Erosion behavior assessment for scour prediction of Japanese offshore sand using Erosion Function Apparatus (EFA)

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ABSTRACT

Scour, the erosion of seabed materials caused by water flow, threatens offshore structural stability. While prior research explored scour around piles in cohesive soils, studies on sandy grounds remain limited. This study evaluates scour depth around a 10 m-diameter monopile installed in Japanese offshore sand. Erosion Function Apparatus (EFA) tests quantified critical shear stress, erodibility coefficient, and power exponent for four soil layers. Results show that S3 is the most erosion-prone due to its low critical shear stress, while S4 demonstrates higher resistance to scour compared to other layers. Using SRICOS-EFA analysis and 25 years of discharge data, the maximum predicted scour depth was 1.6 m, with significant erosion starting in year 5 and removing most of layer S1. Due to the limitations of unidirectional flow data, multi-directional discharge and improved soil characterization need to be incorporated in the following studies.

INTRODUCTION

Scour is a natural phenomenon caused by the erosive action (Wang et al. 2017), and the erosion or removal of streambed or bank material (Kattell 1998). Scours occur in three types, general, contraction, and local scour (Wang et al. 2017). Especially in the case of bridge scour, scour is the main cause of bridge collapses (Briaud et al. 2007; Imam and Chryssanthopoulos 2012). Around the world, there have been numerous instances of bridges falling because of scour, resulting in significant damage (Maddison 2012; Bergamo et al. 2015). To prevent structural instability caused by scour, it is very important to accurately predict and design for the scour depth that may occur around the structure.

To precisely predict the scour rate around the structure caused by water current, numerous studies using diverse methods have been conducted. Especially, large-scale experiments have been conducted to evaluate and predict scour depth. Sheppard et al. (2004) used large scale tests to investigate the effect of circular pile diameter and sediment diameters on scour depth. In addition,

research has also been conducted to predict the scour depth of pile foundations induced by waves using both small-scale and large-scale experiments (Hu et al. 2023). Khosronejad et al. (2020) used numerical simulations and small- and large-scale experiments to independently assess and predict the maximum general and local scour depths that occur around longitudinal structures.

SRICOS (Scour Rate In COhesive Soil) was developed as an approach to predict the depth of scour surrounding bridge piers (Briaud et al. 1999). This method can be used to forecast the depth of scour that will develop around abutments and piles placed in cohesive soils. Furthermore, Briaud and Chen created the SRICOS-EFA method (Briaud et al. 2001a; Briaud et al. 2001b), which combines the EFA (Erosion Function Apparatus) and SRICOS methods, and it has been widely used to predict scour depth easily.

However, little investigation has been done on predicting scour in silty and sandy soils surrounding monopiles under different undisturbed ground conditions. Research on the variations in erosion resistance caused by soil characteristics is comparatively lacking. Furthermore, research using SRICOS-EFA as an erosion prediction method is primarily restricted to cohesive soils; therefore, it is necessary to examine the method's applicability and accuracy for a range of ground conditions.

In this study, a feasibility assessment of the installation of a wind turbine monopile in Japanese offshore soil is performed. Scour around the structure caused by currents and waves can have a significant negative impact on structural stability. Soil properties are evaluated by conducting an on-site geotechnical investigation on a ground composition consisting of sand. Erosion Function Apparatus (EFA) tests are performed to predict the scour depth around monopile. Furthermore, the scour depth around a monopile with a diameter of 10 m is predicted using the erosion parameters determined from the EFA tests. From this, the most vulnerable strata of each formation to scour are assessed, and further studies are suggested.

MATERIALS AND METHODS

Offshore sand. The offshore sands were obtained from a borehole survey located off the coast of Japan. The ground level was located at a depth of 13.88 meters below the water surface. The soil compositions, classifications and physical properties of each soil are shown in Table 1.

Table 1. The compositions and properties of soil samples.

