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Flow Pattern and Wave Reflection in Front Breakwaters During the Scour Development: A Review

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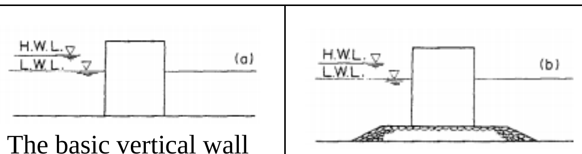
***Abstract*- Scour induced by waves and in combined wave-current is the main cause of coastal breakwater failure as a result of a lack of its efficiency. The maximum scours depths need to be estimated for the scours of breakwater foundations. Mechanisms of local scour and predictions of its maximum depths have been studied extensively for many years. Despite the complexity of the scour process, a lot of satisfying results and processes have been achieved by many investigators. So, this review focuses on the effect of changing flow patterns and inducing wave reflection in front of vertical breakwaters on scour processes. In addition, different coefficients were studied to investigate the efficiency of vertical breakwaters and their result in changing the scour patterns and depth during the scour development. These coefficients were the breakwater distance from the shoreline, structure geometry, sediments, wave characteristics, and angle of wave strike. To get a comprehensive review of local scour for vertical breakwaters, major progress made by researchers is summarized in this review. Finally, conclusions and future research directions are addressed.**

***Keywords*- Currents, Scour Depth, Scour Pattern, Vertical Breakwaters, Wave Strike.**

I. INTRODUCTION

Breakwaters are one of the most widely found, man-made interventions in the coastal environment. The main purpose is to protect the coastline against the eroding action of waves and currents. However, the direct impact of the waves is not the only mechanism that endangers the stability of these structures. The scour generated as a result of wave-seabed-structure interactions is one of the main causes of breakwater failure even in milder wave conditions than the design conditions to efficiently control or deviate the sediment transport equilibrium of crucial. Scour is the removal of sediment around or near structures located in seawater. It means the lowering of the seabed level by water erosion thus, there is a tendency to expose maximum scour around the foundations of a breakwater. The presence of the breakwaters changes the flow patterns in its immediate vicinity and induces wave reflection and breaking (Sumer, B.M. 2002). These processes are achieved by increasing the local sediment transport when the critical value of bed shear stress of the soil for scouring is reached by increasing the fluid shear stress at the bottom (Whitehouse, 2006). Breakwaters can be classified according to their shape and the water level in front of them. For the breakwaters shape; 1) Fixed types such as mound sloping, and vertical walls. The original concept of the vertical breakwater was to reflect waves, while rubble mound breakwater was to break them. Fig. 1 shows four vertical types of breakwaters having different mound heights. 2) The special type of breakwaters is generally adopted for specific site requirements and therefore not commonly applied. Due to the classification according to the sea water level in front of breakwaters, there are two types, submerged and unsubmerged breakwaters. Submerged breakwaters are entirely beneath the surface of the water. It allows part of wave energy to overtop and transmit to the harbor side for better circulation of water and to minimize reflection. The unsubmerged breakwaters 'crest protrudes above the mean water level (MWL) (Young, 2008).

For the marine structures in the port region, vertical breakwaters had appeared in different sites worldwide for their importance in protecting the shoreline against scour. So, this review focuses on the effect of changing flow patterns and inducing wave reflection in front of vertical breakwaters on scour processes. In addition, different coefficients have been concluded for the efficiency of vertical breakwaters and resulted in changing the scour patterns and depth during the scour development such as breakwater distance from the shoreline, structure geometry, sediments, wave characteristics, and angle of wave strike.



The basic vertical wall breakwater

Rubble mound foundation, (the low mound)

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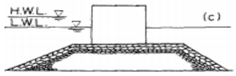
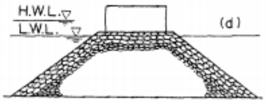
 Relatively high mound lower than L.W.L. (occasionally generates impulsive wave pressure due to wave breaking)	 (high-mound) mound higher than the low water level (L.W.L)

Figure 1. Vertical breakwaters (Takahashi, 2010).

II. FAILURE MODES OF VERTICAL BREAKWATERS

When water waves attack unsubmerged vertical breakwaters; the underlying seabed is affected in two ways, directly from water waves and indirectly by the breakwater motion induced by water wave loads. Both may result in failures of the foundation, which can affect especially the seabed local failure of the structure including sea bed scour and toe erosion (Elsafti, 2015).

Oumeraci, 1994 classified the reasons for vertical breakwater failures to be due to the structure itself, hydraulic conditions (wave load) or foundation, and morphological conditions (geotechnical failures and scour). Sea bed scours as the most common mode of failure for caisson breakwaters is illustrated in Fig. 2.

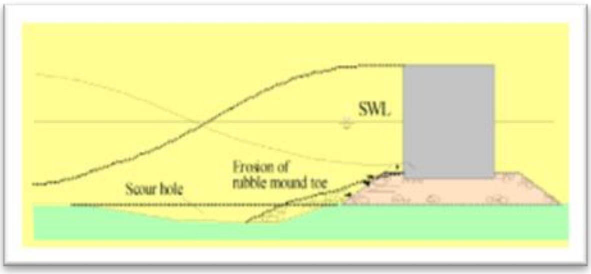


Figure 1. Local bed scours fail for a monolithic marine structure (Oumeraci, 1994).

Oumeraci, 1994 reported that most of the failed vertical breakwaters models had a low crest (submerged and unsubmerged) and consequently heavily overtopped when the water depth increases rapidly.

Generally, the depth at the toe of the structure is larger than 15 m in coastal engineering. The reason for the seaward tilt failure has been attributed to several mechanisms, including seabed scour by excessive wave overtopping impacting directly the seawards, resulting in the caisson's tilt seaward. (Elsafti, 2015) as shown in Fig. 3.

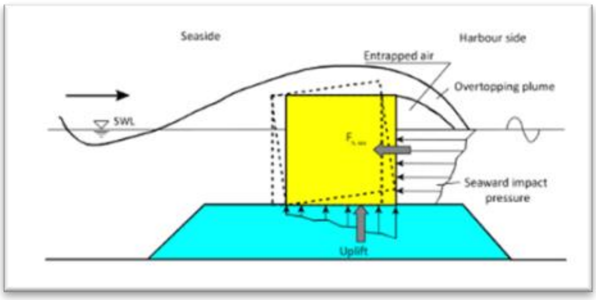


Figure 3. Failure due to excessive overtopping via seaward tilt (Elsafti, 2015).

