‘Maximum-class’ Japan Sea tsunami scenarios are less than maximum-class

—An error, left uncorrected, is a recipe for another ‘unforeseeable’ disaster

Kunihiko Shimazaki

Professor emeritus, The University of Tokyo

“Maximum-class” Japan Sea tsunami scenarios, which the central government of Japan has set forth as unified models to be used by prefectural governments, are underestimated. There could be a repeat of “unforeseeable” damage if tsunami countermeasures were to proceed like this. It should not be forgotten that the Central Disaster Management Council and Tokyo Electric Power Co. (TEPCO) ignored a 2002 forecast of a tsunami earthquake, causing an “unforeseeable” disaster to occur nine years later. The “maximum-class” tsunami scenarios have insufficient heights because a land ministry panel has underestimated their seismic source sizes. Another nuclear accident could be triggered by “unforeseeable” earthquake ground motion if those underestimations were to turn into an accomplished fact.

Culprit of the ‘unforeseeable’ disaster hidden in the darkness

The act of leaving tsunami risks ignored caused the devastating damage from the Great East Japan Earthquake and tsunami, and the severe accident at TEPCO’s Fukushima Daiichi nuclear power plant. Five years have passed, but the livelihoods lost to the disasters have yet to be restored. To make sure that nothing like that will be allowed to happen again, it should be brought to light what kind of study processes had led the tsunami risks to go ignored.

But a panel of the government’s Central Disaster Management Council (Committee for Technical Investigation on Countermeasures for Earthquakes and Tsunamis Based on the Lessons Learned from the “2011 off the Pacific Coast of Tohoku Earthquake”), which was supposed to have “learned lessons” from the disasters of that year, ended its mission with a mere recommendation that approaches different from the previous ones should be taken in the future[1]. There was no discussion, whatsoever, about what was the culprit of the wrong conclusion, how precisely it had been derived, whether expert seismologists or public administrative officials should be held responsible, and other questions. As a member of that panel, I requested a review of the whole process, only to see my comments ignored.

An organizational framework has survived, unchanged and intact, whereas the background of the erroneous administrative decision has been left hidden in the darkness.

TEPCO reportedly long continued to ignore the forecast of a tsunami earthquake along the Japan Trench, which was released by the central government in July 2002, until it finally calculated tsunami behavior on the basis of that forecast for the first time in March 2008[2]. The calculations found the tsunami waves would reach a height of 15.7 meters in a southern part of the Fukushima Daiichi nuclear power plant site. But TEPCO took no measures against the tsunami, which was expected to far exceed the plant ground level of 10 meters, until the plant was flooded by a 15.5-meter tsunami on March 11, 2011. This is what the “unforeseeable” tsunami was all about.

According to newspaper reports, however, TEPCO and the Federation of Electric Power Companies of Japan are refusing to submit documents pertaining to their trial calculations on tsunami and on vulnerability to tsunami, despite court demands as part of lawsuits going on at the Kobe District Court and elsewhere[3].

The background of the erroneous decision remains hidden in the darkness on this front, too.

Another panel of the Central Disaster Management Council (committee for technical investigation on countermeasures for trench-type earth-

Originally printed in *Kagaku (Science Journal)*, Vol. 86, No. 7 (July 2016), pp. 653–660

Translated by Taku Tada from the Japanese

quakes in the vicinity of the Japan Trench and Chishima Trench) decided to have the scenario of a tsunami earthquake along the Japan Trench, released in 2002 by the Earthquake Research Committee, a separate body of the central government (i.e. the same tsunami earthquake scenario that TEPCO ignored as stated above), excluded from the countermeasures and prepare for a recurrence of the Meiji Sanriku tsunami of 1896, whose chances were low. The decision was the product of high-handed proceeding of sessions, which ignored the opposing views of many panel members[4].

The panel estimated that a recurrence of the Meiji Sanriku tsunami would result in a maximum of 2,700 deaths[5]. By contrast, the Great East Japan Earthquake and tsunami left more than 18,000 dead or missing. Nearly 80% of all those victims perished in areas flooded by tsunami waves that measured at least twice the heights of the Meiji Sanriku tsunami[6]. So big was the death toll from the wrong forecast.

An error, left unmended, is a recipe for another error. This time around, risks of tsunami in the Sea of Japan are being underestimated.

