First Results of Undersea Muography with the Tokyo-Bay Seafloor Hyper-Kilometric Submarine Deep Detector MAGMA-HKMSDD Collaboration

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First Results of Undersea Muography with the Tokyo-Bay Seafloor Hyper-Kilometric Submarine Deep Detector

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Abstract

Tidal measurements are of great significance since they may provide us with essential data to apply towards protection of coastal communities and sea traffic. Currently, the tide gauge stations, satellite-based, pressure-based and ultrasonic-based techniques are commonly used. However, with these techniques, sensors have to be either floated on the sea surface or sunk onto the seafloor. The former option makes it difficult to conduct the tide measurements in high traffic maritime sea channels, and the latter option requires the construction of undersea electric and telecommunication infrastructures to support real time monitoring. On the other hand, with muography, sensors can be located underneath the seafloor inside, for example, an undersea tunnel where the electric and telecommunication infrastructures are more readily available. In this work, the world's first under-seafloor particle detector array called the Tokyo-bay Seafloor Hyper-Kilometric Submarine Deep Detector (TS-HKMSDD) was deployed underneath the Tokyo-Bay seafloor for conducting submarine muography. Time-sequential muographic data were converted to the tidal levels above the detector and compared with the data acquired from the nearby tide gauge station. The results were consistent, indicating that submarine muography could be an alternative tool for tide measurements. We anticipate that if the length of the TS-HKMSDD is extended from 100 m to a full-scale as large as 9.6 km to provide continuous tidal information along the tunnel, muography will become an established standard, demonstrating its effectiveness as practical tide monitor for this heavy traffic waterway in Tokyo and in other important sea traffic areas worldwide.

Introduction

Sea levels have been continuously measured and modeled extensively in the last

decades in order to evaluate the global and local climate change and ocean variability. In particular, for coastal communities, reliable sea-level information is essential since coastal flooding is increasingly occurring in many areas^{1,2}. The heights of coastal barriers or breakwaters are typically designed by considering the superimposed effects of tides, surges, waves, and relative sea-level rise³. However, the distribution of tide gauge stations (TGSs) is generally dispersed sparsely, and it usually depends on local topography and the distribution of people, infrastructure and economic activity along the coast. However, even within the Tokyo metropolitan bay area, one of the most populated areas in the world, TGSs are still sparsely distributed; along the 770 km of coast making up the Tokyo bay of Japan, there are only four TGSs with long-term data taking capabilities. For the safety of coastal communities and maritime navigation, understanding how coastal high waves happen, or identifying which meteorological and tide conditions produce high waves are important, and for this, more detailed sea level monitoring will be required because the local tides are highly variable, depending on local topography and bathymetry⁴.

Remote sensing techniques provide a more flexible solution for analyzing sea level changes in comparison to TGSs. The two main remote sensing techniques used are global-navigation-satellite-system (GNSS) buoys and interferometric synthetic aperture radar (InSAR). GNSS buoys are a new type of a tide gauge that has been developed with GNSS satellite positioning technology, allowing us to distribute the tide gauges in the offshore region, and it can measure tidal level with high precision and relatively fast time resolutions (30 s – 1 day)⁵. However, installing a large array of GNSS buoys in the high traffic coastal areas is not practical due to the obstruction it would create to sea traffic and the high cost of deployment. InSAR enables spatially continuous measurements. InSAR has been applied to detecting water level change with 3–5 cm accuracy over wide wetland areas^{6–9} and tidal inundation, propagation and mapping the tidal zone of the wetland¹⁰. However, InSAR is only applicable to detecting tidal changes that occur within longer spans of time, ranging from a few days to a few weeks^{9,11}. For example, the revisit interval of current in-orbit InSAR satellites, such as TerraSAR-X and COSMO-SkyMed, is ~15 days⁵, which is too long to image rapid sea level variations. In order to acquire data with faster time resolution, it would be necessary to launch additional, shorter revisit cycle InSAR satellites. Moreover, with

the current technique, horizontal and vertical motion cannot be distinguished, and only the unsteady tidal contribution can be extracted by differencing two separate InSAR pairs that originate from a combination of several SAR images¹².

Ocean bottom pressure gauging and ultrasonic gauges are also alternative methods that have been developed for detecting the sea level changes from the seafloor¹³. However, the pressure gauging technique has an intrinsic drift error, and moreover, the sensors have to be directly located on the seafloor, and thus it is challenging to prepare the electric and telecommunication network that are required for real-time monitoring. Like pressure gauges, ultrasonic gauges do not have to float on the sea surface, and there are no intrinsic drift errors either. This technique measures the propagation time of the ultrasonic signals between the sea surface and the sensor located at the seafloor. However, in particular, at shallow depths of seawater near coastal areas, sound propagation is strongly affected by solar radiation, seasonal cycles, mixing of the water due to sea currents, and the presence of rivers or waste waters¹⁴. On the contrary, the muon propagation properties are much less sensitive to the oceanic environment, e.g., variations in salinity, temperature, internal density waves in the upper-ocean, or motor sound in comparison to techniques that measure acoustic signals¹⁵. More importantly, since muons propagate through solid and liquid materials in a similar manner, the sensors can be located underneath the seafloor; for example, muon detectors can be placed inside an undersea tunnel where the electric and telecommunication infrastructures are not only convenient and well-arranged but often readily available and an important part of the original tunnel design.