Scour induced damage under wave action was examined by (Franco 1994; Oumeraci 1994 and Takahashi 2010). Franco 1994 remarked on breakwater damages. The breakwater in Gela is one of Franco's breakwaters which was damaged in 1991 after a storm with a significant wave height of 6 meters. The depth of scour at the tip of the structure reached 1.5 meters. Oumeraci, 1994 mentioned the Mustapha Breakwater in Algeria as an example of scouring-induced damage by tilting on its side under the worst conditions, soft soil, and breaking waves. Oumeraci, 1994 noticed that the scour depth in front of vertical breakwaters may reach values up to 0.7 times the initial water depth. Takahashi, 2010 examined the damage situation of the built breakwaters by observing on site the design of vertical wall breakwaters, among the main causes of damage is the scour around the breakwater.

III. LOCAL SCOUR AROUND VERTICAL BREAKWATERS

The scour failures tend to occur without prior warning and have led to economic loss every year. A significant amount of work has been conducted on breakwaters scour. Such efforts can be broadly classified into two major categories, namely science-driven and engineering driven. The science-driven research focuses on understanding the scour mechanism and aims to explain the cause of scour due to different factors. Meanwhile, engineering-driven research focuses on the estimation, monitoring, and countermeasures of breakwater scour. Local scour occurs not only in the operation stage when the breakwater is settled into the sediment but also in the construction stage when the breakwater is suspended in water. Local scour is the lowering of the bed in the direct vicinity of a structure due to local accelerations and decelerations of the near-bed velocities and the associated turbulence (vortices) leading to an increase in the local sand transport capacity. Once a scour hole is formed, flow separation takes at the edge of the hole and a mixing layer develops increasing the turbulence intensities and stimulating further scour of the bed (Wang et al., 2017).

- *Types of Local Scour*

There are two kinds of scour around a vertical-wall breakwater: one is the scour in front of the structure along the length of the trunk section as shown in Fig. 4 point A, and the other is that around the head of the breakwater, point B, in

Figure 2. When the waves attack at right angles to the breakwater, the scour in front of the breakwater will be a two-dimensional process. On the other hand, head scours is always a three-dimensional process (Sumer and Fredsoe, 1999).

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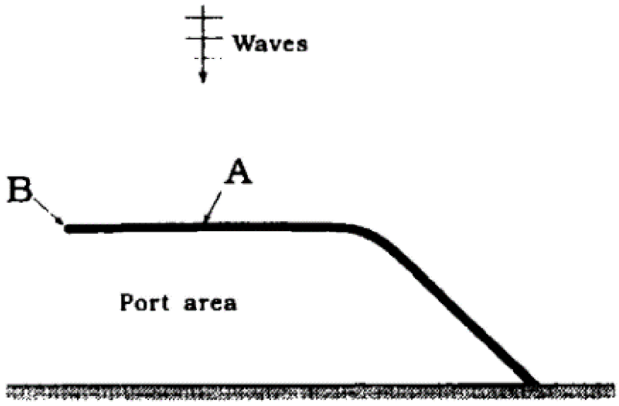

Figure 2. Definition sketch of local scour kinds (Sumer and Fredsoe, 1999).

Mechanism of the Local Scour

The presence of the vertical breakwater exposed to vortices, turbulence, and currents in a marine environment, will change the flow pattern in its immediate neighborhood, resulting in one or more of the following phenomena (Sumer, B.M. 2002) and (Board, 2015), as shown in Fig. 5.

1- Contraction of the flow.
2- Formation of a horseshoe vortex when the wave breaks in front of the structure.
3- Formation of lee-wake vortices (with or without vortex shedding) behind the structure.
4- Steady streaming along the water column in front of the structures, when incoming waves and reflected waves create standing waves.
5- Generation of turbulence during the interaction of flow and current with the structure.
6- Occurrence of reflection, diffraction of waves, shoaling of waves, wave plunging, and wave breaking in front of the structure.
7- Pressure differentials and seepage flow in the groundwater beneath the structure, when a wave trough passes over the seabed.
8- Changes in water depth and therefore changes in flow interaction and dynamics because of cyclic tidal variation.
9- Seepage flow because of water level difference during tidal variation.

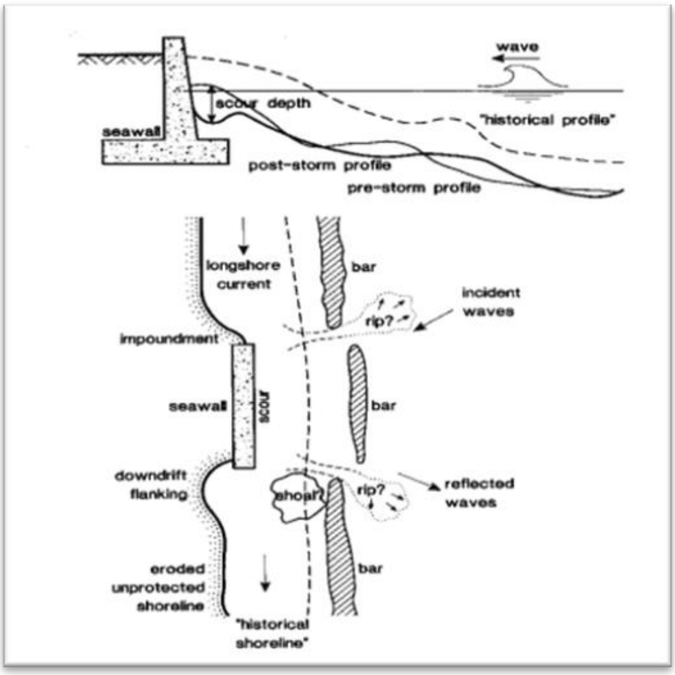

Figure 5. The effects of sea walls on the beach (Rijn, 2018)
Top: Scour at the toe of the wall, Bottom: Scour at the end of the wall.

To understand the mechanism of breakwater scour, many investigators have studied breakwater scour in Laboratory such as (Shigeo Takahashi, Ken-Ichiro Shimosako, 2001), (Sumer, 2001), (Fatemeh Hajivalie and Yganeh-bakhtiary, 2012), (Papadopoulos, 2012), (Jayaratne et al., 2016), (Xiang et al., 2020), (Yeganeh-Bakhtiary et al., 2020) and (Karagiannis et al., 2020). Also, the soft computing results are compared with some numerical equations.

