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RECENT DEVELOPMENTS ON ARTIFICIAL REEF APPLICATIONS IN TURKEY: HYDRAULIC EXPERIMENTS

F. Ozan Düzbastılar, Altan Lök, Ali Ulaş, and Cengiz Metin

ABSTRACT

Environmental design criteria for artificial reefs (ARs), including wave and current interaction, were investigated in an unidirectional wave channel to account for conditions encountered in the Black Sea. Wave and current data were obtained from a multifunctional observation system in the Black Sea and analyzed for use in the wave channel experiments. Regular wave conditions were modeled in the channel. The wave channel had a 1-on-30 bottom slope. Reef models were constructed according to *Froude* similarity law with the scale of 1/30. AR concrete block stability and the scour contact area between the reef blocks and sand bottom were determined. In total, seven wave sets with 35 wave runs over 30-min spans were performed in the experiments to determine stability of the blocks. Tests were run using three various-sized reef models and four different bottom depths (33, 50, 66, and 83 cm). Local scour formations on the sand bottom were observed and measured over model runs that tested seven different wave heights (5, 6, 6.5, 7.5, 8.5, 9.5, and 10 cm) and a constant wave period (1.13 s) in 15 min duration comparing two water depths (33 and 50 cm). Local scour depth was determined at these deeper water depths for the reef models. At the conclusion of the study, a stability chart was compiled to determine accurate settling, design, and installation parameters depending on reef size, water depth, and local wave conditions.

Artificial reef (AR) applications have the the potential to reduce conflicts between fisherman and legal authorities in Turkey (Lök et al., 2002). ARs, constructed with reinforced concrete, have been used in the western coasts of Turkey for more than 15 yrs (Fig. 1, Table 1).

ARs have been deployed along many coasts to decrease wave energy and prevent beach erosion (Bruno, 1993), enhance fisheries aquaculture and diving tourism, protect habitats, and foster research (Seaman and Jensen, 2000) for years. During these various uses of ARs, data have been collected on deployment methods (Grove and Sonu, 1985), design and construction processes (Sato, 1985; Grove et al., 1989; Bohnsack, 1991; Seaman, 1996), assessment of efficiency (Brock and Norris, 1989; Seaman and Jensen, 2000), and environmental influences on ARs (Grove and Sonu, 1985; Nakamura, 1985; Sheng, 2000; Grace, 2001).

Durability of the material and stability of the reef block are the most important design characteristics. AR blocks must be durable and stable during and after installation. Knowledge of the density and stability of concrete blocks has led to their use for protection of seagrass from illegal trawl fisheries by Seaman (1996). Although biological effects of ARs have been considered to be the most important factor while designing reef units, their physical and economical characteristics are now receiving increased attention. Physical characteristics include elements of the reef units, materials, structural integrity, block strength, as well as the environment in which the reefs are deployed. According to Sheng (2000), the environment of reefs can be divided into large-scale (circulation, wave climate, and sediment dynamics) and small-scale (local current and wave, bottom sediments, temperature, and salinity) environments. While designing the reefs, environmental effects such as wave and

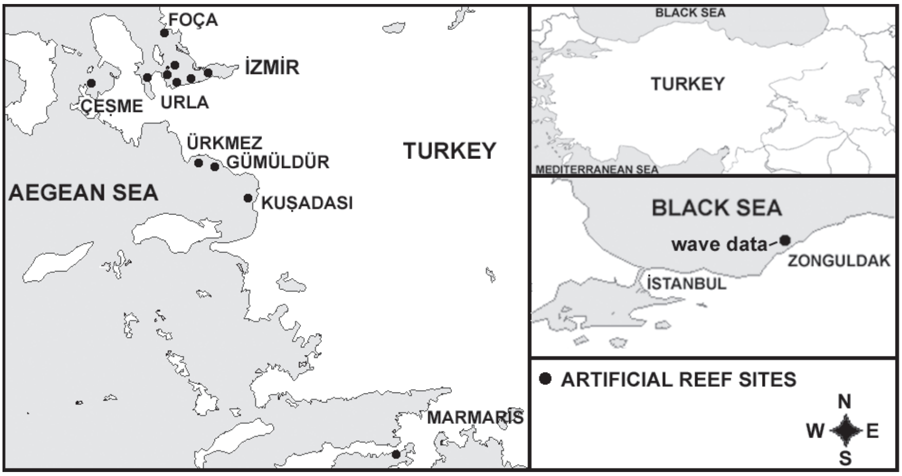

Figure 1. Artificial reef projects in Turkey Seas.

