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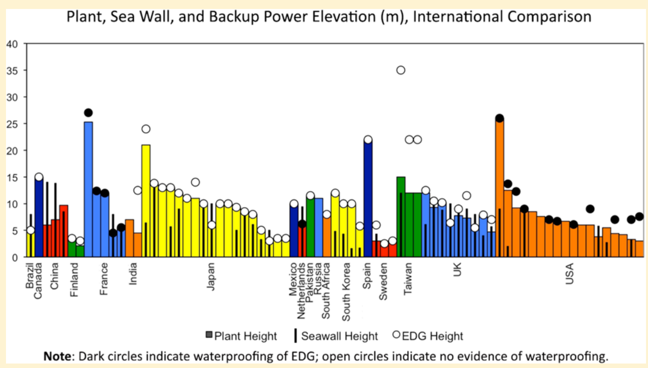
The Fukushima Disaster and Japan's Nuclear Plant Vulnerability in Comparative Perspective

Phillip Y. Lipscy,[†,*] Kenji E. Kushida,[‡] and Trevor Incerti[§]

[†]Department of Political Science and Shorenstein Asia-Pacific Research Center, Stanford University, Stanford, California 94305
[‡]Walter H. Shorenstein Asia-Pacific Research Center, Stanford University, Stanford, California 94305
[§]Walter H. Shorenstein Asia-Pacific Research Center, Stanford University, Stanford, California 94305

Supporting Information

ABSTRACT: We consider the vulnerability of nuclear power plants to a disaster like the one that occurred at Fukushima Daiichi. Examination of Japanese nuclear plants affected by the earthquake and tsunami on March 11, 2011 shows that three variables were crucial at the early stages of the crisis: plant elevation, sea wall elevation, and location and status of backup generators. Higher elevations for these variables, or waterproof protection of backup generators, could have mitigated or prevented the disaster. We collected information on these variables, along with historical data on run-up heights, for 89 coastal nuclear power plants in the world. The data shows that 1. Japanese plants were relatively unprotected against potential inundation in international comparison, but there was considerable variation for power plants within and outside of Japan; 2. Older power plants and plants owned by the largest utility companies appear to have been particularly unprotected.



INTRODUCTION

The Fukushima disaster, triggered by an earthquake and tsunami on March 11, 2011, affected several nuclear plants in Japan simultaneously. We show that three variables were crucial during early stages of the disaster: plant elevation, sea wall elevation, and location and status of backup generators. Higher elevations for any of these three variables, or watertight protection of backup emergency diesel generators (EDGs) and electrical circuits, would have likely prevented the disaster at Fukushima Daiichi NPP. The nature of the Fukushima disaster also allows for comparative study that was not possible for earlier nuclear accidents, which had complex causes not easily subject to quantification. We present data on vulnerability to inundation for all seaside NPPs worldwide (89 NPPs in 20 countries).

Most existing studies of the Fukushima disaster have singled out failures specific to Japan. These include inadequacies in Japan's nuclear regulatory structures,[1−8] insufficient disaster preparedness,[1−9] and even culture.[4] However, these conclusions are primarily based on the outcome at a single plant, Fukushima Daiichi. Without domestic and international comparisons, it cannot be established that problems specific to Japan were responsible for the disaster.

The March 11, 2011 earthquake and tsunami affected four plants: Fukushima Daiichi (INES 7), Fukushima Daini (INES 3), Onagawa (INES 1), and Tōkai Daini.[10] Table 1 presents information on the impact of the earthquake and tsunami for each of these plants. The first three columns present information on distance from earthquake epicenter, ground acceleration associated with the earthquake, and tsunami height. As the table shows, the severity of the earthquake and tsunami is not directly related to the outcome at each plant. Onagawa was closer to the epicenter and hit by a tsunami about as high as the one at Fukushima Daiichi, but survived relatively unscathed.