Major advancement has already been made during the past few decades in understanding coastal flow dynamics and related erosion phenomena and their mitigation measures. In 1990 among others, Dean, 1987 measured the influence of the seawall on the coastline. The results indicated that the presence of the seawall leads to changing in the seabed profile and increasing scour at the seawall toe. Oumeraci, 1994 concluded that the key mechanism of scouring is the standing waves that create steady streaming, which results in scour and deposition in front of the breakwater.

Properties of Scour Initiation

Scour, deposition, and their alternating positions around coastal structures depend on the properties of the seabed, the type and pattern of the structure, and the intensity of the shear stress. Initiation of the scour on the seabed can be determined by: the amplification factor, Shield parameter, Keulegan-Carpenter numberand mode of sediment (KC), transport (Sumer, B.M. 2001, 2002).

a) Amplification factor (α)

The flow changes exert additional shear stress on the seabed adjacent to the breakwater, which increases local sediment transport capacity. Thus, turbulence leads to scouring or erosion around blocks of the breakwater. The degree of turbulence and flow current in the vicinity of the structure

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regulate sand transport either in suspension or no suspension mode or both. The increase of the bed shear stress is expressed as the amplification factor "α", which can be defined as follow (Sumer, B.M. 2002)

$$\alpha = \frac{\tau}{\tau_{\infty}} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (1)$$

Where τ is the increased bed shear stress around the breakwater due to changes in the flow pattern and τ_{∞} is the normal bed stress of the undisturbed flow.

If α > 1.0, then the sand around blocks presumably erodes while α < 1.0 means the sand deposits around blocks. Severe scour during a storm normally is backfilled by sand deposition within a considerable time scale, and in this process of scour and deposition, structure units sink in the sandy seabed (Board, 2015).

b) *Shield parameter*

The Shield parameter is the most important criterion for sediment movement and transport research in the marine environment. Consequently, it is an important criterion in determining to scour extent and pattern of the sandy seabed around blocks of breakwater. The undisturbed Shield parameter "*θ*" can be defined as follows (Sumer, B.M. 2001, 2002).

$$\theta = \frac{u_f^2}{g(s-1)d} \ldots\ldots\ldots\ \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ \ldots\ \ldots\ \ldots\ (2)$$

Where θ is the Shield parameter, u_f is the undisturbed bed shear velocity $\sqrt{\frac{\tau_{\infty}}{\rho}}$, ρ is the water density, *g is the* gravity acceleration, *s* is the specific gravity of the sand grains, and *d* is the sand grain size.

The critical value of the Shield parameter "θ_{cr}" corresponds to the initiation of the sand particle's movement in the seabed and it is a function of the Reynolds number *(R)* which can be defined as follows:

$$R= \frac{du_f}{\nu} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (3)$$

Where R is Reynolds number, ν is the kinematic viscosity. An empirical relationship exists between *(R)* and "θ_{cr}" for marine sandy seabed (Sumer, B.M. 2002) and (Board, 2015) in Fig. 6.

If < θ_{cr} then sediment transport does not take place far from the structure, and if θ > θ_{cr} then sediment transport prevails over the entire bed.

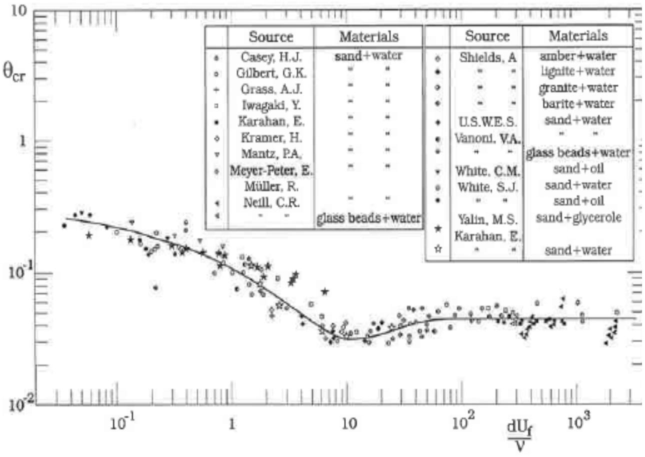

Figure 6. Relation between Shields critical parameter and Reynolds number (Sumer, B.M. 2002).

c) *Keulegan-Carpenter number*

Keulegan-Carpenter number is a parameter in determining to scour initiation at the round head of the breakwater because of horseshoe vortex and turbulence created by incident waves and tidal currents. The Keulegan-Carpenter number *(KC)* can be defined as follows (Sumer, B.M. 2002).

$$KC = \frac{u_m T_m}{D} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (4)$$

Where KC is the Keulegan-Carpenter number, U_m is the maximum orbital velocity of water particles at the seabed and T_m is the wave period.

If orbital velocity is assumed to be sinusoidal, then $KC = 2\pi/a$, where "a" is the amplitude of the orbital motion of the water particles at the bed and "B", is the width of the entire roundhead of the breakwater, if the whole section is considered as a single unit (Board, 2015).

d) *Mode of sediment transport*

When wave actions and currents originate a sediment particle movement *(α > 1.0 and θ > θcr)*, it may be transported either on sliding over the seabed (no suspension mode of sediment transport) or into suspension (suspension mode of sediments transport). Generally, very fine sands, silts, and clay come into suspension and move into the place where the flow equilibrium stage prevails (deposition) *(α≤ 1.0 and θ≤* θ_{cr}*)*. Sand particles that come into suspension remain and are transported in suspension only when the following condition is fulfilled $\omega/u_f < 1.0$ (Where ω is the fall velocity of the sand particle and U_f is the bed shear velocity). While coarse sands move on sliding at ω /U_f> 1.0 until it reaches the flow equilibrium.

• *Effects of Scour on Vertical Breakwaters*

a) *The local effect around block units*

Flow vortices and turbulence agitate sands and fine sediments into suspension around the breakwater units. (Sumer, B.M. 2002). Board, 2015 argued that the vortices that are formed in the holes in between structure units are

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keys to the suction process. The vortices move sand out of the holes causing the sinking of structure units and thus leading to a lowering bed layer of the structure. In this process, when sands move out from the bottom perimeter of the structure units, the bearing capacity of the soil fails and structures units settle down into the soil. This process repeats until the flow dynamics around the structure unit reach the equilibrium stage. Fig. 7 presented the local scour around the structure unit.