Cosmic-ray muons are relativistic particles with a rest mass of 105 MeV. They travel almost at the speed of light through any kind of material and their speed is not affected by the media condition they travel as long as their energies are within the relativistic region. They are produced in the Earth's atmosphere via the collision between primary cosmic rays, which are mainly galactic cosmic rays (GCRs), and atmospheric nuclei, such as nitrogen and oxygen. These particles are ubiquitous and thus, available everywhere on the Earth. GCRs arrive at the Earth isotropically, because before arriving at the Earth, GCRs are deflected multiple times during their propagation in the galaxy, and lose their initial directional information. However, due to different atmospheric

thicknesses and density gradients for different GCR's arrival angles, the muon energy spectrum varies for different zenith angles. As a consequence, the vertical muon flux is higher than the horizontal flux, but the average energy of vertical muons is lower than the horizontal ones. The vertical muon flux is $\sim 10^2 \text{ m}^{-2} \text{ s}^{-1} \text{ sr}^{-1}$, but this flux is respectively reduced to ~ 10 and a few muons $\text{m}^{-2} \text{ s}^{-1} \text{ sr}^{-1}$ at the depths of 10 m and 100 m in water¹⁶. Muons are called heavy electrons. Due to the mass of a muon, they experience much less radiative energy loss processes (bremsstrahlung, direct pair production, and photonuclear interaction) than electrons, and consequently are much more penetrative than electrons. In conjunction with this penetrative nature and this universality, muography has been widely applied to visualizing the internal structure of gigantic objects such as volcanoes, highway & railway tunnels, natural caves, and cultural heritage in Africa^{17, 18}, the Americas^{19, 20, 21}, Asia^{22, 23, 24, 25, 26, 27, 28, 29, 30}, and Europe^{31, 32, 33, 34, 35, 36, 37}.

Undersea particle detectors have been deployed on the seafloor at large depths: in the past DUMAND³⁸ and presently ANTARES³⁹ and the under construction detector KM3NeT^{40,41}. However, it is difficult to utilize them for the purpose of muography because they are originally designed for the detection of neutrino (another elementary particle which is very light and extremely difficult to detect). Recently KM3NeT has measured⁴² the muon flux as a function of the depth reporting an uncertainty on the measured absolute value of about 15%. For the purpose of muography, being only the variation on the muon flux important, the relative values are important. This will reduce the total uncertainties to about 9%. The main systematic uncertainties are due to the reduced efficiency of the photomultiplier tubes (PMT), due to the combined effect of sedimentation and biofouling effect⁴⁰, and to the variation of the sensitivity to Cherenkov radiation due to change in turbidity (absorption length) within sea water. In addition to these in these submarine detectors, the optical sensors are anchored to the seafloor by weight at the bottom and equipped with a buoy at the top (subsurface mooring). There are several negative issues associated with subsurface mooring when applied to muography, which include the stretching of the tether string as it ages and gradual sinking of the anchor by its weight on unconsolidated sediment. Summarizing the total uncertainty does not allow the measurement of depth variations of the orders of meters.

The world's first under-seafloor detector array for conducting submarine muography called the Tokyo-bay Seafloor Hyper-Kilometric Submarine Deep Detector (TS-HKMSDD) was deployed underneath the Tokyo bay seafloor on March 5, 2021 (Figure 1). The ten installed muon sensor modules (MSMs) were anchor-bolted inside the undersea tunnel called the Tokyo-bay Aqua-tunnel; this tunnel provides an ideal environment for submarine/under-seafloor muography and overcomes the aforementioned issues. The detector collects near vertical muons after they have passed through the seawater and upper layer of the seabed of Tokyo-bay existing directly above the tunnel. The time-sequential muographic data were collected and converted to the tide levels above the detector. The results were compared with the data acquired from the nearest neighbor tide gauge station. The potential and prospects of this first combination of muography in the undersea tunnel environment is discussed in the following sections.

Figure 1. Conceptual view of the Tokyo-bay Seafloor Hyper-Kilometric Submarine

Deep Detector (TS-HKMSDD) deployed underneath the Tokyo bay seafloor (A) and the photograph (B). HKMT drew this image and holds the copyright. HKMT holds the copyright of the photograph.

Results

The Tokyo Bay Aqua-Line (TBAL), which is also known as the Trans-Tokyo Bay Expressway, is a combined bridge and tunnel structure spanning the entire width of Tokyo Bay, Japan (Figure 2). Tokyo Bay has some of the highest maritime traffic sea channels in the world, and 500-1000 ships travel over or under the span of TBAL every day. TBAL consists of a 4.4-km long bridge (30% of TBAL) and a 9.6-km long tunnel (70% of TBAL) underneath the bay. The tunnel section is called the Aqua-Tunnel. The average sea depth is 20 m in most of the region where the Aqua-Tunnel was constructed, and the tunnel was constructed at a depth of 20 m underneath the seafloor. In this work, 30 muographic sensor modules (MSMs) were deployed inside the Aqua-Tunnel to construct a linear array of MSMs called the Tokyo-bay Seafloor Hyper-Kilometric Submarine Deep Detector (TS-HKMSDD). Each MSM consists of two scintillation detectors, a high-voltage power supply unit (HVU) (Technoland Z-SYS 070HV), and a discriminator-coincidence unit (DCU) (Technoland Z-SYS 070DC) (Figure 3). When a muon passes through the detector, the scintillation light is transported to the photomultiplier tube (PMTs) (HAMAMATSU R7724 ASSY) attached to these plastic scintillators (10 cm wide, 150 cm long) (ELGEN EJ-200) via acryl light guides (Figure 3A). The signal outputs from these PMTs are transferred to the DCU to select only the events that pass through both of these scintillators at the same time. Although we did not expect secondary cosmic charged particles at a depth of more than 40 m water equivalent (m.w.e.), a 2-cm thick lead block was inserted between these plastic scintillators to remove background radiation that could emit from the concrete wall of the tunnel (see the Method section for a more detailed description about the MSM design). Tokyo Bay was chosen for conducting submarine muography because various maritime data sets including seawater and atmospheric temperature data, barometric data, salinity data, wind speed and direction data, precipitation data, humidity data, etc. are available, enabling more comprehensive comparison and evaluation of our

muographic results.

