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Numerical Modeling of Structural Response of IMTA System to Environmental Loading of the Gulf of Mexico

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ABSTRACT

Integrated Multi-Trophic Aquaculture (IMTA) systems incorporate species from different trophic levels to promote sustainability through nutrient recycling and reduced environmental impact. This study presents a numerical investigation of the structural response of an IMTA system developed by the University of New Hampshire for potential deployment in the Gulf of America (Gulf of Mexico). The system's behavior under site-specific environmental conditions—including steady currents and 1-year and 50-year return period storms—is simulated using Hydro-FE, a dynamic fluid-structure interaction tool integrated with the Hexagon Marc solver. Mooring line tensions and safety factors are evaluated to assess their performance under extreme loading. It is shown that stresses in structural components can be evaluated, offering a basis for future fatigue and lifecycle assessments.

Keywords: IMTA; finite element model; nonlinear structural analysis; multi-scale marine modeling; Morison equation; Hydro-FE; mooring tensions.

1 INTRODUCTION

Amid growing population pressures and climate change, marine aquaculture has emerged as a key strategy for ensuring food security. Intensive aquaculture practices have raised concerns due to their significant environmental and social impacts. To address these challenges, sustainable approaches such as Integrated Multi-Trophic Aquaculture (IMTA) have been proposed to promote a more eco-efficient and socially responsible aquaculture industry (Alexander et al., 2016; Sara et al., 2018). In IMTA systems, uneaten feed and waste products from one species are recovered and utilized as inputs—such as feed or fertilizer—for another species, enhancing overall profitability and reducing environmental impact. One practical example is the IMTA system developed by the University of New Hampshire for deployment in the Gulf of America (Gulf of Mexico), designed to sustainably cultivate 4,000 red drum (*Sciaenops ocellatus*) as the fed species integrated with eastern oysters (*Crassostrea virginica*) and graceful red seaweed (*Gracilaria tikvahiae*) promoting nutrient recycling and minimizing environmental footprint (Chambers et al., 2024).

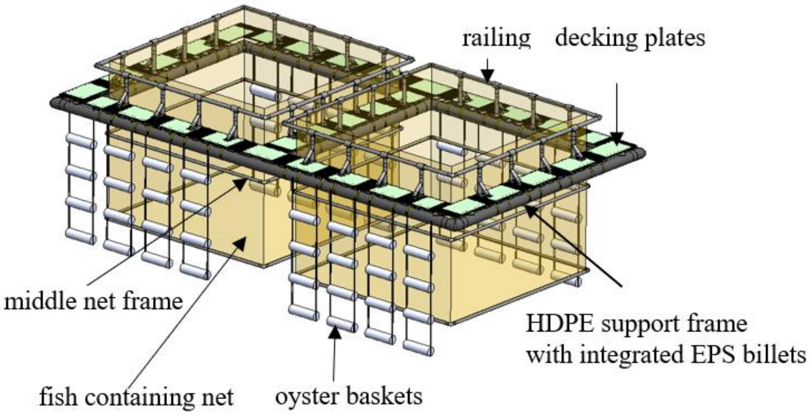

Figure 1: Integrated Multi-Trophic Aquaculture (IMTA) system with suspended oyster baskets.

In this paper, we analyse the structural performance of an IMTA system AquaFort schematically shown in Fig. 1. Potentially, the system can be deployed as two fish cages with oyster baskets suspended from the side and containing *Crassostrea virginica* and *Gracilaria tikvahiae*. Such an arrangement will not make it nitrate-neutral but can be utilized as part of a larger aquaculture system with more shellfish and macroalgae to approach 0% nitrate impact. For the numerical modeling presented in this paper, only the fish growing arrangement (a buoyant frame with suspended fish containment without oyster baskets) is analyzed. The system is considered for deployment at an 11.25 m deep site in the Gulf of America (Gulf of Mexico) southeast of Dauphin Island in the state waters of Alabama. The rest of the paper is organized as follows. Section 2 describes the system, its mooring, and the considered loading conditions. Section 3 presents the numerical model. Section 4 discuss the results of the simulations. The conclusions are given in Section 5.