The last three columns of Table 1 show the post-tsunami status of off-site power and on-site EDGs and INES levels. The plants and reactors in which either off-site power or on-site backup electricity generation capacity survived avoided core meltdowns. Those that lost both—Fukushima Daiichi reactors 1−3—suffered meltdowns. While the earthquake severed off-site power lines, the tsunami was the crucial factor that led to disaster. The tsunami destroyed Fukushima Daiichi's primary seawater pump cooling system, and rendered the EDGs necessary to run the backup pumps inoperable. Had the earthquake been an isolated incident, the plant's EDGs would have provided backup power until off-site power was restored. Fukushima Daiichi lost 12 of 13 EDGs.[10] As a result, reactors 1, 2, 3, and 4 were unable to be cooled, leading to the meltdowns in reactors 1−3. The plant's one functional generator cooled

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Table 1. Damage and INES Level of Four Japanese NPPs Hit by Earthquake and Tsunami

	distance from epicenter	ground acceleration (maximum gal)	tsunami height	sea wall height	plant height	EDG hight	surviving off-site power lines	srviving EDGs	INES lvel
Fukushima Daiichi	180 m	550 gal	13 m	10 m	10 m	10 m	0/6	1/13	7
Fukushima Daini	190 m	305 gal	9 m	9 m	12 m	12 m	1/4	3/12	3
Onagawa	70 m	607 gal	13 m	14 m	13.8 m	13.8 m	1/5	6/8	1
Tōkai	280 m	214 gal	4.6 m	6.1 m	8 m	8 m	0/3	2/3	0

reactors 5 and 6, which were undergoing maintenance at the time.

At Fukushima Daini, 3 of 12 EDGs survived the tsunami, enabling reactors 3 and 4 to be cooled until the surviving off-site power lines were rerouted.[10] At Onagawa, 6 of 8 EDGs remained intact.[10] Tōkai Daini lost all off-site power for two days, but the survival of 2 of 3 EDGs enabled the reactor to be cooled until off-site power was restored.[10]

Off-site power can be severed by a variety of events, such as terrorism, tornadoes, hurricanes, and other disasters. During such events, maintaining the integrity of on-site backup power is crucial. The Tōkai Daini NPP illustrates this; the plant experienced a complete loss of off-site power, but achieved cold shutdown because most EDGs survived the tsunami.

In the Japanese NPPs, off-site power was compromised due to the earthquake, while on-site backup power sources were damaged by the tsunami.[1,3−7,9,10] Table 1 also includes information on plant elevation above sea level, seawall heights, and EDG elevation above sea level. Comparing the plants affected by the tsunami, clear variation exists in plant height and sea wall height relative to the tsunami. The Onagawa power plant's 14 m sea wall was adequate for a 13 m tsunami, the same height as the tsunami that overwhelmed the 10 m sea wall at Fukushima Daiichi. Although the height of the tsunami was below plant elevation at Fukushima Daini, the plant was partially flooded as water reached as high as 14.5 m in part of the plant location due to local geography.[11] Tōkai Daini was partially flooded by a 4.6 m tsunami as its 6.1 m seawall was being retrofitted at the time and was not watertight.[12]

Higher values for plant height, seawall height, and/or EDG height, or adequate waterproofing of EDGs, would have prevented or substantially mitigated the disaster at Fukushima Daiichi.[1−7,9] Higher plant elevation would have prevented the tsunami from damaging the plant's critical systems, including the EDGs, which were located at an elevation equivalent to plant height. The tsunami would likewise not have reached the EDGs if the seawall protecting the plant was taller, or the generators were placed at higher elevations.[9] With the seawater pumps required for cooling destroyed by the tsunami, the availability of backup power to start the emergency cooling system became critical.[13] Due to low plant height, seawall height, and EDG height, both the primary and secondary cooling systems were compromised, leading to disaster. This conclusion is consistent with the findings of reports by the Japanese Diet Fukushima Nuclear Accident Investigation Commission, the International Atomic Energy Agency (IAEA), the European Nuclear Safety Regulators Group (ENSREG), the United States Nuclear Regulatory Commission, and the Carnegie Endowment for International Peace.[1,2,7,8,10]

