

MODELLING SCOUR IN FRONT OF DUNE REVETMENTS IN A SURF-BEAT MODEL

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This paper presents adaptations to the XBeach model aimed at including the relevant processes for the generation of scour holes at the toe of a revetment. Dutch assessment rules for the safety of sea defenses need to be adjusted to cope with a combination of sandy dunes and hard elements. To that end, the XBeach model is prepared to be incorporated in the assessment rules. Until now, XBeach did not model scour hole development in front of dune revetments accurately. We suggest to include the advection of turbulence as well as the effect of backwash of short waves that creates additional turbulence in the model. Verification with three physical model experiments shows that with the suggested adaptations of the model a scour hole with significant depth can be modeled.

Keywords: dune erosion; XBeach; scour; dune revetment

INTRODUCTION

In the past assessment rules for the safety of Dutch sea defenses were developed either for dunes or dikes. Nowadays sea defenses more and more consist of a combination of dunes and hard elements. This requires the development of new safety assessment rules.

Combinations of sandy dunes and hard elements are for example sea dikes or seawalls adjacent to sandy dunes, non-flood defense structures such as relic Atlantic Wall bunkers or parking garages, or hybrid sea defenses such as dune revetments at the toe of a dune, a dike-in-dune structure in which a hard sea defense is covered by a sandy dune for esthetical appearances.

Current assessment rules prescribe the empirical dune erosion model Duros+ (Van Gent et al., 2008) to calculate a post storm erosion profile. Application of this model is limited to sandy dunes only and does not allow an assessment of the complete Dutch coast. New assessment rules are being developed to overcome these limitations. The new assessment rules need to also address (1) the impact of hard structures on dune erosion, and (2) the stability of structures in case of scour. To that end, hard structures will be incorporated in the XBeach model (Roelvink et al., 2009) and this model will be included in the Dutch safety assessment rules.

This paper presents part of the research that has been carried out in anticipation of the new assessment rules. Previously the influence of a fixed structure on dune erosion at an adjacent dune was investigated with physical model tests (Van Geer et al., 2009; Boers et al., 2011) and compared with XBeach calculations (Van Geer et al., 2012). Physical model experiments by Van Gent (2008) show the influence of a collapsed dune foot revetment on erosion rates in a cross-section. For the assessment of dune revetments in a cross-section, Van Thiel De Vries (2012) already improved the modeling of dune erosion above the revetment.

PROBLEM DEFINITION

Scour in front of a fixed structure (such as a dune foot revetment) deteriorates the stability of that structure and leads to greater wave loads. Adequate prediction of this process therefore is one of the requisites of a future assessment tool to predict the safety of a dune protected by a dune foot revetment. One of the known limitations of the current XBeach model is the inability thereof to calculate a scour hole with significant depth in front of a fixed structure.

Scour hole development in front of a structure

The subject of scour hole development in front of a structure is not new in coastal engineering. Many physical experiments have been carried out to study the development of scour holes in front of a seawall or revetment (Barnett and Wang, 1988; Steetzel, 1988; Sutherland et al., 2006; Tsai et al., 2009). From these studies it becomes clear that several parameters are important when predicting the final shape and depth of a scour hole:

- Slope of the foreshore
- Slope of the structure

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- Wave conditions (relative wave height and steepness)
- Relative water depth at the toe of the structure

Depending on the relation between relative water depth and the slope of the foreshore it was found that even accretion can occur instead of the formation of a scour hole. This knowledge is incorporated in several empirical formulations to predict the maximum scour depth (Fowler, 1992; Wallis et al., 2009). Zou et al. (2012) present a comparison between numerical model results and the results of a physical experiment. In their model all individual waves were calculated.

Scour hole development in XBeach

XBeach (Roelvink et al., 2009) was initially developed for the computation of barrier island erosion under hurricane attack (McCall et al., 2010). The model solves the 2D horizontal conservation of mass and momentum with wave group forcing, sediment transport, dune avalanching and hard (non-erodible) structures, which may be covered by sediment. In principle, all the processes to compute dune erosion are accounted for. However XBeach does not explicitly compute short intrawave processes (it only calculates the short wave energy balance and does not contain phase information of the short waves). As a consequence of the absence of a short wave signal, some processes that govern scour hole development are not represented in the model by default. This also makes the previously developed empirical formulations and full numerical descriptions of the relevant processes unsuitable for application in XBeach. This paper proposes improvements to XBeach aimed to compensate this shortcoming of the model and presents validation thereof against laboratory data (Steetzel, 1987a).

