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地　震　　第２輯
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1948年福井地震 ($M=7.1$) に伴う地殻変動と震源断層モデル

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Crustal Movements Associated with the 1948 Fukui Earthquake ($M=7.1$) and Its Fault Model

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Conventional triangulation and leveling data are analyzed to estimate crustal movements associated with the 1948 Fukui earthquake and its fault model. Horizontal displacement vectors at 84 triangulation points and vertical displacements of 82 leveling benchmarks are inverted to estimate slip distribution on the fault plane. Although two surface traces of faults were found after the earthquake, most of the seismic moment was released from a main fault on the west, and an eastern sub-fault played only a complementary role. The dip angle of the main fault is not well constrained. However, geodetic data are fairly consistent with an assumption of a vertical fault. Estimated fault mechanism is mostly left-lateral strike slip with the maximum slip of 6m. The seismic moment of the Fukui earthquake is estimated as 2.4×10^{19} Nm ($M_w=6.8$), which is consistent with another estimation based on seismic data. The Fukui earthquake was comparable to the 1995 Kobe earthquake in its size, but the heterogeneity of slip distribution is different each other. The Fukui earthquake fault had a much longer preparatory period before the 1948 event, and fault strength might be completely recovered before the earthquake, which resulted in a rather homogeneous slip distribution. In the case of the 1995 Kobe earthquake, a short recurrence time along the Rokko-Awaji fault after the 1596 Keicho-Fushimi earthquake might result in a rather heterogeneous slip distribution.

Key words: Fukui earthquake, Crustal movements, Triangulation, Leveling, Geodetic inversion, Fault model.

§1. はじめに

福井地震（1948年6月28日，$M=7.1$）は死者3769名，全壊家屋36184戸という甚大な被害をもたらした．この数字は今世紀に日本で発生した地震のうち，1923年関東大地震 ($M=7.9$) と1995年兵庫県南部地震 ($M=7.2$) に次ぐものである．福井地震については，都市直下の活断層で発生した点，また地震の規模そのものにおいて兵庫県南部地震との類似性が指摘されている．

このような内陸直下型地震は非常に大きな被害をもたらす場合が多く，その発生過程を研究し将来の防災に役立てることは地震学の重要な課題である．地震現象の多様性を考えると，できるだけ多くの事例を研究することが必要だが，観測網の整った地域で内陸直下型地震の全貌を明らかにできるような機会は非常に限られている．福井地震は，少々古い観測例ではあるが，そうした観測データを提供する貴重な例である．

福井地震に伴う地殻変動に関しては，SATO (1973) が地震後に実施された震災復旧測量の結果をまとめたが，報告されたデータは実際に行われた測量の一部分のみであった．また，佐藤 (1989) には SATO (1973) のデータを用いた断層モデルの解析結果が二例載っているが［吉岡 (1974)，長谷川 (1986)］，これらのモデルは一枚ないし数枚の一様な矩形断層から成るものであり，豊富な測地測量データを十分に生かした結果とは言えず，また，と

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1948 年福井地震の震源パラメーター

—1 倍強震計記録の解析—

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Source Parameters of the 1948 Fukui Earthquake Inferred from Low-gain Strong-motion Records

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Seismograms in 1940's are usually recorded on smoked paper. Owing to the recent development of photocopy and image processing techniques, we can reconstruct feasible waveform data by tracing, digitizing, and correcting the arc effect due to inclined lever. Using low gain strong motion data at several observatories of Japan Meteorological Agency and Kyoto University, we investigate the source process of the 1948 Fukui earthquake. In the waveform inversion we consider the uncertainty of instrumental constants (pendulum period, magnification and damping constant), timing, and chart speed. The rupture process is then modeled by moment-rate functions at grid points on a fault plane with a spacing of 10 km. It is shown that a rupture initiated at a depth of about 10 km, moved upward, and then propagated mainly to the south. The rupture front velocity was about 2.5 km/s. The largest moment release occurred around 10 km south of the epicenter. The main source parameters are: strike=170±5°, dip=70±5°, rake=−10±10°, seismic moment=2.1×10^{19} Nm, M_w=6.8, fault area=30×10 km^2, average dislocation=2.3 m, stress drop=10 MPa.