■ MATERIALS AND METHODS

Based on these observations about Fukushima Daiichi and other Japanese plants affected by the tsunami, we conducted a comparative analysis of protection against tsunami at global coastal NPPs (plants located either immediately adjacent to the coast or within the mouth of a river adjacent to the coast). We collected data for the following variables at all global coastal NPPs: base plant elevation, seawall height, emergency power system elevation, waterproofing of backup power systems, construction and commission date, maximum water height, average wave height, and Soloviev−Imamura tsunami intensity. Since our goal is to compare disaster protection at the time of the Tohoku Earthquake, all data refers to NPP infrastructure as it existed prior to March 11, 2011.

The first set of variables are plant-specific characteristics identified in the preceding section as vital to the Fukushima disaster. Base plant elevation is a measure of the height of critical components of the NPP above mean sea level. As seen in the previous section, elevation above sea level is a primary determinant of an NPP's vulnerability to tsunami inundation. We typically measured elevation at the base of the reactor building. However, where components deemed critical for reactor operation or safe shutdown are located at elevations lower than the reactor building, the lower elevation is recorded. Primary sources for elevation data include national nuclear regulatory agencies, the International Atomic Energy Agency (IAEA), European "stress tests" conducted in response to the Fukushima disaster, and primary source information from nuclear plant operators.

Seawall height is similarly recorded as the maximum height of a seawall, flood barrier, levy, or natural barrier (such as sand dunes or barrier islands) above mean sea level. In the event that a plant does not possess a seawall or other barrier, or the barrier in question is not designed for protection against tsunami or storm surge, the height is recorded as zero. Sources are identical to base plant elevation.

Emergency power system elevation is a measure of the elevation of critical backup power supply systems above mean sea level. These systems include emergency diesel generators, gas turbine-driven generators, and battery systems. Data sources for emergency power system location include national nuclear regulatory agencies, the IAEA, European "stress tests," and plant operators. However, in several cases, this information was not publically available due to national security concerns.

Because the viability of emergency power systems is determined by flood protection in addition to elevation, waterproofing of emergency power supplies is also recorded. Specifically, this is an assessment of whether emergency power systems are located behind flood proof doors or in watertight bunkers. This is recorded as a dichotomous variable (1 for yes, 0 for no). Sources are identical to base plant elevation and seawall height, with greater relative reliance on information collected directly from power operators and regulators.

