A theory of the Krakatoa tide gauge disturbances

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ABSTRACT

Tide gauge disturbances detected at many places around the world after the explosive eruption of Krakatoa in 1883 cannot be explained as free ocean waves travelling by the shortest sea route from Krakatoa, but were clearly correlated with the air wave. Previous explanations of the way in which the air wave caused the tide gauge disturbances are shown to be unsatisfactory from the point of view of both theory and observation. It is suggested that these disturbances were in fact free waves generated by the air wave at major changes in depth in the ocean, notably the continental slope. This mechanism is investigated for both normal and oblique incidence of the air wave on a step. The tide gauge disturbances observed after the eruption of Krakatoa are shown to be consistent in arrival time, time scale and amplitude with the predictions of the theory.

1. Introduction

The explosive eruption of Krakatoa in 1883 generated an atmospheric pressure pulse which propagated round the earth with approximately the speed of sound, and was detectable at many places on at least three circuits of the earth (Symons, 1888). The eruption also gave rise to a powerful tsunami which was recorded at many places for which there is a direct (i.e. great circle) sea route from Krakatoa. However, disturbances were also recorded by tide gauges in distant places for which no direct sea route from Krakatoa exists, such as San Francisco, Colon on the Panamanian isthmus, and several English Channel ports. A careful investigation of all these sea waves was carried out by Wharton (1888), and the results published in the comprehensive Royal Society report edited by Symons (1888). (A brief summary of many of the conclusions of this fascinating report is given by Lane, 1966.) Wharton assumed that the sea waves in the Pacific, the Caribbean and the English Channel travelled by the shortest possible sea routes from Krakatoa (though, as mentioned, these were not great circles, but required diffraction of the waves around land masses), and on the basis of the travel times he calculated the average depth implied. This turned out to be much greater than is known to be the case, and so Wharton concluded that the Pacific and Caribbean tide gauge disturbances were due to causes other than the explosion of Krakatoa. He also expressed doubt on the cause of the disturbances in the English Channel, though the data here was not so definite.

Ewing & Press (1955) suggested that these sea waves were in some way coupled to the air wave, and they showed that for many distant stations there was a strong correlation between the arrival time of the air wave and the first sea wave. In comparing the arrival times they allowed for the travel time of the sea wave in shallow water, as calculated by Wharton, who took "shallow" for this purpose to mean less than 1000 fathoms. So in fact the sea wave arrived some time later than the air wave. Ewing & Press gave no reason for allowing for the travel time of the wave in shallow water, though we shall see later, on the basis of the explanation in this paper, that there is a very good reason for doing so. Ewing & Press also remark that the sea waves were observed only when the air wave was travelling from ocean to land, and not vice versa.

They discuss the coupling of surface seismic waves to the atmosphere, and by analogy they are led to expect that the Krakatoa air wave could only transfer significant amounts of energy to the sea if the coupling is very nearly resonant. They suggest either that a free wave exists in the ocean with the same phase speed as the air wave, though none is known to exist, or that significant coupling can in fact take place off resonance.

These two possibilities are both readily dismissed. No free wave in the ocean travelling as fast as the atmospheric pressure pulse is theoretically possible, except in water of far greater depth than is observed, nor has such a fast moving free wave ever been observed. Theoretical examination of the sea level disturbance caused by a pressure pulse moving much faster than free waves in the water gives a displacement far too small to account for the observations (see § 2 here). Moreover, such a disturbance would arrive at the same time as the air wave, rather than minutes or hours later, as is observed.

Harkrider & Press (1966, 1967) make the further suggestion that an atmospheric wave might exist which propagates with the same phase speed as ocean waves, and on the basis of computed dispersion curves for an ocean-atmosphere system, they point out that a gravity wave of the right speed could, in fact, exist in the atmosphere. They argue that such a wave could "jump" land barriers and resonantly re-excite the sea waves whenever it reached the ocean. If such an air wave was generated by Krakatoa, then it was too small to be detected by the barographs that detected the main pulse. Of course, a small amplitude air wave might suffice, but it seems fundamentally unsatisfactory to explain one observed phenomenon in terms of a different phenomenon which was not observed. There are also certain theoretical difficulties associated with the mechanism proposed by Harkrider & Press, notably those connected with the difference between the phase and group velocities of the atmospheric gravity wave, and with horizontal variations in ocean depth, but it suffices to point out that their theory is inconsistent with many of the observations. This is readily ascertained by an examination of Fig. 9 of their 1967 paper, in which it is seen that in three cases out of four their resonantly excited sea wave could not have arrived until some time after the tide gauge disturbances actually commenced. In particular, at Colon the time lapse is about 7 hours. This does not rule out their mechanism altogether, though it needs considerably more justification, but merely shows that some other explanation is required for at least the earlier parts of the disturbances.

