19. *Rayleigh- and Love-waves transmitted through the Pacific Ocean and the Continents.*

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Attempts to determine the structure of the earth's crust by means of the arrival time of surface waves have been made by a number of investigators, namely, Gutenberg,[1] Jeffreys,[2] Stoneley,[3] Matuzawa,[4] Byerly,[5] Carder,[6] etc. But, the surface waves studied by them for that purpose were chiefly of the Love-type, the reason for which is probably the fact that the dispersion curves that are easily obtained are for the Love-waves and not for Rayleigh-waves. Provided the epicentral distance is not small, say not less than 20 degree, it does not seem that the identification of the initial phase is more difficult in the case of Rayleigh-waves than it is in that of Love-waves. As a matter of fact, in a case of this kind the two kinds of waves are identified with comparative clearness. Having worked out the mathematical calculation of the dispersion curves of Rayleigh-waves for various cases,[7][8] it may be in order now to reexamine the structure of the earth's crust with the aid of the results of our calculations.

There are quite a number of observed results with regard to the arrival times of Rayleigh-waves and Love-waves that could be drawn upon for comparison with our mathematical results relating to dispersion curves. However, because of the ease with which the original records could be confirmed and in view of the reliability of the results, we used Matuzawa's data[9] that appeared in our Bulletin for 1929. Matuzawa's result with respect to the relation between the velocities

1) B. GUTENBERG, *Z. f. Geophys.*, **1** (1925), 100~106; *Phys. Z.*, **27** (1926), 111~114; *Proc. 5th Pac. Sci. Congr., Canada*, **3** (1934), 2511~2521.

2) H. JEFFREYS, *M. N. R. A. S., Geophys. Suppl.*, **1** (1925), 282~292.

3) R. STONELEY, *M. N. R. A. S., Geophys. Suppl.*, **1** (1928), 527~532.

4) 9) T. MATUZAWA, *Bull. Earthq. Res. Inst.*, **6** (1929), 213~229.

5) P. BYERLY, *Gerl. Beitr. z. Geophys.*, **26** (1930), 27~33.

6) DEANS S. CARDER, *Bull. Seism. Soc. America*, **24** (1934), 231.

7) K. SEZAWA, *Bull. Earthq. Res. Inst.*, **3** (1927), 1~18.

8) K. SEZAWA and K. KANAI, "M_2 Seismic Waves," *Proc. Imp. Acad.*, **11** (1935), 96~98.

of transmission and the periods of oscillation of the respective initial phases of L-waves and M-waves will be found reproduced in Figs. 1, 2. Since it is possible for different kinds of surface waves[10] to exist even in the case of Rayleigh-waves and it seems that the usual surface waves, generally speaking, correspond to that kind having maximum group velocities, the enveloping curves drawn in these figures seem to give the approximate values of the velocities of transmission of the usual surface waves.

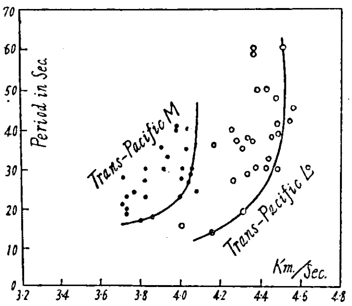

Fig. 1.

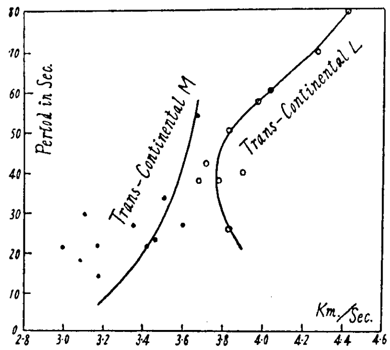

Fig. 2.

