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学位の種類	博士（理学）
学位記番号	理博第2559号
学位授与年月日	平成22年3月25日
学位授与の要件	学位規則第4条第1項該当
研究科，専攻	東北大学大学院理学研究科（博士課程）地球物理学専攻
学位論文題目	Near-Field Tsunami Forecasting from Ocean Bottom Pressure and Onshore GPS Data （海底圧力・陸上GPS観測による近地津波予測）
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論文目次

Abstract

Submarine earthquakes or landslides can generate tsunamis that cause loss of life as well as severe damage to houses and infrastructures in coastal communities. The 2004 Sumatra earthquake (M_w 9.2) generated a catastrophic tsunami that killed more than 283,000 people. One of the reasons for the immense scale of this disaster was lack of information about the impending tsunami, and inadequate procedures for warning communities around the Indian Ocean. This tragedy has driven the international community to reaffirm the importance of mitigating the effects of tsunamis. Forecasting tsunami events and providing timely evacuation warnings to communities that may be affected is one of the most effective ways to reduce the loss of human lives and the damage to communities. Accurate and rapid dissemination of information about impending tsunamis is essential for successful reduction of damage to property and loss of life. Until now, various methods of tsunami forecasting have been proposed for both of near-field and far-field events. For near-field tsunamis, there are currently no warning systems that use tsunami data. Near-field tsunamis in areas close to subduction zones can reach the coast in a few tens of minutes or less, and can cause catastrophic damage. Therefore, the time window for issuing warnings of arrival times and amplitudes of near-field tsunamis is much shorter than that for far-field tsunamis. Despite this difficulty, development of a system to provide reliable forecasts of tsunamis caused by local earthquakes is important for effective mitigation of damage and loss of life in coastal communities.

In this study, I have developed methods for near-field tsunami forecasting from cabled ocean bottom pressure gauge (OBPG) data and onshore GPS data based on the method developed by *Tsushima et al.* [2009], named tsunami Forecasting based on Inversion for initial sea-Surface Height (tFISH). tFISH is a versatile

algorithm allowing rapid estimation of coastal tsunami waveform. The tsunami waveform calculation is based on the initial sea-surface height distribution inverted from OBPG data. By expressing a tsunami source as initial sea-surface displacement distribution, no specific assumptions are required for the source parameters, such as fault geometry, in performing the inversion. tFISH is equipped with very fast tsunami waveform calculation made by superposition of Green's functions calculated in advance and stored in a database. By virtue of the fast calculation, tFISH is applicable to real-time forecasting. Another merit of tFISH is that the inversion and waveform synthesis are performed repeatedly by progressively updating the OBPG data to improve accuracy of tsunami forecasting. In spite of these merits, tFISH has three major deficiencies required to be remedied.

One of the shortcomings of tFISH is that it cannot be directly applied to the OBPG records acquired within tsunami source region. In tFISH, the effect of the permanent seafloor deformation on the bottom pressure measurements is not taken into account. Therefore, the actual pressure variation due to the permanent seafloor deformation would cause artifacts in the inverted sea-surface displacement, which degrades the accuracy of the coastal tsunami forecasts. This shortage can be overcome by applying an appropriate correction for the seafloor deformation to the Green's functions used in tFISH.

The second issue is that tFISH may underestimate coastal tsunami height depending on the spatial relationship between the tsunami source and the OBPG stations. This shortage mainly comes from the anisotropic tsunami radiation from an elongated source, which is difficult to be modeled by sparse azimuthal coverage of OBPGs. To improve this shortage, use of an elongated source model in the inversion will be effective.

The third deficiency is that the prediction accuracy of coastal tsunami by tFISH may not be high enough immediately after the earthquake occurrence. This shortage is caused by that the sufficient data to estimate parameters of a tsunami source are not acquired at OBPGs. If a great tsunami occurs near the coasts, the tsunami forecasting based only on tsunami data may not provide accurate predictions before actual tsunamis reach the coastal communities. This shortage can be overcome by estimating a preliminary source model (reference solution) from independent geophysical observations other than OBPG data.