Figure 2. Location of the Tokyo Bay Aqua-Line (TBAL) in Japan (red lines) (A) and the cross-sectional view of the tunnel section (Aqua-tunnel) of TBAL (B). The symbols CTGS and HKMSDD-SEG respectively indicate the locations of the Chiba tide gauge station and the HKMSDD segment. The name Umihotaru indicates the service area that marks the transition between the bridge and tunnel part. HKMT drew the map and the image with the Microsoft PowerPoint software and holds the copyright.

Figure 3. Configuration of the HKMSDD segment. The schematic of the muographic sensor module (MSM) (A) is shown along with a photograph of the MSM (B). The abbreviations DCU and HVU respectively indicate the discriminator-coincidence unit and the high-voltage power supply unit. The block diagram of the data collection scheme (C) is shown along with a photograph of the Data Acquisition Center (DAC) (D). The network cameras (NW Cameras) are respectively used for monitoring the MSM LEDs and the DAC 7-segment LEDs. The HKMSDD server hosts a closed network. The schematic view of the HKMSDD segment is also shown (E). HKMT holds the copyright of the photographs.

An HKMSDD segment consists of ten MSMs, each spaced evenly at an interval of 10 m and the data acquisition center (DAC) located at the center of the segment (Figure 3E). Since the size of the scintillator of each MSM is 1500 cm^2 , each HKMSDD segment has an active area of 1.5 m^2 . Each segment measures 100 m in length (See Method section for more detailed description about the HKMSDD segment). In this work, one HKMSDD segment (SEG) was installed in the Aqua-Tunnel. The SEG was placed

within the region 500-600 m from the station called Umihotaru (the Japanese word for *Vargula hilgendorfii*, a local bioluminescent, ostracod crustation) that marks the transition between the bridge and tunnel part. Umihotaru is located in the middle of Tokyo Bay, and is located at almost the same distance from three major coastal cities (30 km from Tokyo city, 27 km from Chiba city and 22 km from Yokohama city) (Figure 2A). Directly above the tunnel in which the SEG is installed is a 10 m thick rock overburden (the seabed) and approximately 20 m thick column of water. (Figure 2B). The operation of the SEG started on March 5, 2021. The muon signals detected by MSMs are transferred to DAC, counted, and transferred in real time to the external server located in Kyoto, Japan. These numbers of counts are also locally displayed on the LED panel attached to DAC. Each DCU has an LED light that flashes when the detector is triggered, and both local LED panels and LED lights are monitored with the surveillance camera for remote monitoring.

Figure 4 shows the time-sequential plot of the lunar-daily (24 hours and 50 minutes) muon counts. The data were taken in the period between March 5 and May 10, 2021. Here, the lunar day refers to the period between moonrises. Therefore, by taking the lunar-daily average, instead of a standard day of 24 hours, variations in the astronomical tide levels are canceled. The muon rate is almost constant and the average muon counts per lunar day and standard deviation (S.D.) were respectively 1,145,080 and 2,780 (~2.5 per mille). As is described later, this fluctuation corresponds to the systematic error in determination of sea level of 5 cm S.D. (see Figure 6).

Figure 4. Time-sequential plot of the lunar-daily muon counts.

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272 Variations in the atmospheric pressure are compensated with the column density of
273 seawater and thus, it was expected that the muon counts are insensitive to the
274 atmospheric pressure variations. Muon counts are also insensitive to the sea level
275 variations due to the thermal expansion of the sea because this kind of variation does
276 not change the column density above the detector. The seawater density is also a
277 function of salinity, but again the density variations of seawater will be compensated
278 with the atmospheric pressure.

279

280 Figure 5A shows the time-sequential plot of the number of muon counts collected every
281 5 minutes. The data points were smoothed by taking a moving average with a time
282 window of 2 hours. The daily tide variations along with a longer cycle of spring and
283 neap tides are clearly seen as an anti-correlation with the results from the Chiba tide
284 gauging station (CTGS) (Figure 5B). When the tide level rises, the muon counts
285 decrease and vice versa. The height difference between high and low tides during the
286 neap tide period was 20-30 cm, and this level of tide variations can be clearly
287 distinguished with the current HKMSDD segment, justifying the tide gauging accuracy
288 we derived in the previous paragraph.

289

Figure 5. Time-sequential plot of the number of muon counts collected every 5 minutes (A) and the tide gauging results measured at the Chiba Tide Gauging Station (B)⁴³. The red box indicates the period we used for the detailed analysis in Figures 6 and 8.