current conditions, distribution of bottom material around the reef blocks, and deployment depths are particularly important (Nakamura, 1985). Grove et al. (1991), examined the environmental design criteria under four different topics: wave design, current design, current forces acting on reef block, and scour and burial.

In this study, we investigated the stability and local scour problem of AR units due to internal waves and related currents in shallow waters. We conducted hydraulic experiments for an AR site in the Black Sea that is subjected to unique wave conditions.

Material and Methods

Wave and Current Data.—Environmental design criteria for ARs, including wave and current interaction, were investigated in a unidirectional wave channel to account for conditions encountered in the Black Sea. In situ wave and current data (i.e., wave height (H), period (T), and direction, and current velocity (u) and direction) were obtained from a multifunctional observation system in the Black Sea and analyzed by engineers of Port Hydraulic Research Centre for use in the wave channel experiments. Analyzed variables were: frequency distribution of significant wave height ($H_{1/3}$) and significant wave period ($T_{1/3}$), average current velocity (u_{av}) and maximum current velocity (u_{max}) (Table 2). Converted data were adapted to the scale of laboratory experiments; i.e., from prototype to model sizes (H_p: prototype wave height, H_m: model wave height, T_p: prototype wave period, T_m: model wave period, L: wave length, H/L: wave steepness) (Table 3).

Calculation of Model Scale and Construction of Models.—The model scale for hydraulic experiments was calculated from the ratio of median grain diameter (4.60 mm) of the sediment of the Black Sea AR site and median grain diameter (0.15 mm) of the laboratory sediment (Table 4). According to model scale (1/30), three different AR models were constructed from concrete with the converted dimensions of 1.5 m–5 cm, 1.2 m–4 cm, and 1 m–3.3 cm, respectively.

Wave Channel Installation.—The dimensions of the unidirectional two-dimensional wave channel were 40 m length, 1.2 m depth, 0.6 m width, and a 1 on 30 bottom slope (Fig. 2). Waves were propagated by a mono-pedal wave generator. Hydraulic experiments were carried out under regular wave conditions in four different water depths (33 cm equivalent to 10 m, 50 cm equivalent to 15 m, 66 cm equivalent to 20 m, and 83 cm equivalent to 25 m). Four

Table 1. Some characteristics of artificial reef units in Turkey.

Projects	Date	# of units	Name of units	Shape of units	Total volume (m^3)	Total weight (t)
Izmir Inner Bay	1989	10	Old bus		600	30.0
Hekim Island	1991	30	Hollow cube		30	24.2
Foça	1994	30	Plus		30	18.7
Dalyanköy	1995	50	Hollow cube		50	40.0
		50	Plus		50	31.2
Inner Izmir Bay	1997	107	Multi holes		19	16.0
Outer Izmir Bay		43	Multi holes		8	6.5
Urla	1997	50	Octo-reef		18	38.0
Ürkmez	1998	160	Pentagon dome		320	276.0
		5	Octo-reef		3	6.0
Gümüldür	1998	180	Hollow cube		310	270.0
Zonguldak	1999	50	Hollow cube		170	137.0
Marmaris	2000	75	Hollow cube		130	112.0
Kusadası	2003	475	Hollow cube		822	710.0

laboratory wave gauges were installed at each water depth so as to measure both wave height and wave period.

Measurement of Local Scour and Loss of Stability.—To determine local scour depth, the distance between the water surface and the sand bottom was measured before and after wave generation using a digital sand surface meter as well as by ruler. In the local scour experiment, different wave heights (5, 6, 6.5, 7.5, 8.5, 9.5, and 10 cm), constant wave period (1.13 s), and three different size models were used at 33 and 50 cm water depths during the 15- min wave propagation.