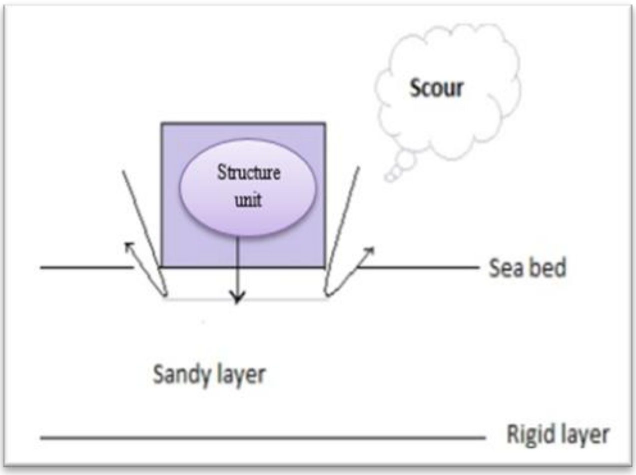

Figure 3. Local scour around structure unit (modified from Board, 2015).

b) Global effects of scouring

Similar to the individual structure units, scour occurs around the whole section of the breakwater. In that case, the whole section acts as an individual unit because wall units/blocks are considerably close to each other. The scouring process in every unit affects others. Scour process transports sand from the whole section of the breakwater to the place where the flow dynamics are at the equilibrium stage concerning (α, θ, and KC) (Sumer, B.M. 2002). Local scour ultimately contributes to global scour. Global effects of scouring are responsible for the gradual sinking of a whole section of the breakwater either at the toe of the trunk or at the round head (Fowler, 1992) and (Board, 2015).

- *Steady Streaming*

When waves reflect in front of the breakwater, steady streaming occurs along the water column as shown in Fig. 8A. This is caused by the superimposition of the incoming waves and the reflected waves in front of the structure, where characteristics of standing waves prevail (Sumer and Fredsoe, 2000). Steady streaming (vertical flow circulation) erodes the seabed at the node position of the standing wave and deposits sands at the anti-node position of the standing wave as shown in Fig. 8B.

A separate bottom circulation is also found consisting of suspended sand particles beneath the steady streaming. Bottom circulation is responsible for sand transport at nodes and antinodes by the process of scouring and deposition. Node and anti-node positions depend on wave characteristics (height, length, and period) (Board, 2015).

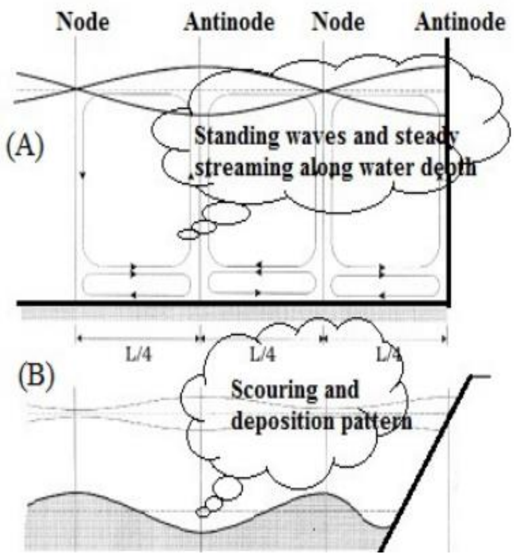

Figure 4. (A) Steady streaming and (B) Scour-deposition profile (Board, 2015).

- *Scour Depth*

Scour depth is an important design parameter in determining the extent of sinking of the breakwater in response to various scour processes, especially steady streaming. Scour depth depends on various factors such as amplification factor, Shield parameter, scouring process, size and shape of the breakwater unit, breakwater type, and dimension. Scour depth *(S)* utilizing steady streaming correlates with water depth *(h)* and wave parameters (wave height, *H*, and wavelength, *L*). Steady streaming may induce any shear stress at a deeper water depth. Therefore, *S/H* tends to 0, when *h/L* tends to ∞ (Board, 2015).

For the factors affecting scour depth (Tsai et al., 2009) conducted experimental studies of toe scour of seawall on a steep seabed with a slope of 1:5 under the action of breaking waves. They indicated that the depth of the toe scour increased as the steepness of the incoming wave increased, but an increase in the water depth at the toe makes it decrease. Moreover, they deduced that the scour depth due to a plunging breaker is larger than that of a spilling breaker or non-breaking wave in front of the seawall. Pourzangbar, 2012 predicted numerically the maximum scour depth due to breaking waves with various combinations of input parameters such as reflection coefficient, relative water depth at the toe of the structure, the serf similarity parameter, Shields parameter, breaking wave steepness and the wave breaking depth, The results showed that the relative water depth at the toe (h_{toe}/l_0) and reflection coefficient (*Cr*) are the most important ones. Negm and Nassar, 2016 investigated both vertical and sloping seawalls to determine the optimal wave reflection characteristics of seawalls for protecting beaches against erosion. Their results could be applied to optimize the design criteria of shore protection structures such as vertical breakwaters.

- *Trunk section*

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There are 3 well-known formulas to predict S_{max} based on experimental tests at the trunk section of vertical breakwaters (Table1); (Fredsoe and Sumer, 1997; 2000) have proposed modified empirical methods for determining maximum scour depth at the trunk section in the vertical breakwater. Xie, 1981 predicted the maximum scour depth at the vertical wall breakwater, and (Lee and Mizutani, 2008) performed laboratory tests on the non-breaking waves induced scour at vertical impermeable submerged breakwaters due to the bed load transport. But they did not look at the effects of the seabed sediment properties independently. Moreover, their proposed formula can only be used for partially standing waves (Cr <1).

Pourzangbar et al., 2017 predicted the scour depth at breakwaters induced by non-breaking waves .Three different combinations of dimensionless input parameters have been examined to achieve the most accurate and simplest models. Then, the results of the developed models have been compared with those of literature equations (Xie, 1981), (Fredsoe and Sumer, 1997; 2000) and (Lee and Mizutani, 2008). The results show that the relative scour depth is mainly affected by wave reflection.

a) Roundhead

Scour process at the round head of a breakwater is different from that at the trunk section and therefore, the prediction process is also different. *(KC)* has an important role in this scour process. Fredsoe and Sumer, 1997 proposed an empirical expression for the (S) at the round head of a vertical wall breakwater,

$$\frac{S}{B}=0.5C\left(1-exp\left(0.175(kc-1)\right)\right) \dots\dots\dots\dots\dots\dots\dots (5)$$

Where *B* is the width of the breakwater at the head section and *C* is an uncertainty factor with a mean value of 1.0 and a standard deviation of 0.6. For plunging wave breaker induced scour, maximum scour depth does not depend on *KC* but depends on wave parameters *(h, Hs, and peak period T_p)*. Fredsoe and Sumer, 1997 presented the following expression:

$$\frac{S}{H_s}=0.01C\left(\frac{T_P\sqrt{gH_S}}{h}\right)^{1.5} \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots (6)$$

Where C is 1.0 and a standard deviation of 0.34.