Key words: Source parameter, Historical seismogram, Fukui earthquake, Strong motion record.

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地 震 第 2 輯
第 52 巻 (1999) 129–150 頁

1948 年福井地震の強震動

――ハイブリッド法による広周期帯域強震動の再現――

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Strong Ground Motions during the 1948 Fukui Earthquake

—Estimation of Broad-band Ground Motion Using a Hybrid Simulation Technique—

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We simulate strong ground motions during the 1948 Fukui earthquake with the JMA magnitude 7.1 based on a heterogeneous source model and the hybrid simulation technique. So far there are no existing source models available for simulating strong ground motions from the 1948 Fukui earthquake. Most of the source models have been assumed to have uniform slip distribution on rectangular fault plane. Such models could generate ground motions only available longer than several seconds, underestimating shorter period motions (< 1 sec) of engineering interest. The objective of this paper is to construct a heterogeneous source model for simulating strong ground motions in a broad period band during the 1948 Fukui earthquake. We assume two source models to examine: Model 1 is a reverse fault model determined from the analysis of geodetic data by YOSHIOKA (1974) and Model 2 is a normal fault model from strong motion displacement data by KIKUCHI *et al.* (1999). Heterogeneous slip distribution on fault plane is estimated based on the self-similar scaling relationships of seismic moment versus asperity areas and slips by Somerville *et al.* (1999). Then we obtained the standardized source model consisting of two asperities to have the average characteristics of asperities for the seismic moment of the Fukui earthquake. Relative locations and rupture times of the asperities on the fault plane are determined following the source model by KIKUCHI *et al.* (1999). The maximum asperity corresponding to the second event in their model has an area of $12 \times 12\ \mathrm{km}^2$ and slip of 1.7 m and is located under the most heavily damaged area along the buried fault, known as the Fukui earthquake fault. The smaller asperity corresponding to the first event is located north of the maximum asperity. Rupture was initiated at the northern edge of the smaller asperity, propagated toward south, then broke to start the maximum asperity 7 seconds after the initial rupture. Large ground motions from both models, Model 1 and 2, are spread over the Fukui basin, although peak velocity distributions are rather different between the two models. Areas over 30% collapse ratio during the Fukui earthquake correspond to those with peak velocity over 60 cm/s for Model 1 and over 80 cm/s for Model 2. The level of the peak velocity in the areas with more than 30% collapse ratio are estimated to be over 80 cm/s connected with both results by MOROI *et al.* (1998) and MIYAKOSHI and HAYASHI (1998). Pseudo velocity response spectra in the center of the Fukui basin for

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Model 2 have almost the same level of the observed ones at Takatori (TKT) and the simulated ones at Fukuike (FKI) within the damage belt during the 1995 Hyogo-ken Nanbu earthquake. We conclude that the damage distribution during the Fukui earthquake is well explained by strong ground motions simulated for Model 2 combined with the normal fault model by KIKUCHI *et al.* (1999) and a standardized heterogeneous source model developed by SOMERVILLE *et al.* (1999).

Key words: the 1948 Fukui earthquake, strong ground motion, heterogeneous source model, asperity, collapse ratio.

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1948 年福井地震の強震動
—建築物・墓石等の倒壊方向と震源過程—

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Strong Ground Motion Generated from the 1948 Fukui Earthquake —Directions of Simple Bodies' Overturn and Buildings' Collapse, and the Source Process—

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The 1948 Fukui earthquake provided the detailed data for damage of buildings and collapse or overturn of simple bodies, such as chimneys, grave stones, etc. The overturning directions of simple bodies and the falling directions of wooden houses seem to have characteristic features of distribution with scatters. From the northern to the central part of the fault trace (strike=170°), the fault normal directions are predominant. On the other hand, from the central to the south but apart from the fault trace, the fault parallel directions are predominant. These distributions are simulated by 3D dynamic rupture model, and the details of the fault rupture processes are suggested.