A report released in September 2014 by a panel of the Ministry of Land, Infrastructure, Transport and Tourism (investigation panel on large-scale earthquakes in the Japan Sea; presided by Katsuyuki Abe, a professor emeritus of seismology with the University of Tokyo and head of the Association for the Development of Earthquake Prediction) estimated models of "maximum-class" tsunami faults in the Sea of Japan and presented tsunami height forecasts for different locations[7]. But the report underestimates tsunami scenarios in the western part of the Sea of Japan, or to be more specific, west of the Noto Peninsula. The tsunami height estimates are not only less than "maximum" in scale, but sometimes even fall short of being average in scale[8]. The advent of another "unforeseeable" tsunami disaster would not be surprising in the least if countermeasures were to be taken on the basis of those wrong assumptions.

This article will first present a case where a "maximum-class" Japan Sea tsunami scenario is less than maximum-class, and subsequently show the reason lies in the use of the formula of Irikura and Miyake (2001)[9] (hereinafter referred to as the Irikura-Miyake formula) for estimating the seismic source size. I will compare it with other formulas proposed in the past and show that its forecasts are much smaller than actual values. I will also take the example of the April 16, 2016, Kumamoto earthquake and conclude that the Irikura-Miyake formula should not be applied to vertical and near-vertical geological faults. I will finally give a few words about how dreadful the consequences would be if the use of the Irikura-Miyake formula were to turn into an accomplished fact.

How Japan Sea tsunami scenarios are underestimated

Underestimated here are the scenarios of tsunami in the western part of the Japan Sea—to be more specific, along coastlines west of the Noto Peninsula, for reasons to be explained later. The tsunami height forecasts are smaller, because the seismic source sizes have not been estimated properly. That is why the tsunami height estimates are less than "maximum" in scale, and sometimes even fall short of being average in scale. Most of those tsunami waves are expected to be generated by seismic sources along vertical or near-vertical geological faults underground. The sizes of those seismic sources have been underestimated because an inadequate formula has been used, and the tsunami waves have been underestimated accordingly.

Let me take one example here to study the scenario of a tsunami that is labeled "maximum-class." The same would go for any other example.

I am taking the case of a vertical fault off the Tango Peninsula, which is called the "F54 fault" in the tsunami fault models report. It represents an extension of the Gomura fault, an active geological fault on land. The report says the highest possible tsunami along the Japan Sea coast of Hyogo Prefecture, namely in the city of Toyooka, the town of Kami and the town of Shin-Onsen, would be generated by this fault. The report cites the fault as 58 km long, 14 km wide and with a surface area of 799 km^2.

A source of earthquake shocks (seismic source) is formed when underground rock bodies slip past each other, namely, when a geological fault is generated. Faults have near-rectangular shapes. The surface area of a fault can therefore usually be obtained from the fault length (length of the longer side of the rectangle) and width (length of the shorter side). Simple formulas have been proposed to describe the relationship between the fault area and what I will call the "seismic source size" ("seismic moment" in scientific terms). As shown in the following, there are also formulas that associate the "seismic source size" with the fault length.

The report on the Japan Sea tsunami scenarios used the Irikura-Miyake formula, which can be rewritten and simplified into equation (1) below, where S (km^2) refers to the fault area and M_0 (Nm) is the "seismic source size":

$$M_0 = 5.562 \times 10^{13} \times S^2. \qquad (1)$$

Likewise, the amount of slip along the fault, u (in meters; strictly speaking, the slip averaged over the fault surface, or the mean slip), can also be obtained by equation (2) below:

$$u = 1.622 \times 10^{-3} \times S. \qquad (2)$$

These and the following equations merely represent formulas for calculating numerical values, so I have rewritten them into a format that non-experts will find easier to understand.

A fault slip of 1.30 meters is obtained by using equation (2) from the surface area of the F54 underwater fault off the Tango Peninsula. The report on the Japan Sea tsunami fault models follows the practice of adding 1.5 meters to take account of possible variance in slip values from one seismic event to another. This is a recommendable practice to be used in evaluating maximum-class tsunami heights. Following the addition, the slip is obtained as 2.80 meters, which is precisely the three-digit figure given in Table 6 of the report.

"Large-slip zones," with twice the mean slip, were defined in the Japan Sea tsunami fault models. This assumption, intended to be realistic, was rightly taken into account for evaluating maximum-class events. Furthermore, vertical shift components were added, wherever faults are believed to shift horizontally, so that the tsunami heights will be larger, which is also thought to be an adequate approach. Given that all these measures were taken, even experts may be led to believe, at first glance, that the models do represent "maximum-class" events.

