様　式　Ｃ－１９、Ｆ－１９－１、Ｚ－１９　（共通）

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研究課題名（和文）Investigation of site amplification at Ocean Bottom stations in the Japan Trench area for earthquake early warning

研究課題名（英文）Investigation of site amplification at Ocean Bottom stations in the Japan Trench area for earthquake early warning

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研究成果の概要（和文）：日本海溝周辺で発生したマグニチュード4～7.5程度の地震について、S-netの全150観測点で記録された約2,000地震の地震動データを調べた。主な目的の1つは、硬い基盤層の上にある堆積層によるS-net観測点でのサイト増幅を同定することであった。この目的は、高品質のデータを慎重に選択し、周波数領域でS波の震源、伝播、サイト因子を分離することで達成された。得られたサイト増幅係数は明らかに周波数に依存し、また値は海溝付近の陸側と海側で異なるなど、適度に地域的に分布していた。推定されたマグニチュードは、カタログ値と非常に近かった。これらの結果は、査読付き学術論文として発表され、学術界で認められた。

研究成果の学術的意義や社会的意義
The amplification factors estimated in this study will help to construct the underground model of the seafloor area, while these results can be incorporated to develop algorithms to estimate ground motion intensity at target sites on land for earthquake early warning.

研究成果の概要（英文）：We examined the ground-motion data from about 2,000 earthquakes recorded by all the 150 stations of S-net for magnitudes between about 4 and 7.5 that occurred in and around the Japan Trench area after the start of the network. One of the primary objectives was to obtain the site amplifications at the S-net observation sites due to the sedimentary layers lying over the hard base layer. The objective was achieved by careful selection of high-quality data and performing separation of source, path, and site factors of S waves in frequency domain. The obtained site amplification factors were clearly frequency dependent and also the values were moderately regionally distributed such as the values near the Trench in the landward and the ocean sides were different. The estimated magnitudes based on the source factors were very similar to the catalog values. These results were published in peer-reviewed journal and were recognized in academic community.

研究分野：構造工学および地震工学関連

キーワード：S-net　Site amplification　Japan Trench　Earthquake early warning　S waves　Quality factors　Ocean bottom seismograph

## １．研究開始当初の背景

After experiencing the 2011 great Tohoku-oki earthquake, the inadequacy of the monitoring network in the oceanic area became evident for early warning of tsunamis during great earthquakes. Moreover, the existing earthquake early warning system underestimated the earthquake magnitude. Hence, the forecasted seismic intensity was smaller than the recorded intensities in the Tokyo metropolitan area during the 2011 great Tohoku-oki earthquake. To overcome the abovementioned problems, a large-scale **S**eafloor observation **n**etwork for **e**arthquakes and **t**sunamis along the Japan Trench (S-net) consisting of 150 stations equipped with multiple sensors and connected by approximately 5,500 km of optical fiber cables was established. To use the ground motion data recorded by the S-net effectively for earthquake early warning application, it is essential to understand the local amplification effects of the sediments on the recorded motions at the recording stations. This will help estimate the input motions from the earthquake source at the base of the sediments and facilitate the study of the earthquake source processes. Thus, we have researched the site amplification study at the S-net sites.

## ２．研究の目的

During earthquakes, S waves, also known as secondary waves, arrive after the P waves (primary waves) and are more destructive than the P waves. Sediments can amplify the incoming seismic waves from the source, and the amplification characteristics depend on the material properties of the soil layers and their thicknesses. The primary objective of the present research was to estimate the amplification characteristics of S waves due to the unconsolidated sediments lying over the base rocks at the S-net seafloor sites based on the earthquake data recorded at the sites.

## ３．研究の方法

We collected the available number of earthquake records at each site of S-net from earthquakes with magnitudes between 4 and 7 and picked the S-wave parts of earthquake records for analysis. We examined the signal-to-noise ratios for the selected parts of the records. After carefully reviewing the earthquake records and listing the good-quality records, Fourier spectra were computed. The Fourier spectra were then decomposed into the source, path, and site terms using the spectral inversion technique, commonly used in the study of site amplification and earthquake source properties using the earthquake records. In this technique, a trade-off exists between the source and site terms. The trade-off was minimized by selecting two reference sites on land, where we estimated the S wave amplification factors theoretically based on the observed records. It has also been known that the amplification factors depend on the level of input motions at the base of the sediments. Therefore, spectral ratios between the horizontal and vertical components were computed for the weak and strong motions, and the nonlinear site amplification properties were evaluated for the case of strong input motions. It was also important to assess the ground motions at the S-net sites in relation to the ground motion records at the land sites. Thus, comparisons of the ground motions between the land and S-net sites were also carried out to understand the site amplification effects at the S-net sites.

## ４．研究成果

When the Kakenhi research project was started by us in 2020, the largest earthquake that struck beneath the S-net stations was the 2016 off Fukushima Prefecture earthquake of magnitude 7. One hundred and twenty-five stations of five segments of S-net except for the outer rise segment, which was not in operation during the earthquake, successfully recorded the seismic motions during the earthquake. We examined the ground motion records for the earthquake at the S-net stations. We found that induced rotations of the sensors contaminated the records at the stations near the epicenter because of poor coupling between the S-net sensor houses and sediments. The sensors consisted of three component records, and the component parallel to the long axis of the sensor house (cylindrical pressure vessel) was found to have a smaller degree of rotation. Ground motions from this earthquake were compared with those at the land stations. We found that the peak ground accelerations (PGAs) and peak ground velocities (PGVs) at the land stations adjusted for site amplification effects generally followed the attenuation curves based on past data. However, the observed PGV values at the S-net stations were larger by a factor of about three at distances < 200 km

and by a factor of about four at distances > 200 km on average. By trial and error, we estimated the shallow S wave velocity of about 100-125 m/s in the upper 30 m of the seafloors to explain the difference. We examined the ground motion data from damaging moderate-magnitude earthquakes (magnitude lower than 6) and found that most of these events occurred beneath the land. However, it was found that a few offshore earthquakes with magnitudes > about 5.5 also caused damage in the land areas. The study suggested that the S-net data could provide valuable information regarding offshore earthquakes' size and probable impact.

