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THE IMPACT OF NAVIGATION CHANNELS ON BERTH PROTECTION

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Abstract

There has been a significant and sustained growth in port and terminal infrastructure in recent years to accommodate the changes in container, oil, gas (LPG and LNG), bulk and other general cargo trade. Many of these new build ports and terminals require long, deep navigation channels through shallow water to allow access. Deep channels can have a significant effect on the propagation of waves and it is important to consider this interaction at an early stage of design and the consequences for wave disturbance at berths. This paper reviews the processes involved in the propagation of waves across a dredged channel and presents examples where the orientation of navigation channels can be beneficial or detrimental to wave conditions at terminal berths. Some innovative ways to reduce wave conditions at terminal locations through the optimisation of channel alignment and dredged area design are described.

1 Introduction

The growth in vessel sizes in recent years means that a significant number of port and terminal facilities are now approached through a deep dredged channel. Engineers and scientists have recognised the effects on waves of refraction and internal reflection from the side slopes of navigation channels for hundreds of years (e.g. Zwamborn and Grieve 1974, Beltrami *et al* 2003). As dredged channels get deeper, to accommodate larger vessels, these effects become more important to the design and may provide a contribution to sheltering the berth areas or even exacerbate wave penetration to the berth. In some cases the effects of the channel may be sufficient to give adequate shelter at the berth without a requirement for additional protection provided by a breakwater. Clearly this is a site specific effect but it is important to understand the physical effects on wave propagation of deep dredged channels and have the appropriate technical tools to evaluate this effect as part of the design process.

In this paper we review the processes involved in the propagation of waves across a dredged channel, the effect on wave conditions in and around the channel and also the use of numerical wave models to investigate the interaction between waves and channel as part of the design process.

The objective of the paper is to alert designers to the interaction between waves and deep navigation channels and the implications for ports, structures and wave disturbance at berths. We provide three examples where proposed navigation channels would significantly alter the wave propagation to the berth areas. In the first, the channel has a beneficial effect. In the second and third cases, the dredged approach channels are likely to exacerbate wave conditions at berth protected by a breakwater, resulting in potentially unacceptable conditions for safe loading and unloading of moored ships. In these cases, extensive numerical model tests resulted in novel solutions to reduce wave disturbance at the berth.

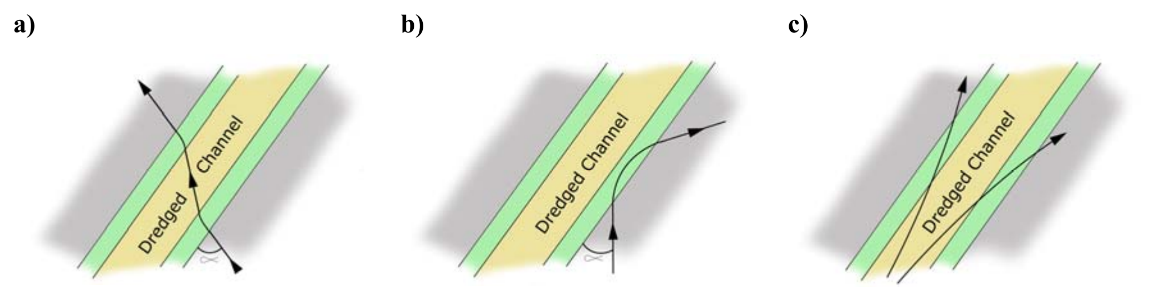

Figure 1 The path of waves travelling over a dredged channel: a) α > critical angle, b) α < critical angle, c) α ≈ zero.

2 The influence of a dredged channel on waves

It is well known that a dredged channel will affect the propagation of waves in shallow water. The effect of the channel on the waves is dependent on both wave period and direction relative to the orientation of the channel.