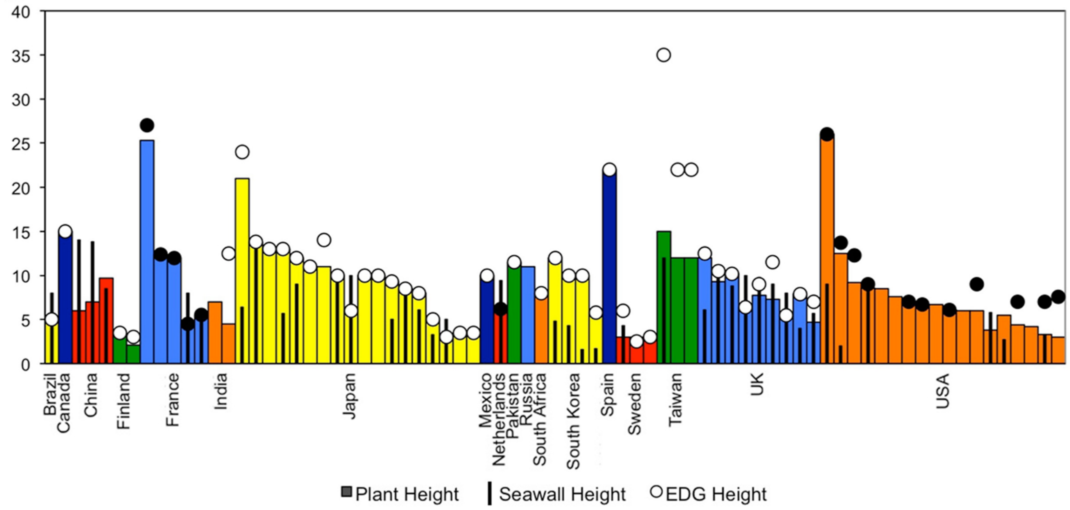

Figure 1. Plant, sea wall, and backup power height (m), international comparison. Note: Dark circles indicate waterproofing of EDG; open circles indicate no evidence of waterproofing. No circle indicates plant operator declined to release information on EDGs. No vertical bar indicates no sea wall.

Construction and commission dates refer to the dates construction was initiated and the reactor became commercially operational. Where reactors have been decommissioned or are currently undergoing decommissioning, the decommissioning date is also noted.

We also collected several variables that proxy for an NPP's potential exposure to high waves and inundation. Maximum water height is a measurement of the maximum historically reported water or wave height recorded within a 150 km radius of an NPP. We use the 150 km radius as recommended by the IAEA in 2002 (in 2010, this radius was expanded to 300 km).[14,15] It is common for PRAs conducted by plant operators to focus on a narrower radius in the immediate vicinity of the plant. However, this approach can lead to underestimation of vulnerability, as historical events producing extremely large waves are rare events, and waves actually observed in a very specific location may reflect idiosyncrasies specific to those events; for example, the precise location of the epicenter of an earthquake or the landfall location of a hurricane. This problem is illustrated by PRAs conducted by Japanese plant operators prior to the 3/11/2011 Tohoku Earthquake, which underestimated risks based on the use of narrow radii. One example is the risk assessment performed by Tohoku Electric for the Onagawa plant. The highest waves recorded in the immediate vicinity of the plant site, based on a study of the four largest historical earthquakes, were found to be 6−8 m. However, much higher waves (10−25 m) were recorded about 100 km to the north in Iwate Prefecture; these waves were discounted as being irrelevant for the plant location. The implicit assumption was that local conditions at the plant site made the location less susceptible to high waves compared to the region slightly to the north. However, the 3/11/2011 wave height reached about 13 m at the plant site, considerably higher than estimates based on a narrow radius, but consistent with records from the 150 km radius we use for this study.

The primary sources of historical tsunami data are the National Geophysical Data Center (NGDC) Global Historical Tsunami Database and the Russian Academy of Sciences (RAS) Novosibirsk Tsunami Laboratory Historical Tsunami Database. Where possible, relevant government and academic reports were also consulted for confirmation.[16−29] We use all historical data available on past events. Several caveats about this data should be recognized: Historical data is more readily available for certain geographical regions. Importantly, historical wave height data for the United States is not available prior to European settlement. The measure therefore likely understates vulnerability for North and South America compared to other regions of the world. Additionally, maximum water height is not always associated with earthquakes. Landslides are also a common source of large waves. In the eastern United States, waves generated by hurricane-induced storm surges typically reach heights greater than those caused by seismic events.

We also collected information on the highest *average* wave height associated with a historical event within a 150 km radius of each NPP. Compared to maximum wave height, average wave height is less likely to be influenced by extreme outliers induced by local geographic conditions. For several recent episodes, we were able to obtain data on average wave directly from original sources. However, in most cases, we calculated average wave height from the Soloviev−Imamura (S−I) tsunami intensity scale, which is available in the NGDC and RAS tsunami databases. The S−I scale is used to assess the relative strength of tsunamis and is calculated according to the following formula:

$$I = \frac{1}{2} + \log_2 H_{av}$$

where H_{av} is the average wave height along the nearest coast. We calculated the H_{av} for each NPP based on the historical event associated with the highest S−I intensity within a 150 km radius.