While the report used the Irikura-Miyake formula, it is customary, in the screening of "design basis tsunami" at nuclear power plants, to use the formula of Takemura (1998)[10] to estimate the "seismic source size." The latter formula can be rewritten and simplified into equation (3) below, where L (km) denotes the fault length:

$$M_0 = 4.365 \times 10^{16} \times L^2. \qquad (3)$$

Likewise, the fault slip u (in meters) can also be obtained from equation (4) below:

$$u = 1.273 \times L/W, \qquad (4)$$

where W (km) represents the fault width.

The F54 underwater fault has a length L=58 km and a width W=13.9 km, so the slip is obtained as 5.3 meters, which becomes 6.8 meters when the variance is included. That is more than twice the estimate of 2.8 meters from the Irikura-Miyake formula and, even without the inclusion of the 1.5-meter variance, nearly twice the latter.

In a similar manner, the formula of Yamanaka and Shimazaki (1990)[11] allows the "seismic source size" and the slip to be obtained as follows:

$$M_0 = 3.802 \times 10^{16} \times L^2 \qquad (5)$$

$$u = 1.108 \times L/W. \qquad (6)$$

The above equation gives a slip of 4.6 meters, or 6.1 meters when the variance is included, which is much larger than the output of the Irikura-Miyake formula. The same goes for other examples.

Column: Seismic moment

The seismic moment M_0 (referred to as the "seismic source size" in this article) is equal to the product of the fault area S, the slip u, and the modulus of rigidity μ[12], or

$$M_0 = \mu \times u \times S,$$

where the modulus of rigidity is the indicator of a certain kind of rock stiffness. It indicates the difficulty of rock deformation in response to application of forces that work to cause a fault to slip. The report on the Japan Sea tsunami fault models set the modulus of rigidity at 3.43×10^{10} Nm, so I am using that same value in this article.

Equation (2), which gives the amount of slip, is derived from the above equation and equation (1); equation (4) from the above equation and equation (3); and equation (6) from the above equation and equation (5).

The report says that tsunami waves generated by the F54 fault would be up to about 3 to 5 meters high along the coast of Hyogo Prefecture. But the tsunami could be up to at least about 6 to 10 meters high if Takemura's, or Yamanaka and Shimazaki's, formula were to be more appropriate. It should never be forgotten that 80% of all victims of the Great East Japan Earthquake and tsunami were killed or went missing in areas flooded by at least twice the tsunami height forecasts.

Irikura-Miyake formula as compared with available alternatives

One is tempted to ask why the outputs of the formulas are so different.

While Yokota et al. (2016)[13], where Yokota is a member of the panel on the Japan Sea tsunami fault models, have set about studying the formulas, I suppose the reason lies in the different data that were used to derive those formulas. The Irikura-Miyake formula dealt with data from around the world, whereas the other formulas dealt with data from Japan alone.

This article calls into question only tsunami waves in the western part of the Japan Sea or, to be more specific, west of the Noto Peninsula. Those tsunami waves are generated by vertical or near-vertical geological faults, which mostly shift horizontally. On the contrary, most geological faults in the eastern part of the Japan Sea are inclined and have large vertical shift components. Earthquakes that occur beneath the Japanese Islands and the surrounding waters, including but not limited to the Sea of Japan, have similar characteristics.

The Irikura-Miyake formula is problematic only when the geological fault being studied is vertical or near-vertical. Many geological faults in western Japan fit that description. No problem arises, by contrast, when the geological fault being studied is inclined. That is why this article does not call into question tsunami waves in the eastern part of the Japan Sea.

I will now explain why problems arise only with vertical or near-vertical faults.

Earthquakes that generate tsunami waves are shallow events. The lower end of the faults of shallow earthquakes that occur beneath the Japanese Islands and the surrounding waters (including the Sea of Japan) have a near-invariant depth of about 15 km. The F54 fault, illustrated above, is vertical, with a lower end depth of 15.0 km and an upper end depth of 1.1 km, and is therefore 13.9 km wide.

Why, then, do faults have an invariant lower end depth?

Earthquakes occur within what is called the seismogenic layer, which is about 15 km thick, and do not occur at greater depths. When a fault grows larger, the bottom of the seismogenic layer defines the lower end of the fault, because the latter cannot outgrow the seismogenic layer. That sets a limit on the fault width[14], which is about 14 km for a vertical fault. Faults do not have an upper end at 0 km, because near-surface soil is made of relatively soft rock, which is believed to be incapable of generating earthquakes.

Even when the fault length remains the same, an inclined fault has a larger width, and hence a larger area. The fault width is the smallest, and so is the fault area, when the fault is vertical. As shown in equation (1), the smaller the fault area, the smaller is the "seismic source size" to be estimated by the Irikura-Miyake formula. Even when the fault length remains the same, the Irikura-Miyake formula gives the smallest "seismic source size" when the fault is vertical, and a larger "seismic source size" as the fault inclination comes closer to being horizontal.