To explain the mechanisms involved, we first consider the idealised case of regular, uni-directional waves encountering a straight dredged channel. As waves propagate over the leading slope from shallow water to the deeper channel, they refract so that the wave direction relative to the orientation of the channel, decreases (Figure 1a). As the incident wave angle, α, relative to the channel decreases, the refracted wave direction, over the bottom of the channel, becomes parallel to the channel. This is the critical angle. Waves with incident angle less than the critical angle are internally reflected off the channel slope (Figure 1b). Linear wave theory (Snell's Law) predicts, for a regular wave, that the critical angle, α_c, is defined by

$$\alpha_c = \frac{\pi}{2} - \sin^{-1}\left(\frac{c_1}{c_2}\right)$$

where c_1 and c_2 are the wave celerities at the top and bottom of the slope respectively. In shallow water, nonlinear processes become significant; the effect of these on α_c depends on the wave height relative to the water depth and is therefore case dependent. In practice, the non-linear critical angle is typically between 0° to 10° less than that predicted by Snell's Law (Tao and Long 2001).

Hence, regular waves propagating over dredged channels can be placed in three categories dependent on the incident direction relative to the channel, α (Zwamborn and Grieve 1974, Yu *et al* 2000, Misra *et al* 2008, Sarker *et al* 2008):

- α > critical angle: waves propagate across the channel (Figure 1a).
- α ≤ critical angle: waves reflect off channel slope leading to concentration of wave energy on the waveward side of the channel and reduced wave energy in the channel and on the leeward side (Figure 1b).
- α ≈ zero: waves are refracted away from the centre of channel leading to concentration of wave energy on both sides and reduced wave energy over the channel (Figure 1c).

One consequence of this is that a harbour at the landward end of a deep navigation channel may experience the least wave disturbance when wave direction is directly along the alignment of the channel (Zwamborn and Grieve 1974, Sarker *et al* 2008). When the wave direction is at the critical angle, waves will be directed along the edge of the channel and may lead to greater wave activity in the harbour. Where there is total internal reflection, the reflected wave will interfere with the incident wave leading to amplification of the wave height on the edge of the channel.

Figure 2 Interaction between incident waves and a dredged channel in a physical model test. The hexagonal shaped wave crests close to the channel slope are due to interference between the incident wave and the wave reflected off the channel slope.

The above scenarios are dependent on the wave period. Short period waves are affected by refraction less than long period waves and so the critical angle is smaller. Also, if the wave period is long and therefore the wave length is significantly greater than the channel width, the waves will not notice the channel and will propagate straight across where shorter wave periods will be reflected. Physical model tests also reveal the concentration of wave energy from the slope of a dredged channel (Figure 2) and show the patterns that are created by interference between the incident wave and the wave component reflected off the channel. Such interference can lead to small areas of considerable amplification of the wave height. The interference pattern can be seen in 2-dimensional figures of time-averaged significant wave height as bands of higher and lower wave heights (anti-nodes and nodes respectively) running parallel to the channel. The width of the bands depends on incident direction but is typically of the order of half a wavelength.

Irregular sea conditions can be described in terms of 2-dimensional frequency and directional spectra. Different components of the spectrum refract differently over the channel slope. This leads to a reduction of the amplification on the channel edge compared to a regular wave (Zwamborn and Grieve 1974, Yu *et al* 2000) as wave energy is partially transmitted, partially reflected and the interference patterns are smoothed.

In some instances these effects can be potentially beneficial in terms of achieving acceptable wave conditions at berths, especially if wave energy that could disturb moored ships is deflected away from the berth. Conversely, at other locations or when waves approach from a different incident direction, wave energy that can affect moored ships may be focused towards the berth. This indicates that unless both wave heights and periods are correctly simulated as they approach the berth, the designer could draw erroneous conclusions regarding berth viability and the requirements for breakwater protection. In many circumstances, the propagation of waves into and within a port is influenced more by refraction from the access channel slopes than by diffraction (Booij *et al*, 1992).

The incident wave direction is an important factor to consider. The largest offshore waves, approaching from a particular direction, may be significantly deflected or focused onto the berth. Waves from a slightly different direction may be affected in a very different way. Hence it is important to consider a range of incident directions as well as conditions as small changes in offshore wave directions can have large impacts at the berth. Where the predominant incident waves are uni-directional within a very limited sector it may be possible to configure the channel in such a way so as to mitigate wave conditions at the berth.

3 The use of numerical wave models with navigation channels

To properly evaluate the effect of a channel on wave activity it is important that the tools used to investigate the design retain appropriate information on the wave parameters. For the level of detail required for this type of assessment, information on spectral parameters must be retained throughout the use of linked computational models, which is the methodology often used in evaluation of such studies.