After a prolonged study of the subject it is our conclusion that it is urgently necessary to obtain, mathematically, the dispersion curves of Rayleigh-waves as well as those of Love-waves that are transmitted through stratified bodies in such cases of (i) $\rho=\rho'$, $\lambda=\mu$, $\lambda'=\mu'$, $\mu/\mu'=2$, (ii) $\rho/\rho'=1{\cdot}14$, $\lambda=\mu$, $\lambda'=\mu'$, $\mu/\mu'=1{\cdot}65$, where ρ', λ', μ', ρ, λ, μ are the densities and elastic constants of the stratum and the subjacent medium respectively. The dispersion curves of Rayleigh-waves of case (i) was obtained some time ago,[11] that of case (ii) has been elabolated by Mr. Kanai,[12] while the dispersion curves of Love-waves were constructed with very little difficulty. All these curves are shown in Figs. 3, 4, 5, 6. The values for the group velocities were obtained in the usual way.

A careful comparison of the enveloping curves in Figs. 1, 2 with the curves indicating the group and phase velocities in Figs. 3, 4, 5, 6, shows that the four cases of surface waves, namely, trans-Pacific and trans-Continental Rayleigh-waves as well as Love-waves, approximately agree with the present four mathematical results. It should, however, be borne in mind that the curves giving the phase velocities in Figs. 3, 4, 5, 6 were necessary not only for calculating the group velocities,

10) 12) K. SEZAWA and K. KANAI, *loc. cit.*
11) K. SEZAWA, *loc. cit.*

but also for deriving the lengths of the actual waves from the periods of oscillation as well as from the velocities of transmission. It will thus be seen that it is possible to find eventually the proper thickness

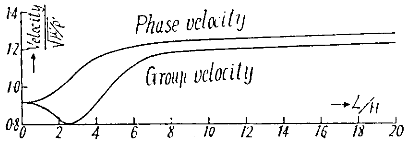

Fig. 3. Rayleigh waves. $\rho=\rho'$, $\mu/\mu'=2$.

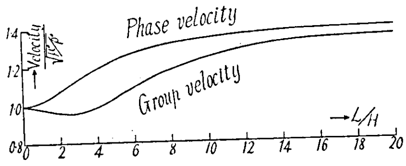

Fig. 4. Love waves. $\rho=\rho'$, $\mu/\mu'=2$.

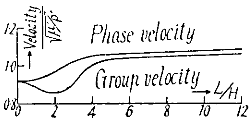

Fig. 5. Rayleigh waves. $\rho/\rho'=1{\cdot}14$, $\mu/\mu'=1{\cdot}65$.

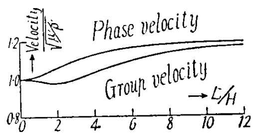

Fig. 6. Love waves. $\rho/\rho'=1{\cdot}14$, $\mu/\mu'=1{\cdot}65$.

of the stratum as estimated from every feature of dispersion corresponding to the trans-Pacific Rayleigh-waves, trans-Pacific Love-waves, trans-Continental Rayleigh-waves, and the trans-Continental Love-waves. From the nature of the trans-Pacific Rayleigh-waves we get $H=9$ km, $\rho=\rho'$, $\lambda=\mu$, $\lambda'=\mu'$, $\sqrt{\mu'/\rho'}=3{\cdot}2$ km/sec, $\sqrt{\mu/\rho}=4{\cdot}5$ km/sec; from that of the trans-Pacific Love-waves we obtain $H=5$ km, $\rho=\rho'$, $\sqrt{\mu'/\rho'}=3{\cdot}2$ km/sec, $\sqrt{\mu/\rho}=4{\cdot}5$ km/sec; from that of the trans-Continental Rayleigh-waves we find $H=12$ km, $1{\cdot}14\rho'=\rho$, $\lambda=\mu$, $\lambda'=\mu'$, $\sqrt{\mu'/\rho'}=3{\cdot}1$ km/sec, $\sqrt{\mu/\rho}=3{\cdot}7$ km/sec; while from that of the trans-Continental Love-waves we have $H=40$ km, $1{\cdot}14\rho'=\rho$, $\sqrt{\mu/\rho'}=3{\cdot}7$ km/sec, $\sqrt{\mu/\rho}=4{\cdot}5$ km/sec.

The thickness of the sub-Pacific stratum estimated from Rayleigh-waves does not differ much from that estimated from Love-waves, so that we may be justified in taking the mean value $H=(9+5)/2=7$ km on the assumption that the bottom of the Pacific Ocean consists of a crust of a single surface stratum. The fact, that the maximum velocity of Rayleigh-waves is less than that of Love-waves by about 10%, seems to support this conception.