Key words: 1948 Fukui earthquake, Strong ground motion, Source process, Earthquake damage, Strong ground motion simulation.

§1. はじめに

断層近傍の地震動の特徴として 1966 年 Parkfield 地震で断層直交成分が卓越することが AKI (1968) によって示されて以降，1994 年 Northrigde 地震や 1995 年兵庫県南部地震を契機として，破壊伝播効果によるパルス波の成因と，その構造物の影響は多くの研究者により議論されている［HEATON *et al.* (1995)，入倉 (1995)，纐纈 (1996)，WALD (1996)，久田 (1998)］．筆者らは動的破壊過程を現実の地震へ適用する動力学モデルによる震源過程の再現の研究［MIKUMO and MIYATAKE (1995)，MIKUMO *et al.* (1998)，MIYATAKE (1992a, b)］を行ってきた．その応用として震源近傍強震動シミュレーションを行い、震源の性質により，断層近傍の地震波がどのように変化するのか［INOUE and MIYATAKE (1997, 1998)］，また実際の地震でどのような地動が生じていたのかを議論し，上記パルスの成因なども考察してきた［島田・他 (1996)，宮武 (1998)］．本稿では 1948 年福井地震にこれを応用する．

この地震では，詳細な被害調査がなされ，被害率の空間分布，墓石・石碑・煙突などの転倒方向，建築物の倒壊方向の空間分布についても調査報告されている［北陸震災調査特別委員会 (1951)］．断層近傍での被害の特徴は震源過程の影響を強く受けているはずであるが，そのような視点で上記データの解析はなされていない．本稿ではこのようなデータに震源力学の立場から解釈を加える．またこのような被害の特徴から震源過程の推定の可能性も議論する．

§2. 福井地震の物体・建築物の倒壊方向

Fig. 1 は，北陸震災調査特別委員会 (1951) による物体・建築物の転倒方向（ベクトルの向きは区別していない）の分布図を元に，武村・他 (1998) が描きなおした物である．図中，黒丸付きの短い線分で示した Simple Body の倒壊方向とは，墓石・石碑・煙突などの倒壊方

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福井地震断層付近の地下構造調査

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Survey of Underground Structure across the Fukui Earthquake Fault

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Some geophysical explorations were conducted to investigate the underground structure around the Fukui Earthquake Fault, FEF, reported by TSUYA (1950). A seismic reflection survey was carried out at a dry river bed along the Kuzuryu River across the FEF. The gravity survey was also performed around the seismic reflection survey line. The seismic reflection profile shows that the Quaternary sedimentary cover is 200 to 300 m in thickness and tilts gently westward. The profile also shows an existence of somewhat peculiar block with width of several hundred meters at the FEF. This block corresponds to the lower gravity anomaly zone obtained from the local gravity analysis. We concluded that the FEF with many ground failures induced by the earthquake has not been effectively displaced in vertical movement and the successive fault movement related in the FEF has thickened fault gouge layer along the FEF.

Key words: Fukui Earthquake Fault, seismic reflection survey, gravity anomaly, fault gouge.

§1. まえがき

典型的な都市直下型地震の１つと考えられる福井地震 (1948. 6, 気象庁マグニチュード $M=7.1$) は，福井平野のほぼ全域にわたって大きな被害を発生させ，死者約3,800人，全壊家屋数は36,000を超えるという大惨事となった．この地震では家屋倒壊率が多くの地域で90% を超えたことから，通常では考えられないような大きな地震動が発生したとみられ，これを機に気象庁震度階に１ランク上のVIIの導入が検討されることとなった．通常みられるような地震断層は観察されなかったが，多くの地点で連続する地割れが生じ，地震後の測量による変位と地割れの分布から福井地震断層が推定されている．

