DAMAGE PROGRESSION ON CUBE ARMORED BREAKWATERS

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In this paper a new failure mode of mound breakwaters is presented, denoted as Heterogeneous Packing (HeP) and also a new method to measure dimensionless armor damage is proposed, taking into account both the armor unit extraction and the HeP failure modes. Moreover, a new armor unit has been developed to prevent the HeP failure mode, it is the Cubipod armor unit and preliminary tests show very high hydraulic stability of Cubipod compared to cube. Finally, the n50% parameter of the wave-to-wave exponential model (Gomez-Martin and Medina, 2004) has been estimated for concrete cubes using the data obtained from physical tests. This method allows estimating armor damage progression on mound breakwaters in non-stationary wave conditions and gives good agreement with laboratory observations.

1. Introduction

Over the years, mound breakwaters have always been very important in coastal structures and one of the most significant failure modes is the loss of stability of the armor layer. At first only natural quarrystone was used, later, this became insufficient and concrete cubes were used. Since 1950, many different armor units have been developed around the world, as tetrapod, acropod, dolos, core-loc and etcetera. However, in Spain concrete cubes are very common in mound breakwater constructions.

Studies on armor layer stability reveal the importance of density of placement (d'Angremond et al., 1999). Vandenbosch et al. (2002) analyzed the influence of placement density on the stability of a mound breakwater with two layers of concrete cube armor units. Cubes for armor layers are cheap and simple to produce; the failure function is not brittle and unit breaking is not a significant problem. However, cubes and parallelepiped blocks have serious problems with face-to-face packing. The natural increase of packing density in the lower part of the breakwater, as a result of small unit movements and frequent face-to-face arrangements, usually generates significant changes of porosity in different parts of the breakwater. The increase of the packing density below the still water level (SWL) is balanced by a corresponding reduction in packing density above and near the SWL, which is denoted in this paper as the Heterogeneous Packing (HeP) failure mode. The HeP is a failure mechanism of mound breakwaters which tends to reduce the packing density of the armor layer near the SWL without extracting armor units but only moving slightly within the armor layer. Most of the researches about mound breakwater stability take into account only the armor unit extraction failure mode to obtain the damage produced by the wave attack and classical methods to measure damage consider only the extraction of armor units, but they do not take into account changes in porosity of the armor layer. In this paper, a new method to measure dimensionless armor damage is proposed taking into consideration both the extraction of armor units and the HeP failure modes. Moreover, preventing the HeP, the Universidad Politécnica de Valencia (UPV) has patented a new armor unit designated as Cubipod. The main goal of this new armor unit is to use the advantages of cubes, like the easy construction and placement, the high structural stability and the low risk of progressive failure; but avoiding their major problems such as the extreme HeP and their low hydraulic stability. To obtain this, the Cubipod has protuberances which are meant to separate the adjacent units and to increase the friction with the under layer.

A number of formulae have been described to predict armor damage. One of the most popular armor stability formula was published by Hudson (1959) based on the pioneering work of Iribarren (1938). Hudson's formula was originally proposed for regular waves, but SPM (1984) adapted the formula for irregular waves using the equivalence $H=H_{1/10}$ as representative of the wave height of irregular waves. Van der Meer (1988) developed a formula including wave period, permeability and storm duration; however, none of the formulae include the cumulative effects of previous storm conditions. Nonstationary wave climate conditions can be considered using the method proposed by Medina (1996) based on an exponential model applicable to individual waves of the storm. Melby and Kobayashi (1998) developed relationships for predicting temporal variations of mean damage with wave height and period varying with time for breaking wave conditions. Recently, Gómez-Martín and Medina (2004) adjusted the wave-to-wave exponential model to estimate the n50% parameter for rubble mound breakwaters. In this paper, the n50% parameter of the wave-to-wave exponential model is estimated for concrete cubes using the data obtained from physical experiments at the Wind and Wave Test Facility (30.0x1.2x1.2 meters) of the Laboratory of Ports and Coasts at the UPV.

2. Experimental Design

The stability experiments designed for this research were carried out in the wave flume of the Laboratory of Ports and Coasts of the UPV. This wave flume is 30x1.2x1.2 meters. The breakwater models were built in deep water conditions and high enough to avoid overtopping. Figure 1 illustrates the longitudinal cross section of the UPV wave flume, the position of the wave gauges and the mound breakwater model.