The thickness of the surface stratum of the Continental crust estimated from Rayleigh-waves is exceedingly small compared with that estimated from Love-waves. Since the energy of the Rayleigh-waves accumulates with considerable intensity quite close to the surface whereas that of the Love-waves is distributed in a sinusoidal form within the stratum,[13] it is probable that the two kinds of waves are dispersed through different strata. Thus, the Continent may be assumed to consist of a double surface strata, the thicknesses of the upper one and the next being 12 km and 28 km respectively. Rayleigh-waves are practically unaffected by the lower layer, while the energy of the Love-waves is distributed uniformly, relatively speaking, within the effective layer of a thickness 40 km. This is also evidenced, on the one hand, from the fact, that in the case of the Continents the maximum velocity of Rayleigh-waves is too small compared with that of Love-waves, and, on the other, from the fact that the amplitudes of trans-Continental Love-waves are extremely small compared with those of trans-Continental Rayleigh-waves. Were both kinds of waves dispersed through a common stratum, the difference in the respective maximum velocities would not be very great, and the difference in the general amplitudes of the respective waves would be of such order as indicated in the trans-Pacific surface waves. Now, the conclusion we have reached from our investigation with the aid of the nature of Rayleigh-waves as well as that of Love-waves is as follows.

The sub-Pacific basin is stratified with a basaltic layer about 7 km thick with a density of 3·0; the transverse waves there being transmitted with a velocity of 3·2 km/sec. The subjacent medium, through which the transverse waves are transmitted with a velocity of 4·5 km/sec, consists of a dunite of probably varying densities, though slight, ranging from 3·0 at the top to 3·5 at a depth of 30 km from the bottom of the basaltic layer. It seems that at such a depth the medium is completely ultrabasic and of density 3·5, although the velocity of transmission of transverse waves differs very little from 4·5 km/sec, being the same as in dunite.

The Eurasian Continent has two superficial layers. The uppermost stratum, which is about 12 km thick, is granitic, of density 2·7, the velocity of the transverse waves being 3·1 km/sec. The second layer, which has a thickness of 28 km seems to be composed of a gabbro of density 3·1, the velocity of transverse waves through this medium being approximately 3·7 km/sec. The third layer, in which the velocity of the transverse waves is 4·5 km/sec, may be an ultrabasic rock of density 3·5.

Figs. 7, 8 are diagrammatic sketches showing the distribution of the proper velocities of transverse waves as well as the densities in the superficial structure of the earth. From Fig. 8 it will be seen

13) K. SEZAWA and K. KANAI, "Periods and Amplitudes of Oscillations in L- and M-phases," *Bull. Earthq. Res. Inst.*, **13** (1935), 18~38.

that at a depth of 40 km from the level of the Continental surface the masses are practically in isostatic equilibrium. The problem of distribution of density, however, is not important in the present problem; it merely confirms that the estimated distribution of materials

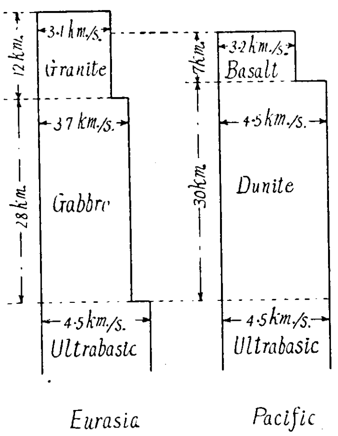

Fig. 7. Velocity of transverse waves.

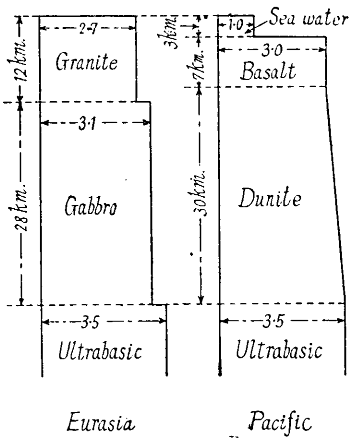

Fig. 8. Density.

as deduced from the nature of wave transmission does not differ very greatly even from the distribution of the density proper to each material.

