ON THE POSSIBLE HAZARD ON THE MAJOR CITIES CAUSED BY ASTEROID IMPACT IN THE PACIFIC OCEAN

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Abstract. Semi-quantitative investigation is made of hazard expected from an asteroidal impact in the Pacific. An impact of d (diameter) = 200 m asteroid has a probability of hitting somewhere in the Pacific once in 15000 y. By carrying out a Monte Carlo simulation, such an impact, on average, is shown to create a tsunami as high as 16, 14, 15, and 21 m at Japan, Taiwan, Shanghai and Hawaii, respectively. Wooden houses, stone and brick houses, and reinforced concrete buildings are likely to be demolished by tsunamis of height 2, 7 and 20 m respectively. Thus, there is a probability of 1% or so that most of the artificial constructions on the coast lines of the Pacific be destroyed in the next century by an asteroidal impact.

1. Introduction

Owing to researches made by astronomers, geologists and physicists over the past decades or so, it has become increasingly apparent that the Earth has experienced impacts of small bodies, ranging from meteors to large asteroids and comets. The scale of the energy released by such impacts ranges from an equivalent of a megaton of TNT to a billion megatons of TNT. Although an impact which would produce a crater as large as 180 km in diameter at the well known K/T boundary takes place only once in tens of millions of years, smaller ones take place more frequently. It is estimated that an impact of the scale of Tsunguska event of 1908 takes place once in every 2–3 centuries, while an impact by an asteroid or a comet with diameter 1.5 km which could kill 1.5 billion people is estimated to take place once in every half a million years or so (Chapman and Morrison, 1994).

Now although a direct land impact is serious enough to kill many people and destroy buildings, the area destroyed is limited. On the other hand, an impact in an ocean could bring about far serious consequences, because waves created by an oceanic impact propagate long distances and upon reaching shores, the wave in general becomes a tsunami, increasing the height by a factor close to 15. From the point of view of hazard resulting from cometary or asteroidal collisions, the oceanic impacts are expected to be far more serious. Thus, it seems important to quantify the degree of hazard expected, should such an impact occur.

In this paper, it is proposed to discuss the hazards that are expected to occur should such an impact take place. We consider the Pacific ocean. The Pacific is undoubtedly the largest and the probability of an impact there is the largest. It is also important in that there are many major cities along the coast. The Atlantic is

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also important for reasons that need not be stated. We feel however not capable of discussing the Atlantic and other oceans. We restrict ourselves to the impacts that have a probability of occurrence of 1% or so in the next century.

2. Method of Assessing Hazard

The method we propose to assess the hazard may be stated as follows. First, there is now available an estimate on frequency of impact (comet or asteroid) as a function of diameter. For instance, there are review articles by Chapman and Morrison (1994) and by Weissman (1994) which provide such a frequency.

Second, there is an empirical relation based on numerical simulation and explosion experiment between the energy of impact (detonation) and the height of the wave at a distance from the epicentre. Thirdly, a number of numerical simulations as well as past observations of tsunami wave have yielded a result which provides information on how the oceanic wave is amplified in height as it approaches a shore. These results put together would provide information how often a tsunami of such a height one should expect to occur. In this way, it will be possible to know how the coast lines of an ocean would be exposed to tsunami hazard.

3. Impact Rate and Waves Generated

The frequency of impact as a function of asteroidal diameter may be estimated as follows. The probability of an Earth-crossing asteroid hitting the Earth is 4.2 $\times\ 10^{-9}\ \mathrm{y}^{-1}$, while the number of such asteroids with diameter d, greater than 1 km is estimated at 1030 (Chapman and Morrison, 1994) or 2100 (Rabinowitz, 1994). We adopt the latter figure. Then, the probability that such an impact will take place in the next century is $4.2 \times 10^{-9} \times 100 \times 2100 = 8.8 \times 10^{-4}$. As argued by Weissman, this is a small probability for the impact event to be perceived as an immediate threat. However, if we consider a smaller asteroid, situation would be different. The number distribution of asteroids with diameter greater than d is proportional to $d^{-\alpha}$, where α is close to 2. Then, an asteroid with diameter 200 m say, will have a probability of 2.2% hitting the earth in the next century. This can no longer be regarded as a negligibly infrequent event. Such an impact will have a 2/3 probability of taking place somewhere outside the continents. On the other hand, the wave generated by an impact at distance r from the epicentre is given by (Hills *et al.*, 1994)