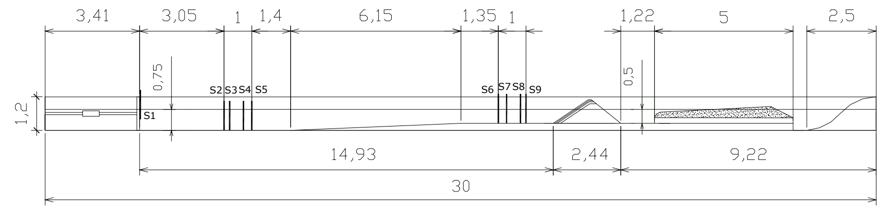

Figure 1. Longitudinal cross section of the UPV wave flume (in meters).

Two groups of four wave gauges (S2 to S9) were placed to analyze incident and reflected waves; one group was placed near the model and the other near the wave maker. The LASA V method (Figueres and Medina, 2003) was used to analyze incident and reflected waves.

Two Mound Breakwaters were tested, one of them with cubes in the armor layer and the other one with Cubipods. Both models consist of a core, a filter and two armor layers with porosity (p) of 40%. However, the Cubipods are lighter (W_{50}=108g) and they also have smaller concrete density (ρ_s=1.86 T/m^3) than cubes (W_{50}=140g and ρ_s=2.18 T/m^3), because a higher hydraulic stability of Cubipods was expected. Armor elements, cubes (D_{n50}=4cm) and Cubipods (D_{n50}=3.85cm) were painted in different colors, the first armor layer was painted white (cube model) or black (Cubipod model) for contrast and the second armor layer in bands of different colors to be able to observe the damage. Armor damage was measured before and after each run of waves, using the Visual Counting method and the new Virtual Net method described later. Gomez-Martin and Medina (2004) considered Visual Counting was the most precise and reliable method for low and moderate damage levels if porosity of the armor layer was constant, but they did not take into account the HeP failure mode in natural rock experiments.

The stability experiments were done with Iribarren's number (Ir) being constant and increasing wave height, from zero damage to destruction. Tests with regular and random waves were conducted to produce damage.

- In the case of regular waves, runs of 25 (cubes) and 50 (Cubipods) waves were generated until 500 waves for each wave height, with periods corresponding to $Ir=(1/1.5)/(H_{reg}/L_0)^{0.5}$ =2.5, 3.0, 3.5 and 4.0.
- Irregular wave tests were conducted with runs from among 900 and 1000 waves for each significant wave height, with mean periods corresponding to $Ir=(1/1.5)/(H_{reg}/L_{01i})^{0.5}$ =2.5, 3.0, 3.5 and 4.0. Taking into account the relationship $H_{reg}=1.4*H_{m0i}$.

In both cases, damage was measured before and after each run. Regular and irregular cube tests were repeated three times from zero damage to destruction except the Ir=4.0 test that was done only once. Regular Cubipod tests were done twice and irregular Cubipod tests once, moreover an extra irregular test with Ir=2.0 was done with Cubipods.

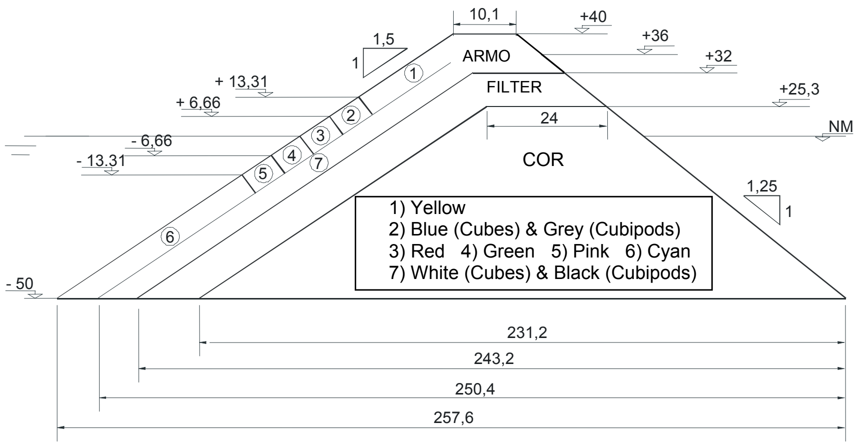

Figure 2. Cross section of the cube and Cubipod mound breakwater with armor elements in different colors (in centimeters).