As a matter of consequence, it gives an estimate that is close to the output of Takemura's and the other formulas when the inclination is near-horizontal. This is why problems arise only when the fault is vertical or near-vertical, and only with tsunami waves in the western part of the Sea of Japan.

Let me now take the simple example with a fault width W of 14 km. Equations (2), (4) and (6), which give the amount of slip, can then be rewritten into the following equations (7), (8) and (9), respectively, all in the same format. The same goes for the equations for the "seismic source size."

$$u = 2.27 \times 10^{-2} \times L \quad \text{[Irikura-Miyake formula]} \; (7)$$

$$u = 9.04 \times 10^{-2} \times L \quad \text{[Takemura's formula]} \; (8)$$

$$u = 7.91 \times 10^{-2} \times L \quad \text{[Yamanaka-Shimazaki formula]} \; (9)$$

For a typical vertical fault with a width W of 14 km, the Irikura-Miyake formula gives a slip estimate that is about 3.5 to 4 times smaller than the output of the other formulas, irrespective of the fault length L.

Underestimations by the Irikura-Miyake formula (for vertical and near-vertical geological faults)

I have demonstrated that estimates obtained from the Irikura-Miyake formula are smaller than the output of the other formulas. But all estimates have to be compared with the actual values so as to find out which of the formulas being proposed is the best. One way to do so is to study earthquakes that occurred in the past in Japan, for which the fault area, the fault length and the "seismic source size" are known, and to find out which of the formulas gives the best fit.

I have to point out that, in fact, another question is involved here—the question of prior information. In other words, accurate estimates of the fault area and the fault length are not available before a seismic event happens. That could lead to inaccurate estimates of the "seismic source size."

The formulas that have so far been proposed are based on information obtained after an earthquake. The relationship between the fault area and the "seismic source size," and the relationships between the fault length and the "seismic source size," were derived by using information that was obtained post-seismically, but was unknown pre-seismically. The question of underestimations can therefore be divided into two component parts[15]:

[1] The fault area and the fault length become definitely known only after a seismic event. Their values are not necessarily equal to estimates that are available in advance. In fact, they sometimes exceed prior estimates. In the case of the April 16, 2016, magnitude-7.3 Kumamoto earthquake, the source fault extended 7 km further east of the eastern end of the active fault estimated in advance[16].

[2] When the fault being studied is vertical or near-vertical, the Irikura-Miyake formula gives a "seismic source size" estimate that is significantly smaller than the output of the Takemura formula and the Yamanaka-Shimazaki formula. As will be shown below, it is about 3.5 times smaller than the actual "seismic source size." This article focuses on question [2]. I will later refute the argument that question [1] is more relevant.

I evaluated the "seismic source sizes" of earth-

Table 1—"Seismic source size" (seismic moment) estimates from the different formulas being proposed, and the realized values (in units of 10^{19} Nm)

	Realized value	Equation (1) [Irikura-Miyake]	Equation (3) [Takemura]	Equation (5) [Yamanaka-Shimazaki]
1891 Nobi earthquake	18	5.2	21	18
1930 Kita-Izu earthquake	2.7	0.79	3.2	2.8
2011 earthquake in eastern Fukushima Prefecture	1.1	0.55	1.7	1.4

quakes that actually occurred in Japan by using fault lengths that had been, or would have been, estimated in advance, and found that the output of the Irikura-Miyake formula did represent underestimates. The fault lengths that "would have been" estimated beforehand, which I mentioned above, cannot be completely free of subjectivity. Table 1 shows three cases, which supposedly gave the most objective results.

In studying the 1891 Nobi earthquake, I used a figure from "*Active Faults in Japan: Sheet Maps and Inventories*" (revised edition)[17] to define the distance of 69 km, measured from the northern end of the Nukumi fault to the eastern end of the Mitahora fault, as the length of the source fault. The "seismic source size" of the event, estimated by Fukuyama et al. (2007)[18] from seismometer records in Tokyo, was used for its realized value.

Another figure from "*Active Fault in Japan*" (revised edition) was used to study the 1930 Kita-Izu earthquake, whereby the distance of 27 km, measured from the northern end of the Kita-Izu fault system b to the southern end of the Sano fault, was defined as the source fault length. The "seismic source size" estimate of Abe (1978)[19], who used geodetic survey results, was used as the realized value.

