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その他（別言語等）のタイトル	断層モデルから津波のエネルギー及び効率を評価する試み
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journal or publication title	Bulletin of Nippon Dental University. General education
volume	8
page range	23-34
year	1979-03-25
URL	http://doi.org/10.14983/00000169

Estimation of tsunami energy and efficiency on the fault model

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(Received October 20, 1978)

日本歯科大学紀要　　第 8 号　　1979年3月

BULLETIN OF NIPPON DENTAL UNIVERSITY, GENERAL EDUCATION

断層モデルから津波のエネルギー及び効率を評価する試み

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要　　旨

津波に関するエネルギーの議論を行う場合，地震によって海水に与えられるエネルギー（全エネルギー）とそれによって生じた海水面の変化分に応じたエネルギーつまり動的エネルギーを区別することが重要である。このような議論の基礎は三好（1954）や梶浦（1970）らによって与えられている。ここではこの基礎の上に立って，水深と海底の変位場を断層モデルによって具体的に与えて，両エネルギーの値及び効率を評価することを試みた。その目的は地震が放出するエネルギー――これはまだ正確に評価されていない――のうちどの程度が津波にきいてくるのかを論議する上での一つの基礎としたいためである。

海底が瞬間的に変位したとすると動的エネルギー及び全エネルギーは梶浦（1970）によって次式で与えられる。

$$E_D=\frac{1}{2}\rho g\iint_S D^2\,ds \quad \cdots\cdots (1)$$

$$E_T=\rho g h\iint_S D\,ds \quad \cdots\cdots (2)$$

ここで ρ は海水の平均密度で 1.02g/cm^3, g は重力加速度で 980cm/sec^2, S は変動領域，D は海底変化の垂直成分，h は海水の深さである。これを用いて効率を

$$E_f=\frac{E_D}{E_T} \quad \cdots\cdots (3)$$

と定義する。エネルギー配分の考え方からすれば三好（1954）の定義した

$$\frac{E_D}{E_T+E_D} \quad \cdots\cdots (4)$$

よりもこの方が良い。一方傾斜断層の静変位場は Mansinha と Smylie (1971) によって

解析的に与えられているが，これによる変位を (1), (2) の D に入れて，変動域全域にわたって積分することにより動的及び全エネルギーがもとめられる。解析的にはむづかしいので数値的に評価する。この変位場を決める断層パラメーターの中で，座標の取り方によって消える3個を除いた残りの6個に対して，スリップアングル90°，転位量 1m，長さと巾の関係 $L=\frac{1}{3}W$ を仮定し，長さ L，傾斜角 δ，断層の深さ d に対する両エネルギー値及び効率の変化をしらべた。この変化をしらべる時には他の2変数は一定としなければならないがその基準として $L=100$km, $S=30°$, $d=0.01L$ を選んだ。結果は動的エネルギーは $\frac{1}{2}\rho g U^2 LW$，全エネルギーは $\rho gh ULW$ で規格化して縦軸にとり，横軸に L, δ, d/L をそれぞれとって示した。

その結果容易に推定されるように，両エネルギーとも長さに比例し，効率は長さによらず一定であることが確かめられた。又傾斜角による変化は10°～80° の範囲で，全エネルギーは50° の点に最大値を持つ上に凸の曲線で表わされるが，動的エネルギーは 90° にむかって単調に増加する。効率は下に凸の曲線で表わされ，50° で最小値を取る。最後に断層の深さの影響では d/L を0.01から1までとってしらべた。この範囲では，全エネルギーは深さとともに減衰するに到らず，1での値に漸近するように増え続けるという結果が得られた。これは変位の深さによる減衰よりも変動域の広がりの効果が大きいことのあらわれとみられる。一方動的エネルギーは山下と佐藤 (1974) 及び相田 (1972) によって指摘されているように表面からやや地下にもぐった所で最大値を示しその後は深さとともに減衰する曲線が得られた。その最大値を示す点は $d/L=0.05$ の地点である事が判る。又効率の深さによる変化では単調減衰曲線が得られるが，地表面から 0.5L の深さに対しては