3. Heterogeneous Packing (HeP) failure mode

The HeP failure mode of the armor layer is characterized by a decrease in the porosity of the armor layer without extracting elements, generating zones with low porosity and corresponding zones with high porosity, with fewer armor units per unit surface. This failure mode is highly significant in the case of regular armor units, such as cubes or parallelepipedic blocks, which tend to generate undesired face-to-face arrangements under the SWL, leaving upper zones with less packing density.

The HeP failure mode is similar to the erosion caused by extracting armor units since the reduction of the packing density can facilitate the extraction of units from the secondary layer. Therefore, armor damage could be produced by two different failure mechanisms: extraction of armor elements and HeP. In both cases, the result is similar: a decrease in the armor layer thickness near the SWL. The relative impact of the HeP failure mode depends on four main factors: (1) type of armor unit, (2) difference between the initial porosity and the minimum porosity, (3) slope of the armor layer, and (4) friction coefficient between the armor layer and the secondary layer.

In order to avoid this failure mode, the UPV has developed a new armor unit named Cubipod. The aim of this invention is to use the advantages of cubes, like easy construction and placement, flexible behavior under wave attack, high structural stability and low risk of progressive failure, but avoiding their serious disadvantages such as the high HeP, their low hydraulic stability and the loss of friction with the under layer.

The Cubipod is designed to form the protective layer of mound breakwaters, seawalls and piers in order to protect coasts, hydraulic or maritime constructions, or in general to resist wave breaking. The aim of its design is a massive cubic or parallelepipedic element with one or more protuberances on its sides to avoid the face-to-face arrangement between units and to increase the interlocking with the quarrystone layer below. A common problem in the design of armor units is having to choose between hydraulic stability and structural stability: armor units can increase their hydraulic stability by interlocking but this always requires a less compact form, which decreases the structural strength of the unit. The Cubipod pretend to be a balanced solution between hydraulic and structural stability, by this reason the shape chosen was a cubic element with equal protuberances on every side which have the form of truncated pyramids with a square section.

Figure 3. 3D view of the Cubipod.

3.1. *Armor Damage Analisys*

Armor damage analysis could be done in a quantitative or a qualitative way. Qualitatively, the damage levels of Initiation of Damage (IDa), Initiation of Iribarren Damage (IIDa), Initiation of Destruction (IDe) and Destruction (De) were defined through a visual analysis of the photos after every test run. These damage levels were compared to the quantitatively obtained damage measurements and with the wave height that caused each of the damage states. Moreover, the four damage levels provide an internationally known basis for comparison with other test results.

To verify qualitatively the commented damage levels, a method needs to be defined. Based on experimental information, in this research four damage levels were considered: (1) Initiation of damage (IDa), this situation is reached when the upper armor layer presents a few holes of an armor unit size; (2) Initiation of Irribarren Damage (IIDa), occurs when the damage suffered by the upper armor layer is sufficiently developed to permit extraction of pieces from the secondary armor layer, this is a qualitative definition proposed by Iribarren (1965). In practice, the Initiation of Iribarren Damage is defined to occur when the hole in the upper armor layer is large enough that an armor unit of the second layer and all its surrounding pieces are visible; (3) Initiation of Destruction (IDe), is defined as the Initiation of Damage of the secondary armor layer, when one or more units of the second layer have been removed and parts of the filter are clearly visible; and (4) Destruction (De), occurs when both armor layers are severely damaged.

Furthermore, a quantitative analysis was carried out, but damage measurements cannot be done using classical methods because the HeP failure mode. Some of these classical methods are: visual counting, photo measurements and profile measurements. All of them assume that the porosity of the armor layer is constant during damage progression. However, when HeP is produced it is not true. By this reason, the quantitative analysis was done using both, the classical visual counting method and the new Virtual Net Method, proposed in this paper. The visual counting method defines the eroded area by equation 1 and the dimensionless damage by equation 2, in which N_e= number of eroded armor units, D_{n50}= equivalent cube size, p= constant porosity of the armor layer, b= studied width, A_e= armor erosion and S= dimensionless armor damage. The main problem of this method is that do not take into account changes in porosity of the armor layer.