Any theory of the tide gauge disturbances must certainly depend in some way on the air wave, but it must produce sea waves of sufficient amplitude, arriving some time after the air wave, and probably only observed when the air wave approaches from the seaward side. The explanation which will be proposed in this paper is based on the idea that free ocean surface waves are generated by the atmospheric pressure pulse at any abrupt change in the depth of the ocean, and in particular at the continental slope. The theory of this will be developed, and it will be shown that free waves generated at the continental slope, and also at other places in the ocean, could have accounted for the observed disturbances.

2. The forced sea wave

Barograms of the first two pressure pulses, corresponding to the direct wave and the wave through the antipodes, from eight selected stations are shown in Fig. 1, redrawn from the Royal Society report (Symons, 1888) which also shows the third and fourth pulses for these stations. Although no scales are shown on the original figure, the data published by Scott (1883) indicates a crest-to-trough amplitude of approximately 3 mb for European stations and it seems that the duration of the pulse was about an hour. The motions excited in the ocean would have the same time scale as the air wave, and we may use the shallow water approximation, valid for wavelengths much greater than the depth of the ocean. The velocity components (u, v) with respect to horizontal coordinates (x, y) are then independent of depth, and the pressure is hydrostatic. If $\eta(x, y, t)$ is the surface displacement on water of mean depth $h(x, y)$ and $p_s(x, y, t)$ is the excess surface pressure, then the linearised equations of motion and continuity are

$$\varrho \frac{\partial u}{\partial t} + \frac{\partial p_s}{\partial x} + \varrho g \frac{\partial \eta}{\partial x} = 0 \tag{2.1}$$

$$\varrho \frac{\partial v}{\partial t} + \frac{\partial p_s}{\partial y} + \varrho g \frac{\partial \eta}{\partial y} = 0 \tag{2.2}$$

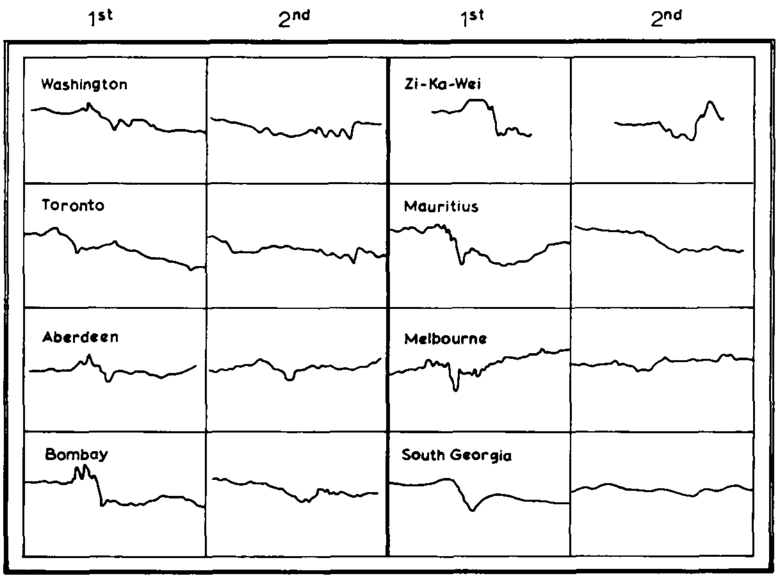

Fig. 1. Barograms of the first two air waves from Krakatoa (redrawn from Symons, 1888).

$$\frac{\partial \eta}{\partial t} + h\frac{\partial u}{\partial x} + h\frac{\partial v}{\partial y} + u\frac{\partial h}{\partial x} + v\frac{\partial h}{\partial y} = 0. \tag{2.3}$$

In the absence of the excess surface pressure, and with h constant, this system has plane wave solutions with phase speed $\sqrt{gh}$. We shall first investigate the forced disturbance, in water of constant depth, due to a travelling surface pressure distribution $p_s = p_0 F(t-(x/c))$. In fact the atmospheric pressure pulse must be slightly dispersive (e.g. Garrett, 1969), but the effect of the dispersion will be very small and we shall neglect it here. We may take $v=0$, and eliminating u from equations (2.1) and (2.3) we have

$$\frac{\partial^2 \eta}{\partial t^2} - gh\frac{\partial^2 \eta}{\partial x^2} = \frac{h}{\varrho}\frac{\partial^2 p_s}{\partial x^2} \tag{2.4}$$

of which a particular integral, representing a forced surface wave, is (e.g. Proudman, 1952, § 146)

$$\eta = \frac{h}{\varrho(c^2-gh)} p_0 F\left(t-\frac{x}{c}\right) \tag{2.5}$$

and hence

$$u = \frac{c}{\varrho(c^2-gh)} p_0 F\left(t-\frac{x}{c}\right). \tag{2.6}$$

As $c^2 > gh$, we see that equation (2.5) implies an elevation of the free surface under regions of high pressure. This apparently paradoxical result is standard for any simple harmonic oscillator being forced at a frequency greater than its natural frequency. It occurs because most of the response of the system to the forcing effect is in the acceleration produced, rather than in the displacement.