To assess wave conditions within a port, it is usual that the modelling of wave conditions from offshore to the site is required. A wide range of well established computational shallow water wave models now exist and are frequently used within coastal engineering studies. Studies have examined the performance of various types of wave model in representing the processes involved in the propagation of waves over a navigation channel (Li *et al*, 2000, Misra *et al*, 2008). Phase average spectral wave transformation models, such as TOMAWAC, SWAN and Mike NSW, can represent the refraction and reflection of wave energy, provided sufficiently fine resolution is employed over the channel slopes. However, as these models do not resolve the wave length, the patterns created when the reflected wave interferes with the incident wave are not seen and the predicted wave height is a spatial average. The severe local amplifications caused by interference may be important, particularly where breakwaters and other structures are close to the edge of the channel. Hence, in most cases, a phase resolving computational model, (e.g. Boussinesq, mild slope equation) is required to adequately model the wave conditions within the port, at the berth and at locations where navigation or structures are likely to be affected by wave interference patterns.

Deep navigation channels are likely to be long and in most cases it is impractical to model the full extent of the channel with a phase resolving model. Modelling is therefore usually carried out in a two stage process: a phase average spectral wave model to transform waves to close to the entrance to the harbour or terminal, followed by a phase resolving wave disturbance model to predict wave conditions within a port and in the near approaches. The transformation model can efficiently model waves over a wide area but the more computationally expensive wave disturbance model is required in the port or terminal area to represent the diffraction, reflection and interference effects that may be important within a harbour or berth area and close approaches.

Considerable care must be taken at the boundary between the two models; the wave conditions are likely to vary significantly along the boundary, particularly inside and outside the channel. In addition, there are likely to be complexities in the directional and frequency spectra due to interaction with the channel. It is therefore important to pass both the spatially varying nature of the waves and as much of the 2-dimensional wave spectrum as possible from the wave transformation model to the boundary of the wave disturbance model. This can best be achieved by a one-way coupling between the spectral wave transformation model and wave disturbance model (Tozer and Durand, 2002, Cruickshank *et al* 2008).

As stated above the key benefit is that this methodology minimises the data loss between the models leading to a more accurate approach than would be achieved by imposing a constant wave condition based on integrated parameters on the wave disturbance model boundary. The coupling also allows the area represented in the wave disturbance model to be smaller than previously considered, resulting in improved computational efficiency. This technique has been employed in the examples presented in the following Section.

4 Case studies

4.1 Case 1 Development of the Cochin (Kochi) LNG Terminal

The case study described here was carried out for Petronet LNG Ltd (Petronet) who are planning to set up an LNG Receiving and Regasification Terminal at Cochin (in Kerala, southern India) with a 2.5mtpa nominal capacity with provision for expansion up to 5mtpa. The site is shown in Figure 3.

Figure 3 Case 1: Site of the Cochin LNG Terminal.

The initial design for the terminal included a 900m detached breakwater located to the south-west of the terminal site on the south side of the channel in order to provide adequate shelter for the berth. As part of the development of the Front End Engineering Design (FEED) package, a more thorough wave analysis and modelling study was carried out to determine whether the breakwater was required.

4.1.1 Overview of wave modelling study

The proposed LNG terminal is located on the north side of the entrance to the existing Port of Cochin, SE India. The current approach channel to the port runs due westward from the harbour entrance and it is proposed to deepen this channel to -14.5mCD to allow access to the LNG terminal. The wave climate at Cochin is dominated by ocean swell from the south west so the prevailing direction of waves is across the navigation channel from the LNG terminal berth. Hence, the processes described in Section 2 are particularly relevant to this situation.

The wave modelling study followed the methodology outlined in Section 3 using the phase averaged wave model TOMAWAC (Benoit et al., 1996) coupled to the phase resolving mild slope equation model ARTEMIS (Aelbrecht et al., 1997a,b). Various options for the repositioning of breakwaters, changes in their length or their removal were investigated.

The extensive modelling study revealed that the natural bathymetry and the proposed layout of deep navigation channel combined to refract or reflect wave energy away from the berth. For the important southwesterly waves, significant wave energy reflected off the southern slope of the channel reducing the wave energy in the channel and at the proposed berth.