Soil layer	Thickness (m)	Depth (m)	USCS	γ_d (kN/m^3)
S1	1.85	1.85	SW	13.0
S2	0.80	2.65	SP	15.8
S3	0.23	2.98	SP	15.7
S4	37.12	40.10	SP	13.9

All soils consisted of sand, with a cemented core at the center of the soil samples. The soil samples were placed in shelby tubes to conduct the erosion test. The inner diameter of the shelby

tube was 71 mm and the outer diameter was 76 mm. To prevent evaporation of water from the soil, the top and bottom of the shelby tube were filled with paraffin.

Erosion Function Apparatus (EFA). To assess the erosion properties of sands, the state-of-the-art Erosion Function Apparatus (EFA) with real-time P-wave sensors was used. EFA was first developed by Briaud et al. (2001b) and is a simple device for scour prediction. In the EFA test, the erosion criterion for soil is the time it takes to erode 1 mm, expressed in mm/hr. In this study, the EFA at the Korea Institute of Civil Engineering and Building Technology (KICT) was used and shown in Figure 1. The EFA has a maximum capacity of flow rate of 7.7 m/s. The water channel of EFA has a width of 100 mm and a height of 50 mm.

P-wave monitoring method was used to quantitatively assess the amount of soil erosion in real time. Three pairs of ultrasonic wave sensors were installed on the top of the acrylic channel. Using the ultrasonic wave sensors, the eroded depth of the soil was measured by tracking the change in the arrival time of the P-wave. The travel length of the P-wave was 100 mm. The P-wave velocity in water was 1,480 m/s. The change in the height of the soil was tracked using the change in the time (Δt) after the soil was eroded.

Figure 1. The overview of EFA at KICT.

Erosion rate and parameters. The EFA test incorporates the time it takes to erode 1 mm of soil height under water-induced shear stress to determine the erosion rate. Equation (1) can be employed to calculate the water-induced shear stress τ (in Pa), which is a function of the water velocity v,

$$\tau = \frac{1}{8} f \rho v^2 \tag{1}$$

where f is the factor of friction derived from Moody's chart (Moody 1944), which is represented by Reynolds Number and relative pipe roughness, and ρ is the density of water (1000 kg/m^3). The

formula for relative pipe roughness is ε/D, where D is the water channel's hydraulic diameter and ε is the relative roughness. According to Briaud et al. (1999), the relative roughness is half of D_{50}.

The erosion rate is a function of the shear stress developed by the flow rate. If the shear stress on the soil is less than the erosion resistance of soil, erosion does not occur. On the other hand, erosion occurs when the shear stress is greater than the threshold erosion resistance. This point is called the critical shear stress (τ_c). Since the commencement of erosion, the erodibility coefficient (k_d) has been introduced to express the rate of increase of erosion rate with increasing shear stress. Many studies have been conducted to express the erosion rate – shear stress relation (Temple 1992; Hanson and Cook 1997), and Ham et al. (2018) proposed the equation (2),

$$\dot{z} = k_d(\tau - \tau_c)^{\theta} \tag{2}$$

where, θ is the power exponent. Power exponent, erodibility coefficient, and critical shear stress were used in this study to assess soil erosion behavior.

RESULTS AND DISCUSSIONS

The erosion test results. EFA tests were conducted to assess the erosion behavior of offshore sand, and the test results are shown in Table 2 and Figure 2. EFA test results were expressed as the erosion rate - shear stress correlations. As shown in Table 2 and Figure 2, the highest τ_c occurred in S4, and S3 was shown to start erosion at very low shear stress. In the case of erodibility coefficient (k_d), the soil with the steepest erosion curve was S3. Also, the power exponent expresses the shape of the curve in the erosion rate – shear stress relationship. In the case of power exponent, the curves of S1, 2, and 4 soils indicated concave shapes, and only the curve of S3 soil showed a straight shape.

The erosion rate – shear stress correlations determined through EFA tests can determine the erosion vulnerability of soils. Among the offshore sands, the most vulnerable layer to erosion was considered to be S3. This is because it has the lowest critical shear stress, which means that erosion starts at the lowest shear stress. The soil layer with the highest erosion resistance is S4. This is because S4 is assessed to have the highest critical shear stress. However, in the case of S4, erosion increases at a very high rate once erosion starts, so once erosion starts, the soil can be removed at a very high rate.