It is worth considering the amplitude of this forced wave in both deep and shallow water. Denote by η_b the purely hydrostatic response to a surface pressure of the same magnitude as that used above (i.e. take $c=0$ in the coefficient of $p_0 F$ in equation (2.5)). Then

$$\eta/\eta_b = \frac{-gh}{c^2-gh}. \tag{2.7}$$

For simplicity let us take $c = 300$ m/sec (though in fact the speed of the air wave from Krakatoa varied between about 300 m/sec and 325 m/sec (Symons, 1888)). Then if $h=4000$ m (corresponding to the deep ocean and giving $\sqrt{gh}=$ 200 m/sec) we have $|\eta/\eta_b| = 0.8$, while for $h = 250$ metres (corresponding to fairly shallow water and giving $\sqrt{gh} = 50$ m/sec) we have $|\eta/\eta_b| = 0.03$. Now 1 mb of surface pressure corresponds to an amplitude of about 1 cm for η_b. The amplitude

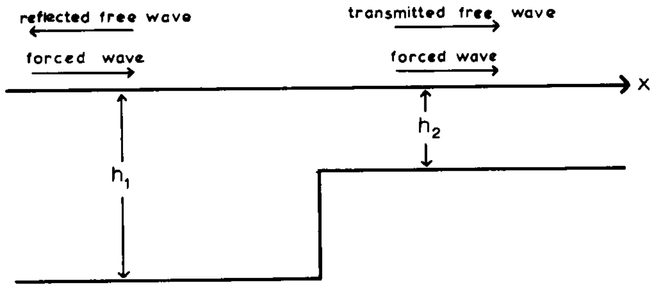

Fig. 2. Waves generated at the step (normal incidence).

of the atmospheric pressure wave from Krakatoa was probably a few millibars in most places, but as tide gauges were situated in water at least as shallow as 250 m, the forced displacement of the sea surface as the pressure wave passed would be much less than 1 cm, and so undetectable, as mentioned in § 1, even though in the deep ocean the surface displacement might be a few centimetres.

3. Free waves generated at a discontinuity in depth

(i) *The Matching Conditions*

Consider the situation illustrated in Fig. 2, in which the depth h is a function of x only, and changes abruptly at $x=0$ from h_1 to h_2. The matching conditions across $x=0$ are well-known and easily derived by integrating equations (2.1) and (2.3) across the discontinuity. The conditions are (assuming that p_s is continuous):

(a) η is continuous (3.1)

(b) hu is continuous.

Of course, the shallow water approximation is no longer valid at a discontinuity in h, but Bartholomeusz (1958) showed that the above matching conditions are correct for determination of the far fields for the reflection and transmission of long waves at a step, and so we use them here.

(ii) Normal Incidence

Equation (2.4) has possible free wave solutions

$$\eta = aG\left(t \pm \frac{x}{\sqrt{gh}}\right) \tag{3.2}$$

to which correspond

$$u = \mp a\frac{g}{\sqrt{gh}}G\left(t \pm \frac{x}{\sqrt{gh}}\right). \tag{3.3}$$

We shall see that we have to introduce these in order to satisfy the conditions (3.1) at the step, given a pressure pulse $p_s = p_0 F(t-(x/c))$ incident on the step from water of depth h_1. It is clear from causality that we can only generate at the step a transmitted wave in the water of depth h_2 and a reflected wave in the water of depth h_1. The physical situation is illustrated diagrammatically in Fig. 2.

Denoting $c_1 = \sqrt{gh_1}$, $c_2 = \sqrt{gh_2}$ and with $p_s = p_0 F(t-(x/c))$ as before, the solution in $x<0$, where $h=h_1$, is given by

$$\eta = \frac{h_1 p_0}{\varrho(c^2-c_1^2)}F\left(t-\frac{x}{c}\right) + aF\left(t+\frac{x}{c_1}\right) \tag{3.4}$$

$$u = \frac{cp_0}{\varrho(c^2-c_1^2)}F\left(t-\frac{x}{c}\right) - \frac{ga}{c_1}F\left(t+\frac{x}{c_1}\right). \tag{3.5}$$

In $x>0, h=h_2$ and

$$\eta = \frac{h_2 p_0}{\varrho(c^2-c_2^2)}F\left(t-\frac{x}{c}\right) + bF\left(t-\frac{x}{c_2}\right) \tag{3.6}$$

$$u = \frac{cp_0}{\varrho(c^2-c_2^2)}F\left(t-\frac{x}{c}\right) + \frac{gb}{c_2}F\left(t-\frac{x}{c_2}\right). \tag{3.7}$$