This is illustrated in the model results shown in Figure 4. For an example 210ºN offshore wave condition, the predicted wave conditions at the berth are compared for layouts with the proposed breakwater (Figure 4a) and without the breakwater (Figure 4b). In both figures the circular line marks the transition between the phase averaged and phase resolving models. Comparison of waves in the berth area show there is limited additional benefit in terms of reduction of wave height to be gained from introduction of the breakwater. More detailed analysis, covering a range of incident wave directions and return periods, clearly indicated that the layout without the breakwater provided acceptable downtime. The interference between incident waves and waves reflected off the channel can be seen in Figure 4b as stripes running approximately parallel to the channel.

The preferred design was subsequently tested, using random waves from 2 directions, in a physical model, which also included moored ships to measure motion and mooring response (Figures 6). The results from the physical model validated the wave conditions from the computational model showing the refraction and reflections that occurred around the dredged channel. In particular, it confirmed that there was no requirement for a breakwater at this site as predicted in the earlier (pre-FEED) computational model studies. The physical model also provided more information on moored ship motion during operational (ship on berth) and extreme design cases (needing the ship to depart). In addition, the mooring line layout was optimised enabling the vessel to remain on the berth under more extreme conditions.

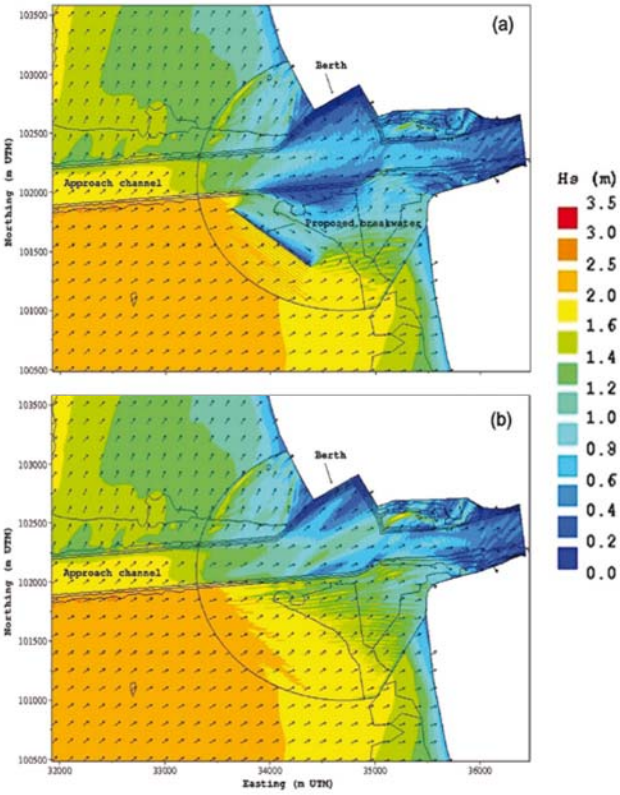

Figure 4 a) Case 1: Cochin LNG - Layout including a detached breakwater. Significant wave height and mean wave direction predicted by TOMAWAC and ARTEMIS. The black lines are bathymetry contours at 3m intervals.

b) Case 1: Cochin LNG – Layout without the breakwater. Significant wave height and mean wave direction predicted by TOMAWAC and ARTEMIS. The black lines are bathymetry contours at 3m intervals.

Figure 5 Case 1: Physical model experiments of the Cochin LNG Terminal in the HR Wallingford laboratory. The incident waves and waves reflected off the channel can be seen in the centre as perpendicular wave crests.

Figure 6 Case 1: Physical model experiments of the Cochin LNG Terminal in the HR Wallingford laboratory. Mooring tests at the Cochin LNG berth.