2 AQUAFORT AND ENVIRONMENT CONDITION

The floating structure, IMTA AquaFort, includes two fish containment sections, as shown in Fig. 2. The frame is constructed of high-density polyethylene (HDPE) pipes along with expanded polystyrene (EPS) billets for flotation. The billets are made of EPS foam wrapped in a rotationally molded linear low-density polyethylene (LLDPE) shell with a nominal thickness of 3.81 mm. The walkway, 25.4 mm thick fiberglass reinforced plastic (FRP) decking plates have been used. Railing and the supporting stanchions are made of HDPE. The nets are attached to the railing above the water. The net system consists of two net materials: the bottom portion is made of copper (Cu) net, and the upper portion is made of polyethylene terephthalate (PET), divided by the middle net frame made of HDPE.

Fig. 2 presents the schematic of the mooring system considered for deployment of the IMTA in 11.25 m of water depth at the site. The mooring system consists of four main components: anchor chains, mooring lines, mooring plates, and bridle lines. The system includes four 18.3 m long mooring chains made of 19 mm long links connected to the mooring lines. Each mooring line is connected to two bridle lines through a mooring plate. For both the mooring and bridle lines, 12-strand polysteel rope is used—40 mm in diameter for the mooring lines and 32 mm for the bridle lines. The anchor chains are made of galvanized steel, providing the highest stiffness at 180 GPa. The geometric and material properties of the mooring system components are given in Section 3.

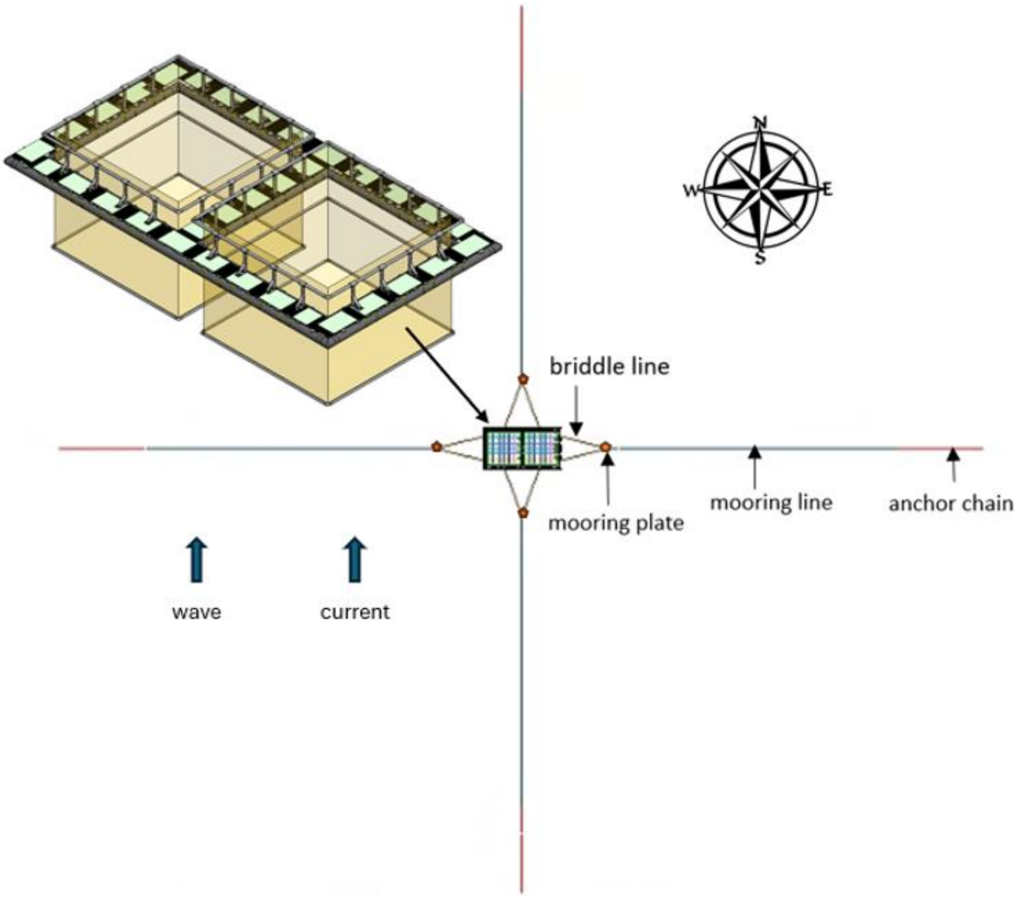

Figure 2: IMTA mooring configuration.