- ### *Un Submerged Vertical Breakwaters*

UN submerged breakwater is a kind of offshore structure, with its top above seawater, and is usually constructed parallel to the shoreline. As mentioned before there are two kinds of local scour around un-submerged vertical breakwaters: trunk scour and head scour.

a) Trunk scour

The scour in front of the breakwater in the case of the trunk scour has been investigated by (Irie, and Nadaoka, 1984 and Xie, 1981). The key mechanism is the action of standing waves, leading to a steady streaming pattern in the vertical plane (Sumer and Fredsoe, 2000 and Xie, 1981), as the majority of sand is moved as a suspended load, which presumably results in a distinct scour and deposition pattern in front of the breakwater in the form of alternating scour and deposition areas lying parallel to the breakwater (Sumer and Fredsoe, 1999).

Table 1. Summary of the maximum scour depth prediction empirical relations

Reference	Waves action	Empirical relation	Experiment conditions
(Xie, 1981)	−Regular and irregular −Non-breaking waves	Suspension-mode sand transport (fine sand) $\frac{S_{max}}{H}=\frac{0.3}{(\sinh(\frac{2\pi h}{l_0}))^{1.35}}$ No-suspension-mode sand transport (coarse sand) $\frac{S_{max}}{H}=\frac{0.4}{(\sinh(\frac{2\pi h}{l_0}))^{1.35}}$	-Vertical wall breakwater −Impermeable breakwater −Bed slope (β): 1:30; starts at the distance of 6 m from the wall −Wave paddle distance from the wall: 32.9 m −Sand particles diameters: 106, 150, 200, and 780 μm
	Accepted range	$0.05 \leq \frac{h}{l_0} \leq 0.175$ $0.0083 \leq \frac{H_0}{L_0} \leq 0.0375$	

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(Fredsoe and Sumer, 1997; 2000)	−Regular and irregular −non-breaking waves	$\frac{S_{max}}{H} = \frac{f(\alpha)}{(\sinh(\frac{2\pi h}{l_0}))^{1.35}}$ $f(\alpha) = 0.3 - 1.77\exp(\frac{-\alpha}{15})$	−Sloped breakwater −Permeable and rubble-mound breakwater −Wall slope (α): 1:1.2 and 1:1.75 −Two kinds of breakwaters were implemented: extended into the sand bed and seated on the bottom −water depth along the flume: 0.31 m −Wave paddle distance from the wall: 22 m −Sand particles diameters: 0.2 mm −No-suspension sand transport mode
	Accepted range	$0.045 \leq \frac{h}{l_0} \leq 0.200$ $0.008 \leq \frac{H_0}{L_0} \leq 0.058$ $30^0 \leq \alpha \leq 90^0$ $0.07 \leq \theta \leq .16$	
(Lee and Mizutani, 2008)	−Regular waves	$\frac{S_{max}}{H_0} = \frac{0.06}{(1 - c_r)(\sinh(\frac{2\pi h}{l_0}))^{2.04}}$	−Vertical impermeable submerged breakwater −Mean sand diameter: 0.2 mm −Bed-load transport mode −Water depth at the wall: 20 and 30 cm −Submerged depth: 4 and 14 cm −Breakwater width: 20 and 50 cm
	Accepted range	$0.076 \leq \frac{h}{l_0} \leq 0.168$ $0.019 \leq \frac{H_0}{L_0} \leq 0.052$ $0.028 \leq C_r \leq 0.68$	

Fig. 9 Shows that the steady streaming pattern under the standing waves emerges in the form of recirculating cells. The key point in the generation of these recirculating cells is that the response of the boundary layer at a point near the bottom is asymmetric between the two successive half periods. This effect presumably leads to a non-zero period-averaged velocity, resulting in the formation of the bottom cells. Once the bottom cells are formed, these cells will drive the top ones. Thus, sand particles will be moved according to the circulation pattern of mass transport in the standing waves. This means that the direction of sand transport is from node to antinode as that of the net current near the bottom, so the mass transport is assumed as the driving current for sand transport at first (Xie, 1981). Xie, 1981 found that the scouring pattern depends on the grain size and the wave conditions by conducting experiments using the same grain size under different wave conditions. The morphological response was different, meaning that a finer grain size would lead to a typical "coarse grain size" pattern and vice-versa.

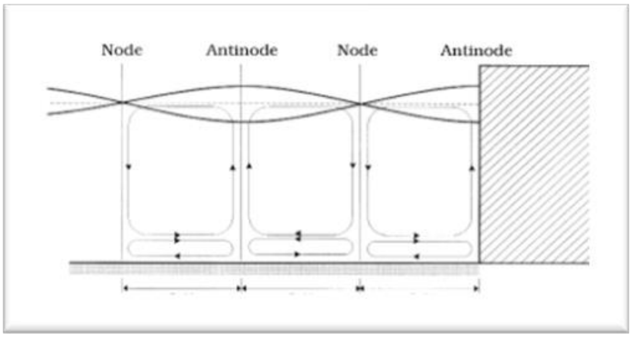

Figure 9. Streaming pattern in the vertical plane due to standing waves in the case of the 2-D scour (Sumer and Fredsoe, 2000).

It is known that the formation of the standing waves triggers the sediment movement and finally forms the seabed morphology when it comes to vertical breakwaters. As seen in Fig. 10 there are two kinds of scour and deposition patterns, depending on the sand size. If the sand size is relatively small, the sand stirred up by the waves and brought up into suspension will be carried to higher elevations, therefore, it will respond mostly to the top cells as sketched in Fig. 10(a) it seems that the scour is formed under the node of the standing waves and deposition at the position of the antinodes. In the case of relatively coarse sand, the sand will respond mostly to the bottom cells and the result will be the pattern shown in Fig. 10(b) as the deposition is formed under the node of the standing wave and the scour appears between the node and the antinode with the seabed remaining almost intact at the position of the antinodes. Sumer and Fredsoe, 2000 also found the same scouring pattern for relatively coarse sediment.