$$E_f=k(h)\ exp(-4.0\ d/L) \quad \cdots\cdots(5)$$

で近似できることがわかる。ここで $k(h)$ は h によって決まる定数である。

この結果をもちいて1933年三陸地震津波の両エネルギー及び効率を評価すると $E_D=2.0\times10^{21}$ erg, 及び $E_T=-6.7\times10^{24}$ erg が得られた。ここでエネルギーのマイナス値はエネルギーの流れが海水から固体地球へというように正断層の場合は逆断層の逆になることを表わすものである。又効率はこれらの値を水深 3000m の場合に適用して -3.0×10^{-4} となる。

Estimation of tsunami energy and efficiency on the fault model

Abstract

The efficiency of a tsunami is modified to define the ratio of the dynamic energy to the total one. The dynamic energy, total energy and the efficiency are calculated for the incompressible sea water with a uniform depth. The displacement field of the sea bottom is due to the fault model and the generation is approximated to be instanteneous. The effects of the fault length, dip angle and fault depth on these energies and efficiency are investigated. Both the energies are proportional to the length. The total energy has a maximum value at a dip angle of 50° for the dip-angle dependence and does not decrease with a fault depth for the range of a unit depth. The efficiency does not depend on the fault length. It shows a concave curve for the dip-angle dependence and is approximated to be an exponential decrease for the fault depth.

Introduction

An earthquake is an sudden release of the strain energy stored in the earth's crust. Most of the released energy is exchanged into the seismic wave energy and the generating energy of the fault. A part of it is exchanged into the thermal energy accompanied with a generation of the fault plane. If the earthquake has a focus under the sea bottom, it is necessary to take into consideration of the sea water in addition to the solid earth. In this case a part of the fault energy is exchanged into the potential energy of the sea water. As a result of the energy transmission, the sea surface elevates or depresses. This deformation of the sea surface is the origin of a tsunami. Thus a part of the total energy which the solid earth gave the sea water is exchanged into the tsunami energy.

In relation to this problem Miyoshi (1954) took notice of both the energies on the sea surface and at the bottom, and he proposed a concept of the efficiency. Kajiura (1970) obtained an expression for the total energy, which the solid earth gave the sea water, consisting of a static energy and dynamic energy based on a hydrostatic condition and he discussed a time dependence of the dynamic energy for a circular model and a rectangular model.

Meanwhile a fault theory was developed by Mansinha and Smylie (1971) etc. made it possible to explain the co-seismic deformation on the earth's surface. Since Aida (1972) used the fault model as the generation model of the 1968 Hyuganada tsunami, many tsunamis occurred near Japan have been investigated on it. He also showed that the dynamic energy is estimable if all the fault parameters are known. In addition to the dynamic energy it is important to estimate the total energy given to the sea water in the consideration of the energy balance in an earthquake. In this paper variatons of the total energy, dynamic energy and the efficiency are systematically investigated for the fault length, dip angle and fault depth.

Total energy, dynamic energy and efficiency

In case of the instantaneous deformation, the total energy transferred to the water, E_T, and dynamic energy, E_D, are written by Kajiura (1970) in the form of

$$E_D=\frac{1}{2}\rho g\iint_S D^2 ds \qquad (1)$$

$$E_T=\rho gh\, V=\rho gh\iint_S D ds \qquad (2)$$

in which ρ is a density of the sea water, g is the acceleration due to gravity and h is a constant depth of the sea. Here D is the vertical displacement of the sea bottom, S is the total area of the deformation and V is the total volume of the bottom deformation.

Miyoshi (1954) defined the efficiency, ε, and according to the notation described above it is written in the form of

$$\varepsilon=E_D/(E_T+E_D) \qquad (3)$$

When it is considered from the viewpoint of the energy balance, it is better to define the efficiency, E_f, as the transmission rate. That is

$$E_f=E_D/E_T \qquad (4)$$

For the numerical estimation the difference between ε and E_f is small enough to be neglected when the sea depth, h, is large enough to the displacement, D. In that time E_f is nearly equal to ε snce E_T is much larger than E_D.