$$h_w = 7.8\,\mathrm{m} \times \left(\frac{1000\,\mathrm{km}}{r}\right)\left[\left(\frac{d}{200\,\mathrm{m}}\right)^3\left(\frac{V}{20\,\mathrm{km\,s^{-1}}}\right)^2\left(\frac{\rho}{3\,\mathrm{g\,cm^{-3}}}\right)\right]^{0.54} \tag{1}$$

where d is the diameter, V the velocity and ρ the density of the impacting body. We have noted that an asteroid with d = 200 m has a probability of hitting the

TABLE I

Average value of 1000 km/r

	Latitude	Longitude	Average of 1000 km/r	Stan. dev.
Japan	34°39′ N	135° E	0.200	0.145
Taiwan	23° N	121° E	0.181	0.167
Shanghai	31°13′ N	121°25′ E	0.190	0.263
Hawai (Honolulu)	21°19′ N	157°50′ W	0.272	0.609

earth once in every 5000 y. Since the Pacific occupies 30% or so of the earth surface, an impact in the Pacific occurs once in every 15000 y. In other words, there is a 1% or so probability that an asteroid with $d = 200$ m hit the earth in the next century. Note that if one takes into account the situation that asteroidal orbits have small inclinations, the probability of hitting the Pacific will be greater.

Now, if one knows the distance between the epicentre and a particular city or a nation facing the ocean, it will be a straightforward matter to calculate the tsunami height. In reality, even if an asteroid in a collision course is identified, it will not be possible to predict precisely where it will hit the earth. Thus what one can do is to calculate the likely tsunami height resulting from such an impact.

To evaluate the likely hazard, we generate random points on the earth so that they may be uniformly randomly distributed and pick up those points that are within the Pacific Ocean, say. In our simulation 1000 points have been generated, of which 302 were in the Pacific. Mention should be made of what is meant by the Pacific. There is no sharp boundary of the Pacific, except where it meets a continent. For the part between Australia and New Zealand, the sea south of latitude 40° S is not taken into account, because it is unlikely that a wave generated there will propagate long distances to the northern part of the Pacific. Again the Bering Sea or the Sea of Okhotzk are not taken into account. It is however, assumed that small islands in the Pacific are no obstacles to the propagation of impact generated waves. Given the latitude and longitude of a particular location, say, Japan, it is possible to obtain the average value of $1/r$ in Equation (1). Table I gives the average value of $1/r$ so calculated for several localities on the periphery of the Pacific.

4. Hazard Expected at the Coasts

When a wave such as generated by an earthquake reaches a shore, it will increase its height. This is called runups. The precise factor depends much on the topography of the shore but on average, the height increases by a factor of 15. In the case of the 1960 Chile earthquake, the height increased 25 fold in the Northern