The nearest neighbor tide station was located at the Chiba port (25 km NE of Umihotaru). Since the distance between the Chiba tide gauge station and Umihotaru is close enough, the astronomical tide variations could be directly compared between the muographic data and the CTGS data within the time scale of 5 minutes. Figure 6 compares the tide levels converted from the muon counts with the tide gauging results measured at CTGS. In this plot, the dates when the observed tide levels were close to the astronomical tide estimation were chosen. As is described later, generally, tidal levels cannot be directly compared with the muographic data due to the inverse barometer effect (IBE), and thus in Figure 6, the dates when the minimum barometric effect was observed have been chosen.

Figure 6. Tide levels converted from the muon counts. The data points (dark blue filled circles) are shown along with the statistic error bars (1 standard deviation) (sky blue lines). The tide gauging results measured at CTGS (red filled circles) and the theoretical calculation results of the astronomical tide levels (green line) are also shown (43).

Since muography measures the integrated density along the muon paths, the local seafloor topography and the average density of the seabed above the tunnel affects the absolute sea level gauging. For example, uncertainty of 5 cm for the topography or that of 1 per mille in seawater density will respectively correspond to an uncertainty of 7.5 cm and 2 cm in sea level when considering the sea depth of 20 m and assuming the seabed density of 2.5 g/cm^3 . For this reason, the technique to measure the relative tide variations without the necessity of the knowledge of these external factors was developed by using a simple relationship between muon flux and matter thickness they travers (see Figure 7).

In muography, the muon range as a function of the incident muon energy is incorporated in the open-sky muon spectrum as a function of the zenith angle (θ). Once both the muon path length and the average density along the path are known, the

thickness (X) can be calculated by multiplying them, and thus the minimum energy (E_c) of muons that can penetrate through a material. By integrating the open-sky spectrum $I(E, \theta)$ from E_c to infinity, we obtain the integrated muon intensity $N(E_c)$, which represents the number of muons that have enough energy to escape from the target of interest:

$$N(E_c, \theta) = \int_{E_c}^{\infty} I(E, \theta) dE, \quad (1)$$

where $I(E, \theta)$ is the zenith-angle-dependent open-sky muon energy spectrum, and E_c is the cutoff energy as a function of thickness, X . Due to the geometric acceptance of the detector, and the slant depth of both seawater and seabed, most muons arrive from the near vertical direction (50%, 70%, and 90% of the total muons respectively arrive within the angle region 0° - 20° , 0° - 33° , 0° - 50° from zenith). The integrated muon flux calculated with Eq. (1) is shown in Figure 7 for small variations in the matter thickness muons traverse. In this plot, only the range between $4,000 \text{ hg cm}^{-2}$ to $4,100 \text{ hg cm}^{-2}$ is shown. As shown in this figure, if the deviation (ΔX) in X in Eq. (1) is significantly smaller than X , the relative penetrating muon flux (ΔN) is a linear function of ΔX . By utilizing this flux-thickness relationship, the muon counts were calibrated with the astronomical tide height variations measured at the Chiba tide gauge station as reference data and only the relative difference (ΔX) was considered for conversion from the muon counts to the tide height. This method has an advantage for cases when we do not have accurate information about the factors that increase the uncertainty in the total rock-water thickness X . As shown in Figure 6, once the relative muon counts (ΔN) calculated by subtracting the local maximum from the local minimum respectively were observed at 0:00 and 6:00 April 15, these data were calibrated with the low and high tides respectively observed at 0:10 and 6:00 April 15, the next low tide height at 12:25 on the same day was reproduced accurately with this technique. In the period between 21:00 April 14 and 17:00 April 15, muographic results, astronomical tide, and the actual tide observed at the Chiba tide gauge station were almost the same. However, before this period, muographic results were significantly deviated from the tide gauging results. This reason will be discussed in the next section.

Figure 7. Muon flux expected at the Hyper-Kilometric Submarine Deep Detector (HKMSDD) segment placed within the region 500-600 m from Umihotaru (SEG1) for various matter thicknesses.

Discussion

It was shown that muography has the potential to provide an alternative and practical tide measurement technique that can complement preexisting tide gauging techniques. This technique enables us to measure tide levels at the locations where the conventional tide measurements are difficult to conduct. However, since muography measures the integrated mass above the detector, the measurements are influenced by some factors that do not have to be considered with the conventional techniques.

In the near future, TS-HKMSDD will be extended to a full scale of 9.6 km throughout the Aqua-tunnel. In this section, we discuss how the undersea environment can possibly

affect the muographic measurements and how these errors can be corrected or suppressed. After that, we summarize our prospects based on the potential of the proposed full-scale detector array.

Atmospheric Effect. Most muons are generated at the lower part of the stratosphere and lose their energies during their propagation through the troposphere. These muon energy losses depend on the “thickness” of the troposphere. When high pressure covers the area of the observation, less muons arrive, and vice versa. These atmospheric pressure variations affect the time-dependence of the muon flux on ground⁴⁴; hence muographic results are affected accordingly. However, for submarine muography, the muon flux is not affected by these atmospheric pressure variations since fluctuations in the sea level have a complementary relationship with the atmospheric pressure fluctuations above. This effect is called inverse barometer effect (IBE). If the atmospheric pressure is reduced by 1 hPa, the sea level rises by 1 cm. On the other hand, for the purpose of the muographic tide gauging, there is a contributing factor to the actual tide height. In Tokyo, meteorological information including the atmospheric pressure is collected every 10 minutes and reported to the public⁴⁵. Figure 8A shows barometric variations measured in the same period of Figure 6 in Tokyo, Japan, which is located 30 km north from Umihotaru. Although the pressure data were collected on land, they were converted to the values at sea level. As was described in the previous section, the muographic data shown in Figure 6 (April 14-15, 2021) matched well with the astronomical tide variations but there was a significant deviation from the Chiba tide gauge station data. It was expected that this deviation came from this inverse barometric effect. In Figure 8B, the muographic results with the barometric correction are shown. There is also a stratospheric temperature effect on the muon flux^{44,46,47}, but this effect only affects high-energy muons with energies above a few hundred GeV, which are far beyond the energies (~10 GeV) we are discussing here, and therefore it is beyond the scope of this work.