The vertical displacement D is calculated on the analytic expression by Mansinha and Smylie (1971). The fault geometry and coordinate system is shown in Figure 1. The reverse fault with a pure dip slip ($\lambda=90°$) is most effective in the tsunami generation since the horizontal component is the smallest in the displacement vector. Accordingly only the reverse fault with a pure dip slip is dealt in

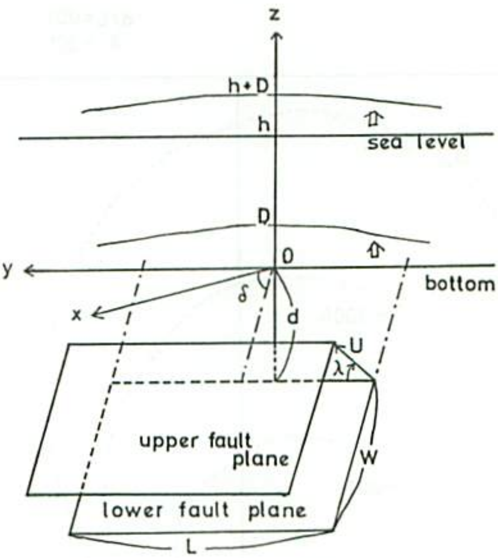


Figure 1. Fault geometry and coordinate system.

this paper. The vertical displacement field due to the normal fault with a pure dip slip is also obtainable from the result of the reverse fault with exchanging the sign of the displacement.

Before the energy estimation the fault geometry is simplified and the width is fixed in the relation of

$$W=\frac{1}{3}L \qquad (5)$$

This relation gives a smaller width than that on the seismological evidences obtained by Abe Ka (1975) and Geller (1976), independently and is based on the researches for the tsunami generating model, for example, by Abe Ku (1976, 1977) and Aida (1977). The dynamic energy E_D, total energy E_T, and the efficiency E_f are estimated from the formulas (1), (2), (4) with a numerical integration. For the estimation a grid interval is selected to be L/25 because of the computing time. The integral range is taken from 0 to 8L along the y axis and from $-W+(d/3)\tan\delta$ to $-W+(d/3)\tan\delta+2.4L$ along the x axis.

Convergence of integration

An example of the vertical displacement field is shown in Figure 2. This figure is obtained for the reverse fault of a small depth and low dip angle. Matsuura and Sato (1975) discussed the relation between the displacement pattern and

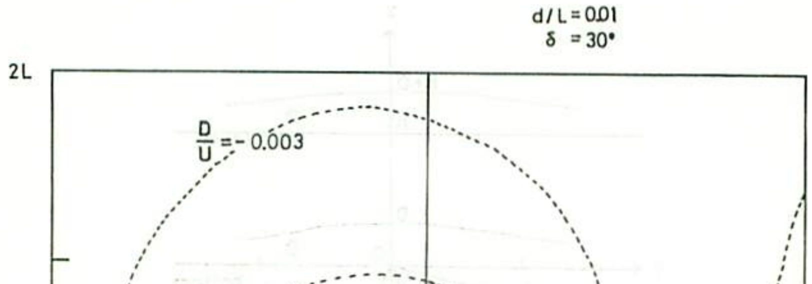


Figure 2. An example of the vertical displacement field calculated for the reverse fault with a pure dip-slip component. The rectangle with a solid line is the fault plane projected on the sea bottom. The lower half is neglected because of the symmetry.

the fault parameters to determine the fault model from the observed co-seismic deformation at the earth's surface. From this figure it is found that the equi-displacement line, for example, in the case of $D/U=-0.003$, expands far away and comes to the distance of 2L in the strike direction. This decrease of the displacement field due to the distance has an important relation for getting an exact solution. Thus a convergence of the solution was investigated for two energies. A typical fault model of $L=100$km, $W=33$km, $d=1$km, $\delta=30°$ and $U=1$m was taken for this purpose. Both the energy values were calculated for various integration areas, which include an epicentral region, under the constant grid interval of $L/25$. The result is shown in Figure 3a. An exactness of the solution is estimable from this figure. The dynamic energy shows a fast convergence and three figures were obtained for $20S_0$, in which S_0 expresses the fault area. On the other hand the total one shows a slow convergence and only one figure was obtained for $42S_0$. It takes a long calculation time to obtain an exact value for the total energy. With a short one two figures for the total energy were obtainable as follows; From this convergence curve the solution is assumed in the form of