Three load cases for the selected site were considered: a steady-state current-only scenario, and dynamic sea states corresponding to 1-year and 50-year return period storms. Tab. 1 summarizes the environmental loading parameters applied in the numerical analysis of the AquaFort. To model waves, we utilized the JONSWAP wave spectrum (Hasselmann et al., 1973) corresponding to a frequency range of 0.01–0.31 Hz. The waves and current both are assumed to act in the northward direction in the both 1-year and 50-year storm conditions based on the site data (Kelson Marine, 2023).

Table 1: Environmental loading parameters used in the IMTA numerical analysis

Load parameters	Current-only	50-year storm condition	1-year storm condition
Current ($\mathrm{m\ s^{-1}}$)	0.48	0.48	0.36
Significant wave height (m)	-	5.3	3.1
Peak wave period (s)	-	10.4	8.9

3 NUMERICAL MODEL

The IMTA frame components and net frame are modeled as 3-d beam elements, while the mooring system is modeled using 3-d truss elements. The equivalent area was defined to ensure accurate estimation of hydrodynamic forces—such as drag and inertia—as well as hydrostatic buoyancy. The net components are modeled using the consistent net element technique (Tsukrov et al., 2003) for both PET and Cu netting. The finite element (FE) model parameters used in the simulation are described in Tab. 2, and the model is shown in Fig. 3.

The structural response of the system to the considered load cases was analysed using Hydro-FE, a dynamic fluid-structure interaction software integrated with the Hexagon Marc solver (Drach, 2015; Knysh et al., 2021) for the three loading conditions described in Tab. 1. Hydro-FE builds upon and modernizes the proven methodology of the Aqua-FE program—originally developed at the University of New Hampshire (Gosz et al., 1996; Tsukrov et al., 2000; Fredriksson et al., 2003)—for analysing partially or fully submerged flexible structures in marine environments. The hydrodynamic forces acting on the AquaFort components in the presence of waves and currents are expressed with a Morison equation approach (Morison et al., 1950). It was initially developed for cylindrical-shaped piles and later expanded to the case of moving cylinders (Goodman and Breslin, 1976).

The normal, dF_n , and tangential, dF_t, projections of the force exerted on a differential section dL are:

$$\begin{gathered} dF_n = \rho_w \frac{\partial u_n}{\partial t} dV + C_a \rho_w \left(\frac{\partial u_n}{\partial t} - \frac{\partial v_n}{\partial t} \right) dV + \frac{1}{2} C_d \rho_w |u_n - v_n| (u_n - v_n) dA_n \\ dF_t = \frac{\pi}{2} C_t \rho_w |u_t - v_t| (u_t - v_t) dA_t \end{gathered} \quad (1)$$

where u_n and v_n are the normal projections (perpendicular to the cylinder axis) of the fluid and body velocities, respectively, associated with the section dL . Similarly, u_t and v_t are the components of fluid and body velocities aligned tangentially (parallel to the cylinder axis), relevant to the tangential drag force. C_d and C_t are the normal and tangential drag coefficients. ρ_w is the water density, and C_a is the added mass coefficient. dA_n and dA_t denote the normal and tangential projected areas, respectively.