Figure 8. Hourly barometric variations measured in Tokyo, Japan (A). The values were converted to those at sea level. Tide levels converted from the muon counts with the barometric corrections. The data points (dark blue filled circles) are shown along with the statistic error bars (1 standard deviation) (sky blue line). The tide gauging results measured at CTGS (red filled circles) and the theoretical calculation results of the astronomical tide levels (green line) are also shown⁴³.

TS-HKMSDD as a **tide monitor on the heavy traffic waterway**. The undersea tunnels are constructed to allow shipping to pass above them without traffic congestion. Bridges with opening or swinging mechanisms also allow shipping to pass, but they can cause traffic congestion. Moreover, longer bridges are more difficult to open or swing.

Alternatively, building higher bridges will help to avoid having to add opening and swinging mechanisms; however, these bridges are more costly and more fragile against high winds. Inversely, the locations where the undersea tunnels were constructed are prone to having both heavy automobile and maritime traffics. Therefore, it is difficult to perform conventional tide measurements with buoys in the waters above these undersea tunnels in spite of the advantages they provide for the safety of the navigation. As a consequence, there is a clear incentive to investigate if muography can be used to fill in this gap and conduct tide measurements in heavy traffic waterlines that are now vulnerable.

Urbanizations have historically occurred in the bay areas because they are relatively safer against storm surges in comparison to land facing the open ocean. Storms occurring over the open ocean can generate large waves called swells. Large swells generated by the storms propagate outward from the storm, traveling over long distances across the ocean, but their energy is conserved or weakly dissipated during their propagation, and they release most of their energy on the open coasts with high waves (sometimes more than 10 m). The negative effects of large swells are generally mitigated by using some sort of blocking mechanism, like narrow entrances that characterize many of the bays⁴⁸. However, some of the swells can nonetheless pass through bay entrances, and may consequently cause damage to the coastal infrastructure. For example, the largest presence of such bay swells occurs in the region of Central Bay between the Bay Bridge and the Richmond-San Rafael Bridge, San Francisco, CA⁴⁹. Another region that sometimes attracts extraordinarily large waves is Tokyo Bay. For example, the swells generated by Typhoon-15 reached all the way to Tokyo Bay and damaged the breakwater of Yokohama port in 2019. After analyzing the meteorological data collected there, it was found that the ocean-driven swells had overlapped with the local waves and the wave height reached 5.57 m. By considering the astronomical tide and the wave pressure applied to the breakwater, it was estimated that the maximum height of the wave reached 9.18 m at the coast⁵⁰. As is evident in such an example, these ocean-driven swells have a potential impact on coastal land. However, the swell heights are difficult to predict⁵¹. Utilizing trans-bay undersea tunnels, muography offers an alternative solution to measure the tidal levels on heavy traffic water lines from locations underneath the seafloor. This technique is applicable to waterways throughout

the world with undersea tunnels.

Understanding of the regional tide streams in the inner bay is important for the safety of navigation and environmental assessments, as well as studying about the regional seawater circulation types and pollution distribution. For this reason, tidal flow fields have been numerically modeled in various waters⁵²⁻⁵⁶. In order to conduct the tidal stream simulations, the boundary conditions have to be set between the region in which the simulations are conducted and the coast or the region in which the simulations are not conducted. In these simulations, which are designed to reproduce the tidal stream as a result of tidal level variations, tidal levels are given as the boundary condition, and therefore the accuracy of these values will directly influence the quality of the simulations. Conventionally, the tidal data obtained from the tide gauge stations have been used as the boundary condition. However, since the locations of these tide gauge stations are spatially dispersed, the data have to be interpolated. As a result, the interpolated data have a tendency to be more erroneous as a function of the distance from the stations. In order to solve this problem, other researchers have developed numerical-model-based interpolation methods⁵⁷. Undersea muography will provide alternative and complementary boundary conditions to apply to these tidal flow field simulations. A full-scale extension of TS-HKMSDD will constrain the modeling results of the tidal stream in Tokyo Bay. The final deployment of ~100 HKMSDD segments across Tokyo Bay would directly provide the open boundary condition for the modeling of the northern half of Tokyo Bay. The HKMSDD segments are applicable to other undersea tunnels in the world. For example, the Transbay Tube in San Francisco, CA. As can be seen in Figure 9A, a full-scale deployment of HKMSDD segments throughout the Transbay Tube would provide the open boundary condition in the similar way to model the tidal current in the southern part of San Francisco bay.