IMPROVEMENTS TO THE XBEACH MODEL

To accurately model scour development in front of a structure we include two processes in XBeach that are not accounted for in the initial release. First we add terms to model advection of turbulence. Second, we introduce production of additional turbulence at the toe of the revetment due to backwash. Both processes can play a role in creating a scour hole in front of a revetment.

In XBeach, propagation of wave energy is modelled by keeping a wave action balance (Equation 1, Roelvink et al. (2009)):

$$\frac{\partial A}{\partial t} + \frac{\partial c_x A}{\partial x} + \frac{\partial c_y A}{\partial y} + \frac{\partial c_\theta A}{\partial \theta} = -\frac{D_w}{\sigma} \quad (1)$$

The wave action (A) equals the wave energy density (S_w) divided by the intrinsic wave frequency (σ):

$$A(x, y, t, \theta) = \frac{S_w(x, y, t, \theta)}{\sigma(x, y, t, \theta)} \quad (2)$$

In the wave action balance θ represents the angle of incidence of the waves, c_x , c_y , c_θ represent the wave action propagation velocities in the horizontal (x, y) and directional (θ) dimensions and D_w represents the dissipation of wave energy. Once wave energy is dissipated ($D_w > 0$) this is contributed to a roller energy balance, which models the propagation of the roller (Equation 4).

$$\frac{\partial S_r}{\partial t} + \frac{\partial c_x S_r}{\partial x} + \frac{\partial c_y S_r}{\partial y} + \frac{\partial c_\theta S_r}{\partial \theta} = -D_r + D_w \quad (3)$$

With the roller energy in each directional bin represented by $S_r(x, y, t, \theta)$. c_x , c_y , c_θ now represent the roller energy propagation speeds in the various dimensions. This relation states that the roller energy is balanced by the contribution from the wave action balance (D_w) and dissipation of the roller energy (D_r). The total roller energy dissipation is calculated according to Reniers et al. (2004):

$$D_r = \frac{2g\beta_r E_r}{c} \quad (4)$$

which combines the concepts of Deigaard (1993) and Svendsen (1984). XBeach assumes that part of this dissipation term is contributed to generation of turbulence which stirs up sediment.

Advection of turbulence

The XBeach model follows Battjes (1988) and assumes that production and dissipation of turbulence are balanced and that spatial gradients in turbulence are negligible (Equation 5). In this way turbulence generated over a revetment is not advected back to the toe of the structure and will not cause additional erosion. Turbulence intensity can then direct be calculated from the dissipation term of the roller balance:

$$k = \left(\frac{D_r}{\gamma_d \rho} \right)^{\frac{2}{3}} \quad (5)$$

Where D_r denotes the roller energy dissipation following from the roller balance, γ_d represents a calibration coefficient (1.0 in this study), ρ is the density of water and k represents the depth averaged turbulence intensity due to wave breaking. By abandoning these assumptions and including turbulence advection we allow turbulent kinetic energy that is generated over the revetment to be advected towards the toe area. When it dissipates at the toe of the structure, this can lead to enhanced erosion creating a larger scour hole. k now follows from Equation 6.

$$\frac{\partial kh}{\partial t} + \frac{\partial kh u}{\partial x} + \frac{\partial kh v}{\partial y} = \frac{D_r}{\rho} - \gamma_d k^{\frac{3}{2}} \quad (6)$$

In which h represents the local water depth and u and v denote the flow velocity in x and y direction.

Backwash induced turbulence

When waves approach a sloping structure, wave runup on the revetment will occur followed by backwashing waves. Depending on the water depth in front of the structure this backwash will penetrate the water column and increase turbulence at the sandy bed in front of the structure. This will stir up additional sediment and lead to a deepening of the scour hole in front of the revetment (Steetzel, 1987b). Similar to Steetzel (1987b) we model this process by contributing a small percentage of the incoming energy flux at the toe of the revetment to the local generation of turbulence (see Equation 7).

$$k = k + \gamma_{jet} \left(\frac{E \sqrt{gh}}{h/\alpha} \right)^{\frac{2}{3}} = k + \gamma_{jet} \left(\alpha E \sqrt{\frac{g}{h}} \right)^{\frac{2}{3}} \quad (7)$$

In which γ_{jet} is a calibration factor (we used 0.1 for the verification with the measurements), E represents the short wave energy at revetments toe, \sqrt{gh} equals the shallow water group velocity and h/α denotes a dissipation lengthscale where h is the water depth and α is the slope of the revetment.