The scouring in front of the un-submerged vertical breakwater has been studied mostly experimentally over the last decades (Lee and Mizutani, 2008, Sumer and Fredsoe, 2000, and Xie, 1981). Sumer and Fredsoe, 2000 studied the scour in front of vertical breakwaters ending up in the same as (Xie, 1981) scouring patterns for unsubmerged vertical breakwaters. There are also some interesting numerical attempts (Bing, 2007; Gislason et al., 2009; Fatemeh Hajivalie and Yeganeh-bakhtiary, et al., 2012) compared with (Sumer and Fredsoe, 2000) results described the hydrodynamic field by solving the (Engelund and Fredsoe, 1976) equations to estimate the sediment transport bed load. Their results were satisfactory for vertical breakwaters.

An Euler–Lagrange two-phase model was also implemented by (Fatemeh Hajivalie and Yeganeh-bakhtiary, et al., 2012) with a RANS hydrodynamic

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module and a Lagrange sediment transport model, Numerical results were provided for the local scour depth and scouring patterns, but only at a short distance of half wavelength from the breakwater. Karagiannis et al., 2020 discussed the scour depth and pattern. The hydrodynamic model is applied first to simulate the wave propagation under any given seabed morphology and wave conditions. Then, the morph dynamic model was implemented using the hydrodynamic results and describing the sediment transport and cross-shore seabed morphology evolution. Model results are compared satisfactorily with (Xie, 1981) experimental data, for surface elevation, orbital velocities, scour depth, and scour pattern. The predicted scour depth results were accurate for fine and coarse sands as shown in Fig. 11 while the results for the scouring pattern are not limited to a short distance from the breakwater but are provided for the total length of the sandy seabed.

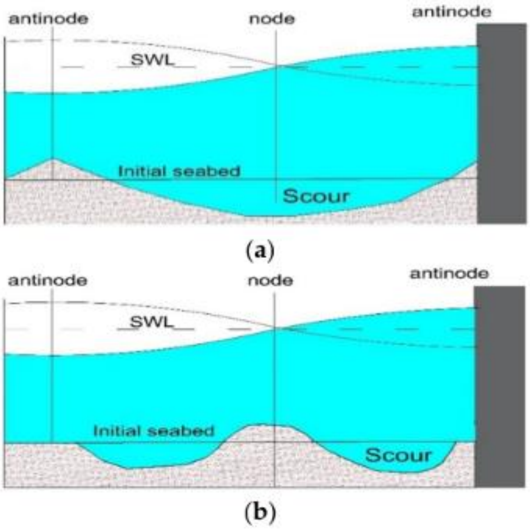

Figure 10. Scour patterns in front of vertical breakwaters for (a) relatively fine sand and (b) relatively coarse sand (Sumer and Fredsoe, 2000).

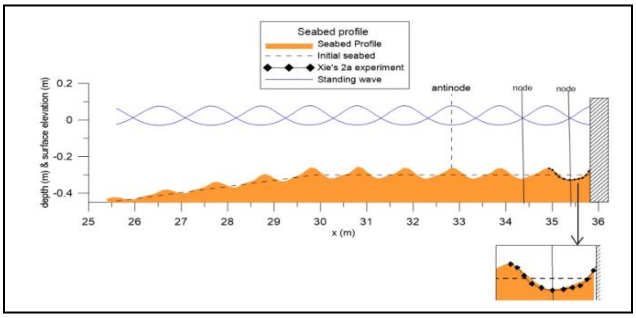

Figure 5. Further compares the numerical results for the scouring depth in front of the breakwater (Karagiannis et al., 2020).

b) Head scour

Separation vortices forming at the lee side of the breakwater play a major role concerning the scour processes. Also, the so-called horse-shoe vortex is a spiral type of vortex generated near the bed in front of and along the tip of the wall due to the rotation of the approaching flow. A large amount of knowledge has accumulated in the area of scouring around offshore and coastal structures such as piles where the scouring action of the separation vortices is the key element behind the scour processes (Fowler, 1992). There are similarities between the scour process around a pile and that around the head of a breakwater. In both cases, the major flow structures which cause scour are the vortices, either in the form of lee-wake vortices or form a horse-shoe vortex, or both, depending on the actual flow environment. The two cases differ, however, in several aspects. The lee-wake vortices in the case of pile form at the two side edges of the structure and interact with each other so strongly, that may lead to vortex shedding. The horseshoe vortex is influenced rather strongly by the small width of the pile. Whereas, in the case of the breakwater, the lee-wake vortex forms at the tip of the breakwater, and there is only one vortex forming in each half cycle of the waves. The horseshoe vortex is affected heavily by the extremely large length of the breakwater. These considerations imply that the resulting scour process in the case of breakwater will be different from that around piles (Asadi et al., 2014).

Flow and scouring processes around cylindrical structures are studied with 3D numerical models, (Roulund et al., 2005); (Zhao and Cheng, 2006) ; (Zhao et al., 2010); (Stahlmann and Schlurmann, 2012) and (Baykal et al., 2015). Roulund et al., 2005 studied the flow conditions around a cylindrical structure that was exposed to a steady current for the equilibrium state. However, they couldn't take into account the lee-wake vortices as the sediment transport load is taken as bed loads only. Stahlmann and Schlurmann, 2012 took into account the irregular flow regimes and suspended sediment transport with the free water surface under live bed conditions.

Fig. 12 depicts the different flow regimes around the rounded head of a vertical wall breakwater. The Keulegan-Carpenter number, based on the diameter of the breakwater head, *B*, is the key parameter that governs the flow processes. Usually, *KC* is very small in real-life situations as the vortices are not generated for *KC<1*; but generated at the lee-side zone of the wall for *KC= 1* to *12*, and lee-side vortices and horse-shoe vortices are generated for *KC>12* when there is a current component perpendicular to the breakwater (Fredsoe and Sumer, 1997).

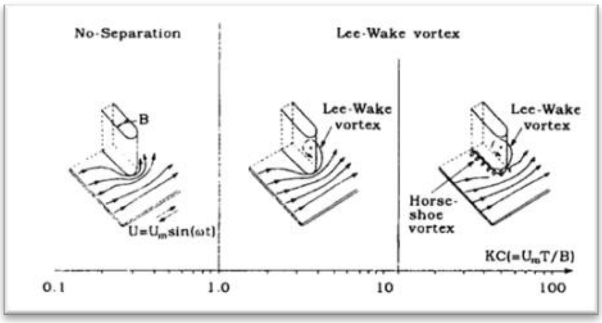

Figure 6. Near-bed flow regimes around the head of a vertical-wall breakwater (Sumer and Fredsoe, 1999).