The free waves have been taken to have undetermined (as yet) amplitude, but the form of $F(t)$ at $x=0$, as this is clearly necessary if we are to satisfy the matching conditions for all time t. Conditions (3.1) then given, after some simple manipulation,

$$R(c, c_1, c_2) \equiv \frac{g\varrho a}{p_0} = \frac{c^2(c_1 - c_2)}{(c + c_2)(c^2 - c_1^2)} \tag{3.8}$$

$$T(c, c_1, c_2) \equiv \frac{g\varrho b}{p_0} = \frac{c^2(c_1 - c_2)}{(c - c_1)(c^2 - c_2^2)}. \tag{3.9}$$

The "reflection coefficient" R gives the ratio of the amplitude of the reflected free wave to the hydrostatic depression of the free surface corresponding to a surface pressure $p_0 F$, so that a pressure pulse of amplitude 1 mb produces a reflected wave of amplitude R cm. The "transmission coefficient" T gives the amplitude of the transmitted free wave, similarly non-dimensionalised. We note that $R(c, c_1, c_2) = T(-c, c_2, c_1)$ and $T(c, c_1, c_2) = R(-c, c_2, c_1)$, as one would expect on physical grounds.

If we regard the continental slope as a step between the deep ocean of depth $h_1 = 4000$ m ($c_1 = 200$ m/sec), and the continental shelf with $h_2 = 250$ m ($c_2 = 50$ m/sec), and taking $c = 300$ m/sec, then we get $R = 0.8$ and $T = 1.5$. Thus for a pressure pulse of a few millibars amplitude, incident normally on the continental slope from the deep ocean, the transmitted free wave should have an amplitude of several centimetres and be quite detectable. It may, of course, be amplified (like $h^{-\frac{1}{4}}$) by further gradual shallowing of the water, and also possibly by ray convergence.

The continental slope is by no means a step, though it has a slope generally greater than 3°, and extends over about 50 to 100 km, which is rather less than the length scale of the Krakatoa air wave. Thus it should behave more like a step than like a gradual variation in depth, on a scale much greater than a wavelength, for which no free waves would be generated. So although the values of R, T that we have found may be a little large in practice, free reflected and transmitted waves should certainly be generated at the continental slope, and at changes in depth with similar gradients elsewhere in the ocean.

If an atmospheric pressure pulse from a large explosion is normally incident on the continental slope from the deep water at one time, then at some other time the pulse through the antipodes will be incident on the continental slope travelling in the opposite direction, i.e. from the shallow water. The amplitude of the sea wave generated in the shallow water will in this case be determined from

$$R^*(c, c_1, c_2) \equiv R(c, c_2, c_1). \tag{3.10}$$

$$= \frac{-c^2(c_1 - c_2)}{(c + c_1)(c^2 - c_2^2)}. \tag{3.11}$$

An interesting quantity is $|R^*/T|$ which gives the ratio of the amplitude of the reflected free wave generated at the continental slope by an air wave travelling towards the ocean, to the amplitude of the sea wave generated by an air wave of the same amplitude travelling from the ocean. From equations (3.9) and (3.11) we have

$$\left|\frac{R^*}{T}\right| = \left|\frac{c - c_1}{c + c_1}\right| \tag{3.12}$$

which, curiously, is independent of c_2. It is generally small; for $c = 300$ m/sec and $c_1 = 200$ m/sec, $|R^*/T| = 0.2$. The implications of this will be discussed further in § 4.

We see from equations (3.8) and (3.9) that R and T will be small unless the difference between c_1 and c_2, i.e. between h_1 and h_2, is fairly large. Apart from the free waves generated in situations already considered, the following two types of free wave are relevant to the tide gauge disturbances associated with the eruption of Krakatoa: (a) the transmitted free wave when the air wave is travelling towards the ocean. With c, h_1, h_2 as before we have $T(c, c_2, c_1) = 1.1$, suggesting that free waves generated in this way might travel across the ocean and, after transmission at the continental slope the other side of the ocean (with an amplification factor of approximately 2, see Bartholomeusz (1958)), by detectable at tide gauges there; (b) the reflected free wave when the air wave is travelling from the ocean. With c, h_1, h_2 as before we have $R(c, c_1, c_2) = 0.8$, and as in (a) this wave may now travel back across the ocean to be detected at the other side.

Free waves will also be generated at oceanic ridges if the difference in depth is sufficient. (a), (b) and this possibility will be discussed further, in the light of observations, in § 4.

Another interesting question is whether slow-moving pressure fluctuations associated with the weather can generate noticeable free waves at large changes in depth, such as the continental slope. Taking $c = 10$ m/sec., $c_1 = 200$ m/sec.