We compared the high-quality ground motion data recorded by the K-NET and KiK-net stations on land located in and around the Kanto basin and MeSO-net in the Kanto basin with those at the S-net stations for three earthquakes of magnitudes close to 6 that occurred near the Kanto basin. We found that the PGAs and PGVs for the P-wave parts on the vertical-component records of S-net were, on average, much smaller than those of K-NET/KiK-net records. The low-frequency PGAs at the S-net sites were similar to or larger than those of the MeSO-net borehole records in the deep areas of the Kanto basin. The significant durations between the S-net and MeSO-net for low-frequency motions were generally comparable. The results suggested that the sedimentary layers primarily influenced the S-net records in the offshore regions. We also compared the ground motions from several earthquakes recorded in broader areas of northeast Japan and the S-net stations. We found that the average short-period ground motions were comparable between the land and S-net stations. In contrast, the long-period ground motions were generally larger, on average, at the S-net stations than those on land stations. The difference was primarily attributed to thick sedimentary layers in the seafloor areas. The PGAs at the buried stations were, on average, smaller than those at the unburied stations, while the long-period ground motions were, on average, larger, at the unburied stations than those at the buried ones. To understand the cause of the differences described above, we performed spectral inversion of the S-wave Fourier spectra at the S-net sites using more than 6000 high-quality records from over 600 earthquakes with magnitudes between 4 and 7. We obtained the following results.

The peak site frequencies based on the abovementioned spectral inversion analysis were between 0.2 and 10 Hz, and the peak amplification factors ranged between 10 and 50 at the S-net sites. The peak frequencies and amplification factors generally differed from site to site. However, a moderate regional trend was observed. The peak frequencies were mostly higher than 2 Hz at the sites in the open seafloor, while they were lower than 2 Hz at many sites on the landward sides of the Trench axes. The amplification factors at higher frequencies, around 10 Hz, were generally much smaller at the sites close to the Trench axes than those near the coast. The amplification factors from the inversion were larger in the regions where the sedimentary layers were thicker in the Japan Seismic Hazard Information Station (J-SHIS) model. However, the amplification factors were considerably underestimated by the J-SHIS model at many sites in the deeper water regions over wide frequencies. It was also found that many unburied stations included dominant peaks at frequencies between 4 and 10 Hz as artifacts due to the natural vibrations of the sensor houses. We recommend avoiding the Y-component records if the site spectra between 4 and 10 Hz are required at the unburied stations for any application.

Finally, we performed the horizontal-to-vertical spectral ratio analysis of S-wave records at the S-net stations to see the nonlinear amplification effects during three magnitude 7 class earthquakes. We found that the selected S-net sites might have experienced substantial degrees of nonlinear site response (NLSR) during the three earthquakes with peak accelerations greater than about 60 $cm/s^2$. To investigate whether the features of NLSR obtained were realistic at the S-net sites, we also examined the NLSR at nine KiK-net sites, which recorded the data from all three earthquakes. We found that the characteristics of NLSR obtained at the KiK-net and S-net sites were generally comparable. The NLSR affected the ground motions at frequencies higher than 1 Hz at both Kik-net and S-net sites. However, the degree of nonlinearity tended to be larger at the S-net sites. The results discussed above were presented at several national and international conferences and have been published in detail in five different Journal papers. It is expected that the abovementioned results contribute to the development of ground motion prediction methodology for offshore earthquakes in particular and serve as a basis for more detailed future studies regarding the source properties of the subduction zone earthquakes, the quality factor of the crust and mantle, and improvement of the subsurface velocity models in the region, in general.

５．主な発表論文等

〔雑誌論文〕　計5件（うち査読付論文　5件／うち国際共著　0件／うちオープンアクセス　4件）

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| １．著者名<br>Dhakal Yadab P.、Kunugi Takashi | ４．巻<br>11:1180289 |
| ２．論文標題<br>Preliminary analysis of nonlinear site response at the S-net seafloor sites during three Mw 7 class earthquakes | ５．発行年<br>2023年 |
| ３．雑誌名<br>Frontiers in Earth Science | ６．最初と最後の頁<br>1-10 |
| 掲載論文のDOI（デジタルオブジェクト識別子）<br>10.3389/feart.2023.1180289 | 査読の有無<br>有 |
| オープンアクセス<br>オープンアクセスとしている（また、その予定である） | 国際共著<br>－ |

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| オープンアクセス<br>オープンアクセスではない、又はオープンアクセスが困難 | 国際共著<br>－ |

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〔図書〕　計0件

〔産業財産権〕

〔その他〕
日本海溝のS-net観測点で観測されたS波からスペクトルインバージョン法により推定した震源
、伝播経路及びサイト増幅特性
https://www.mowlas.bosai.go.jp/research/20230103/

６．研究組織

| | 氏名<br>（ローマ字氏名）<br>（研究者番号） | 所属研究機関・部局・職<br>（機関番号） | 備考 |
|---|---|---|---|
| 研究分担者 | 山中　浩明<br>(YAMANAKA Hiroaki)<br>(00212291) | 東京工業大学・環境・社会理工学院・教授<br>(12608) | |

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|---|---|---|---|
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７．科研費を使用して開催した国際研究集会

〔国際研究集会〕　計0件

８．本研究に関連して実施した国際共同研究の実施状況

| 共同研究相手国 | 相手方研究機関 |
|---|---|