For the event that occurred in eastern Fukushima Prefecture a month after the Great East Japan Earthquake, I used TEPCO's prior estimate of 19.5 km for the length of the Idosawa fault[20]. The "seismic source size" estimate of Hikima (2012)[21], obtained from strong motion records, was taken for the realized value.

Table 1 shows it is never easy to accurately forecast the "seismic source size" in advance of an earthquake. The evaluations based on the Irikura-Miyake formula, however, obviously represent underestimates with respect to the other formulas. They are about 3.5 times smaller than appropriate values, if the output of the Yamanaka-Shimazaki formula is to be deemed appropriate.

When I had an opportunity to give a talk on what I believe to be the underestimations of the Japan Sea tsunami fault models (a Friday seminar at the Earthquake Research Institute, the University of Tokyo, December 2015), one member of the investigation panel on large-scale earthquakes in the Japan Sea presented a counterargument, whereby he said that fault length data were not used in working out the tsunami fault models, which are instead based on source fault areas estimated from the output of underwater seismic explorations, and which are therefore reliable.

He was arguing, in essence, that question [1], or that of prior estimation, is the more relevant of questions [1] and [2], which I mentioned above. As illustrated by the example of the Kumamoto earthquake, the actual fault length is certainly sometimes larger than the fault length estimated from active fault studies. While the Futagawa fault was believed to have an eastern end at the foot of Mount Aso's caldera wall, the fault of the Kumamoto earthquake extended further east into the Aso caldera[22].

Things like that may sometimes be the case, but the main culprit is the underestimations by the Irikura-Miyake formula. In one earthquake that actually happened (the example below), the "seismic source size" and the fault slip, calculated by using data obtained after the earthquake and the Irikura-Miyake formula, turned out to be much smaller than their actual values. Regardless of the question of prior estimation, there invariably is the question of underestimations by the Irikura-Miyake formula.

Let me take one example.

The Kita-Izu earthquake, included in Table 1, occurred on vertical geological faults (including the Tanna fault). Abe (1978) estimated its fault length at 22 km, its fault width at 12 km, and the amount of slip at 3 meters. These estimates well explain actual geodetic survey results. In the meantime, the slip is obtained as 0.43 meter when the fault area S is set at 22×12 km^2 in equation (2), which is based on the Irikura-Miyake formula. Adding a variance of 1.5 meters on top of that only makes 1.9 meters, which is short of the slip of 3 meters that was estimated by Abe (1978).

By contrast, equations (4) and (6) give slip estimates of 2.3 meters and 2.0 meters, respectively. They both exceed the slip of 1.9 meters estimated with the approach used in defining the "maximum-class" tsunami fault models (the slip amount obtained by adding variance on top of the slip estimate from the Irikura-Miyake formula). This implies the "maximum-class" tsunami scenarios are not only less than "maximum-class" but sometimes even fall short of being average.

A geological fault about the same size of that of the Kita-Izu earthquake has been modeled beneath the Japan Sea—the "F50 fault" off southern Ishikawa Prefecture. It is 23.7 km long, 11.8 km wide and is inclined at 60 degrees. The slip estimate is 1.95 meters, including the 1.5-meter variance. By contrast, the slip is obtained as 2.5 meters and 2.2 meters from equations (4) and (6), respectively. These exceed the "maximum-class" estimate of 1.95 meters, even without the inclusion of a 1.5-meter variance. Addition of the 1.5-meter variance makes 4.0 meters and 3.7 meters, respectively, about twice the "maximum-class" estimate.

2016 Kumamoto earthquake and the Irikura-Miyake formula

Let me now apply the Irikura-Miyake formula to the magnitude-7.3 Kumamoto earthquake of April 16, 2016, which occurred along the Futagawa-Hinagu fault zone. Global Navigation Satellite System (GNSS) stations in Kyushu have shown evidence of large crustal deformations accompanying this earthquake, which was generated by a right-lateral horizontal shift across a northwest-dipping fault.

The Geospatial Information Authority of Japan (GSI) initially estimated, on a provisional basis, the source fault surface to be inclined at 60 degrees, 27.1 km long and 12.3 km wide (provisional solution 1), with a fault area of 333 km^2. The GSI later said the source fault comprises three surfaces, with a total fault area of 416 km^2 (provisional solution 2)[23]. Substitution of these values into equation (1) gives "seismic source size" estimates of 0.62×10^{19} Nm and 0.96×10^{19} Nm, respectively (the former follows from provisional solution 1, whereas the latter follows from provisional solution 2; the same goes hereinafter). Likewise, the slip is obtained from equation (2) as 54 cm and 67 cm, respectively. These estimates based on the Irikura-Miyake formula are much smaller than the slip of 3 meters in the single-fault model (provisional solution 1) and any of the slip amounts of 4.1 meters, 3.8 meters and 2.7 meters on each of the three fault surfaces, respectively (provisional solution 2; the mean slip is 3.6 meters).