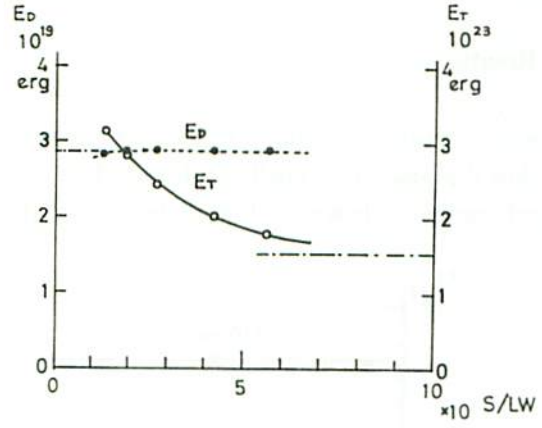
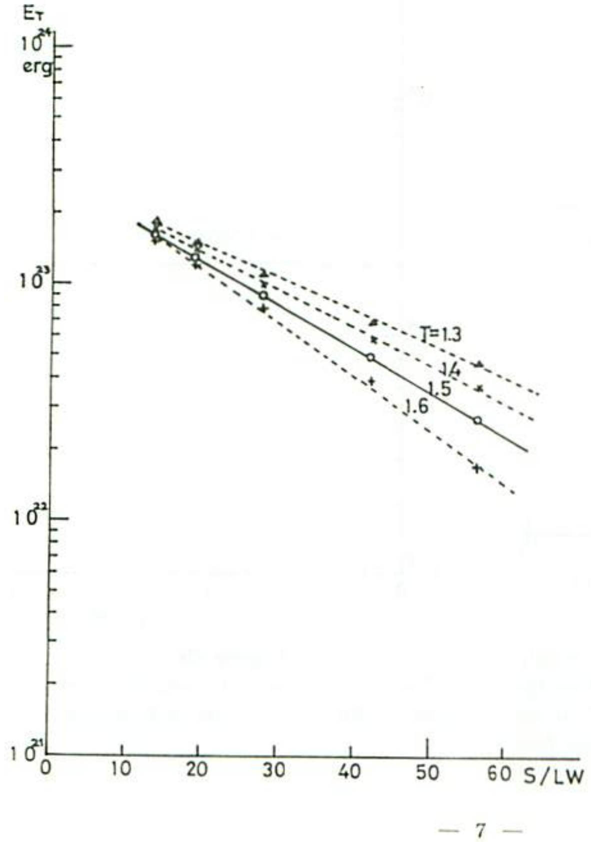


Figure 3a.
Convergences of the integrated values. S and LW represent the integration area and the fault area, respectively.



·igure 3b.
Curve fitting to determine the integrated value.

$$E_T = T + e^{-\mu S/S_0} \quad \cdots\cdots (6)$$

where T is the final solution at the infinity of the area S and μ is a constant. For various values of T the best fit value is obtained from the curve fitting as shown in Figure 3b. Thus the value obtained is 1.5×10^{23} erg. All the values which will be discussed later were calculated in this method. Two figures are accurately obtained for the total energy.