$$A_e = \frac{N_e D_{n50}^3}{((1-p)b)} \tag{1}$$

$$S = \frac{A_e}{D_{n50}^2} \tag{2}$$

When significant HeP is generated, the porosity of the armor layer is not constant; therefore, the equivalent dimensionless damage should be measured taking into account the difference of porosity in each of the zones of the armor layer in regard to initial porosity. A new method to measure the equivalent dimensionless armor damage is presented here. This method requires projecting on the photographs a Virtual Net over the armor layer dividing it into strips (number of strips = j), each of which is n times width the size of the equivalent cube (D_{n50}). The number of armor units in every strip (N_c) is counted, and with these number of units, the porosity of every strip (p_i) could be calculated using equation 3, in which $a=n*D_{n50}$ and b=0.75m are the strip dimensions. Accordingly, the dimensionless damage in each strip (D_i) can be obtained with equation 4, in which n is an integer, p_i is the porosity after the wave attack and p_0 is the initial porosity in each strip. Integrating these damages over the slope, the equivalent dimensionless armor damage (D_e) could be obtained using equation 5. This method takes into account both the armor unit extraction and the HeP failure modes, and thus the fact that the porosity of the armor layer is not constant.

$$p_i = 1 - \frac{N_c D_{n50}^2}{(a * b)} \quad (3)$$

$$D_i = n\left(1 - \frac{1-p_i}{1-p_0}\right) \quad (4)$$

$$D_e = S = \sum_{i=1}^{j} D_i \quad (5)$$

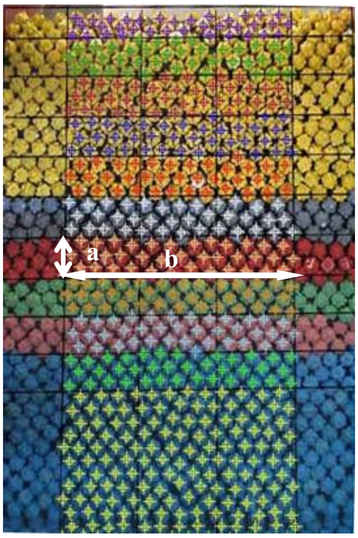

Figure 4. Virtual Net over the slope and counting of the armor units.

4. Results

4.1. *Damage measurements*

A first group of results from the experiments are the damage measurements, for cube and Cubipods models. The results of dimensionless damage measurements obtained with cubes for each of the significant damage levels obtained with the visual counting method is lower than the equivalent dimensionless damage obtained with the new Virtual Net method. The reason is that classical methods do not take into account the HeP produced in the upper armor layer and underestimate the real damage on the armor layer, then is possible that the level of damage in the breakwater was "start of damage" due to HeP but none of the units had been extracted, and then the visual counting method provided zero damage values. In the same way, classical measurements of dimensionless damage obtained with the Cubipod model are lower than Virtual Net measurements. However, in the case of Cubipods, the differences between both methods are smaller than with cubes, because the HeP is also lower due to the effect of the protuberances which were designed to avoid the HeP failure mode.

		DAMAGE MEASUREMENT METHOD	
		Classical	VIRTUAL NET
Dimensionless Damage (S=De)	CUBES	0.1	1.3
		0.8	2.5
		7.2	10.6
	CUBI PODs	0	1.4
		1.5	2.4
		9.5	10.3

Figure 5. Dimensionless damage measurements with classical and Virtual Net method for cube and Cubipod models.

Therefore, if HeP is produced, the porosity of the armor layer is not constant and classical methods are not valid because they underestimate the damage. However, the new Virtual Net method seem to provide good measurements of the equivalent dimensionless damage, taking into account the difference of porosity in each of the zones of the upper armor layer. But, it is important to notice that this new method does not take into account changes in porosity of the bottom armor layer. Moreover, the difference between the Virtual Net method and the classical method is highly significant in case of regular armor units, such as cubes.

4.2. *Wave-to-Wave Exponential Model*

To estimate the evolution over time of the armor damage of rubble mound breakwaters in deep water conditions, any proposed model should fulfill the following conditions:

1. Under regular wave attack, the maximum damage should be limited by the existence of an equilibrium profile.
2. Under random wave attack in deep water conditions, there is no equilibrium profile, the damage must necessarily increase with the duration of the storm.
3. The armor damage should be insensitive to small waves.
4. The largest waves should have a significant effect on the armor damage.
5. The method must be applicable to non-stationary conditions.