The following estimates were obtained for the "seismic source size" of this earthquake from the analysis of various waves observed around the world, strong-motion records taken near the seismic source, and other data: 4.06[24], 4.46[25], 4.66[26], 4.67[27] and 5.3[28] (in units of 10^{19} Nm). These far exceed the estimates of 0.62 and 0.96, obtained above by using the fault areas of the GSI fault models and the Irikura-Miyake formula. The median of these values, namely the estimate of 4.66×10^{19} Nm obtained by the U.S. Geological Survey, will be used hereinafter.

The actual fault area could have been larger than presumed in the GSI models, which were obtained by using the assumption of constant slip. The surface outcrop distribution of the earthquake faults, which has been studied closely, gives a fault length estimate of 31 km[29]. If the fault, inclined at about 60 degrees, is assumed to be 16 km wide, that gives a fault area estimate of 496 km^2. This, combined with the Irikura-Miyake formula, gives a "seismic source size" of 1.37×10^{19} Nm from equation (1). The actual value was 3.4 times that estimate, which evidently shows an underestimation by the Irikura-Miyake formula. The slip is calculated, from equation (2) based on the Irikura-Miyake formula, at 80 cm, which is again smaller than the actual value.

Strong motion near a seismic source depends on behavior of the fault slip (how it varies from one location to another and how it changes with time), so the forecast of strong motion requires detailed analysis. When it comes to assessing "design basis earthquake ground motion" at nuclear power plants, however, a proposal has been made to use a formula saying that the short-period spectral levels are proportional to the cubic root of the "seismic source size" (seismic moment) (Dan et al., 2001)[30]. That means that, if the actual "seismic source size" were 3.4 times the estimate from the Irikura-Miyake formula as stated above, the actual short-period spectral levels would be about 50% larger than what would be expected on the basis of the Irikura-Miyake formula.

While Takemura's formula is being used in working out design basis tsunami heights, the Irikura-Miyake formula is being used more commonly in working out design basis earthquake ground motion levels. The practice of estimating earthquake ground motion on the basis the Irikura-Miyake formula should be reviewed.

Apart from the 1930 Kita-Izu earthquake mentioned above, I also used the Irikura-Miyake formula in a similar manner to calculate the "seismic source sizes" of the 1927 Tango earthquake and the 1943 Tottori earthquake from the fault areas of the respective events, whereupon I found the estimates were remarkably smaller than measurements[31]. The fault slip estimates, obtained from equation (2), were also much smaller than estimates available from geodetic survey results.

Most part of the deformations that can be shown from geodetic surveys occur co-seismically, so such deformations can be presumed to have been caused by earthquakes, but I had no direct evidence of that for the above-mentioned earthquakes that occurred during the Showa Era (1926–1989). Geodetic survey results of the time may include pre-seismic and post-seismic deformations, so I needed geodetic survey results with higher time resolution in order to show definitely that the Irikura-Miyake formula gives underestimates.

Continuous GNSS observations were active when the Kumamoto earthquake struck, so it is possible to find out when deformations occurred. Observations indicate that no major deformations took place before or after the earthquake[32]. It can therefore be concluded that the amount of co-seismic slip, estimated by using the fault area and the Irikura-Miyake formula, is remarkably smaller than the actual slip as stated above.

Some may argue that the Irikura-Miyake formula may be giving smaller estimates of the seismic moment simply because underestimated fault area values are used. But the spatial extent of the earthquake-induced deformations is known unambiguously from synthetic aperture radar (SAR) observations by the Daichi-2 (ALOS-2) satellite.

Given the "seismic source size" of 4.7×10^{19} Nm, estimated from seismic wave observations, and the fault width of 16 km, the fault length that would satisfy the Irikura-Miyake formula is obtained as 57 km.

But the GSI's interferometric SAR image[33] indicates that the eastern end of the source fault is likely located west of 131.05 degrees east longitude. It is obvious that the fault length is much smaller than 57 km.

When the fault length $L=31$ km is used, by the way, the Takemura formula and the Yamanaka-Shimazaki formula give "seismic source size" estimates of 4.2 and 3.7 (in units of 10^{19} Nm) from equations (3) and (5), respectively. These are both smaller than the actual value of 4.7, but the mismatch is less than 30%, well within the range of measurement errors.