Results

At the first time the relation between energies and fault length was investigated. Under the assumption of the low dip angle and small depth ratio both the energies were calculated and normalized ones are shown in Figure 4a. Normali-

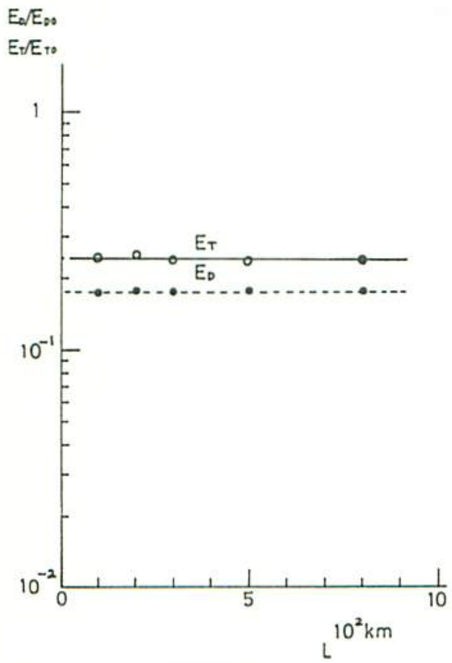


Figure 4a.

Fault length dependence of the dynamic energy E_D and the total one E_T. The dip angle and depth ratio are assumed to be 30° and 0.01, respectively. E_{D0} and E_{T0} are normalization factors.

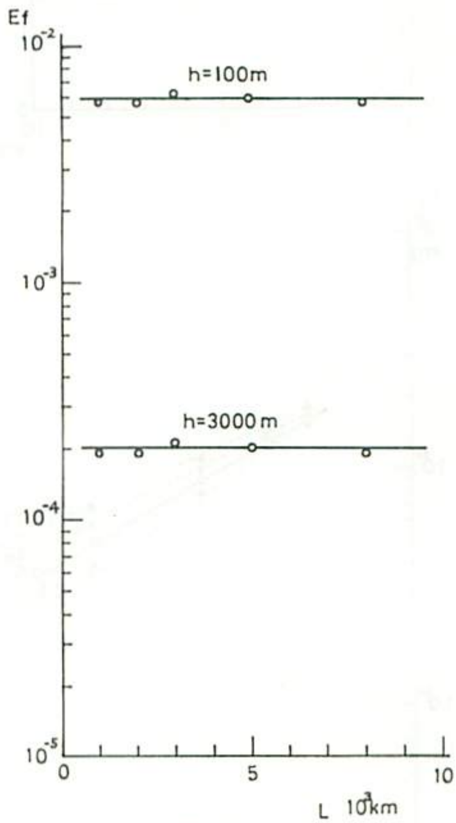


Figure 4b.

Efficiencies versus fault length under the same conditions asshown in Figure 4a.

zation factor are taken to be $\frac{1}{2}\rho g U^2 LW$ and $\rho g Uh LW$ for E_D and E_T, respectively. It is found that they are independent of the fault length. The constants obtained are 1.74×10^{-1} for the dynamic energy and 3.2×10^{-1} for the total one. The fact shows that both the energies are proportional to the fault length. The fault length dependence of the efficiency is shown in Figure 4b. Two cases were calculated for the typical sea depths of 3000m and 100m in the assumption of the unit dislocation. The efficiency is also independent of the length. The constants are obtained to be 1.7×10^{-4} and 5.0×10^{-3} for the sea depths of 3000m and 100m, respectively. Since the dislocation is frequently observed to be a few meter it is found that the tsunami on the shelf of the Japan Sea has one of the order of $10^{-3} - 10^{-2}$. The ratio of U/2h, which is approximately derived from (4), is useful to the order estimation of the efficiency.

In the next place the dip-angle dependence was calculated for a shallow fault

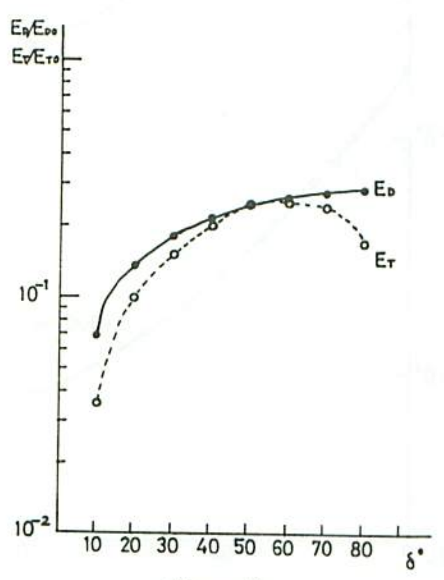


Figure 5a.
Variation of both the energies due to the dip angle. Fault length and depth are assumed to be 100km and 0.1L, respectively.