地震直後から現在に至るまで，TSUYA (1950) をはじめ様々な調査が行われてきた．天池・竹内 (1989) や岡本・他 (1989) らによる弾性波探査やボーリング調査等の結果から，第三系基盤深度が50〜200 m ほど鉛直変位していることが認められ，累積性をもつ断層運動を伴っていたことが指摘された．

平成９年度の科学技術庁地震関係基礎調査交付金により，福井地震断層を含む周辺域に分布する福井平野東縁断層帯の実態を把握するために，反射法地震探査やボーリング調査等の各種地質調査が行われた［福井県 (1998), 衣笠・他 (1999)］．その結果，想定されている福井地震断層付近に撓曲構造が認められたが，上記のような200 m に達する第三系からなる基盤の変位は認められていない．しかし，この断層の東に位置する福井東側地震断層では基盤が東側に向かって急に浅くなっていることが確認されている．このように福井平野東縁断層帯に関する地下構造の概要はしだいに明らかになりつつある．直下型地震の発生に関連した断層の位置や変位を明らかにすることや，断層系全体の構造を調べて活動特性を解明しておくことは，地域防災や都市計画を策定するうえで大変重要となる．

福井地震では地震の際に認められた一連の地割れを，地表に現れた地震断層として認定できるかどうかは，現在のところ必ずしも明らかになっておらず，これらの解明が重要課題として残されている．

ここでは，九頭竜川河川敷における反射法地震探査と，その付近で行った重力探査の結果について概要を述

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福井平野下の活断層について（序報）

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A Preliminary Report of Active Fault Survey in the Fukui Basin, Central Japan

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Subsurface geological structure of the Fukui basin where the 1948 Fukui Earthquake (M 7.1) occurred has been studied by P and S wave seismic reflection survey together with a trench excavation survey at the eastern edge of the basin. In the central part of the basin, no distinctive fault has been detected by the P wave seismic reflection survey. Also, at the eastern edge of the basin, no evidence of faulting associated with the 1948 event has been detected by S wave seismic reflection and trench excavation surveys. However, liquefaction of gravel layer has been revealed in a trench at the eastern edge of the basin and its date is estimated sometime between A.D. 1200. and A.D. 1400. These results suggest that the faulting of the 1948 Fukui Earthquake (M 7.1) is dominant with strike slip component, and hence it is concluded that no earthquake fault appeared on the ground surface other than the intensive surface cracks reported as the evidence of earthquake fault.

Key words: Fukui earthquake of 1948, earthquake fault, seismic reflection, trench excavation, liquefaction.

§1. はじめに

1948年6月28日に発生した福井地震 (M=7.1) は，福井平野の中～東部を震源とし，軟弱な地盤の広がる福井平野に甚大な被害を与えた．この地震によって，福井平野の中央および東縁では地割れ等の発生が認められたが，明瞭な地震断層の発生は確認されていない (小笠原, 1949)．一方，地震前後の測量結果の比較から，平野の中央部に地震断層が推定された (TSUYA, 1950).

福井県では，地震防災対策に資するため，科学技術庁地震関係基礎調査交付金によってこれらの断層の調査を

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1948 年福井地震 (M 7.1) および 1891 年濃尾地震 (M 8.0) の発生と周辺の地震の発生との関連について

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Relationship of the M 7.1 1948 Fukui and the M 8.0 1891 Nobi Earthquakes to the Occurrence of Large Earthquakes in the Surrounding Areas