Figure 9. Possible future HKMSDD deployment sites: (A) Transbay Tube, San Francisco, CA, (B) Channel Tunnel, UK/France, and (C) Glacier Upsala, Patagonia, Chile. Red lines in (A) and (B) indicate the undersea tunnels. Black arrows in (A) indicate the direction of the Pacific swells⁴⁹. Blue lines in (B) indicate the spring maximum current vectors. The numbers indicate the speed in units of cm/s⁶⁶. Red oval shape symbols in (C) indicate the hypothetical HKMSDD buried under the seafloor. HKMT drew the maps in (A) and (B) with the Microsoft PowerPoint software and holds the copyright. HKMT drew the image in (C) based on the work by Brinkerhoff et al⁶⁹.

TS-HKMSDD as a tsunami monitor. Submarine earthquakes sometimes cause large seafloor displacements, which subsequently may generate tsunami events. A minimum triggering earthquake magnitude of 5.5 is suggested for a sufficiently large submarine failure to generate a devastating tsunami and only if the epicenter is located within the continental slope⁵⁸, otherwise a larger magnitude of 7.0-7.5 is required^{59,60}. A tsunami is a large ocean wave that can be triggered by earthquakes, landslides, and mountain collapses. Tsunami waves generally have average wavelengths of 500 km with an initial

propagation speed of more than 200 m/s⁶¹, but since the speed tends to decrease as these waves approach coastal zones, the successive waves overlap, causing wave height to increase. Thus, the tsunami is potentially catastrophic to coastal cities. Another contribution of TS-HKMSDD is to monitor tsunami propagation. Detecting the tsunami and imaging of the wave height distribution prior to its arrival to the seacoast may be possible. It has been predicted that a future large earthquake called the Nankai Trough Earthquake with an assumed magnitude of 9.1⁶² may cause tsunami waves to arrive at the coast of Tokyo Bay with a height of 2.48 m in Koto, 2.46 m in Chuo, 2.44 m in Shinagawa, 2.40 m in Minato, 2.37 m in Ota, 2.07 m in Edogawa and 1.88 m in the reclaimed land of Tokyo bay (such as Odaiba and Palette Town) respectively⁶³. It may be possible to detect this tsunami 30 to 40 minutes prior to arrival at the Tokyo coastal area assuming that the tsunami travels at 30 km/h. The actual height distribution and speed of a tsunami above the Aqua Line tunnel will provide quantitative information of the impending tsunami before it reaches the inner parts of the bay area.

TS-HKMSDD as a sediment accumulation monitor. In the coastal area of Tokyo Bay, many estuaries have been urbanized with heavy traffic in the waterways. There are dozens of ports including three major ports in Tokyo Bay: Tokyo, Yokohama, and Yokosuka ports. In these ports, the navigation channels and harbor basins are getting shallower due to the deposition of discharged sediments from the rivers. These sediments need to be continuously removed from these channels. As a consequence, periodic dredging is required to maintain these navigation channels and harbors in a safe and usable way. Dredging is the excavation of materials from a sea, river, or lakebed and depositing them at a new location for the purpose of reshaping land and water features to alter drainage, navigability, constructing dams, flood and storm protection, and other controls for streams and shorelines⁶⁴. However, dredging activities have potential environmental impacts, either within the dredging area or the deposition site. The dredging process causes sediment resuspension that increases the turbidity of water as well as nutrients and pollutants dispersion, the latter that can cause local water contamination, and possible ecosystem interference (by burying biological habitats, for example). This problem is not restricted to Tokyo Bay, but it is a global issue, applicable to many of the world's ports. Determining the optimized timing and the amount of dredging is essential to minimize the impact on the environment. However,

the sedimentation rate varies depending on many factors including rainfall, seasonality, geology, topography, sea current, etc. and thus, it is difficult to numerically estimate it. Currently, there is no in-situ method to monitor the rate of this deposition.

Sediment monitoring also provides useful insights into the functioning and health of an estuary. Recent studies have shown that sediment loads delivered to estuaries have rapidly increased as a response to the erosion caused by the loss of native vegetation when farms⁶⁵ or urban areas⁶⁶ are introduced to a landscape. Although this estuary-filling rate is particularly accelerated following intense rainfall events, it has been found that in some estuaries this rate has further accelerated during the last few decades in comparison to earlier in the last century⁶⁷. Compared to the vertical accumulation rate, the sediment mass accumulation rate provides more quantitative information about the contamination. There are density variations depending on the depth of the estuarine sediment. These variations are reflected by compaction or changes in the composition of the sediment⁶⁸. Muography will offer a novel method to monitor the sedimentation rate on the seafloor if the mass-driven sea level variation rate (due to the influx from land) is sufficiently smaller than the sedimentation rate.

A fast sedimentation rate is not only occurring in regions near estuaries. A fast tide current also accelerates the sedimentation. For example, in the Kanmon channel, Japan, the seafloor was dredged twice in a last couple of decades (1.5 m in 2001 and 2.0 m in 2006)⁶⁹. The Kanmon channel is used for short-cutting the commercial waterlines between Japan and the Eurasian continent. Consequently, the extensive traffic control is necessary to process boats that pass through this channel every minute. In 1958, a tunnel was constructed under this channel (Kanmon tunnel) to mitigate the land traffic between Honshu Island and Kyushu Island, Japan. In the near future, Kanmon Tunnel HKMSDD will be installed to monitor the sedimentation on the seafloor.