The following Fig. 13 showed the numerical mechanism of the generation of vortices according to the *kc* number

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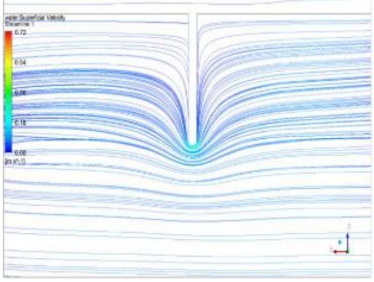
(Asadi et al., 2014). While Fig. 14 illustrated the way of scour development around the breakwater head (taken from video recorded) (Sumer and Fredsoe, 1999). Since the formation and the development of the lee-wake vortex are primarily governed by the *KC* number it might be expected that the resulting scour, too, is mainly governed by this parameter.

For the *KC* importance in scour process. The scour depth was found to increase with increasing *KC* number. The scour depth-versus-*KC* relationship was given by the previous empirical expression (for the live-bed situation) (Sumer and Fredsoe, 1999).

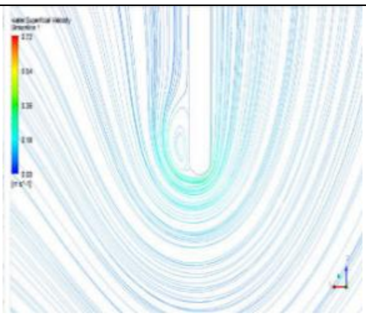
Fredsoe and Sumer, 1997 conducted scour tests for identifying the maximum scour depth and location for different cross sections (rounded and sharp) head of the vertical breakwater with regular non-breaking waves. The maximum scour depth was attained after about 1000 waves. The results were only valid for a vertical breakwater with a maximum width equal to the water depth. The results showed that the scour was maximum at the location of the tip (in the middle of the tip, Fig. 15) of the breakwater. It's found that the maximum scour depth roughly increased by a factor of 2 for a straight wall tip (sharp edge) instead of a rounded tip and increased by about 20% for oblique incident waves.

Asadi et al., 2014 and Karakaş, 2019 studied the scour depth for a vertical breakwater when the head shape is changed from a round shape to a sharp-edged one and both observed that scour depths are from 20% to 25% higher for the sharp-edged structures than the round head structures under random waves which are found to be in good agreement with (Fredsoe and Sumer, 1997).

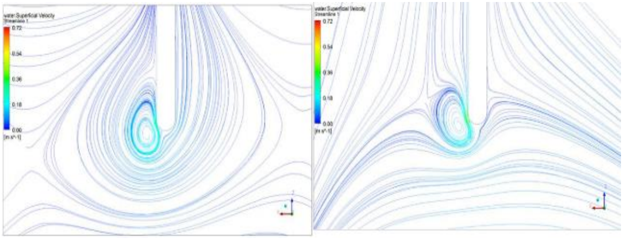
For the effect of changing the *KC* on scour process, Asadi et al., 2014 investigated the near-bed flow patterns, and the bed shear stress amplification using regular waves according to the *KC*. Their results show that the scour depth is confirmed to increase in the presence of a current with increasing *KC*. Karakaş, 2019 investigated, the hydro and morph dynamic processes around the head of a vertical breakwater with no foundation and scour protection. The results indicated that the measuring vortex dimensions increase with the increasing *KC* numbers for regular waves plus no scour formed around the head of the structure when *KC=1.4* as the scour depth increases with the increasing water depth.



Streamlines for un unseparated-flow regime (KC ≤1)



streamlines for Separated-flow regime with no horseshoe vortex (1 ≤ KC ≤ 12)



streamlines for Separated flow regime with a horse-shoe vortex (KC ≥12)

Figure 13. Numerical mechanism of generation of vortices according to the kc number (Asadi et al., 2014).

- *Waveforms Effects on Scour Process*

The scouring in front of a breakwater can be caused by a variety of waveforms, and the stability of the breakwater may be affected by the scouring. The wave motions in front of breakwaters can be classified into three forms: standing waves, breaking waves, and broken waves.

The standing wave is the wave that does not break in front of a breakwater; the breaking wave is defined as the wave which is breaking above the foundation bed and the broken wave is defined as the wave which breaks approximately a half wavelength from a breakwater (Gao, 1998).

For scouring by breaking and broken waves, few results have been obtained because of both waves breaking in front of the breakwater and scouring itself. For example (Sato et al., 1969) studied the scouring in front of a vertical wall by wave breaking due to the locations of the vertical wall on sandy beaches. Trunk scours were investigated by (Hughes, 1993; Irie and Nadaoka, 1984 and Xie, 1981). Xie, 1981 performed laboratory studies for the non-breaking wave induced scour at vertical breakwaters and observed two distinct scour patterns depending on the bed sediment properties and wave conditions. Tsai et al., 2009 studied seawall scour under breaking waves and demonstrated that the maximum scour depth at the seawall toe decreases with an increase in the water depth at the seawall toe. Gíslason et al., 2009 investigated the formation of standing waves and resulting scour at a breakwater placed on a flatbed, as the results agreed well with experiments by (Sumer and Fredsoe, 2000) as S/H_0 decreases with increasing water depth. Zou et al., 2012 attempted to model the same case (Sumer and

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Fredsoe, 2000) by employing the volume-of-fluid (VOF) method to capture the breaking waves. In a recent study, (Ahmad et al., 2019) investigated the hydrodynamics of the breaking waves and the resulting scour at a vertical Bluff with a sloping bed. (Ahmad et al., 2019) investigated the seawall scour due to wave impact on a vertical seawall for different scenarios of seawall locations, incident wave height, and seabed slope. The maximum seawall scour is observed when the seawall is located at the intersection point of the still water depth and the bed slope. A displacement of the seawall from the intersection point leads to a decrease in the wave impact.

- *Structure Geometry*

The function of the vertical breakwater on wave attack is not only the reduction of wave energy in the shoreward of the structures. Modification of spectral shape due to wave breaking on and wave energy dissipation in the structures is the most important function. Seeling, 1980 studied experimentally the wave transmission, reflection, and energy dissipation. The study is conducted on varying forms of (thin, rectangular, trapezoidal, and triangular) vertical breakwaters.

Stamos and Muhammad R. Hajj, 2001 conducted experiments on semi-cylindrical and rectangular rigid breakwater models. The results showed that, for the rigid breakwaters, rectangular models are more effective than semi-cylindrical ones in terms of reduction of transmitted waves. Stamos et al., 2003 carried out a parametric study to differentiate the features of reflection and transmission of submerged semi-cylindrical and rectangular rigid in addition to water-filled flexible breakwater models. The dynamic interaction technique among water waves, a submerged breakwater, a sandy seabed, and a vertical wall is experimentally examined.