Conclusion

The "maximum-class" Japan Sea tsunami scenarios, set forth as unified models to be used by Japan's prefectural governments, are less than maximum-class in the western part of the Sea of Japan. Another "unforeseeable" disaster would result if tsunami countermeasures were to proceed in line with them.

The reason lies in the use of the Irikura-Miyake formula in dealing with vertical and near-vertical geological faults. Their "seismic source sizes" (seismic moments) are underestimated to be about 3.5 times smaller than the actual values. The Irikura-Miyake formula should not be used in estimating the "seismic source sizes" (seismic moments) of large earthquakes that could occur along vertical and near-vertical geological faults beneath the Japanese Islands.

A proposal has been made to use a formula that says that the levels of strong motion (short-period spectral levels) near a seismic source is proportional to the cubic root of the "seismic source size" (seismic moment). It follows from that formula that the actual strong motion levels would be 50% larger than what would be expected from the Irikura-Miyake formula.

Many of the geological faults in western Japan are vertical or near-vertical. The Irikura-Miyake formula is used commonly in the assessment of earthquake ground motion at nuclear power plants. The advent of another "unforeseeable" accident would not be surprising if the actual levels of strong motion (short-period spectral levels) were to be 50% larger than design values.

The Irikura-Miyake formula was used to develop the "maximum-class" Japan Sea tsunami fault models, and accordingly, tsunami scenarios that are less than maximum-class have been set forth as "maximum-class" in the western part of the Japan Sea, or west of the Noto Peninsula. Newspaper reports say more than one prefectural government has already adopted those models[34]. If nothing were to be done about this, the practice of using the Irikura-Miyake formula in dealing with vertical and near-vertical geological faults would turn into an accomplished fact. The use of that formula in the estimation of tsunami heights and strong motion levels could induce a repeat of an "unforeseeable" disaster or accident. The same error should not be repeated.

Supplementary Note

The Central Disaster Management Council's "committee for technical investigation on countermeasures for Tonankai, Nankai and other earthquakes" also dealt with inland earthquakes in the Chubu and Kinki regions[35]. As a member of that panel, I worked with the secretariat in developing fault models of earthquakes that occur along active faults. The formula adopted by the Central Disaster Management Council at the time can be rewritten, in the same format used in this article, as:

$$M_0 = 1.950\times10^{16}\times L^{2.2}.$$

When the fault length $L=31$ km is used, the above formula gives a "seismic source size" of 3.7×10^{19} Nm for the Kumamoto earthquake, the same value obtained from the Yamanaka-Shimazaki formula.

The official who was in charge of the matter at the secretariat later pushed the Japan Sea tsunami fault models as a member of the panel that worked them out. I do not quite understand why he preferred to adopt the Irikura-Miyake formula.

References

1—Committee for Technical Investigation on Countermeasures for Earthquakes and Tsunamis Based on the Lessons Learned from the "2011 off the Pacific Coast of Tohoku Earthquake," Central Disaster Management Council: *Report of the Committee for Technical Investigation on Countermeasures for Earthquakes and Tsunamis Based on the Lessons Learned from the "2011 off the Pacific Coast of Tohoku Earthquake*," Sept. 28, 2011, http://www.bousai.go.jp/kaigirep/chousakai/tohokukyokun/pdf/Report.pdf

2—Investigation Committee on the Accident at the Fukushima Nuclear Power Stations of Tokyo Electric Power Company: *Interim Report*, Dec. 26, 2011, http://www.cas.go.jp/jp/seisaku/icanps/eng/interim-report.html

3—See, e.g., "FEPC refuses to submit trial calculations on vulnerability to tsunami," Kobe Shimbun, April 7, 2016; "TEPCO refuses to submit trial tsunami calculations," *Kobe Shimbun*, Sept. 17, 2015 (both in Japanese)

4—Shimazaki, K.: Kagaku, **81**, 1002 (2011) ; Soeda, T.: "*Gempatsu to O-Tsunami*: *Keikoku wo Homutta Hitobito*" (Nuclear plants and the great tsunami: Those who ignored warnings), Iwanami Shinsho (2014) (both in Japanese)

5—Committee for technical investigation on countermeasures for trench-type earthquakes in the vicinity of the Japan Trench and Chishima Trench, Central Disaster Management Council: *Report of the committee for technical investigation on countermeasures for trench-type earthquakes in the vicinity of the Japan Trench and Chishima Trench*, Jan. 25, 2006, http://www.bousai.go.jp/kaigirep/chuobou/senmon/nihonkaiko_chisimajishin/pdf/houkokusiryou2.pdf (in Japanese)