VERIFICATION WITH LABORATORY MEASUREMENTS

Physical and numerical model setup

The suggested modifications will be verified against measurements obtained by Steetzel (1987a), who conducted five large scale physical model experiments in the Deltaflume (230m long, 5m wide, 7m deep), which is operated with an advanced wave paddle including active reflection compensation (ARC) and second order wave steering. Figure 1 shows the setup of these experiments. Tests T1, T2, T3 are performed with shore normal irregular waves (Pierson Moskowitch spectrum), constant water level (4.2 meter above flume floor) and explore the morphological impact of revetments with different heights (see Table 1).

Table 1: Overview of the experiments including information about revetments height and hydraulic boundary conditions.

Test	Height Revetment above max waterlevel [m]	Waterlevel above flume floor [m]	Hm0 [m]	Tp [s]	Spectrum [-]
T1	2.0	4.2	1.52	5.37	PM
T2	1.2	4.2	1.52	5.37	PM
T3	0.6	4.2	1.52	5.37	PM

The initial sandy profile applied in the flume (Figure 1) is the same for all tests and resembles the reference profile that is used to develop the Dutch dune safety rules (with a depth scale of 5 compared to prototype conditions). During the first three experiments the dune face was protected by a concrete cover, representing a dune revetment. All revetments have a slope of 1:1.8, which corresponds to the slope of the non-protected dune. The bottom of the concrete cover reached to 1.7 meters below the maximum waterlevel applied during the experiments, which lies below the maximum observed scouring depth. This revetment reached up to 2.0 meters (T1), 1.2 meters (T2) and 0.6 meters (T3) above the maximum water level. Several measurements were conducted including wave height (wave gauge), flow velocity (EMF's) and sediment suspensions (suction tubes) with a mobile carriage that could be positioned at varying cross-shore positions in the flume during a test. Furthermore, wave runup time series over the (partly) protected dune face were measured using a resistance wire. During the tests, the wave paddle was stopped at the end of pre-defined test intervals to record the morphological evolution with a wheel profiler. In this study the measured profiles are used to verify model performance.

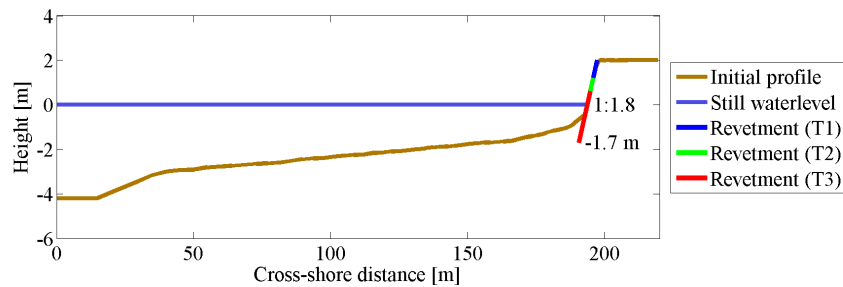


Figure 1: Representation of the initial cross-shore profile and revetment heights as used by Steetzel (1987a)

A 1D XBeach model has been set-up for each model test. The grids are non-equidistant and grid resolution increases in shoreward direction from $dx = 7$ m offshore to $dx = 1$ m in the vicinity of the revetment (also the computational grid is designed such that the top of the revetment coincides with a grid point). Wave and flow boundary conditions are obtained from an analytical Pierson Moskowitch spectrum using the approach as described in Van Dongeren et al. (2003).

Model verification

This section contains a comparison between profiles measured during the experiments and calculated profiles by XBeach. We present both a comparison with an XBeach model that did not include the adaptations suggested by Van Thiel De Vries (2012) and in this paper and to the proposed model that includes these formulations (XBeach V1.20) and with the proposed model that includes these changes. During experiment T1 the complete dune face was covered by a concrete layer representing a dune revetment. Effectively this experiment represents the formation of a scour hole in front of a fixed (sloping) structure.