RESULTS AND DISCUSSION

Figure 1 plots base plant elevation, seawall height, emergency power system elevation, and waterproofing of backup power systems for nuclear plants according to country. Particularly low-lying plants are located in Finland and Sweden, presumably because vulnerability to tsunami is considered negligible. According to this measure, Japan does not look particularly under-protected in international comparison. On average, Japanese plants are located about 10.1 m above sea level and protected by sea walls averaging 4.6 m in height. International averages are 8.8 m for plant height and 3.5 m for sea wall height. Waterproofing of EDGs was not common before March 11, 2011 – this was implemented in France and the U.S. after events highlighted potential vulnerabilities in those countries (flooding at Blayais NPP and the September 11, 2001 attacks).[1]

We now consider vulnerability to inundation accounting for historical wave height. We consider two principal measures: the highest recorded wave run-up and highest recorded average run-up within a 150 km radius[14] of a NPP. Our data includes run-ups caused by seismic activity as well as other sources, such as hurricanes and landslides. These are blunt measures of vulnerability to inundation, but they have several advantages over existing assessments such as PRAs conducted by plant operators. The measures correctly identify Fukushima Daiichi as a vulnerable plant based on data prior to the 3/11 earthquake. PRAs conducted by TEPCO generally concluded that the plant was safe from inundation (TEPCO did conduct a confidential simulation studying the possibility of a 10–15 m tsunami in 2008, but the company considered this "tentative calculations in the research stage" and did not take any immediate action).[5,30] As we will show, these measures also produce rankings that roughly correspond to outcomes during the 3/11 earthquake and tsunami; Fukushima Daiichi is classified as the most vulnerable to inundation, followed by Fukushima Daini, Tokai, and Onagawa.

The first measure we examine is the highest recorded wave run-up within a 150 km radius of a NPP (Figure 2). Plants lying below the 45 degree line in Figure 2 indicate that the plant has an elevation and seawall height lower than the highest recorded wave run-ups. We find that a large number of Japanese plants are characterized by elevations and sea walls lower than the highest recorded run-ups. Japan has recorded particularly high tsunamis in the past. Of the seven plants in our data set that lie in regions where tsunami height has exceeded 20 m, six lie in Japan (the sole exception is Taiwan's Maanshan). However, many Japanese plants have elevations or sea walls that exceed maximum historical water levels, and many plants outside of Japan do not. The following countries also have NPPs with elevation and sea walls below the highest recorded wave run-up: Pakistan, Taiwan, the UK, and the United States.

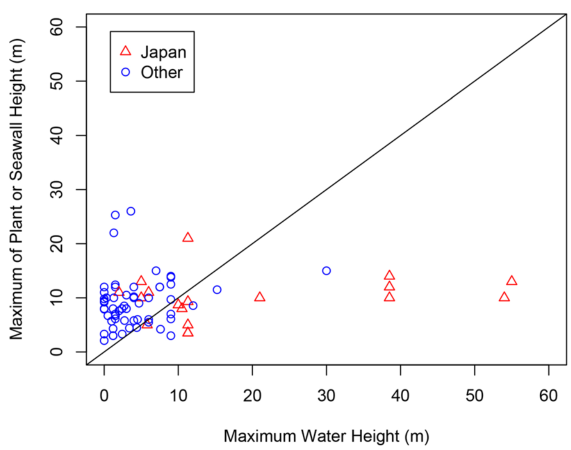

Figure 2. Maximum of plant or seawall height vs maximum water height.

The same analysis can be applied to the elevation of on-site emergency power systems (Figure 3). A large majority of emergency power systems lying below maximum historical water levels in the data are associated with Japanese plants. Pakistan's Karachi plant, as well as four plants in the U.S., are also associated with emergency power systems lying below maximum water levels. The U.S. plants, however, house critical components such as emergency diesel generators in watertight buildings. While not an infallible solution, waterproofing should mitigate the likelihood of a Fuksuhima-type accident. However, this data may overstate Japanese inadequacies, as some plant operators, particularly in the U.S., declined to release information on the status of emergency power systems, citing security concerns. For this reason, we will focus our attention on plant elevation and sea wall height for the remainder of this article.