To overcome the first shortage, I successfully formulated Green's function for the bottom pressure taking the effect of vertical seafloor displacement into account based on general expression of the pressure variation at the seafloor displaced by arbitrary spatiotemporal pattern. The observed pressure variation can be expressed as the summation of two terms: the first term is the pressure variation due to the propagating tsunami from a given initial sea-surface displacement in the source area, and the second term corresponds to the pressure variation resulted from the permanent seafloor deformation at the observing site on the seafloor. Under an assumption that the vertical seafloor deformation in a tsunami source region is identical to the sea-surface displacement is satisfied, the general expression can be reduced to an observation equation relating the bottom pressure to the initial sea-surface height at the source with a modified Green's function consisting of two terms: the first term is identical to the Green's function used in tFISH, and a correction term presenting pressure response to the permanent seafloor deformation. Once the original Green's functions of tFISH are replaced with the modified Green's functions, one can carry out the tsunami waveform inversion including the effect of the permanent seafloor deformation on the bottom pressure. I experimentally applied the inversion using the revised Green's function to the OBPG data of the 2003 Tokachi-oki earthquake whose coseismic seafloor deformation was observed at two OBPG stations near the Kuril Trench. As a result, I succeeded in estimating the tsunami source model which is consistent with the other source models estimated by various geophysical observations. Furthermore, tFISH incorporating the modified Green's function successfully gave synthetic coastal tsunami waveforms matching very well to the observed tsunami waveforms.

The shape of the megathrust earthquake tends to elongate along the strike direction, and therefore the effect of tsunami energy radiation pattern becomes significant and the second shortage of tFISH appears most significantly in tsunami forecasting after megathrust earthquakes. I proposed using a fault-slip inversion, instead of the sea-surface height inversion, for tsunami source estimation as a countermeasure for the shortage. By assuming a fault motion as the tsunami source, the anisotropic radiation pattern of tsunami can be taken into account. The fault-slip inversion and tsunami waveform synthesis using a fault slip model require Green's function of tsunami for a unit slip. I showed that the function can be obtained as a superposition of the pre-computed Green's function corresponding to sea-surface movement. Since the sea-surface displacement field can be derived analytically from fault motion through seafloor displacement field, the Green's function regarding the fault slip can be obtained immediately and the fault-slip inversion can be applied to real-time forecasting scheme. I found that the accuracy of the inverted slip distribution strongly dependent on the location where subfault are assumed. Since the sea-surface inversion of tFISH provides accurate estimation of the spatial extent of the initial sea-surface displacement, its solution can be used to define the location of a target fault for which slip amount is estimated by the fault slip inversion. Once the source location and slip amount can be obtained, coastal tsunami waveforms can be calculated as a superposition of the Green's functions within a short time. I performed a series of numerical experiments and confirmed that the application of the fault-slip inversion to the tsunami forecasting for a megathrust earthquake can improve accuracy of predictions of coastal tsunami height significantly as compared to the prediction derived from original tFISH.

To overcome the third shortage, I tried to use onshore GPS data in tsunami forecasting. Surface displacement due to coseismic slip at a seismic fault can be measured at GPS stations immediately after the earthquake. Furthermore, the extent of an earthquake fault can be estimated from the spatial pattern of coseismic surface displacement at GPS stations. I performed the inversion of the onshore GPS data of the 2003 Tokachi-oki earthquake to estimate the slip distribution, and then I calculated coastal tsunami waveforms. Comparison between the observed tsunami waveforms and the calculated tsunami waveforms shows good agreement, demonstrating that onshore GPS data can provide rapid and fairly reliable tsunami forecasting. It is difficult for onshore GPS data to estimate accurate slip amount for far offshore area where the seafloor deformation can be measured by the OBPG. Therefore, joint use of GPS and OBPG data can improve the reliability of tsunami forecasting. As an example of the joint analysis, I developed an inversion method in which the OBPG data are inverted to improve tsunami source parameters by using the GPS inversion result as a reference model. I applied this new method (differential inversion) to the onshore GPS and the OBPG data of the 2003 Tokachi-oki earthquake to show that the method can provide more reliable forecasting than tFISH immediately after the earthquake. The accuracy of the forecasting progressively increases as the amount of OBPG data increases.