Table 2: Structural and material parameters for FE modeling of the IMTA system

AquaFort Components	Material	Modulus of Elasticity (GPa)	Equivalent Area (m²)	No. of Elements	Element Type
Outer pipe	HDPE	1.07	8.24E-02	101	2-node, 3-d, beam
Inner pipe	HDPE	1.07	8.24E-02	113	2-node, 3-d, beam
Transverse beam	HDPE	1.07	5.88E-03	247	2-node, 3-d, beam
Transverse beam center	HDPE	1.07	1.16E-02	13	2-node, 3-d, beam
Transverse beam ES	HDPE	1.07	5.33E-03	180	2-node, 3-d, beam
Stanchions part 1	HDPE	1.07	1.27E-02	24	2-node, 3-d, beam
Stanchions part 2	HDPE	1.07	1.69E-02	64	2-node, 3-d, beam
Stanchions part 1_center	HDPE	1.07	1.40E-03	8	2-node, 3-d, beam
Longitudinal beam	HDPE	1.07	5.08E-03	275	2-node, 3-d, beam
Railing	HDPE	1.07	1.03E-02	40	2-node, 3-d, beam
Plate left & right	A-Glass Fiber	69	3.04E-02	30	2-node, 3-d, beam
Plate front & back	A-Glass Fiber	69	2.68E-02	54	2-node, 3-d, beam
Plate center	A-Glass Fiber	69	2.61E-02	20	2-node, 3-d, beam
Billet	EPS Foam	0.51	2.22E-01	56	2-node, 3-d, beam
Briddle line	Poly steel 12-strand	3.19	5.10E-04	64	2-node, 3-d, truss
Mooring line	Poly steel 12-strand	3.2	7.76E-04	120	2-node, 3-d, truss
Anchor chain	Galvanized Steel	180	9.21E-04	44	2-node, 3-d, truss
Cu net vertical twine	Copper	117	3.02E-04	204	Net element
Cu net horizontal twine	Copper	117	2.27E-04	156	Net element
PET net vertical twine	PET	3.14	2.69E-04	182	Net element
PET net horizontal twine	PET	3.14	1.96E-04	144	Net element
Net frame	HDPE	1.07	6.21E-03	96	2-node, 3-d, beam

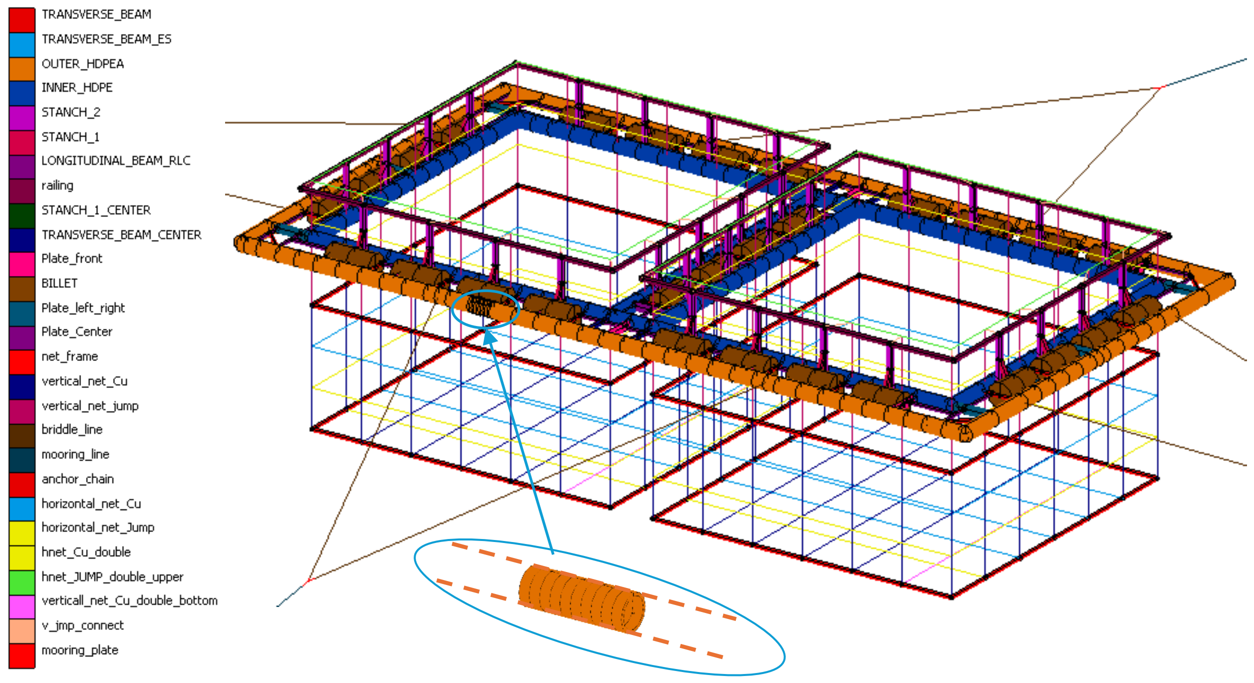

Figure 3: Finite element model of the IMTA system with mooring configuration, with the inset showing the finite element selected to illustrate variation of stress.