To determine stability of AR models, three different models were used in four different water depths (33, 50, 66, and 83 cm). As given in Table 3, seven wave sets with 35 wave runs in a 30 min span were carried out in the wave channel to observe the loss of stability due to scouring around the reef model, and the direct effect of waves acting on the reef model during wave propagation. Loss of stability of AR models such as sinking, sliding, and overtopping were observed and recorded by a digital camera. In each wave run, both the maximum local scour depth and loss of stability of the model were measured and observed.

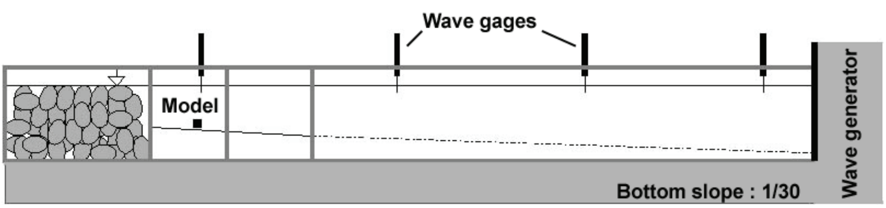

Figure 2. Setting of unidirectional wave channel.

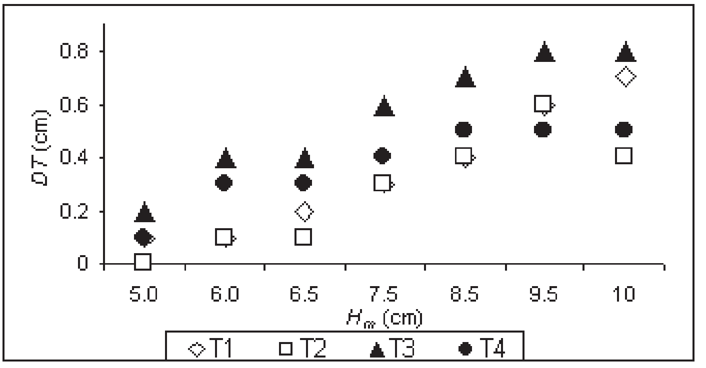

Figure 3. Local scour depths around the all corners of artificial reef model in 33 cm (10 m) water depth with 1.13 s constant wave period.

Results

Local Scour and Ripple Formation on the Sand Bottom.—Maximum local scour depth (approaching 0.80 cm) occurred on the corners of the 5 cm reef model (Fig. 3). As water depth increased, local scour began to decrease (Fig. 4). Scour formations were also apparent for the 4 cm model (0.60 and 0.50 cm at 33 and 50 cm water depths, respectively). Similarly, the 3 cm reef model had 0.60 cm and 0.40 cm scours at those depths.

Wave propagation causes ripples on the floor related to water depth and wave characteristics. In the experiment, ripples began to be observed from the 8th wave run (H_m: 6.57 cm, T: 1.1 s) in 33 cm water depth (Table 3). As the wave height and period increased, ripples became more apparent (Fig. 5).

Stability of the Artificial Reef Model.—Sediment transportation and local scours began forming in circular shapes from the second set of waves. Scouring was usually deeper around the T_1 and T_2 corners of the reef models (Fig. 5). As a result of this scouring, reef models lost stability, moved and slid into the holes. Local scour holes occurred regularly up to the fourth set of wave propagation. At the 29th wave run, the AR model turned 45° in 33 cm (10 m) water depth due to direct wave force. Decreasing local scour formations and loss of stability were observed in the experi-

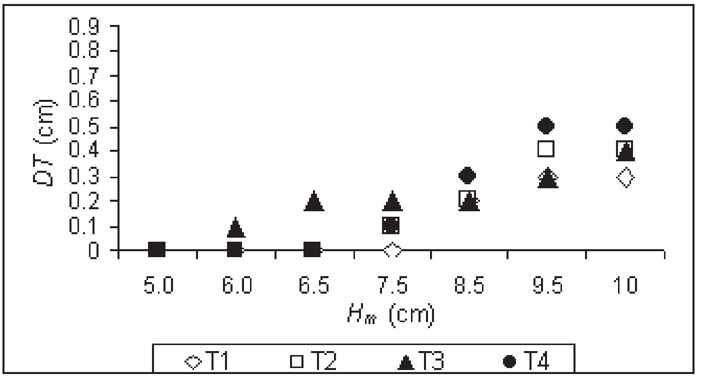

Figure 4. Local scour depths around the all corners of artificial reef model in 50 cm (15 m) water depth with 1.13 s constant wave period.