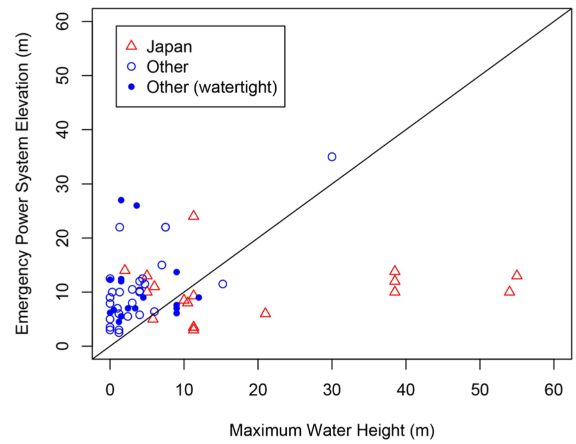

Figure 3. Emergency power system elevation vs maximum water height.

A second measure of tsunami vulnerability we consider is average run-up height, H_{av}. For the sake of presentation, Figure 4 plots the difference between H_{av} and the maximum of plant and sea wall height for NPPs in our data set. As this measure is based on average rather than maximum wave height, and comprehensive data on distribution of wave heights is only available for a subset of historical events, numbers above or close to zero should be considered indicative of potential vulnerability to inundation.[31] As the figure shows, the plant and sea wall height at Fukushima Daiichi was exceeded by the average height of a historical tsunami (the 1896 Meiji-Sanriku Tsunami). Also worth noting is that three plants in Japan are classified as more potentially vulnerable to inundation than Fukushima Daiichi: Mihama, Takahama, and Hamaoka. Other plants that are above or very close to zero include Tsuruga in Japan and the Salem/Hope Creek, Millstone, and Seabrook plants in the United States.

We now examine the H_{av} ratio, calculated as H_{av}/maximum of plant and sea wall height. A number above one indicates that, for a given plant, implied average wave height exceeds the maximum of plant and sea wall height. Within Japan, there is a downward trend in the H_{av} ratio over time (Figure 5). This reflects the fact that several NPPs constructed earlier on in Japan had low plant height and sea walls despite being constructed in areas that had experienced high tsunamis in the past (Supporting Information Figures S1 and S2). Internationally, we find that all plants with a H_{av} ratio exceeding or close to one were constructed between 1965 and 1985 (Figure 6).

Also deserving attention is H_{av} ratios by plant operator in Japan (Figures 5 and 7). Plants operated by the three largest Japanese utilities, TEPCO, KEPCO, and Chubu, tend to have