In the numerical modeling of the AquaFort structure, drag coefficients for cylindrical segments were assigned as C_d = 1.2 and C_t = 0.08 for both truss and beam elements (Knysh et al., 2021). Note that, these coefficients can be adjusted based on Reynolds number, but such an adjustment was not used in the present simulations. For the net elements, appropriate steps were taken to ensure accurate representation of drag and inertia forces by adopting the consistent net element formulation proposed by Tsukrov et al. (2003). This formulation balances the equivalent projected area used for drag force calculation with the actual volume required for accurate inertia force representation.

4 RESULTS

The dynamic response of the IMTA system under different environmental conditions was investigated to evaluate structural behaviour and mooring performance. Fig. 4 illustrates the system's motion by presenting the maximum deformed configurations under three conditions: current-only, 1-year storm, and 50-year storm.

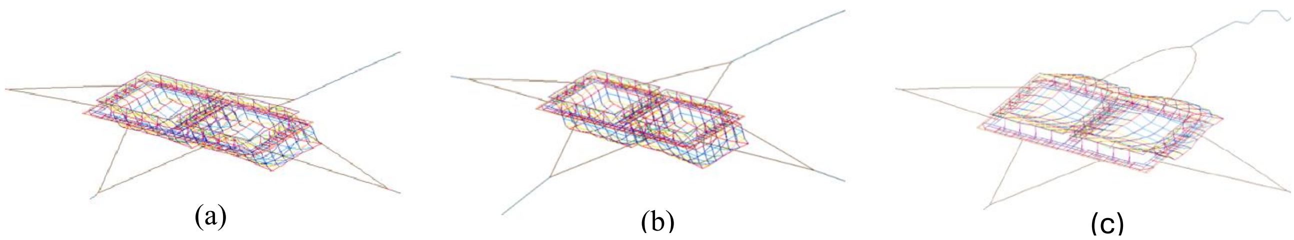

Figure 4: Examples of the deformed shape of the AquaFort structure under (a) current-only, (b) 1-year storm, and (c) 50-year storm conditions.

Fig. 5 presents the time history of mooring line tensions for storm cases. Simulations start from the undeformed configuration, but the initial transient response is excluded from the plots. Mooring line tensions were calculated by multiplying the longitudinal stresses in the mooring components by the corresponding cross-sectional area. The highest recorded tension, 137 kN, occurred in the south mooring line during the 50-year storm scenario, consistent with the assumed northward direction of both wave and current forces.

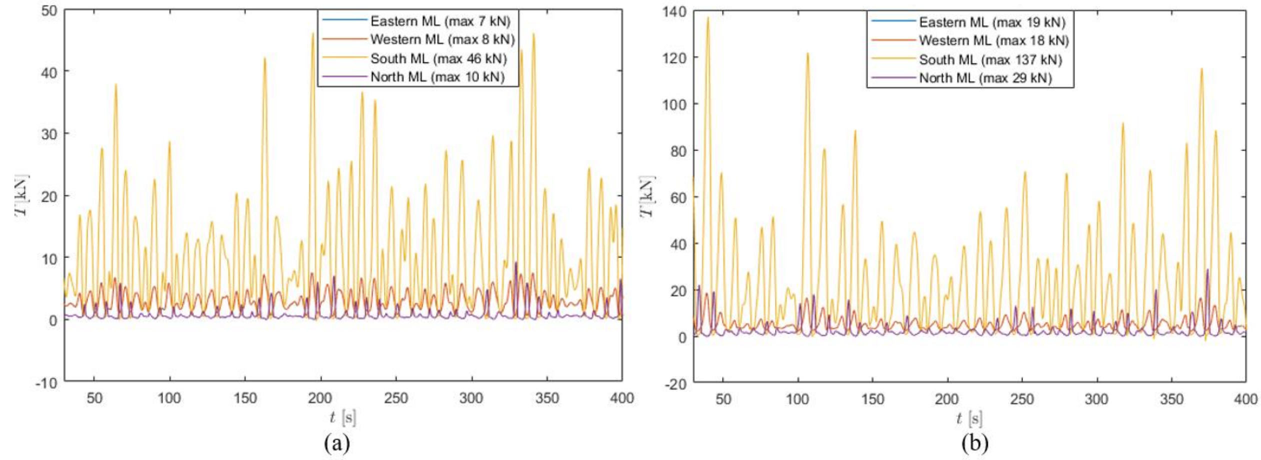

Figure 5: Tension time series of mooring lines (MLs) under the storm conditions with return period of (a) 1 year, and (b) 50-year.