It is also known that fast tidal current of more than 200 cm s^{-1} has been observed in the English Channel. As a result, giant tidal dunes are generated and transported on the seafloor. Most of these sand bodies have been studied with side-scan imagery, high-resolution seismic surveys, and bathymetry^{70,71}. All these studies demonstrate the high mobility of these sand bodies. For example, in the western channel, 8 m high

asymmetric dunes have been monitored for four years and showed an average migration of 20 m yr⁻¹ in the direction of the dominant tidal current to the north. As can be seen in Figure 9B, one of the fastest spring current speed was observed above the Channel Tunnel. HKMSDD installed to the Channel Tunnel can be used for monitoring such a large-scale migration of sand bodies in real time to understand present-day seafloor dynamics.

Imaging tidewater glaciers (TWG) with muography would contribute to our understanding of glaciers cycles in general and their effect on recent climatic global issues. It has been documented that most glaciers are melting and shrinking⁷², although some tidewater glaciers (TWG) have actually been expanding in size recently⁷³. In order to understand this trend, it is important to know the processes and time scales of sediment production, transport, and accumulation near the ablation fronts of retreating tidewater glaciers. In particular, sedimentation transported to the sea via tides affects the tidal water glacier periodicity. For example, Taku glacier, Alaska, has advanced by 5 km since 1933⁷⁴ while Glacier Upsala, Patagonia, is experiencing rapid calving retreat⁷⁵. Brinkerhoff et al.⁷⁴ modeled the periodic cycles of TWG glaciers in the following way. Sediment carried to the terminus is transported to the sea and deposited with a rate of ~1 m yr⁻¹, forming a shoal. The shoal acts as a plug that prompts thickening and promotes the growth of the glacier onto the shoal, but eventually a void at the upstream end of the shoal opens due to its basal motion, and the ice and bed decouple, driving glacier retreat that continues over decades until it is ready to begin the cycle anew. This process repeats every ~300 years. Although it is unlikely that there are tunnels already constructed underneath the seafloor near the downstream end of a glacier, if we position HKMSDD there with optical submarine cable at the downstream end of the retreating glacier (Figure 9C), e.g., Glacier Upsala, real-time monitoring of the aforementioned process will be possible.

Monitoring seawater mass variations. Glacier melting from the Greenland and Antarctic ice sheets could alter regional hydrology⁷⁶, raise global sea level⁷⁷ and increase natural hazards⁷⁸. The global ocean freshening due to large influx of water from land changes the long-term salinity and global and local water cycles. This phenomenon has been investigated at the surface of the oceans at global and local scales^{79,80,81,82}.

Recent developments in satellite technology enable tracking glacier flow in real time^{83,84}. However, due to limited mass loss observations, glacier melting is not fully understood. Sea level gauging also provides indirect information about glacier melting⁸⁵ since the rise of sea level is a combination of glacier melting and ocean thermal expansion. Thus, measurements of the global ocean freshening offers an alternative method for inferring the net ocean mass changes^{86,87,88}. Undersea muography may offer yet another alternative to differentiate local temperature and salinity changes from the sea level rise to derive long-term water influx from land by choosing the location where the sedimentation rate is low. For example, a sedimentation rate of up to 5-10 cm kyr⁻¹ (2-5 cm water equivalent materials are added to the seafloor every 1,000 years) was measured in Sado ridge and Yamato basin at a water depth of 1,000 m, the Akita coast, Japan, which is significantly smaller than the estimated value for global sea level rise that ranges from 1.1 to 3.3 mm yr⁻¹, depending on the measurement method (tide gauge or satellite)^{89,90,91,92}. The result of the stable operation of the HKMSDD system, as shown in Figure 4, indicates that the relative sea level changes can be observed at an accuracy of ~1 cm. HKMSDD does not have intrinsic drift effect and thus can measure the muon rate for many decades without maintenance.

In conclusion, we successfully obtained and reported the first result of undersea muography with TS-HKMSDD. The detector has been operating stably since March 5, 2021, and the lunar-daily-averaged muon rate showed small fluctuations with 2.5 per mille s.d. that corresponded to the error in determination of the relative water level of 5 cm s.d. at the location of the current HKMSDD segment. The 5-minute muon rate showed clear anti-correlation with the tidal levels observed at the nearby tide gauge station with a clear differentiation of the large tide from the small tide (20-30 cm) in the period of neap tide. The results indicated that utilizing an undersea tunnel for muography offers a practical solution for tide measurements in important locations such as near heavy maritime traffic waterlines where the conventional tide monitoring is difficult. Moreover, undersea muography will offer an alternative solution to monitor the sedimentation process on the shallow seafloor where acoustic methods are difficult to implement. It is currently planned that UK-HKMSDD will be deployed in an undersea tunnel in the UK to compare the results under the conditions of a different undersea environment. We anticipate that further knowledge and experience in undersea

muography will be accumulated as other HKMSDDs are installed in tunnels worldwide for the application of this technique to imaging targets such as tides, natural resources and the seafloor topography of coastal regions.

Method

Muographic sensor module. The muographic sensor module (MSM) consists of two scintillation detectors, a high voltage power supply unit (HVU), and a discriminator-coincidence unit (DCU). Each scintillation detector consists of a plastic scintillator (ELJEN EJ-200) with dimensions of 20 mm in thickness, 100 mm in width and 1500 in length that is coupled with a photomultiplier tube (PMT) (HAMAMATSU H7195) via an acrylic light guide. The HVU (Technoland Z-SYS 070HV) is a 2-channel high voltage power supply that can apply a high voltage ranging 0-2000 V to 2 PMTs of the MSM. A 7-segment red LED panel attached to the HVU displays the value of the voltage applied to the PMTs (Figure 3B). The DCU (Technoland Z-SYS 070DC) consists of a 2-channel discriminator and a coincidence circuit. When the DCU triggers the signal, the attached blue LED lights up (Figure 3B). The input signals are negative analogue pulses and the output signals are RS422. The input connector type is LEMO and the output connector type is D-SUB 25 PIN. The MSM's are anchored to the tunnel wall with bolts and frames to fix their position.