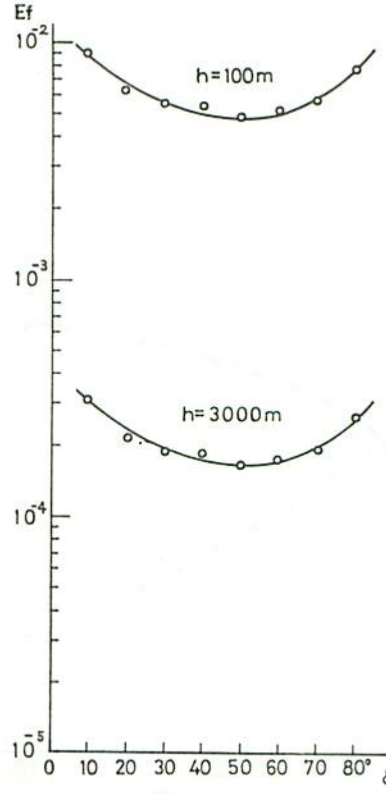


Figure 5b.
Efficiencies calculated for the same parameters as shown is Figure 5a.

of d/L=0.01. The result is shown in Figure 5a. It is found that the total energy describes a convex curve which has a maximum value of 2.9×10^{-1} at 60° and the dynamic energy shows a monotoneous increase toward 90°. Within the range from 20° to 60° both the energies have the nearly equal values and they are approximated to be proportional to the dip angle. The dip-angle dependence of the efficiency was investigated for the same depth and unit dislocation. This is shown in Figure 5b. It is a concave curve to have a minimum at 50°. From this figure the variation due to the dip angle is smaller than that due to the sea depth. It is concluded that the dip-angle effect is small enough to the sea-depth effect. Finally the energy

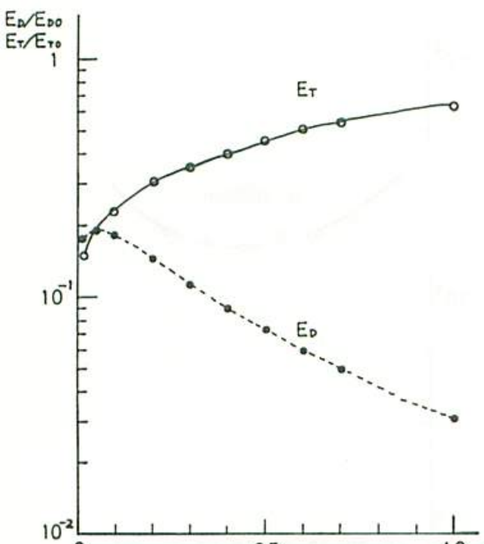


Figure 6a.
Fault dependence calculated for the dip angle of 30°.