Figure 2 shows a comparison between measured and calculated profiles at the end of this experiment. Comparison between the measured final profile and calculated final profile with XBeach V1.20 (Figure 2a) clearly illustrates the problem of an underprediction of the scour hole. Figure 2b shows that the final profile calculated by the proposed model is in better agreement with the measurements. The scour hole in front of the revetment is present in the model results and the maximum scour depth approaches measured values.

An important parameter when judging the stability of a revetment is the depth of the scour hole in front of the revetment. A scour hole that reaches too deep will cause a revetment to collapse. Prediction of the (development of the) depth of a scour hole is therefore essential for a model that will be used for the assessment of these types of profiles and structures. Figure 3 shows a comparison between the calculated maximum depth of the scour hole (relative to the initial bottom level) and the maximum depth of the scour hole obtained from the profile measurements during the experiments. This shows that the calculated development (blue line) is in good agreement with the measurements (grey circles).

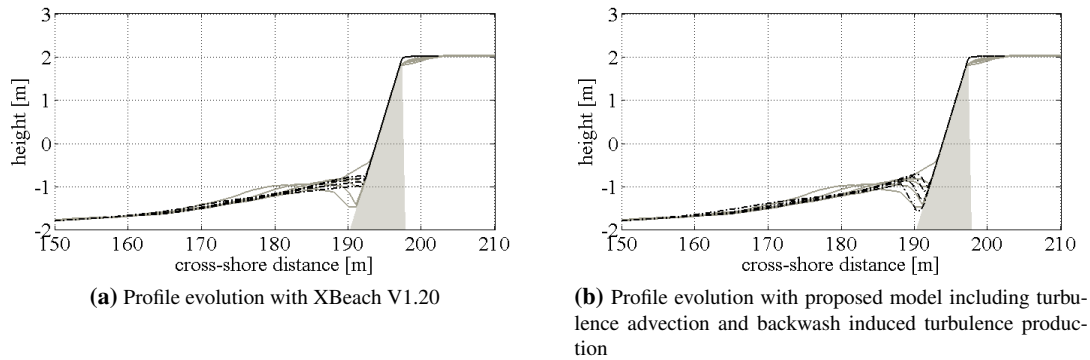


Figure 2: Comparison of profile evolution during T1 of the experiments calculated by the XBeach V1.20 and the proposed model.

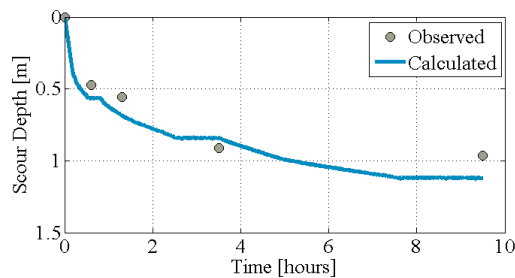


Figure 3: Comparison of observed and calculated development of the depth of the scour hole in time for test T1

For the second experiment, the upper limit of the concrete cover was lowered leaving the upper part of the dune profile unprotected. Next to scour hole development also erosion of the upper part occurs. The eroded sediment partly fills up the scour hole. Compared to the first experiment, this situation comes closer to dune profiles with a dune foot revetment found along the Dutch coast. It also requires that the erosion of the upper part of the profile as well as the formation of a scour hole are modelled correctly. This experiment already led to the improvement of the modelling of scour above a partly protected dune in XBeach by Van Thiel De Vries (2012). Figure 4 shows a comparison between the measured profiles during this experiment and calculated final profiles using XBeach V1.20 and the proposed model. These figures give an image that is similar to the comparison between the models and the results of the first experiment (T1). Where XBeach V1.20 neither calculates erosion above the revetment nor does it calculate a scour hole in front of the revetment, the proposed model does both. Also for this experiment, calculated final profiles by the proposed model seem to be in agreement with the measured final profiles.

Figure 5 compares the calculated development of the maximum depth of the scour hole with the measured depths. Although initially the scour hole appears to develop too fast, in general the development in time is well represented. The final depth of the scour hole in this experiment is slightly underestimated, in contrast to the slight overestimation in the first experiment.