HKMSDD segment. An HKMSDD segment consists of 10 MSMs with an interval of 10 m and the data acquisition center (DAC) located at the center of the segment. Each MSM is connected to DAC with the water-resist D-SUB cables (IP67). The cable lengths are different, depending on the distance of MSMs from DAC, and a pair of 10-m, 20-m, 30-m, and 40-m cables are used. Due to the asymmetric positions of DCU within the HKMSDD segment, the lengths of the cables to the first and 10th detectors are different: 50 m and 55 m. DAC consists of (A) four complex programmable logic devices (CPLD) (Intel 10M08), (B) three green LED panels (Rohm LAP-301 ML), (C) a 10-MHz temperature compensating clock (TCC) (Mita-Dempa MX033-0510-10MHz), (D) switched mode power supply (SMPS) (Technoland Z-SYS 070PS), and (E) a microcomputer board (Raspberry Pi 4). (A) is used for counting the number of signals

output from DCU. (B) is used for displaying the number of counts. Each LED panel has 10 8-digit, 7-segment displays. Three LED panels respectively count the number of single and coincidence counts. (C) is used for measuring the time. A heating device is attached to the clock and the temperature-dependent variation is suppressed to less than 10 ppm for the seasonal temperature variation. (D) is used as a power supply for HVU and DCU. (E) is used for sending the data to the external server. An electric cable and an 8-core optical fiber cable were used for connect between DAC and the electric room of the Aqua-Line to supply electric power to the HKMSDD segment and to transfer the collected data including the text and video data to the external server. The network speed was 1 Gbps on a best-effort basis.

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1227 **Ethics declarations**

1228 **Competing interests**

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Figures

Figure 1

Conceptual view of the Tokyo-bay Seafloor Hyper-Kilometric Submarine Deep Detector (TS-HKMSDD) deployed underneath the Tokyo bay seafloor (A) and the photograph (B). HKMT drew this image and holds the copyright. HKMT holds the copyright of the photograph.

Figure 2

Location of the Tokyo Bay Aqua-Line (TBAL) in Japan (red lines) (A) and the cross-sectional view of the tunnel section (Aqua-tunnel) of TBAL (B). The symbols CTGS and HKMSDD-SEG respectively indicate the locations of the Chiba tide gauge station and the HKMSDD segment. The name Umihotaru indicates the service area that marks the transition between the bridge and tunnel part. HKMT drew the map and the image with the Microsoft PowerPoint software and holds the copyright. Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

Figure 3

Configuration of the HKMSDD segment. The schematic of the muographic sensor module (MSM) (A) is shown along with a photograph of the MSM (B). The abbreviations DCU and HVU respectively indicate the discriminator-coincidence unit and the high-voltage power supply unit. The block diagram of the data collection scheme (C) is shown along with a photograph of the Data Acquisition Center (DAC) (D). The network cameras (NW Cameras) are respectively used for monitoring the MSM LEDs and the DAC 7-segment LEDs. The HKMSDD server hosts a closed network. The schematic view of the HKMSDD segment is also shown (E). HKMT holds the copyright of the photographs.

Figure 4

Time-sequential plot of the lunar-daily muon counts.

Figure 5

Time-sequential plot of the number of muon counts collected every 5 minutes (A) and the tide gauging results measured at the Chiba Tide Gauging Station (B)⁴³. The red box indicates the period we used for the detailed analysis in Figures 6 and 8.

Figure 6

Tide levels converted from the muon counts. The data points (dark blue filled circles) are shown along with the statistic error bars (1 standard deviation) (sky blue lines). The tide gauging results measured at CTGS (red filled circles) and the theoretical calculation results of the astronomical tide levels (green line) are also shown (43).

Figure 7

Muon flux expected at the Hyper-Kilometric Submarine Deep Detector (HKMSDD) segment placed within the region 500-600 m from Umihotaru (SEG1) for various matter thicknesses.

Figure 8

Hourly barometric variations measured in Tokyo, Japan (A). The values were converted to those at sea level. Tide levels converted from the muon counts with the barometric corrections. The data points (dark blue filled circles) are shown along with the statistic error bars (1 standard deviation) (sky blue line). The tide gauging results measured at CTGS (red filled circles) and the theoretical calculation results of the astronomical tide levels (green line) are also shown⁴³.

Figure 9

Possible future HKMSDD deployment sites: (A) Transbay Tube, San Francisco, CA, (B) Channel Tunnel, UK/France, and (C) Glacier Upsala, Patagonia, Chile. Red lines in (A) and (B) indicate the undersea tunnels. Black arrows in (A) indicate the direction of the Pacific swells. Blue lines in (B) indicate the spring maximum current vectors. The numbers indicate the speed in units of cm/s. Red oval shape symbols in (C) indicate the hypothetical HKMSDD buried under the seafloor. HKMT drew the maps in (A) and (B) with the Microsoft PowerPoint software and holds the copyright. HKMT drew the image in (C) based on the work by Brinkerhoff et al. Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.