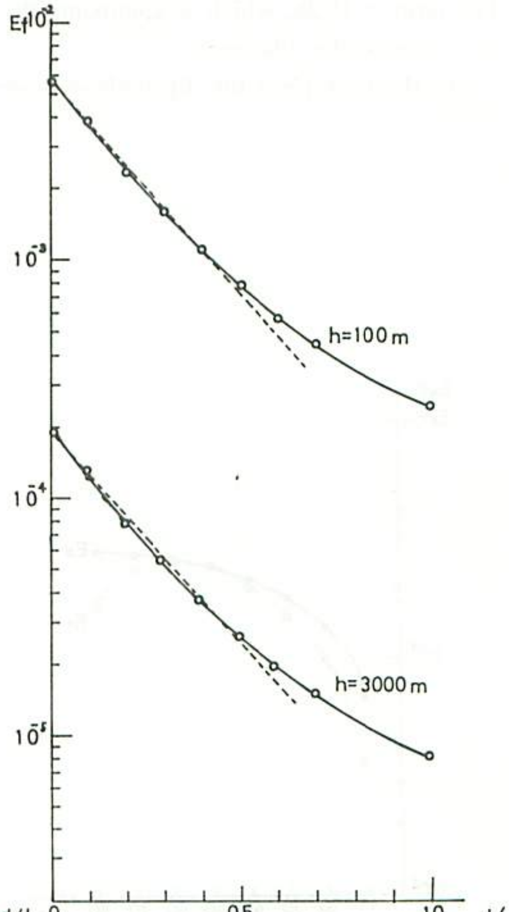


Figure 6b.
Fault depth dependence of the efficiency under the dip angle of 30°. Dotted line is an approximation of the form of $E_f=k(h)e^{-4.0d/L}$

decrease due to the fault depth was calculated for the low dip-angle. In the relation to the fault depth Yamashita and Sato (1974) pointed out the existence of the optimal depth based on the theoretical marigram. Aida (1977) obtained a decreasing curve of the dynamic energy, which is called the potential energy in his paper, due to the fault depth in the process of the research for the past large tsunamis. In our case the calculation was carried out for the dip angle of 30° within the range of the normarized depth from 0.01 to 1.0. It is shown in Figure 6a. Though this result is derived for a slight different dip-angle from the one by Aida (1977), it is found to show the same result for the fault depth. It is important that the effect is expressed as a function of the depth ratio to the length. The maximum value of the dynamic energy represents itself at the depth ratio of 0.05 and beyond the value it decreases rapidly. On the other hand the total energy shows a monotoneous increase toward the depth ratio of 1.0. This result is related to the fact that the deformed area increases with the depth ratio in spite of the decrease of the maximum vertical displacement, at the earth's surface. The efficiency is also calculated under the same condition described above. It is shown in Figure 6b. It shows a monotoneous decrease with the depth ratio. The decreasing curve is approximated with an exponential one for the depth ratio smaller than 0.5. Accordingly the efficiency takes a maximum value for the surface generation.

Discussion

For the 1933 Sanriku earthquake Abe Ku (1978) obtained a fault model consistent with the tsunami data. His model is consisted of the normal fault of the length of 265km, width of 80km, fault depth of 0km, dip angle of 30° and dislocation of −3.3m. The sea depth is assumed to be uniform and 3000m. When the deviations of the width ratio to the length and depth ratio is approximated to be small enough between his model and the example shown in Figure 3a, it is possible to apply this result to his model. Since the normalization factors are calculated as follows ;

$$\frac{1}{2}\rho g U^2 LW = 1.2\times10^{22}\, erg$$

and

$$\rho gUhLW = -2.1\times10^{25}\, erg$$

in which the values of ρ and g are assumed to be 1.02g/cm^3 and 980cm/sec^2, respectively. In the use of the constants shown in Figure 4a the dynamic energy and total one are calculated to be 2.0×10^{21} erg and -6.7×10^{24} erg, respectively. The negative total energy shows the fact that the energy was transmitted from the water column to the solid bottom as shown by Kajiura (1970). The effiiciency is estimated to be -3.0×10^{-4}. The negative efficiency corresponds with the normal fault.

Concluding remarks

1. The efficiency is modified to show the transmission rate of the energy from the solid earth to the sea bottom.

2. The dynamic energy and total energies are proportional to the fault length.

3. The dynamic energy is a monotoneous increasing function with the dip angle. On the other hand the total one describes a convex curve for the dip angle and a maximum value at 60°. The effect of the dip angle for the efficincy is represented with a concave curve with its minimum value at 50°.

4. In the variation for the fault depth the dynamic energy has a maximum value at 0.05d/L and beyond the depth it decreases rapidly. The total one increases monotoneously with an increase of the depth. The efficiency is approximated to be an exponential decrease.

5. It is comparatively easy to get a solution exactly for the dynamic energy but it is difficult to get a solution for the total one because of a slow convergence. In this case it is estimated that the significant figures are three and two for the dynamic energy and total one, respectively.

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