The tsunami forecasting methods presented in this study cannot be applied to laterally small-scale tsunamis. However, this shortage can be overcome by replacing the original Green's functions which are computed based on the linear long-wave theory with the new Green's functions which are calculated based on the linear dispersive-wave theory. Only this simple revision makes the forecasting method applicable to laterally small-scale tsunamis. On the other hand, the methods cannot be applied to tsunamis generated by M9-class gigantic earthquakes because current inversion cannot estimate spatiotemporal development of the source although the rupture propagation cannot be ignored for a gigantic earthquake with huge rupture areas. The following procedure may be practical for tsunami forecasting after the occurrence for M9-class tsunamigenic earthquakes: multiple inversions assuming different values of rupture velocities are performed simultaneously using the real-time data of OBPG. The source model which explains the observed OBPG waveforms best is selected and used to calculate the coastal tsunamis caused by the giant earthquake.

In this study, I have tried to improve the inversion scheme of tFISH by modifying the Green's functions, or including onshore GPS data to enhance versatility of tFISH, but the other process of tFISH is the same as the original version. This indicates that the framework of tFISH can be applied in various ways to be fit to given situations. I conclude that the concept of tFISH is very versatile and can give us good foundation for much more reliable and more robust near-field tsunami forecasting methods in the future.

論文審査の結果の要旨

インド洋沿岸諸国に甚大な津波被害をもたらした2004年スマトラ地震の経験は，迅速かつ正確な津波予測システムの存在の重要性を全世界に示した．本研究では，リアルタイム津波観測のデータから，沿岸での津波到達時刻・波高の予測を迅速かつ高精度で行うための手法の開発を行った．対象とする津波は日本近海に波源をもつ近地津波であり，津波観測波形から津波波源の位置と規模を逆解析により推定し，推定された波源モデルから沿岸での津波波形を合成することにより，津波のリアルタイム予測を実現する．

近地津波予測を実現する上では，近地津波固有の諸問題を解決する必要がある．その一つは，津波を検知する海底圧力計が波源域内にあり，津波波高と海底鉛直変動が同時に観測されるという問題である．本研究では，海底地殻変動が励起する津波波形の表式をもとに，波源域内での観測データを波源推定逆解析に正しく取り込むことのできるアルゴリズムの導出に成功した．第二は，津波予測の信頼度が波源と観測点の位置関係に強く依存するという問題である．本研究では，その要因が津波放射の方位依存性にあることを示し，偏長断層を津波源として逆解析を行うことにより，予測精度を改善できることを示した．第三の問題は，十分な時間長さの津波波形の時系列が得られないと，高精度の津波波源逆解析が難しいため，十分な精度の予測結果を得るためには時間を要するということである．本研究では，地震発生直後に，GPS観測による地殻変動場の逆解析から初期予測を行い，その後得られる津波データを用いた逐次改良解析により予測精度を向上する手法を提案し，地震発生直後の速報的予測と，津波観測による高精度予測を両立させた．そして，提案した津波予測手法を，2003年十勝沖地震（M8.0）の津波・地殻変動観測データに適用し，津波が沿岸に到達するより5～10分前に津波の到達時刻と波高を高精度で得ることができることを示した．

以上のように，対馬弘晃提出の論文は，近地地震による津波の予測精度を一層向上させるための基礎研究を飛躍的に発展させるものである．これは，同人が自立して研究活動を行うに必要な高度の研究能力と学識を有することを示している．よって，対馬弘晃提出の博士論文は，博士（理学）の学位論文として合格と認める．