The third experiment (T3) lowers the revetment even more. A large amount of sediment will erode from the dune face leading to a very small scour hole in front of the revetment (as it is mostly filled by the material that is coming from the dune face). Comparison between measured final profiles and the calculated final profiles by XBeach V1.20 and the proposed model (Figure 6) shows that also in case of this third experiment the calculated final profile is improved by the proposed model. Figure 6b shows a small scour hole that is comparable to the measurements, whereas XBeach V1.20 (Figure 6a) does not calculate any scour hole.

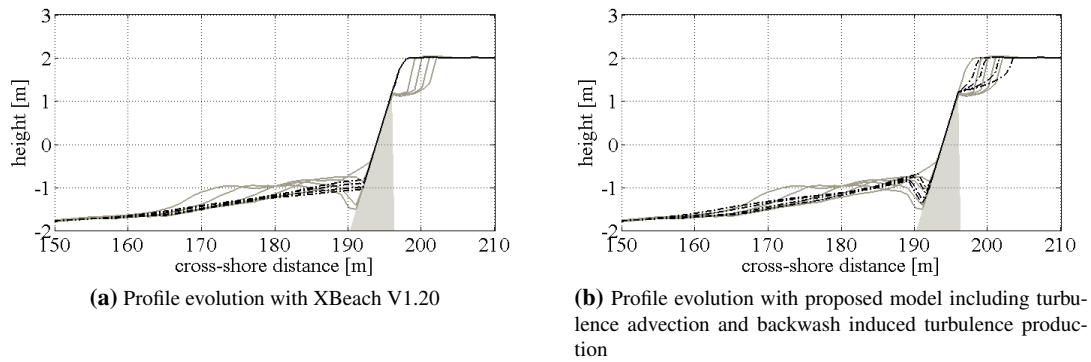


Figure 4: Comparison of profile evolution during T2 of the experiments calculated by XBeach V1.20 and the proposed model.

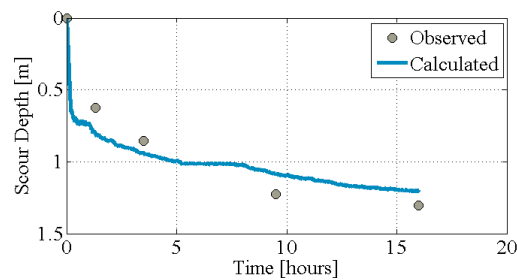


Figure 5: Comparison of observed and calculated development of the depth of the scour hole in time for test T2

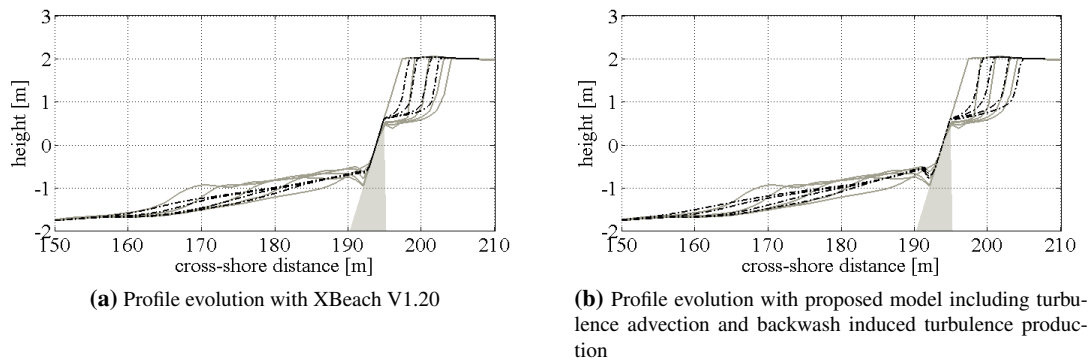


Figure 6: Comparison of profile evolution during T3 of the experiments calculated by XBeach V1.20 and the proposed model.