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The seismic activity in the Chubu region of Houshu, Japan after the M 8.0 Nobi earthquake of 1891 has been remarkably active, with 7 earthquakes of $M \geqq 6.5$. A probabilistic test concludes that this series of earthquake occurrences for the relatively short-period is significant and not random. The Coulomb Failure Function (*CFF*) is used to evaluate effects of static stress loading on the neighboring faults for the earthquakes which occurred in the Chubu region of Honshu. Five of the seven events fall in positive area of change for the Coulomb Failure Function values (ΔCFF). This consistency suggests that the Nobi earthquake changed the stress field of the crust around the hypocenter, triggering many earthquakes. The ΔCFF values are calculated for $\pm 10°$ range of fault strike and dip angles for models of each earthquake. The values are found to vary significantly depending upon fault parameters, but the sense of ΔCFF (positive or negative) is stable throughout the test of different fault orientations. Preceding the M 7.1 1948 Fukui earthquake, an earthquake of M 6.3 occurred in 1930, possibly on the northern extension of the Fukui eastern margin fault system. Along the Fukui earthquake fault, high microearthquake activity has been observed to diminish with time since 1976, when the local seismic network was established. Whether or not the Fukui eastern margin fault system was involved in the Fukui earthquake of 1948 is not certain, and future work is needed to resolve the issue.

Key words: Stress Changes, Coulomb Failure Function, Nobi earthquake, Fukui earthquake.

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地 震　　第 2 輯
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死亡危険度に関する 1891 年濃尾地震，1948 年福井地震，1995 年兵庫県南部地震の比較

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Comparison of Fatality Risk between the 1891 Nobi Earthquake, the 1948 Fukui Earthquake and the 1995 Hyogoken-Nanbu Earthquake

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Fatality risks due to building collapses are investigated for three typical inland earthquakes in Japan; the 1891 Nobi earthquake, the 1948 Fukui earthquake, and the 1995 Hyogoken-Nanbu earthquake. The damage data obtained from these earthquakes are analyzed to evaluate relationships between fatality rate in population and collapse rate of wooden houses. A lethality function normalized for estimated numbers of inhabitants in collapsed houses is also estimated for investigation on normalized fatality risk with respect to building collapses. By comparing the analysis results, we discuss the circumstances of human casualties in these earthquakes: 1) Although different distributions of collapse rate were observed between the Nobi earthquake and the Fukui earthquake, the human casualties in both earthquakes show similar tendency that higher mortality was properly induced in the area with large damage of buildings; 2) The extensive damage by the Hyogoken-Nanbu earthquake was concentrated in limited area as compared with the other earthquakes, however high fatality rates are estimated even in relatively low-damaged regions; 3) The fatality risks in seriously damaged regions are higher than those in moderately damaged regions for every earthquake, while the fatality risks evaluated for the Hyogoken-Nanbu earthquake are two times as large as those of past earthquakes. From these results, we point out that the vulnerability to human casualties by earthquakes is still existing despite the advancement of seismic performance of buildings.

Key words: Earthquake disaster, Human casualty, Fatality rate, Fatality risk, Building collapse.

§1. はじめに

1948 年福井地震は，建築基準法（1950 年）および災害対策基本法（1961 年）の制定以前に生じ，これらの法整備によってその後の自然災害の様相と規模が大きく変化したと言われてきた．1995 年兵庫県南部地震による甚大な物的・人的被害は，この判断の正当性を検証する新たな機会を与えたといえる．宮野・呂 (1995) は，明治期以降に発生した死者 20 人以上の地震について家屋の全損棟数と死者数との関係を求め，福井地震以前では家屋被害・人的被害ともに大きい傾向を表わした．宮野・他 (1996) によれば，兵庫県南部地震の被害規模はこのような古いタイプの地震被害に属する．一方，呂 (1996) は，建物の耐震性の向上や防災行政措置の効果によって，地震による死者数は全般的には減少傾向にあると述べている．これに対し諸井・宮村 (1997) は，気象災害と地震災害による死傷者数の時代的推移を調べ，1960 年前後から顕著な減少傾向が認められる気象災害の死者数に比較すると，地震による死者数に関しては時代的な増減はそれほど特徴的でないことを示している．兵庫県南部地震の被害を，現在でも起こりうる古いタイプの地震被害とみるか，近年では例外的な大規模なものとみるかは議論が分れるところであろう．このことは今後の防災対策を考える上で重要であり，被害の総数ばかりでなく，どのような状況で被害が発生したかという質的な問題も同時に調査する必要がある．

地震による人的被害の大きさを端的に表わす指標とし

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