Table 3. Adjusted wave data used in the hydraulic experiment. Wave period calculated as: $T_m = T_p * n^{-1/2}$ (*n*) $L = 1.56*T^2$. H_p (m) = prototype wave height; H_m (cm) model wave height; *H/L* = wave steepness; T_m = model wave period; T_p = prototype wave period; *n* = model scale; *L* = wave length; *T* = wave period.

Wave heights		*H/L*				
H_p (m)	H_m (cm)	0.045	0.040	0.035	0.030	0.025
1	3.33	0.69	0.73	0.78	0.84	0.92
2	6.57	0.97	1.03	1.10	1.19	1.31
3	9.57	1.19	1.27	1.35	1.46	1.60
4	12.43	1.38	1.46	1.56	1.69	1.85
5	15.33	1.54	1.63	1.75	1.89	2.07
6	18.33	1.69	1.79	1.91	2.07	2.26
7	21.44	1.82	1.93	2.07	2.23	2.45

ment at 50 and 66 cm water depths and by 83 cm (25 m) water depth there was no large local scour around the reef model. It is therefore possible to determine the safe deployment depth of an AR if the wave height (*H*), the wave steepness (*H/L*), the water depth (*h*), and the reef size (h_r) are known (Fig. 6). For example, two different cases of ambient wave design conditions are given in Table 5. Based on known and calculated parameters, three areas can be identified: one that is unsafe, with a potential for sliding local scour; the second, a safe area, where blocks are likely to remain stable; and the third, a critical area, a zone between the unsafe and safe areas.

Discussion

This experiment was conducted under regular wave conditions, which may be quite different from natural sea conditions. Other studies conducted under both random and regular wave conditions (Smith and Kraus, 1991) indicate that these laboratory experiments must be supported with the field experiments in the future.

Many studies have used model experiments in different scales in both circulation and wave channels to examine scouring around and stability of ARs (Kimura and Ingsrisawang, 1992; Kimura et al., 1994, 1996; Kim et al., 1995; Ingsrisawang, et al.,

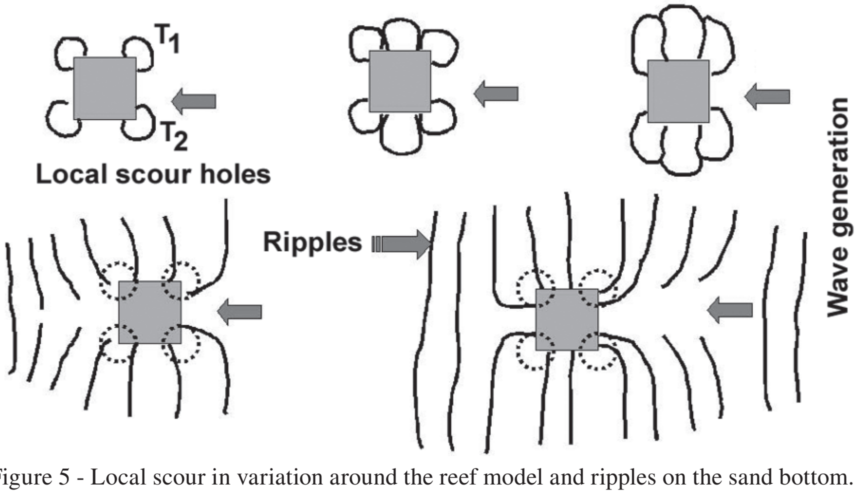

Figure 5 - Local scour in variation around the reef model and ripples on the sand bottom.