A simple method that meets these conditions is the wave-to-wave exponential model, proposed by Gómez-Martín & Medina (2004). The wave-to-wave exponential model for regular waves may be described by equation 6, in which $D_0(H,Ir)$ is the asymptotic maximum damage to the armor layer under a constant regular wave attack and the n50% parameter (mean damage) is the number of regular waves causing 50% of the maximum damage $D_0(H,Ir)$.

$$D(H,Ir,N) = D_0(H,Ir)\left(1-2^{-\frac{N}{n50\%}}\right) \tag{6}$$

The wave-to-wave exponential model for random waves first requires the identification of individual incident waves attacking the structure. The discrete derivative of the equation for regular waves (6) generates equation 7 applicable to random waves:

$$\begin{aligned} D_i &= D_{i-1} + (1/n50\%)_i \ln 2\left(D_{0i} - D_{i-1}\right) && \text{if} \quad D_{0i} > D_{i-1} \\ D_i &= D_{i-1} && \text{if} \quad D_{0i} < D_{i-1} \end{aligned} \tag{7}$$

in which D_i is the accumulated armor damage after the ith wave and D_{0i}= $D_0(H_i,Ir_i)$ is the asymptotic maximum damage corresponding to the ith wave. The mean damage parameter $(n50\%)_i$ is the number of waves in a regular train with the characteristics of the ith wave and causing 50% of the maximum damage, D_{0i}= $D_0(H_i,Ir_i)$.

4.2.1. Mean Damage Parameter n50%

Gómez-Martín and Medina (2004) analyzed the n50% parameter for natural rock, the estimations based on physical experiments showed a dependency on Iribarren's number (n50%=110 waves if Ir=2.5, and n50%=35 if Ir=3.5). In this paper, the n50% parameter has been estimated for concrete cubes, using the data obtained from regular wave tests. For each wave height, damage was measured after each run (25 waves) attacking the structure until 500 waves, which was supposed to be the asymptotic maximum damage (D_0). Damage was measured at 25 wave intervals, thus the number of regular waves which produce 50% of the maximum damage for each run could be obtained with equation 8:

$$n50\% = \frac{D_0 - D_i}{D_i - D_{i-1}} \Delta N \ln 2 \tag{8}$$

Finally, the n50% parameter has been found to be dependent on Iribarren's number and has been estimated as n50%=175 waves for Ir=2.5 and n50%=90 waves for Ir= 3 and 3.5. Figure 6 shows the n50% parameter obtained with natural rocks and cubes for different Iribarren numbers.

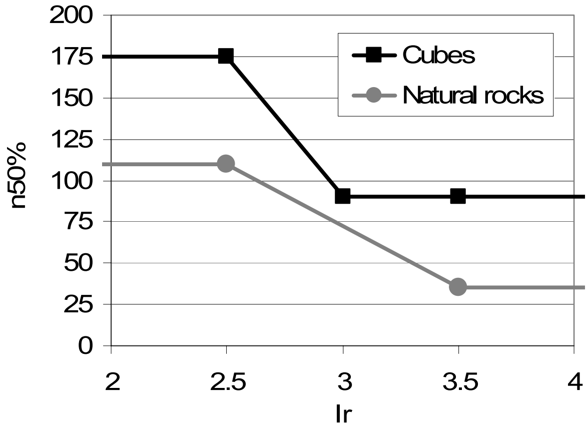

Figure 6. Comparison of n50% parameter for natural rocks and cubes.

4.2.2. Experimental verification

To apply Equation 7 to a given structure, it is necessary to define: (1) the incident wave train {Hi,Ti} to calculate {Hi,Iri}; (2) the damage function $D_0(H,Ir)$ corresponding to regular wave trains, and (3) the exponential parameter n50% found to be dependent on Ir. In this paper, the parameter n50%=175 was used for $Ir \leq 2.5$; n50%=90 was used for $Ir \geq 3$, and 175>n50%>90 was linearly interpolated between 2.5<Ir<3.