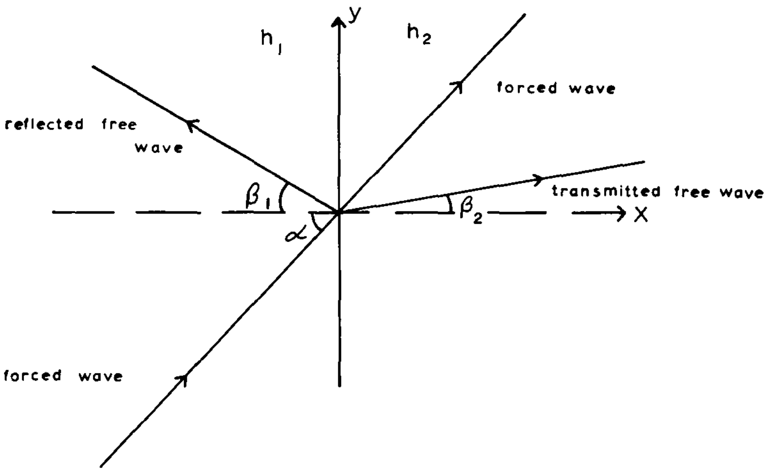

Fig. 3. Waves generated at the step (oblique incidence).

and $c_2 = 50$ m/sec., we obtain $R = -0.006$ and $T = 0.03$. As the pressure amplitude would not be more than a few millibars, the free waves generated would be undetectable, though of course, the direct response to the surface pressure, i.e. the forced wave of § 2, will be quite large in this case, being essentially hydrostatic.

(iii) *Oblique incidence*

We now consider the situation in which the air wave is travelling at an angle to the step. Taking this to be along the y-axis as before, a plan view of the situation is illustrated diagrammatically in Fig. 3. The air wave, and consequently the forced sea waves on both sides of the step, are travelling at an angle to the normal to the step. A free wave is reflected at an angle β_1 to the normal, and a free wave is transmitted at an angle β_2 to the normal. The solutions are now: for $x < 0$

$$\eta = \frac{h_1 p_0}{\varrho(c^2 - c_1^2)} F\left(t - \frac{x \cos\alpha}{c} - \frac{y \sin\alpha}{c}\right) + aF\left(t + \frac{x\cos\beta_1}{c_1} - \frac{y \sin\beta_1}{c_1}\right) \quad (3.13)$$

$$u = \frac{p_0 c \cos\alpha}{\varrho(c^2 - c_1^2)} F\left(t - \frac{x\cos\alpha}{c} - \frac{y\sin\alpha}{c}\right) - \frac{ga\cos\beta_1}{c_1} F\left(t + \frac{x\cos\beta_1}{c_1} - \frac{y\sin\beta_1}{c_1}\right) \quad (3.14)$$

and for $x > 0$

$$\eta = \frac{h_2 p_0}{\varrho(c^2 - c_2^2)} F\left(t - \frac{x\cos\alpha}{c} - \frac{y\sin\alpha}{c}\right) + bF\left(t - \frac{x\cos\beta_2}{c_2} - \frac{y\sin\beta_2}{c_2}\right) \quad (3.15)$$

$$u = \frac{p_0 c\cos\alpha}{\varrho(c^2 - c_2^2)} F\left(t - \frac{x\cos\alpha}{c} - \frac{y\sin\alpha}{c}\right) + \frac{gb\cos\beta_2}{c_2} F\left(t - \frac{x\cos\beta_2}{c_2} - \frac{y\sin\beta_2}{c_2}\right) \quad (3.16)$$

For matching to be possible at $x = 0$ for all y, we require that

$$\frac{\sin\alpha}{c} = \frac{\sin\beta_1}{c_1} = \frac{\sin\beta_2}{c_2}. \quad (3.17)$$

By applying the matching conditions (3.1) and defining $R = (g\varrho a/p_0)$, $T = (g\varrho b/p_0)$ as before, we obtain

$$R = \frac{c^2(c\cos\alpha - c_2\cos\beta_2)(c_1^2 - c_2^2)}{(c_1\cos\beta_1 + c_2\cos\beta_2)(c^2 - c_1^2)(c^2 - c_2^2)} \quad (3.18)$$

$$T = \frac{c^2(c\cos\alpha + c_1\cos\beta_1)(c_1^2 - c_2^2)}{(c_1\cos\beta_1 + c_2\cos\beta_2)(c^2 - c_1^2)(c^2 - c_2^2)}. \quad (3.19)$$