Table 2. Determined erosion parameters of soils.

Soil layer	Critical shear stress (Pa)	Erodibility coefficient (mm/hr/Pa)	Power exponent
S1	10.1	13.3	0.56
S2	1.7	4.6	0.35
S3	0.045	71.7	1.09
S4	53.2	34.9	0.76

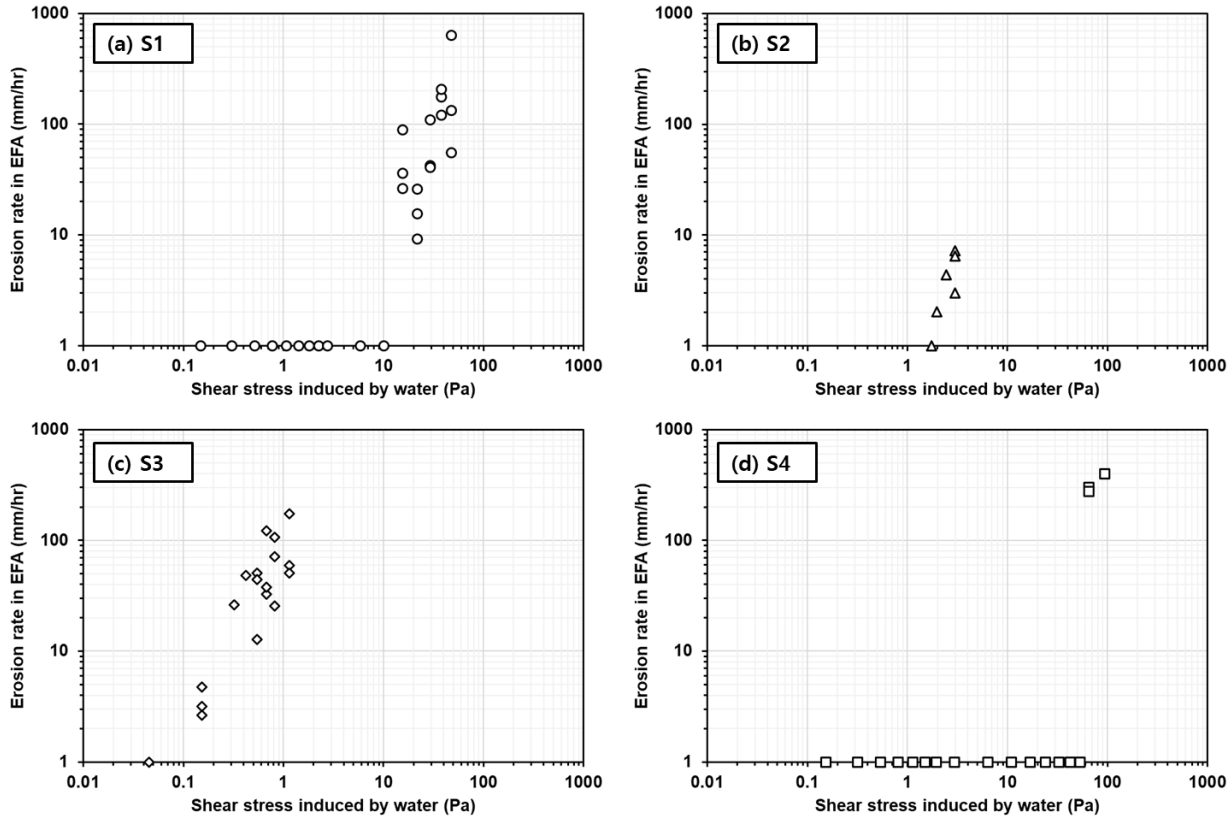

Figure 2. The EFA test results of offshore sands.

Scour prediction through SRICOS-EFA. From the results of the EFA tests, the prediction of scour depth around the monopile was investigated by numerical analysis. SRICOS-EFA program was used for scour prediction of the soil around the monopile. The foundation of the offshore structure was set as a monopile type. The cross section of the monopile is circular and the diameter is set to 10 meters. The width of the water channel is set to 1,000 m because the monopile is installed on a wide coastal ground. For soil data, the thickness of the soil layer shown in Table 1 and the EFA test results shown in Table 2 were used. For hydrograph data, discharge data for 25 years from offshore was used.