The result of the present theorising seems to support the views of both Jeffreys and Stoneley for Eurasia and that of Gutenberg for the Pacific Ocean. It should however be borne in mind that the stratification here postulated is merely an effective one. The actual distribution of these materials would be rather of a gradually varying type.

In conclusion I wish to express my thanks to Mr. K. Kanai for his valuable assistance in the present work.

19. 太平洋及大陸を通過するレーレー波及ラブ波

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表面波の走時關係によつて地表の構造を決定しやうとする試みは既に多くの人によつて手をつけられてゐるが，それは殆ごラブ波の關係を用ひたもののみである．ラブ波の分散曲線を出すことは極めて容易であるけれごもレーレー波のそれを出すことは可なり困難な爲と思はれる．筆者は金井氏等と共に既に種々の場合のレーレー波の分散曲線を出してあるから，それ等を利用し，且つラブ波の特別の場合をもたやすく算定して，實際の測定結果と比較してみたのである．

レーレー波やラブ波の走時の觀測算定は無數にあるけれごも，筆者は松澤博士のそれが原記錄を容易に確め得る事と，又，松澤博士の整理したものは可なり信用できるやうに思はれたのでそれを借用して比較したのである．種々研究の結果，太平洋については $\rho=\rho'$, $\lambda=\mu$, $\lambda'=\mu'$, $\mu/\mu'=2$, 大陸については $\rho/\rho'=1{\cdot}14$, $\lambda=\mu$, $\lambda'=\mu'$, $\mu/\mu'=1{\cdot}65$ といふ場合のレーレー波とラブ波の問題がよくあてはまることがわかつたのである．

一層具體的の結果を示すと，太平洋を傳はるレーレー波は，厚さ 9 キロメートルの表面層があつて，その中のポアツソン比 1/4，横波の速度が毎秒 3·2 キロメートル，下層ではポアツソン比 1/4，横波の速度が 4·5 キロメートルの所を通過すればよく，ラブ波は表面層の厚さが 5 キロメートルで他は同樣な狀態の所を通過すればよいことが知られた．次に，歐亞大陸を通過するレーレー波は，表面層の厚さ 12 キロメートル，ポアツソン比 1/4，その中での横波の速度は毎秒 3·1 キロメートル，下層では毎秒 3·7 キロメートル，ポアツソン比 1/4，表面層と下層との密度比を 1/1·14 とすればよく，又ラブ波については表面層の厚さ 40 キロメートル，その中での横波の速度 3·7 キロメートル，下層中での横波の速度 4·5 キロメートルとすればよいことがわかつたのである．

太平洋ではレーレー波から出した表面層の厚さとラブ波から出したそれの厚さとの平均卽ち 7 キロメートルを取つてもよいと思はれる．それは太平洋を通る兩波の最高速度の比が 10 パーセント位の差があり，共通の一つの層として大して誤がないからである．

大陸の表面層の厚さについては，レーレー波のそれから出したのとラブ波のそれから出したのとは著しく違つてゐるから，兩波は別々の層を通して傳播したとしてもよいのである．實際，レーレー波の勢力は地表の極く附近にのみ集つてゐるものであるし，ラブ波の勢力は或る效果的の層があればその層全體に勢力が分布してゐることが理論的にわかつてゐる．然るに大陸を通過するラブ波の振幅はそのレーレー波のそれに比して著しく小さいことがわかつてゐるし，又ラブ波の最高速度はレーレー波の最高速度に比して著しく高いから，ごうしても前述の理論通りに別々の層を傳はつたとする方が都合がよいのである．從て歐亞大陸では表面に厚さ 12 キロメートルの層があり，次に厚さ 28 キロメートルの層があることになるのである．

かくの如くして彈性の分布狀態を圖示すると第 7 圖の如くなるのである．そのやうな岩石狀態の密度の分布を念の爲に圖示してみると第 8 圖の如くなり，イソスタシーも大體に於て保たれ得ることが確められるのである．

この結果は歐亞大陸については偶然にも Jeffreys や Stoneley の結果とよく一致し，太平洋については Gutenberg の結果と餘り違はぬことが知られるのである．