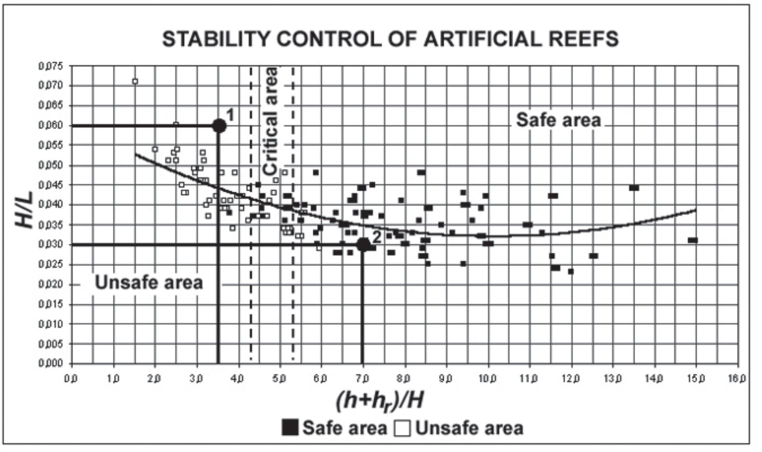

Figure 6 - The graphic to determine deployment area for stability of reefs between the ranges of wave steepness in 0.000-0.075 (ratio of wave height to wave length). The results can be used to decide deployment depth, which is numbered as 1 for the unsafe area and 2 for the safe area for stability of artificial reef block.

1995a,b, 1999; Ingsrisawang, 1996). In addition to waves, currents may also cause local scour leading to embedment. Scouring and sinking of the reef blocks in the sea generally occurs within a few years from both current and wave effects (Ingsrisawang et al., 1995a). Local scour is governed by vortex around the AR (Ingsrisawang et al., 1999), which transports sediments away from the vicinity of the reef. Local scour or removal of those sediments from around the ARs is affected by some attributes as shape and design of reef block, height of block, water depth, wave height and period, current velocity, and median grain diameter of sediment. Our results demonstrated that water depth increased and local scour depth decreased. Further, local scour formations were deeper towards the direction from which waves were propogated. Kim et al. (1995) stated that local scour and its shape not only depend on reef shape and design, but also on wave direction. Although in the first experiment, scours formed in front of the wave, in the sea, local scours would form homogeneously due to random wave directions.

Ingsrisawang et al. (1999) reported that ripple formation depends on wave height, velocity at sand bed, and water depth. In this study, ripples began to form at the 8th wave run and the height of the ripples increased with wave height and period. The local scour holes occurred around the corners of cubic reef model, similar to other hydraulic experiments (Kim et al., 1995; Ingsrisawang et al., 1999).

Formation of local scour may cause some stability problems for ARs even though there may be no direct wave effect on the reef blocks (Düzbastılar, 2001, 2003;

Table 4. Prototype and model sediment analysis results. *P* = prototype sediment; *M* = model sediment; *n* = model scale.

	Specific gravity (t m^{-3})	Grain diameter (mm)	Volume (m^3)	Weight (t)
(*P*)	2.65	4.60	$5{,}0964.10^{-8}$	$1{,}3505.10^{-7}$
(*M*)	2.85	0.15	$1{,}767.10^{-12}$	$5{,}036.10^{-12}$
P/*M*		30.67	28,840.30	26,816.40
Dimension		30.67^1	$28{,}840.30^{1/3}$	$26{,}816.40^{1/3}$
(*n*)		30.67	30.67	29.93

Table 5. Two different ambient conditions for deployment features.

Ambient condition	First condition	Second condition
Wave height (*H*) (m)	6 m	3 m
Wave period (*T*) (s)	8 s	8
Wave length (*L*) (m)	99.84 m	99.84
Deployment depth (*h*) (m)	20 m	20
Reef height (h_r) (m)	1 m	1

Düzbastılar and Tokaç, 2003). Consideration of local scour and loss of stability together has indicated that shallow waters are likely to have a very limited service life for ARs in the Black Sea. Results of this study suggest a minimum deployment depth of 20 m for the deployment of ARs in investigated area in the Black Sea.

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