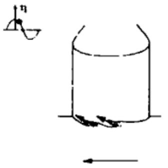
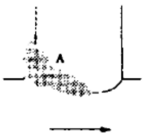
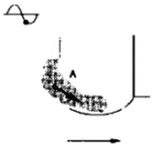
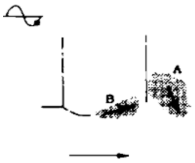
 1- The bed at the head is eroded by the high-speed flow.	 2- The eroded sediment is swept into the lee-wake vortex where the sediment grains are lifted into the upper portion of the lee-wake vortex
 3- As this vortex is washed around the structure by the flow reversal, the sediment trapped in the vortex is carried by this vortex	 4- The sediment eventually deposited away from the structure. In the next half cycle, the process repeats itself; this time, the flow structure B plays the same role as A in the previous half cycle.

Figure 14. Schematically illustrates how the scour develops around the breakwater head (taken from the video record of the actual scour process) (Sumer and Fredsoe, 1999).

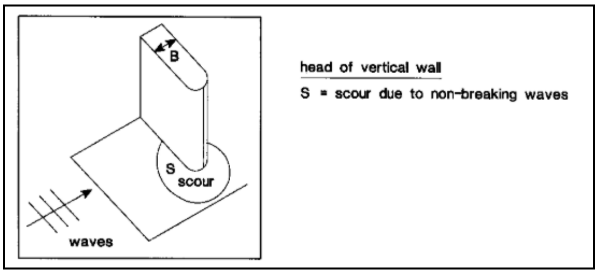


Figure 7. Scour near vertical breakwaters, (Rijn, 2018).

Hajivalie, 2014 studied the scouring around the rectangular breakwater, also (Hajivalie et al., 2015) investigated the performance of vertical breakwaters with different cross sections on transmission coefficient and vortex generation around the breakwaters. They concluded that unless the breakwater width is wider than a certain rate which may vary depend

For the relative submergence depth, The wave energy dissipation un dependent on the breakwater width. It's found that under this specific width, the wave breaking doesn't occur over the submerged vertical breakwater. Considering this finding, the previous estimations that suggested the vertical breakwater can dissipate more wave energy in comparison with other shapes of submerged breakwaters like trapezoidal and semicircular in every circumstance became doubtable, Hajivalie, 2017 studied two different shapes of submerged breakwaters for numerical simulations, rectangular and trapezoidal. The results showed that increasing the crest width can increase the energy dissipation in the rectangular submerged breakwater, however, it is ineffective in the case of trapezoidal ones.

IV. CONCLUSIONS

This study presents a review of the most recent studies on breakwater scours. It divides the current scour research efforts into areas including the mechanism of the local scour process, the formation of recirculating cells, and its effect on the morphological system for unsubmerged vertical breakwaters and the most important factors affecting the

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efficiency of these structures during scour progress, the effective results from this research are indicated below:

1- The most important factor in the development of the scour/deposition pattern in front of vertical breakwaters is the recirculating cells of steady streaming.
2- At the intersection of the head and trunk sections on the lee side, the maximum depth of the lee-side scour is roughly constant. The *KC* (Keulegan-Carpenter number based on the diameter of the breakwater head, *B*) affects where the front side scours and deposition maximum depths are located.
3- For flow around the circular head of a vertical wall breakwater exposed to waves, three types of flow regimes are identified: (a) the unseparated-flow regime, which is observed for $KC < 1$; (b) the separated flow regime with no horse-shoe vortex formation in front of the breakwater observed for $1 < KC < 12$; and (c) the separated flow regime with a horse-shoe-vortex formation in front of the breakwater. This flow regime is observed when $KC > 12$.
4- The *KC* number controls the degree of scour around the head of the structure. When $KC < 1$, it is discovered that the greatest scour depth, *S*, is almost zero. (There may be a minor scour-and-deposition pattern caused by the steady streaming around the head) For $KC > 1$, As the *KC* number increases, the scour depth increases.
5- It has been found that the head shape is important. When changing from a round head to one with a sharp edge, the maximum scour depth may rise by a factor of 2.
6- In the presence of beach slope, wave randomness, wave breaking type, and location, as well as breaking produced wave reflection, greatly modifying the strength and spatial distribution of streaming velocity and bottom orbital velocity along the seabed.
7- The type and location of the breaking are crucial elements in the creation of scour. At low water depth, the wave breaks offshore, and a partial standing wave and relatively small toe scour occur at the wall. The deepest scour depth is found in the result of a plunging breaker on the wall at intermediate water depth. At large water depths, very little breaking happens and near bottom velocity is not large enough to move a significant amount of sediment within the mobile bed area so that scour and deposition are minimum.
8- For the cases where a plunging breaker occurs in front of the seawall, a smaller coefficient of the wave reflection from the seawall is found and results in a larger scour depth.
9- The rectangular breakwater is more effective than semi-cylindrical and trapezoidal breakwater in terms of reduction of transmitted waves and sequentially reduction of scour development.
10-For the sloping bed, the maximum scour depth is located at the intersection point of the still water depth and the bed slope. A displacement of the seawall from the intersection point leads to a decrease in the wave impact.

V. RECOMMENDATIONS

This section elaborates on proposing possible solutions that will fill in the gaps found in this research while extending the range of applicability of this research’s findings:

1- As the KC number controls the degree of the scour development, various KC numbers could be studied varying the structure width and the wave conditions.
2- Breakwater model orientation is sometimes kept constant in more studies. However, waves can approach from different angles to the breakwater. By changing the model placement with various angles, the effect of the angle of approach would be observed.
3- Scour experiments were performed without any rubble base or protective layer. Future studies may be performed with toe protection to investigate its effect on scour progress.
4- Many studies investigated the effect of streaming flow on scouring due to vortices generation but there is a gap in studying this scouring when changing the flow direction as these vortices place changing from one side of the breakwater to the other.
5- A high-performance computer application can be a useful tool for developing advanced computational models to study the mechanism of the scour process.
6- To create a successful countermeasure strategy, factors including the site's state, the relative effectiveness and cost of countermeasures, interactions, and the effects of several risks must be taken into account
7- To guide the design of the scour and the countermeasure, an accurate decision support system is also required.
8- There are still issues where the effects of local scour must be taken into account in the context of longer-term natural changes that may have occurred in a lack of structure.

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