For the 40 mm polysteel 12-strand mooring line, which has a minimum breaking load (MBL) of 274 kN, the resulting safety factors were approximately 6 under the 1-year storm and 2 under the 50-year storm, as shown in Tab. 3. These values remain within acceptable design thresholds but highlight the increasing demand placed on the structure under extreme loading.

Table 3: Mooring line tension and safety factor under different loading condition

Loading condition	Maximum mooring tension (kN)	Mooring line MBL (kN)	Safety factor
Current only	6	274	46
1-Year storm	46	274	6
50-Year storm	137	274	2

Fig. 6 illustrates the time history of stress in a typical HDPE pipe component extracted from the simulation of the 50-year storm. The stress variations in time can be used to predict the component's strength and fatigue life and, thus, to size components and evaluate their safety factors. Such a detailed structural analysis is outside of the scope of this paper and will be published separately.

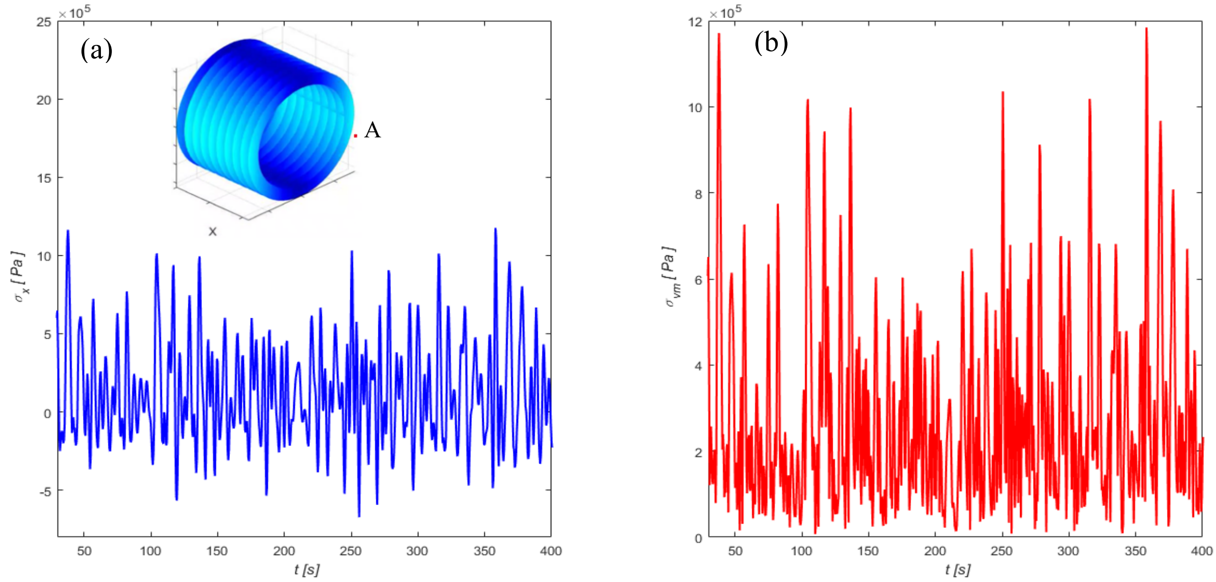

Figure 6: Variation of stress with time for 50-year storm at point A of the selected pipe component: (a) longitudinal stress (σ_x), (b) equivalent Von-Mises stress(σ_{vm}).

5 CONCLUSIONS

This study presents a numerical investigation of IMTA AquaFort using finite element modeling in hydrodynamic software *Hydro-FE*. The simulations were conducted for site-specific loading scenarios, including current-only, 1-year, and 50-year storm conditions of the site, and captured the dynamic mooring tension responses. Results showed that the mooring tensions remained within safe design limits, with adequate safety factors across all simulated conditions.

In addition, it was shown that the simulation can be used to extract the stress history in the structural components of the IMTA frame. This information can be used to perform the fatigue analysis, identify structurally critical components, and estimate the life span and safety factors.

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