To estimate the damage function for regular waves, $D_0(H,Ir)$, a NN model was used; data from ninety regular tests were used. The equivalent dimensionless damage (D_e) observed in regular tests was randomly grouped in the learning data set (80%) and testing data (20%). Two input variables were considered: (1) the relative incident wave height, $H_i/H_{d=0}$, and (2) the incident Iribarren's number, $Ir=(\tan\alpha)/(H/L_0)^{0.5}$. The output variable was the linearized equivalent dimensionless damage, $D^*=(D_e)^{0.2}$. The NN model generated estimations of armor damage with a relative mean squared error of 11% on test data. Figure 7 shows the scheme of the NN model.

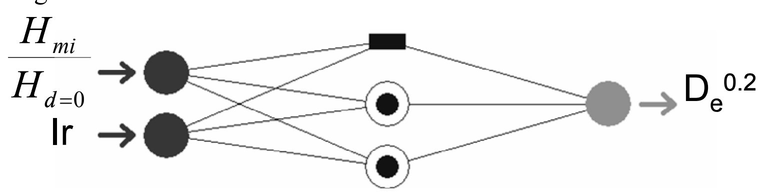

Figure 7. Scheme of the NN model to estimate armor damage for regular waves.

Finally, the wave-to-wave exponential model was applied to each individual wave. Figures 8 shows a typical evolution of observed damage, increasing wave height and estimated damage using the wave-to-wave exponential model for random waves and cube mound breakwater.

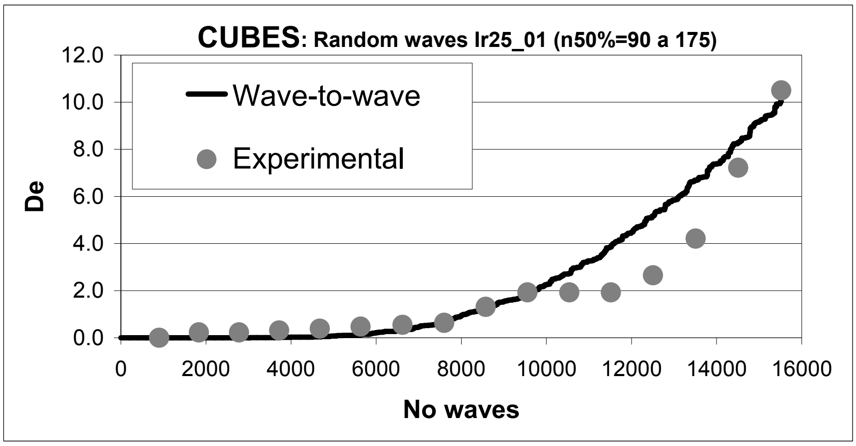

Figure 8. Comparison of measured and estimated armor damage for random waves and Ir=2.5.

The wave-to-wave exponential model shows a good agreement with the experimental damage from low damage to destruction.

5. Conclusions

The hydraulic stability of mound breakwater armor layers depends on many factors, but one of the most important ones is the design and shape of the armor units. Over the years, cubes and parallelepipedic blocks have been the most commonly used concrete armor units, however they have performance problems associated with face-to-face fitting, resulting in an increase of packing density below the still water level (SWL) and the corresponding reduction in packing density above and near the SWL. This change of porosity in different parts of the breakwater has been defined in this paper as the Heterogeneous Packing (HeP) failure mode and also a new method to measure dimensionless armor damage is proposed, taking into account both, the armor unit extraction and the HeP failure modes. Finally, a new armor unit has been developed to prevent the HeP failure mode, it is the Cubipod armor unit. Preliminary tests show very high hydraulic stability of Cubipod compared to cube.

Gómez-Martín and Medina (2004) presented the wave-to-wave exponential model to be applied in non-stationary conditions and analyzed the n50% parameter for natural rock. In this paper, the n50% parameter for concrete cubes is analyzed using the experimental data of aforementioned regular tests carried out in the UPV wave flume. The mean damage parameter n50% has been found to be dependent on Iribarren's number, being n50%(Ir=2.5)=175 and n50%(Ir=3 and 3.5)=90. The damage function $D_0(H,Ir)$ for regular waves was estimated using a NN model. The estimation of accumulated armor damage using the wave-to-wave exponential model showed a good agreement to damage observations in non-stationary conditions.

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