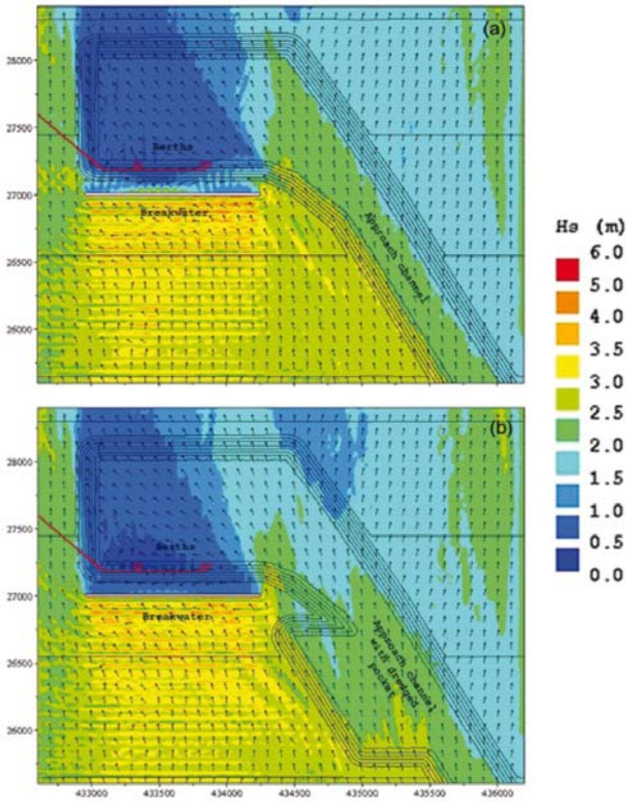

Figure 7 a) Case 2: Base Case Layout with example of southerly swell waves. Predicted significant wave heights and mean wave direction from ARTEMIS. The black lines are bathymetry contours at 1m intervals.

b) Case 2: Revised Layout with example of southerly swell waves. Predicted significant wave heights and mean wave direction from ARTEMIS. The black lines are bathymetry contours at 1m intervals.

4.1.2 Conclusions from Case 1

In this case, despite the location of the terminal on an open coast, we were able to demonstrate by that the configuration of the proposed dredged channel and turning area served to sufficiently redirect wave energy from the berth area.

Our studies indicated that construction of a breakwater would provide no significant benefit at the berth and that it would be a costly investment for the client. The breakwater option was therefore removed from the project, making a considerable saving in capital expenditure. The studies also showed that the operations are more likely to be limited by Pilot transfer and tug efficiency constraints than by unloading downtime when a vessel is on berth. Expected unloading downtime for vessels at the berth, with the final layout, is negligible (less than 1% of the total time of unloading operations), and that the periods when pilot transfer/tug operations may be constrained is also low (around 3%).

Sometimes, as can be seen here, the most appropriate solution to an engineering challenge is one that is lighter in terms of the engineering infrastructure involved and these benefits can be found by an appropriate level of expert study.

4.2 Case 2

The situation described in the Case Study 1 in Section 4 is one where the configuration of the dredged channel and its effect on waves propagating inshore has a beneficial effect on wave conditions at the berth area. In many circumstances, non-hydraulic constraints may mean that the dredged channel cannot be aligned in such a way as to afford adequate wave protection at the berth.

The example presented here is based on a terminal development on an open coastline in an area affected by long-period southerly swell waves. It is a simplified example to illustrate the problems faced. As in Case 1, the phase average model TOMAWAC was coupled to the wave disturbance model ARTEMIS.

The proposed configuration of the dredged approach channel and manoeuvring area was constrained by non-hydraulic considerations and a breakwater was required to provide berth protection. A wave modelling study wave conducted following the Section 3 method and it was found that the dredged areas of the approach channel have a significant effect on wave propagation (Figure 7a).

Since the incident waves are long crested with relatively long period, the dredged approach channel causes waves to reflect north westwards from the western side of the channel. This leads to a higher concentration of wave energy between the breakwater and channel and causes significant wave penetration into the area of the berths.

As a result of this finding, further work was undertaken to develop an optimal means of berth protection. This involved assessing different breakwater lengths and alignments, different channel alignments, and explored the use of dredged pockets to change the wave behaviour. The conclusion of the assessment was that the initial breakwater length and channel alignment could be maintained and that the required level of reduction in wave penetration to the berths could be achieved by installing a dredged pocket on the west side of the channel. This acts to deflect wave energy away from the east end of the breakwater, thereby reducing the wave energy reaching the berths (i.e. the combined sheltering effects of the dredged pocket and the breakwater leads to a wider zone of shelter than would be generated by the breakwater alone). An example layout is shown in Figure 7b.

Having established the principle, further work was then undertaken by the combined use of the computational modelling and physical modelling to develop an optimised design of the dredged pocket.