Regarding R, T as functions of α for given c,

c_1, c_2 we may write equations (3.18) and (3.19) as

$$R(\alpha) = \frac{(c \cos \alpha - c_2 \cos \beta_2)(c_1 + c_2)}{(c_1 \cos \beta_1 + c_2 \cos \beta_2)(c - c_2)} R(0) \quad (3.20)$$

$$T(\alpha) = \frac{(c \cos \alpha + c_1 \cos \beta_1)(c_1 + c_2)}{(c_1 \cos \beta_1 + c_2 \cos \beta_2)(c + c_1)} T(0) \quad (3.21)$$

and hence, defining R^* as before,

$$R^*(\alpha) = \frac{(c \cos \alpha - c_1 \cos \beta_1)(c_1 + c_2)}{(c_1 \cos \beta_1 + c_2 \cos \beta_2)(c - c_1)} R^*(0). \quad (3.22)$$

We note that the reflected free wave vanishes when $c \cos \alpha = c_2 \cos \beta_2$ i.e. when $\sin^2 \alpha = c^2/(c^2 + c_2^2)$. Also $R^*(\pi/2) = T(\pi/2)$ which is only to be expected, since the case in which the air wave travels along the step is the common limit of the air wave being incident from either side of the step. Fig. 4 shows $R(\alpha)$, $T(\alpha)$, $R^*(\alpha)$ as functions of α for the particular case $c = 300$ m/sec., $c_1 = 200$ m/sec., $c_2 = 50$ m/sec.

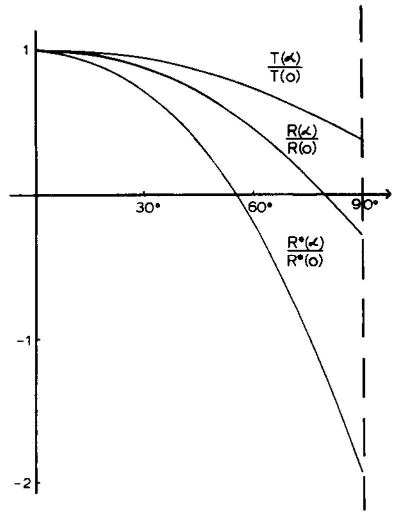

Fig. 4. R, T, R^* as functions of the angle of incidence ($c:c_1:c_2 = 6:4:1$).

4. Comparison with observations

In accordance with the theory developed in this paper, the atmospheric pressure pulse from Krakatoa would be expected to generate, at the continental slope, free sea waves of sufficient amplitude to be detected at coastal tide gauges. If the air wave passes the gauge at time t_0, and t_s, t_a are the travel times of the sea wave and the air wave from the continental slope, then the sea wave would be expected at time $t_0 + t_s - t_a$ (for normal incidence, anyway; the time lag will be somewhat modified for oblique incidence), t_a would be very much less than t_s, so the sea wave would be expected roughly a time t_s later than the air wave. The theory is thus consistent with the general conclusions of Ewing & Press (1955) based on the data of Wharton (1888). In general the data shows the arrival of several sea waves, it is only the first arrival that was considered by Ewing & Press. In many cases the main sea waves arrived much later, and it must be admitted that in some cases Wharton's (1888) identification of disturbances on the tide records is open to doubt.

It should also be remarked that the oscillations on the tide gauge records seem to have had much the same time scale as the air wave, though, as already mentioned, these oscillations continued for rather longer than the air wave, suggesting that free sea waves were generated at other places in the ocean as well as at the continental slope.

It is curious that the extensive Royal Society report (Symons, 1888) contains no mention of the amplitude of the air waves. However, the data published by Scott (1883) shows that in Europe the first two air waves at least (one direct and one through the antipodes) had an average crest-to-trough amplitude of about 3 mb. As Europe is roughly 90° from Krakatoa, the air wave elsewhere would have been rather larger. Thus in view of the theory and discussion of § 3, it seems that the amplitude of the tide gauge disturbances, typically several centimetres, is what would be expected, though focusing and other amplifying effects may well have occurred in some places.

Ewing & Press (1955) came to the general conclusion that no tide gauge disturbances were observed when the air wave was travelling from the land towards the ocean. The present theory predicts that in this case, for normal incidence anyway, a tide gauge disturbance should be registered at time $t_s + t_a$ after the passage of the air wave, but that the amplitude of this sea wave be only about 20 % of that expected for an air wave of the same amplitude travelling from

