structural analysis of the ship.

For a suitable design of the girder ship hull against the loads induced by large episodic waves, it is necessary to be able to predict the likelihood of encountering such waves and also to predict the effects they induce on the hull.

Although the meteorological forecasts are accurate, the abnormal sea phenomena may suddenly appear. An example on this subject is the passenger ship “Oriana” that was hit by a 17-meters wave on September 28th, 2000 [20]. Based on the report of the ship captain, the ship was handling very well before an abnormal wave struck it. In this case, the accident ended without losses, but, often, the economic, human and environmental consequences are enormous.

As a history of the ships accidents, in 2006 there were many ships that sank, so that, from a total of 261 vessels, 75 were over 500 gross tons, from which 25% were lost due to the effects of wind and wave. In that period, there were reported at least 10 rogue wave incidents along with 15 other “large wave” incidents. Among those ships, it could be remembered the bulk carrier Alexandros T that had broken up off the coast of Port Alfred, in South Africa, that being a recognized location for rogue waves [32].

Other two accidents will be mentioned as well: a fishing vessel that has been capsized after a big wave hit it on the starboard bow and another ship has been sudden swamped due to an unexpected large wave. Finally, also other two fishing vessels were capsized by a huge wave in the North Sea, north of Bremerhaven, and the ship Joe Green was hit by a rogue wave in the Atlantic Ocean, off the coast of South Carolina. If we refer at the cargo ships, an example could be the Westwood Pomona that was hit by a wave 70 feet high [32].

Generally, it is assumed that the dangerous unexpected conditions can occur if the sea conditions are fairly rough. From ship accidents reports, due to the heavy sea conditions, it results that some clues may be obtained and these can be possible warnings for navigators. The study of the ship accidents in heavy weather conditions can lead to identify the area more prone to bad weather conditions, in general, and to abnormal waves, in particular.

The analysis must be approached not only with the classical wave parameters (from the wave energy spectrum), but also with geographical and technical parameters (ship characteristics), due to the complexity of the sea-state.

Generally, the accidents might occur due to unexpected sea conditions, as in the case of the rogue waves that might cause the inability to keep the ship under proper, although approximately 80% of shipping casualties are due to human errors in all phases of the process, either design, constructions or/and operation. Moreover, it must be taken into account that, in the last five decades, the ships have greatly increased in size and the cargo often consists of hazardous materials that means it is necessary to have a safe handling and a safe navigation in order to prevent accidents leading to increase risk of life, property and environment.

At the end of this section, it has to be also highlighted that, currently, the rogue waves are not explicitly included in the classification societies’ rules and offshore standards due to the lack of a consensus about the probability of their occurrence.

6. CONCLUSIONS

Abnormal waves, also known as rogue waves, freak or unexpected waves, which have the height greater than is expected for the sea state, from a few seconds to tens of characteristic wave periods. In the real ocean, the rogue waves are waves that are very steep and much higher than the surrounding waves in a wave record, which is usually of 20-minute length. Abnormal waves relatively infrequently occur and have a short lifespan.

Abnormal wave characteristics and the likelihood of their occurrence, in most cases, appear to be consistent with the random wave's theory of two orders.

There is not, until now, a generally accepted theory for the abnormal waves. It admits, however, that, frequently, they are formed in the presence of strong currents or coastal waters, due to the concentration of refraction and diffraction, most likely. In the open ocean, away from the currents and the topography of coastal waters, the occurrence of the abnormal waves is attributed to the change in the Benjamin-Feir instability limit.

The abnormal waves are considered to be likely the cause of the disappearance and destruction of many ocean-going marine platforms and ships. It became a necessity to find an explanation for rogue wave phenomena due to the high number of ship and offshore platform accidents caused by the observed encounters with high waves.

In the last decades, some large ships have been lost and, in many cases, the cause would be a "freak" wave, which is an individual wave with an exceptional wave height or/and abnormal shape. Therefore, for approaching these types of waves that are extremely unlikely from the Rayleigh distribution point of view, it has been introduced the notation of "freak waves". In this direction, it is supposed that the wave height (from crest to trough) exceeds the significant wave height by a factor of 2.

The rogue waves might occur all over the world, in deep or shallow water, but some locations can be more vulnerable than others. Even if these types of waves have been observed in low, intermediate and high sea states, they appear to occur more frequently in low and intermediate sea states.

Nowadays, it is more probably that the ship encounters extreme waves due to the wave climate. Increasingly more maritime accidents produced by the rogue waves might occur if the freak weather events are accompanied by the strong winds [26], [27].

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