The combined berth protection system (breakwater plus dredged pocket) also had an additional advantage in that the dredged area has in built flexibility as it can be easily modified during operations; where as lengthening a breakwater cannot. The solution developed therefore also helped to mitigate the inherent “uncertainty” risk without over design of expensive fixed infrastructure.

4.3 Case 3

Case study 3 is a similar terminal development to Case 2 and subject to a similar wave climate. Here, a coastal harbour was proposed, necessitating a longer approach channel. As with Case 2, a straight channel alignment presented the problem of reflection from the channel slope leading to excessive wave activity at the berth. The phase average model TOMAWAC was coupled to the wave disturbance model ARTEMIS.

In this case there were fewer constraints on the orientation of the channel and it was possible to test a number of channel configurations early in the design process. Here, the configuration of the channel was used to enhance the protection at the berth from the prevailing waves. The use of a curved approach channel (e.g. Figure 8) diverges wave energy away from the berth and manoeuvring area. The configuration clearly has consequences for navigation and whilst initial assessments identified it to be adequate, a rigorous navigational study would be required during the further optimisation of the design to ensure the practicality of the approach.

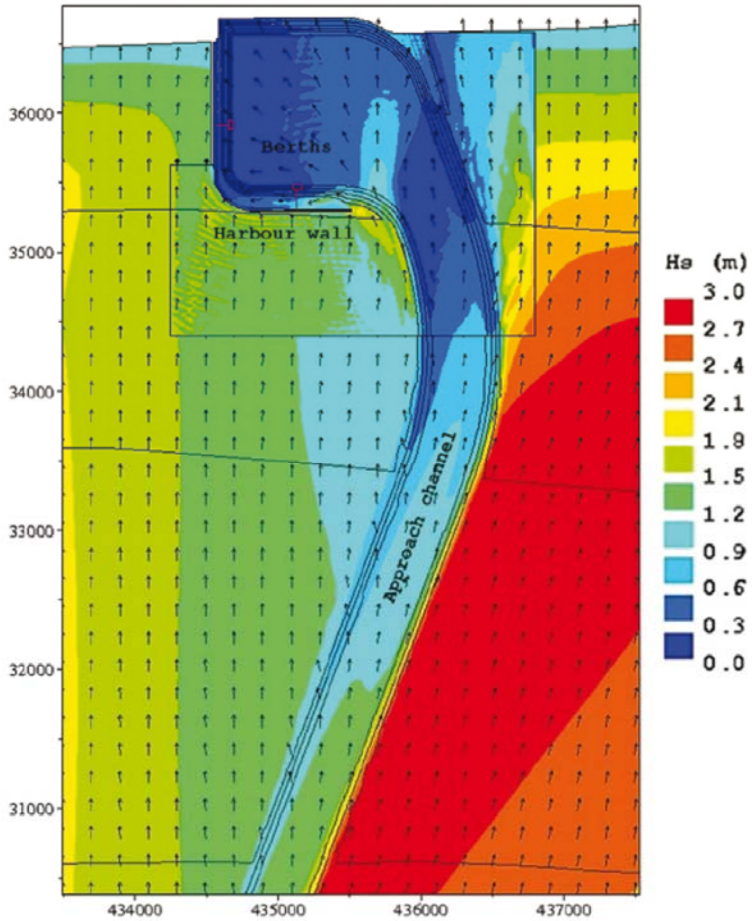

Figure 8 Case 3: Revised Layout with example of southerly swell waves. Predicted significant wave heights and mean wave direction from ARTEMIS. The black lines are bathymetry contours at 3m intervals.

5 Conclusions

Coastal engineers and designers should be aware that as dredged channels increase in depth their influence on wave conditions increases also. Refraction and reflection of waves over the channel side slopes can potentially lead to severe focussing of wave energy but also areas of reduced wave activity. It is essential that the designer recognises these effects and uses them to optimise the design. The appropriate use of numerical models combined with sensitivity checks to assess a range of directions allows the consideration of several options of dredging configuration at an early stage in the design process in order to optimise the design: from both a cost and performance perspective.

This paper has presented some examples which demonstrate the orientation of navigation channels can be beneficial or detrimental to wave conditions at terminal berths. Some innovative methods were described to reduce wave conditions at terminal locations through the optimisation of channel alignment and dredged area design.

6 Acknowledgments

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