In this experiment the scour hole in front of the revetment remains relatively small due to sediment that is eroded above the revetment partly filling up the scour hole. Figure 7 now shows an underprediction of the measured maximum depth of the scour hole by the proposed model. The large amount of sediment that is eroded from the dune face and periodically deposited in the scour hole is clearly visible in the figure. Although the measurements show a gradual increase of the scour depth, the proposed model (similar to test T2) shows a sudden increase followed by a period of almost constant depth of the scour hole. In the model results scour seems to be balanced by the amount of sediment coming from above the revetment. In fact the balance between the large volume of eroded sediment and the amount of sediment that gets eroded from the scour hole determines the development of the depth of the scour hole. Since the amount of sediment that erodes above the revetment increases compared to the other two experiments a small overestimation of the erosion could lead to the underestimation of the scour depth.

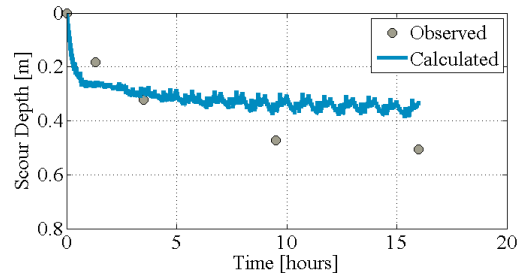


Figure 7: Comparison of observed and calculated development of the depth of the scour hole in time for test T3

When examining the model results it becomes clear that in these three situations the model results were improved by the term that was included to model backwash induced turbulence. Advection of turbulence only had a very small influence. Figure 8 shows that only including advection of turbulence slightly increases the scour depth 5 meters from the toe of the revetment. This sediment is deposited near the toe of the revetment and more offshore. Contribution to the development of a scour hole of this process is limited. However in combination with the effect of backwash (that only directly influences the grid cell at the toe of the revetment) this redistribution leads to a fair representation of the scour holes measured during the experiments. Although in this situation the assumption that was made based on Battjes (1988) seems to hold, the number of large scale laboratory experiments and field observations is too small to conclude that this assumption will hold in all possible situations covered by the application range of the XBeach model.

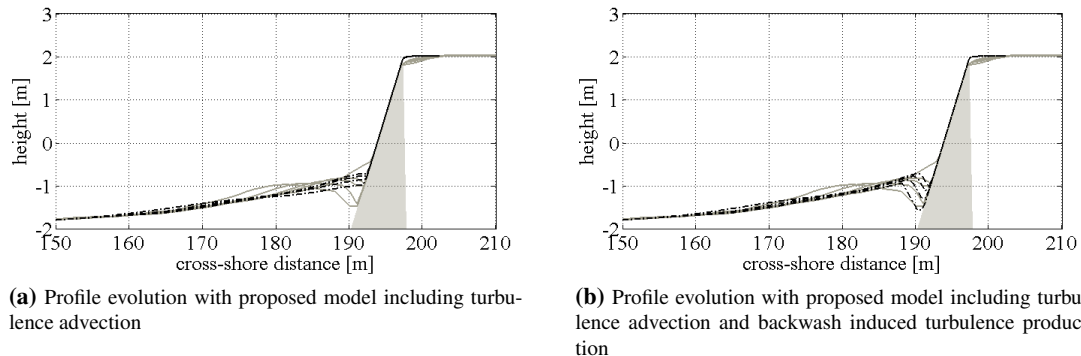


Figure 8: Comparison of profile evolution during T1 of the experiments calculated by the proposed model excluding and including the effect of backwash.

CONCLUSIONS

In this paper we suggest to improve the modelling of scour hole development in XBeach by including two processes that are not accounted for in XBeach V1.20:

- Advection of turbulence
- Backwash induced turbulence

Suggested changes to the model formulations in XBeach improved the prediction of a scour hole significantly. Comparison between model results and measured scour hole development with different revetment heights during three experiments shows that these changes lead to a scour hole development in the model that resembles the measurements. In particular the addition of backwash induced turbulence lead to an improved prediction of the scour hole development.

DISCUSSION

Verification of the model adjustments presented in this paper shows an improved capability of XBeach to calculate scour hole development in front of a dune revetment. However, the experiments used for verification were all executed with the same waterlevel, wave conditions and initial profile. Literature shows that variation of these parameters influences the depth of a scour hole. Although these first results are promising, the verification presented in this paper cannot be seen as a full validation of the capability of XBeach to calculate scour hole development in front of structures. Furthermore the implementation of backwash induced turbulence is only implemented in cross-shore direction. As a consequence it cannot be used when performing 2D(H) calculations with XBeach.

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