6—Shimazaki, K.: *Zisin (J. Seismol. Soc. Japan)*, *Ser. 2*, **65**, 123 (2012) (in Japanese with English abstract)

7—Investigation panel on large-scale earthquakes in the Japan Sea: *Report of the investigation panel on large-scale earthquakes in the Japan Sea*, Sept. 2014, http://www.mlit.go.jp/river/shinngikai_blog/daikibojishinchousa/houkoku/Report.pdf (in Japanese)

8—Shimazaki, K.: *Proceedings of the 2015 fall meeting of the Japanese Society for Active Fault Studies*, O-13, 2015 (in Japanese)

9—Irikura, K., and H. Miyake: *J. Geography*, **110**, 849 (2001) (in Japanese with English abstract)

10—Takemura, M.: *Zisin (J. Seismol. Soc. Japan)*, *Ser. 2*, **51**, 211 (1998) (in Japanese with English abstract)

11—Yamanaka Y., and K. Shimazaki: *J. Phys. Earth*, **38**, 305 (1990)

12—See, e.g., Aki, K., and P. G. Richards: *Quantitative Seismology*, W. H. Freeman (1980)

13—Yokota, T., M. Nemoto, M. Goto, K. Takata, and M. Ikeda: *Japan Geoscience Union Meeting 2016*, SSS31-08 (2016)

14—Shimazaki, K.: *Earthquake Source Mechanics*, 209, American Geophysical Union (1986)

15—Shimazaki, K., *Japan Geoscience Union Meeting 2015*, SSS28-07 (2015)

16—Kumahara, Y.: Surface outcrop distribution and characteristics of the earthquake faults of the 2016 Kumamoto earthquake, *Documents presented at the 211th meeting of the Coordinating Committee for Earthquake Prediction*, *Japan* (2016) (in Japanese)

17—Research Group for Active Faults of Japan: *Active Faults in Japan*: *Sheet Maps and Inventories*, revised edition, University of Tokyo Press (1991) (in Japanese)

18—Fukuyama, E., I. Muramatu, and T. Mikumo: *Earth Planets Space*, **59**, 553 (2007)

19—Abe, K.: *J. Phys. Earth*, **26**, 253 (1978)

20—Tokyo Electric Power Co., *Assessment of anti-seismic safety at the Fukushima Daiichi nuclear power station and the Fukushima Daini nuclear power station in light of the new anti-seismic guidelines (Outline of the interim report)*, April 14, 2008 (in Japanese)

21—Hikima, K.: *Zisin (J. Seismol. Soc. Japan)*, *Ser. 2*, **64**, 243 (2012) (in Japanese with English abstract)

22—See 16

23—Geospatial Information Authority of Japan: *The 2016 Kumamoto earthquake*: *subject of intensive discussions at the 211th meeting of the Coordinating Committee for Earthquake Prediction*, *Japan*, May 18, 2016 (in Japanese)

24—Japan Meteorological Agency: *CMT solution (in detail)*, http://www.data.jma.go.jp/svd/eqev/data/mech/cmt/fig/cmt20160416012505.html (in Japanese)

25—The Global CMT project: The CMT catalog, http://www.globalcmt.org/CMTsearch.html

26—USGS Earthquake Hazards Program: *M7.0-0km ENE of Kumamoto-shi*, *Japan*, *Moment Tensor*, http://earthquake.usgs.gov/earthquakes/eventpage/us20005iis#moment-tensor?source=us&code=us_20005iis_m ww

27—Division of Earthquake Disasters, Disaster Prevention Research Institute, Kyoto University: *Documents presented at the 211th meeting of the Coordinating Committee for Earthquake Prediction*, *Japan* (2016) (in Japanese)

28—National Research Institute for Earth Science and Disaster Resilience: *Documents presented at the 211th meeting of the Coordinating Committee for Earthquake Prediction*, *Japan* (2016) (in Japanese)

29—See 16

30—Dan, K., M. Watanabe, T. Sato, and T. Ishii: *J. Struct. Constr. Eng. (Trans. AIJ)*, **545**, 51 (2001) (in Japanese with English abstract)

31—Shimazaki, K.: *Japan Geoscience Union Meeting 2016*, HDS19-12 (2016)

32, 33—See 23

34—See, e.g., "Fukuoka, Saga prefectures to use central government standards," *Nishinippon Shimbun*, page 3, Feb. 21, 2016 (in Japanese)

35—Committee for technical investigation on countermeasures for Tonankai, Nankai and other earthquakes,
Central Disaster Management Council: *Report on inland earthquakes in the Chubu and Kinki regions*, Dec. 2008 (in Japanese)