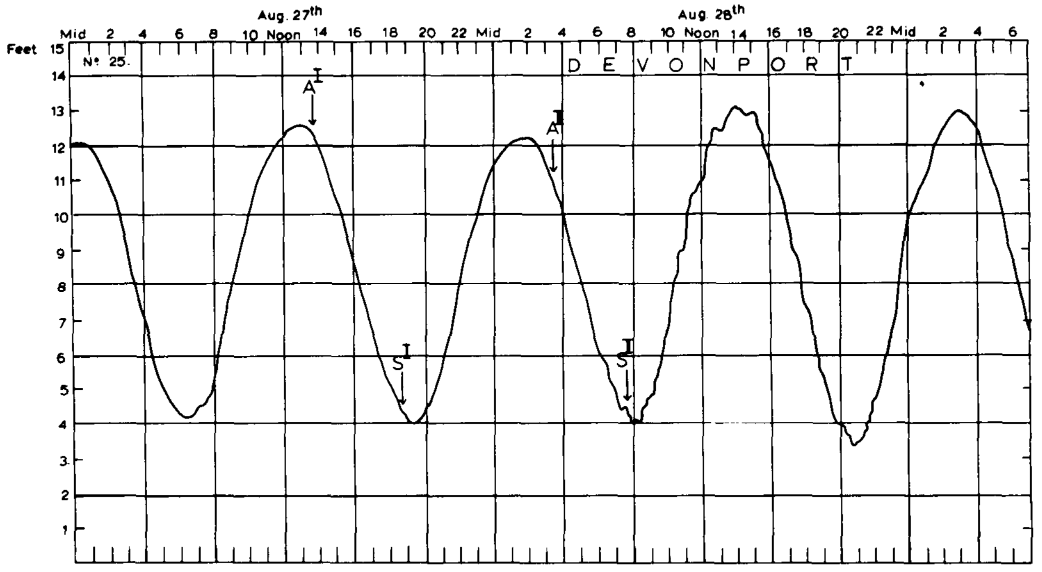

Fig. 5. The Devonport tide record (redrawn from Symons, 1888).

the ocean. (For oblique incidence the situation is more complicated.) In general this was probably too small to be detected, in agreement with the conclusion of Ewing & Press, but a possible identification of it on the Devonport record is shown in Fig. 5. (The tide record is redrawn from Symons (1888).) The arrival times of the air wave are marked A^{I} and A^{II}, A^{I} being the direct wave, off-shore in this case, and A^{II} the wave through the antipodes, onshore here. Both air waves were nearly normal to the continental slope. The first arriving sea wave associated with A^{II} is marked S^{II}. (My identification of the arrival time of S^{II} (0730) differs from that of Wharton (1043) and Ewing & Press (0620).) Taking $t_a = 30$ minutes, the expected time for the arrival of the sea wave associated with A^{I} is marked S^{I}, and we see that there is a slight kink in the record within a few minutes of that. However, this is not very conclusive, especially as there appears to be a similar disturbance at 0700 hours on August 27th! To be sure of any identification of the sea wave generated at the continental slope by the offshore air wave, we need records from a station (with a nearby continental slope) where the amplitude of the air wave, and hence of the sea wave, was large. Colon was such a station as it is near the antipodes of Krakatoa. The tide gauge record from Colon is shown (redrawn from Symons (1888)) in Fig. 6; we see that a seiche of considerable amplitude was initiated shortly after the arrival of the first air wave, which was onshore. The offshore air wave arrived shortly afterwards, it is impossible to say whether it had any effect on the tide gauge disturbance. It is unfortunate that the offshore air wave was not the first arrival.

The largest amplitude sea wave at San Francisco arrived at 1320 hours on August 27th (see Fig. 7) some 5½ hours after the first (onshore) air wave, this must have been generated at a considerable distance from the American west coast, probably at some large change in depth as discussed in § 3. An examination of the depth charts along or near the great circle path from Krakatoa to San Francisco leads one to suspect that the sea wave was generated either as the air wave left the Philippines, or as it passed over the Mariana Ridge south of Japan. The air wave would still have been rather large at both these places, thus generating rather large free sea waves, and a lag of 5½ hours behind the air wave at San Francisco is roughly what one would expect. Some contribution to the San Francisco record could also have come from the "refracted" free waves generated by air waves travelling over the Hawaiian Ridge and over the Aleutian islands, in the manner indicated diagrammatically in Fig. 8.

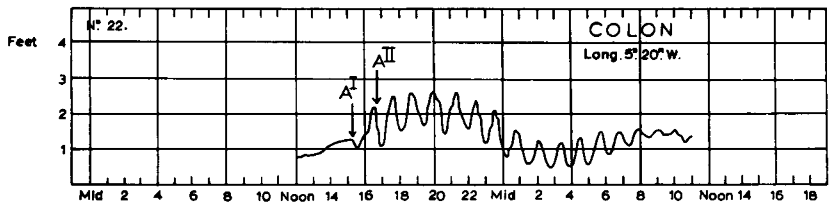

Fig. 6. The Colon tide record (redrawn from Symons, 1888).