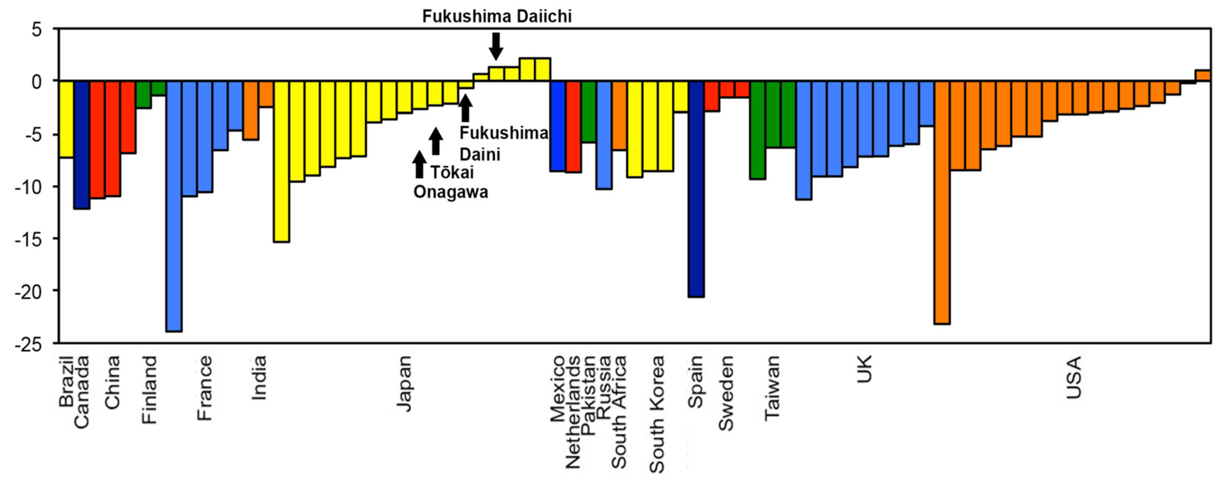

Figure 4. Difference of H_{av} and maximum of plant and sea wall height (m). Note: High numbers imply inadequate protection (i.e., high vulnerability to tsunami and low elevation of plant and sea wall). A number above zero means the plant and sea wall both lie below the average wave height of a historical incident.

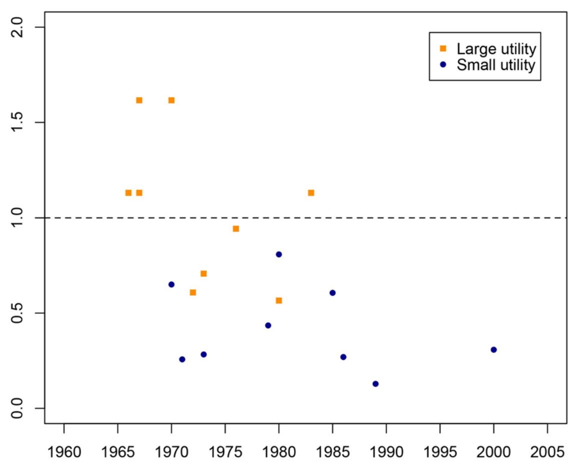

Figure 5. H_{av} ratio by construction date and utility size, Japanese plants.

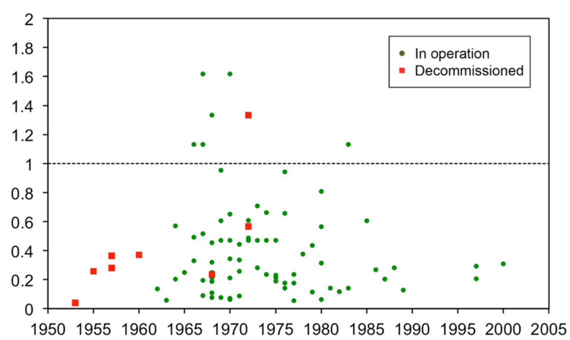

Figure 6. H_{av} ratio by construction date and status, all plants.

high H_{av} ratios. Along with JAPCO— a utility 60% owned by TEPCO, KEPCO, and Chubu—these companies operate all nuclear plants in Japan with H_{av} ratios above one (Figure 7). These companies also were the earliest builders of nuclear plants. A simple linear regression suggests that ownership by a large utility is associated with high vulnerability as indicated by the H_{av} ratio, even after controlling for construction date (Supporting Information Table S1). Large utilities in Japan are

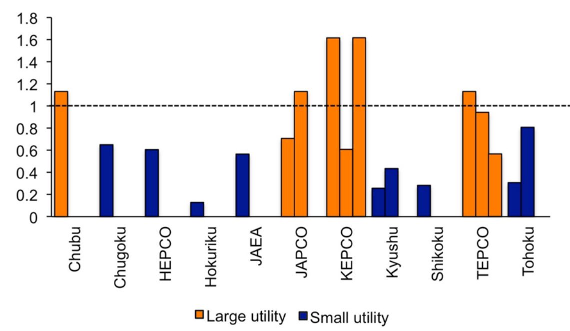

Figure 7. H_{av} ratio by plant operator, Japan.

also associated with low-lying emergency generators in comparison to tsunami vulnerability.