As a result of SRICOS-EFA (Figure 3), the maximum scour depth that will occur around a 10-meter monopile for 25 years was calculated to be 1.6 meters. A rapid scour depth was predicted at an elapsed time of 5 years and beyond. The numerical analysis showed that most of the S1 layer was removed. However, for a more accurate prediction, a numerical analysis that reflects discharge data from all directions is required due to the characteristics of offshore.

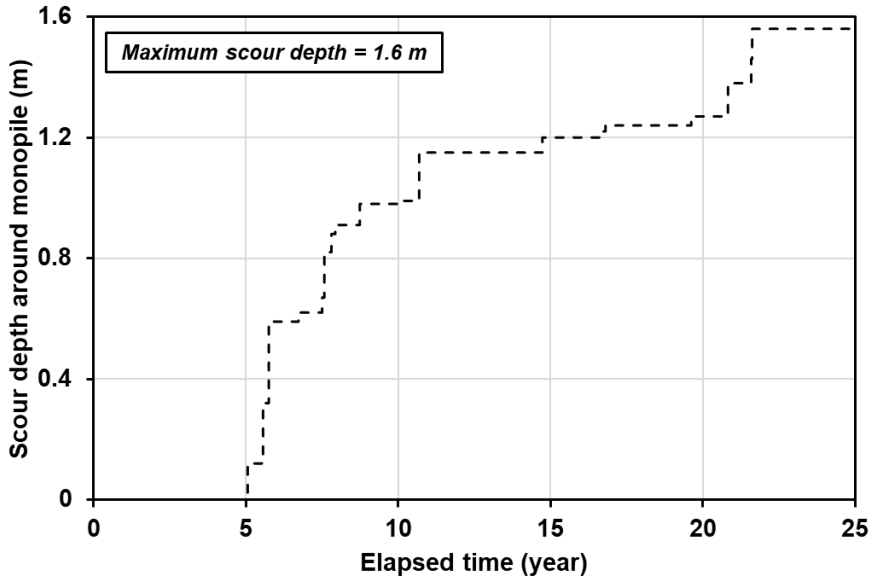

Figure 3. The predicted scour depth by elapsed time.

CONCLUSIONS

This study investigated the prediction of the maximum scour depth around a monopile located offshore. Erosion Function Apparatus (EFA) was used to analyze and evaluate the erosion mechanism of offshore sands. The erosion parameters (critical shear stress, erodibility coefficient, and power exponent) determined from EFA tests were used to assess the correlation of erosion rate with shear stress. The erosion resistance was quantitatively evaluated for each soil layer. The maximum scour depth around the monopile was predicted using SRICOS-EFA based on the EFA test results.

The EFA tests revealed that offshore sand layer S3 has shown the low erosion parameters, commencing erosion at the lowest critical shear stress and presenting the steepest erosion rate. In contrast, layer S4 demonstrated the highest erosion resistance, with the highest critical shear stress. Nevertheless, once erosion begins, it progresses rapidly. These results highlight the erosion rate–shear stress relationship as a valuable indicator of soil vulnerability. Numerical analysis using SRICOS-EFA predicted a maximum scour depth of 1.6 meters around a 10-meter monopile over a 25-year period, with rapid scour beginning around the fifth year. This period resulted in the erosion of most of the S1 layer, highlighting the high vulnerability of specific soil layers to prolonged discharge conditions. However, this study is limited by the use of unidirectional discharge data, which may not fully capture offshore flow dynamics. Future research should incorporate multi-directional data and elaborate soil characterizations to enhance prediction accuracy.

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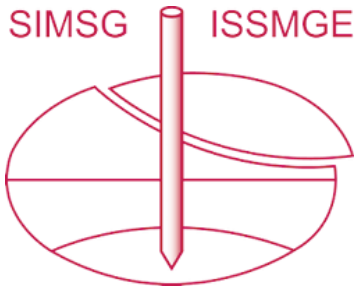

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