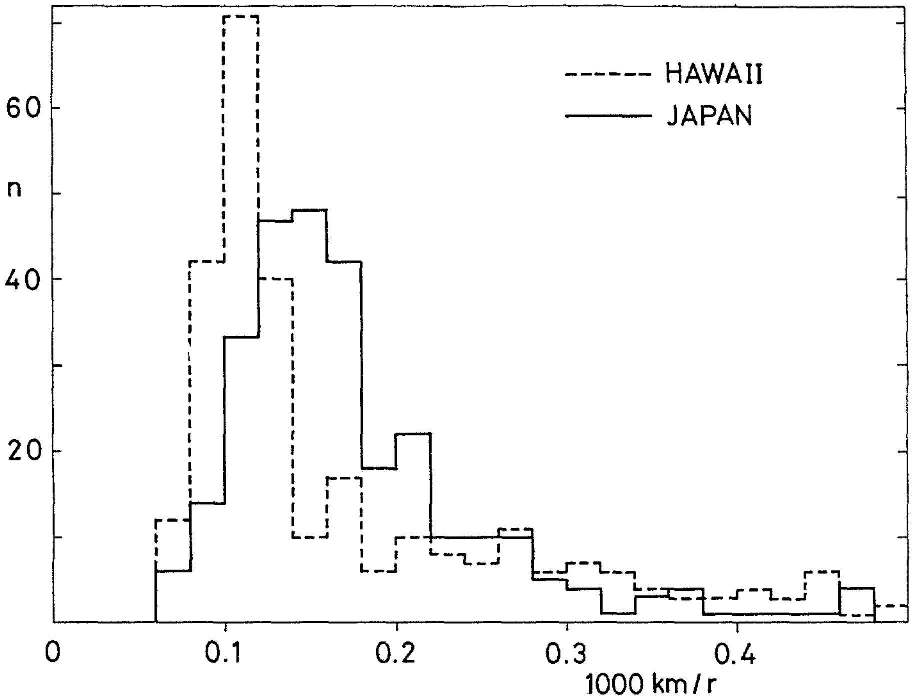

Fig. 1. Histogram distributions of 1000 km/r for two localities in the Pacific.

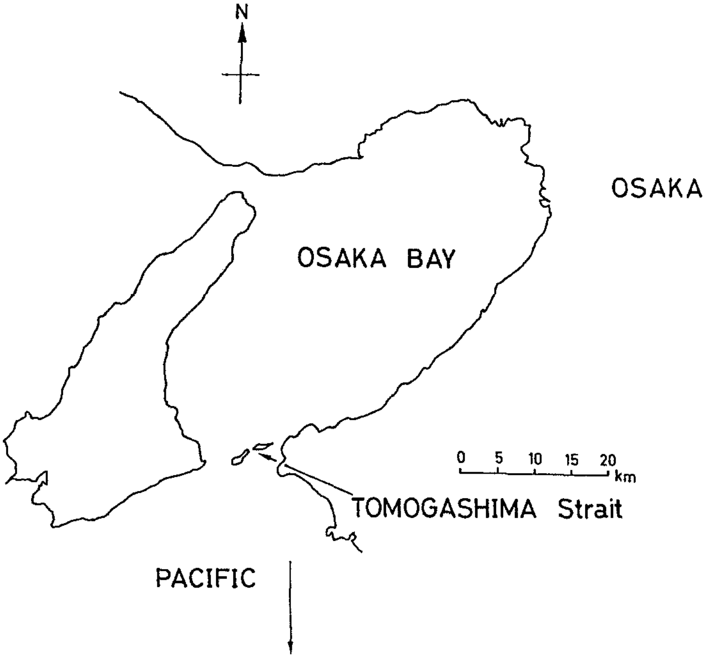

Fig. 2. Geography of Tomogashima strait which is an entrance to Osaka bay.

TABLE II

Average tsunami height expected from an impact in the Pacific, by an asteroid with $d = 200$ m

	Runup factor		
	10	25	40
Japan	16 m	39 m	62 m
Taiwan	14	35	56
Shanghai	15	37	59
Hawaii	21	53	84
San Diego	15	37	59

Island of Japan, but the factor was about 10 on average. For Hawaii, the factor was close to 40 (Mader, 1994). Estimates for runup tsunami heights are given in Table II for cities and countries facing the Pacific.

We find that because Hawaii is located in the middle of the Pacific, the expected tsunami is higher than at other locations that are all at the periphery of the Pacific.

It is not an easy task to assess the damages that are likely to be caused by tsunami, especially records of tsunami as high as 40 m are rare. There is however, a record of tsunami that was 85 m high. This tsunami was observed on the Pacific side of Ishigaki jima Island (lat. = 24°30′ N, long. = 124° E) allegedly due to the Hachinoe-yama earthquake that took place in 1771. At that time the population of the island was 28896, of which 17349 were killed. On the Pacific side, nearly 90% of the population was lost.

According to Shuto (1993) who surveyed damages done to buildings by tsunamis of various heights, wooden houses, stone (including brick) houses and reinforced concrete buildings are demolished by tsunami of height greater than 2, 7 and 20 m respectively. If this result gives a reliable guide, it will be reasonable to expect that a large proportion of buildings (houses, urban buildings, warehouses and factory facilities) will be destroyed in localities facing the Pacific. Among the Japanese cities, Kohchi, Wakayama, Hamamatsu and Shizuoka appear to be most vulnerable to the hazard. We also like to draw attention to a Budda statue which is in the city of Kamakura. It had been housed, but by a tsunami caused by an earthquake of the 16th century, the building (timber) was destroyed. In this case, the runup factor was 40 (Hasegawa, 1994; Mader, 1994).