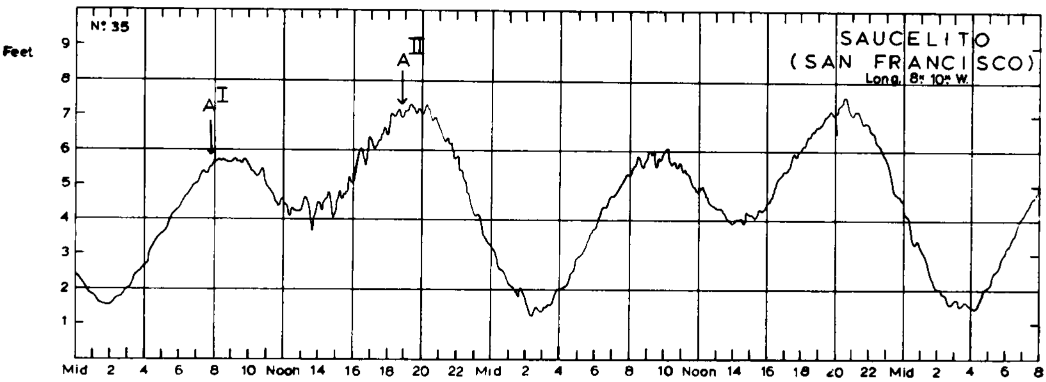

Fig. 7. The San Francisco tide record (redrawn from Symons, 1888).

The main sea wave at St. Paul, Kodiak, arrived at 1645 hours on August 27th (Wharton, 1888), seemingly quite unconnected with the air waves, in fact about 13 hours after the arrival of the first wave and 2 hours before the second. It seems that this could well be a sea wave generated at the Phillippines and then reflected off the North American mainland; rough calculations indicate that such a wave should indeed arrive some 13 hours after the first air wave passed over Kodiak.

Similar arguments may be used to explain the other tide gauge disturbances recorded after the eruption of Krakatoa. We may thus sum up our interpretation of the Krakatoa data as follows: The first arriving sea wave when the air wave arrives from the ocean may generally be explained as a free wave generated at the continental slope. When the air wave is travelling offshore, there is either no detectable sea wave, or the data is uncertain. Sea waves arriving later may generally be explained as free waves generated either at the other side of the ocean or at some other major change in depth. The amplitude of these waves may be partly due to the tendency of variations in depth to focus long waves at certain places.

One might also hope to observe tide gauge disturbances caused by the air wave from large atmospheric nuclear tests. The largest of these was the Soviet test of 30th October 1961, the yield of the bomb being about 57 megatons (Donn & Shaw, 1967). This generated air waves of considerable amplitude, though of rather smaller length scale than for Krakatoa, so that the continental slope, for example, might be rather less a step and rather more a gradual

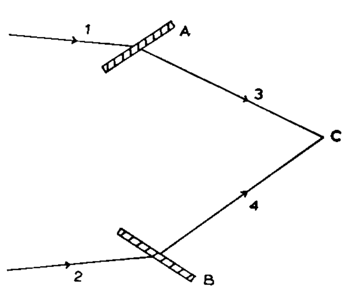

Fig. 8. Possible origin of free waves detected at San Francisco (schematic). 1 and 2: air waves from Krakatoa; 3 and 4: free sea waves generated. *A*: Aleutian Ridge; *B*: Hawaiian Ridge: *C*: San Francisco.

variation in depth. No observations seem to have been reported of sea waves associated with this or other nuclear explosions. I have examined tide gauge records for Newlyn and Devonport (kindly made available by Commander N. C. Glen of the Admiralty Hydrographic Office, London) for the relevant days in the hope of detecting disturbances associated with the explosion of 30th October 1961, but on none of the records are they apparent above the noise level.

Free sea waves generated according to the mechanism described in this chapter by the air waves from large nuclear explosions might be detectable at tide gauges situated in places where the local topography is known to amplify long waves coming from the ocean, but they would only stand out above the noise on exceptionally calm days. Large amplitude of the air wave, as at the antipodes, would also help, but the antipodes of Novaya Zemlya is in the region of Antarctica where there were no tide gagues operating at the right time or at places where one would expect disturbances.

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ТЕОРИЯ ПРИЛИВНЫХ ВОЗМУЩЕНИЙ, ВЫЗВАННЫХ ВЗРЫВОМ ВУЛКАНА КРАКАТОА

Приливные возмущения, зарегистрированные во многих местах на всем земном шаре после взрывного извержения вулкана Кракатоа в 1883 г., не могут быть объяснены как свободные волны в океане, распространяющиеся по кратчайшему морскому пути от Кракатоа, однако, они четко коррелировали с воздушной волной. Показано, что предыдущие объяснения, как воздушная волна вызывала приливные возмущения, оказываются неудовлетворительными с точки зрения как теории, так и наблюдений. Предполагается, что эти возмущения являлись свободными волнами, генерируемыми воздушной волной в месте основных изменений глубины дна океана, прежде всего, на континентальном склоне. Этот механизм исследуется для случаев нормального и наклонного падений воздушной волны на склон. Показано, что предсказания теории в отношении времен прибытия, временных масштабов и амплитуды согласуются с приливными возмущениями, наблюдавшимися после извержения Кракатоа.