Our measures indicate that inadequate protection in Japan is concentrated among the largest utilities. An international comparison underscores this point. For nuclear plants operated by small utilities in Japan (i.e., excluding TEPCO, KEPCO, Chubu, and JAPCO), the average H_{av} ratio is 0.43, indistinguishable from the international average of 0.41. In comparison, the H_{av} ratio for plants operated by large utilities average 1.05, more than twice the international average.

We also consider operator size as a factor for all international NPPs. As a proxy for size of utility companies, we use the log of revenues, measured in 2010 in U.S. dollars. This measure is more meaningful for comparisons of utilities within countries than across countries, as a dollar of revenue is unlikely to have the same meaning in Pakistan as it does in Japan. Hence, we estimate the statistical models with country fixed effects to account for heterogeneity across countries. The results show that, within countries, larger utility companies tend to have weaker protection compared to smaller utility companies (Supporting Information Table S2). This association holds when Japanese plants are excluded from the analysis, suggesting that the tendency for large operators to be less adequately protected for potential inundation is not limited to Japan.

Given the small number of NPPs available for comparison within Japan and cross-nationally, these findings should be considered suggestive rather than definitive. Additional research is necessary to examine the association between large utilities

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and less adequate protection against inundation. There are several plausible explanations that deserve further exploration in future research. One possibility is regulatory capture. The largest utility companies in Japan were generally the most politically influential, offering lucrative retirement positions for former bureaucrats, political contributions, and organized votes.[32−34] Hence, one possibility is that large firms were better able to push back against regulators and secure more lax safety requirements.

However, plants operated by large firms may have been less adequately protected for reasons aside from regulatory capture. Research on pharmaceuticals regulation has shown that regulators may rationally place greater trust in large, well-established firms even if no political influence is exercised.[37,38] This reflects the fact that regulators care about their own reputations, and they may have a better sense of the reliability and quality of information from well-known firms rather than new entrants. In the context of nuclear regulation, large firms tended to be the earliest builders and operators of nuclear plants, and therefore may have been considered known quantities and subject to less stringent supervision compared to smaller operators.

It is also possible that large firms underinvested in protection for reasons unrelated to regulation. Larger utilities generally have more diversified operations, which may reduce incentives to protect against accidents at any specific plant. Similarly, plant operators may rationally under-invest in the protection of older plants perceived to be nearing the end of their life. Large firms may also face other problems such as excessive bureaucracy or lack of focus.

Regardless of what specific factors account for the associations documented here, our results indicate that additional research and regulatory scrutiny is advisable with respect to older plants and plants operated by large utilities. One important question is whether large utilities also exhibit signs of lax safety in areas aside from protection against inundation. A cursory examination of data on total accidents shows that large utility operators in Japan have experienced twice as many accidents as small operators, and the frequency of accidents is about 42% higher when measured on the basis of accidents per plant years in operation.[35,36]

According to our cross-national comparisons, Japan was inadequately protected relative to the severity of tsunamis it confronts. This can be attributed primarily to the fact that Japan faces higher risks of tsunami compared to other countries due to frequent seismic activity. However, not all Japanese plants were inadequately protected against tsunamis, and Japan's lack of protection was not unique. Our findings suggest that older plants and plants operated by the largest utility companies deserve further scrutiny from researchers and regulators.

■ ASSOCIATED CONTENT

Supporting Information

Additional figures and tables are available. This material is available free of charge via the Internet at http://pubs.acs.org.

■ AUTHOR INFORMATION

Corresponding Author

*E-mail: plipscy@stanford.edu.

Author Contributions

Authors listed in order of contribution.

Notes

The authors declare no competing financial interest.

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■ ABBREVIATIONS

EDG	emergency diesel generator
IAEA	International Atomic Energy Agency
INES	international nuclear event scale
JAPCO	Japan Atomic Power Company
KEPCO	Kansai Electric Power Company
NPP	nuclear power plant
PRA	probabilistic risk assessment
TEPCO	Tokyo Electric Power Company

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