The situation is a little different for Tokyo, Nagoya and Osaka that are situated at the bottoms of Tokyo, Ise and Osaka bays, respectively. If Osaka is taken as an example, the entrance to Osaka bay is Tomogashima strait which is 60 m deep. By Green's law (Lamb, 1945), a wave increases its height by the factor

TABLE III

Radius (km) of minor bodies with visual absolute magnitude (V) and albedo (p). For C type asteroid, $p = 0.04$ while $p = 0.16$ for S type

V	$p = 0.05$	0.10	0.15	V	$p = 0.05$	0.10	0.15	V	$p = 0.05$	0.10	0.15
4	469	332	271	13	7.4	5.3	4.3	22	0.12	0.08	0.07
5	296	209	171	14	4.7	3.3	2.7	23	0.07	0.05	0.04
6	187	132	108	15	3.0	2.1	1.7	24	0.05	0.03	0.03
7	118	83	68	16	1.9	1.3	1.1	25	0.030	0.021	0.017
8	74	53	43	17	1.2	0.8	0.7	26	0.019	0.013	0.011
9	47	33	27	18	0.74	0.53	0.43	27	0.012	0.008	0.007
10	30	21	17	19	0.47	0.33	0.27	28	0.007	0.005	0.004
11	19	13	11	20	0.30	0.21	0.17	29	0.005	0.003	0.003
12	12	8	7	21	0.19	0.13	0.11	30	0.003	0.002	0.002

$(D/d)^{1/4}$ where D is the depth where the wave originally was generated and d is the depth at a point concerned. Since the Pacific is 4000 m deep on average, the wave will have increased the height by a factor 3 as it arrives the Tomogashima strait. The straight is about 10 km wide. But the Kii straight which lies between Wakayama and Kochi prefectures is much wider (40 km or so). So it is expected that the wave will increase the height by a further factor $(40/10)^{1/2} \simeq 2$ by the time the wave reaches the Tomogashima strait. It remains to be seen how the wave is modified as it advances deep into the bay. The same situation would also apply to Tokyo and Ise bays. The amplification factor depends on the period of the incident wave and the period of characteristic oscillation of the bay (Kaziura, 1975). In the case under investigation, the period of the incident wave is 2 min or so. The estimate of the wave as it reaches the large cities can probably be made by detailed computer simulations, taking into account geometries of the bays (Mader, 1988). This task is now being undertaken.

5. Conclusions

Densely populated nations on the periphery of the Pacific and large cities in the same locations are exposed to hazard caused by tsunami waves generated by an asteroidal impact. There is a one percent or so chance that such nations and cities are exposed to such hazard in the next century. This is not a negligibly small probability. The expected height of tsunami ranges from 15 to 60 m and nearly all of the man-made buildings will be destroyed. Economic damages will be severe and it is conceivable that even if inhabitants could leave the danger zones before the arrival of the tsunami, the economic aftermath will be drastic. If the tsunami should hit major cities like Tokyo, Nagoya, Osaka and Shanghai, the situation would be even worse. The same would also apply to Taiwan. It may be noted in this respect that because the time scale involved is somewhat longer than that of the recorded history of the inhabitants in the region concerned, one cannot expect to find accounts of such tsunami hazards in the form of legends or history, and the lack of legends or history should not be taken as evidence against the occurrence of such hazards.

We have seen that an oceanic impact of an asteroid with diameter, $d \simeq 200$ m could bring about drastic damages to the countries and cities located at the periphery of the ocean. It now seems worthwhile to discuss how such an object could be detected. According to Hasegawa (1994), the relation between the visual absolute magnitude, V and the radius, r of an asteroid or a comet is as given in Table III.

It is seen that an astroid with $d \simeq 200$ m will have a visual absolute magnitude $21 \sim 22$. As of August 1992, only 11 of Appolo Amor type astroids with the magnitude range >21 have been detected. These asteroids are at the verge of detection, and so far have been found only by chance. It thus seems a worthwhile effort to extend the search of earth crossing objects to at least absolute magnitude, $V = 24$.

Finally, we should mention that the collision probability of 4.2×10^{-9} y^{-1} may be too small. A larger value (8×10^{-9}) may be closer to reality (Steel, 1994). If so, impact probability would be nearly doubled.

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