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Japan's recent earthquake impacts on nuclear plants safety in the wake of Fukushima Daiichi

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Abstract

Once again, the whole world became increasingly alarmed by the devastation caused by the recent 9.0 magnitude earthquake in Japan that struck on March 11, 2011 at about 12:50 (14:56 JST Thursday) to the east of Sendai, Honshu Island. Centered at a depth of about 32 km below the ocean floor, it triggered a huge tsunami, resulting in the deaths of over 14,000 people, with another 10,000 still unaccounted for. In addition, when the Fukushima Daiichi nuclear plant cooling supply system was damaged by the earthquake, it fractured the structure and water supply system to the reactor core leaving the reactor without cooling water followed by a series of explosions due to dry reactor operation, sending high levels of radioactive gases into the air. Furthermore, on March 16, 2011, a fire broke out in the number 4 reactor when workers could not sufficiently cool the reactor core, and sensors gauging radiation levels inside failed to detect the dry operation of the reactor.

Therefore, innovative concepts in performance-based design must be developed by the structural engineering community to better design structures to address the danger of collapse. Simulation is essential for predicting realistic scenarios by mimicking natural disasters. Computing power technology is advancing, and the recent K-computer is nearly the fastest computer operating system in the world, now operating at 8.2 petaflops per second. This system can accomplish the task of simulation to provide us better warning, protection, and disaster reduction.

Japan is rebuilding from deadly March 11, 2011 earthquake and tsunami. With the experience gained from this disaster, planning teams can now design highly resistant nuclear reactor structures, water supply systems with backups to withstand major earthquakes and aftershocks, as well as install early warning systems on the ocean surface, so that, with a better coordination of Japanese government agencies and engineers, the effect of such double catastrophes can be minimized and human life and property can be saved.

We believe that a new generation of disaster simulation technology is necessary, and will emerge from the DS'11 Kobe Symposium. The symposium will further provide a deep understanding how disaster simulation can be modeled, by taking into account 3-D material structures and behaviors from the macro to micro level.

In this paper, we will examine of the earthquake impacts what measures Japanese Government agencies should take in the future to redesign structural safety, structural response control for nuclear power plants, and simulation benefits, so that future natural disasters can be minimized, and greater security against natural disasters can save human lives, properties, and the environment.

Keywords: Earthquake impacts; Nuclear plants safety; Disaster prevention planning; Structural safety; Natural disaster simulation

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1. Introduction

Natural disasters such as earthquakes, tsunami, floods, hurricanes, and typhoons are becoming more common, and the major global threat facing many areas on earth. In Japan, despite its great scale, the earthquake of March 11, 2011 did not cause much structural damage because of Japan' earthquake-resistant building design code and seismic technology adoption proved to be a stronghold except regional damage to civil structures, roads, and bridges. Only minor structural damage to the nuclear reactor building was caused by the earthquake, except to the cooling system, resulting in a loss of reactor coolant, and the plant nuclear core did melt down. Of major concern is whether nuclear power plants will stand safe operation or are vulnerable to much stronger earthquakes. The answer is unknown.

We believe that the main reasons for earthquakes and volcanic eruptions more frequent mode of occurrence, a relatively short time interval of 3-6 years [1], than the previous, longer time interval of 13-16 years as in mainland China [2], provides some clues. These are because the regional or local loading of tectonic plates is becoming heavier, so it does fracture that is to cause the main plate creep movements continuation in space and time of the main plate covering the earth' crust.

We hypothesize that local tectonic plates subduct and then fracture at a relatively shallow depth, caused by the excess loading of an exponentially increasing human population. As an example, we can cite the China' Haicheng earthquake (in 1975; M7.3) and Tagshan earthquake (in 1976; M7.8) which occurred in densely populated cities [3]. The plate loading could be from a natural loading of huge water volumes, or that human activity and goods cause the larger plates' partial movement, leading to partial plate fractures [4], and huge strain stored and built up in rocks, with a sudden release of energy as the rock fractures, resulting in the 'earthquake'. The sudden rupture of a fault also sudden release of buildup strain energy moves as seismic waves with super hypersonic speed that travel outwards with the characteristics of material waves within the earth's interior. The seismic waves propagate in the heterogeneous medium of the earth's crust, made of layers that reflect and refract seismic waves moving from layer to layer. When, seismic waves reach the earth's surface, it rattles the soil, compressing and expanding as it moves forward to produce a strong ground motion. When the strongest waves reach structures with sufficient intensity as they hit the foundations, they cause buildings to shake; thereafter, they cause, the amplitude of the structure exceed beyond its yield point, and to collapse.

The tectonic deformations by subduction of the plates is when denser seafloor crust undergoes the less dense continental crust [5]. The subduction is further enhanced due to the earth's non-uniform rotation [6] around its own axis, which is about 24 hours or a day, which enhances the subduction movements of the plates.

An earthquake below the ocean floor mostly occurs along an ocean floor fault as it runs through the ocean floor. Ocean floor fault enlargement, due to vertical slip displacement creates ocean waves called 'tidal waves' or 'tsunami', which is the Japanese word for 'harbor waves'. It is in the harbors and coastal areas of Japan's great eastern coastlines that tsunami do their damage [7].

2. Background Information

The recent 9.0 magnitude earthquake in Japan struck on March 11, 2011 at about 12:50 (14:56 JST Thursday) to the east of Sendai, Honshu Island. It cantered at a depth of about 32 km below the ocean floor, and triggered a huge tsunami that reached the shore to cause the deaths of many people far from the actual fault. One effect of earthquake shaking was damage to the Fukushima Daiichi nuclear power plant cooling supply system. The damage by earthquake was that it fractured the structure and water coolant system of the reactor fuel rods, leading to a reactor meltdown.

The nuclear core consists of the nuclear fuel in thin zirconium alloy tubes (inside the cylindrical pellets) made of uranium oxide U_20, fitted and stacked up, one atop another, in a thin tube (the thin tube is called cladding. It allows heat to transfer as well as neutrons to pass through) [8]. For a nuclear reaction to occur, externally the neutron flux beam to uranium oxide fuel inside thin tube, activates a nuclear reaction as neutron flux strikes the nucleus of uranium oxide fuel, it causes to split apart of atomic nucleus [9] into proton and electrons. The proton decays into a heavy uranium, and light uranium with electrons. In the core there are also, boron or cadmium made of control rods.

They are used when inserted into core, completely flush with floor, where they absorb many neutrons, as a result of nuclear fission the reaction stops; when boron rods are lifted a few inches from floor by magnetically activated lifts precisely, nuclear fission reaction begins again. Therefore, all these rods together make up the reactor core. The heat is given off and absorbed by water to cool down the hot fuel rods and generates steam that runs a turbine to produce electricity connected to electric grid network [10].

After the day of the earthquake, a series of explosions at four of the reactors followed, due to a gaseous hydrogen interaction with stream at three of Fukushima Daiichi's six reactors [11], most likely due to failure of emergency core cooling system, sending high levels of radioactive gases and steam, particles, and dust outside the reactor core through the ventilation system outside the plant, then into the atmosphere. In addition, on March 16, 2011, a fire broke out in the number 4 reactor when workers could not sufficiently cool the reactor core, or because of a failure of the emergency core cooling system and sensor gauging system to detect high radiation levels released into the air [12]. It is not all that clear what really happened, because TEPCO (which operates the Fukushima Daiichi nuclear power plant) has still not provided a full account of the accident to the public, however, it has provided some detail to the Nuclear and Industrial Safety Agency regulating nuclear plants in Japan. It was only on March 30, 2011, after three weeks, did on-site inspections begin, and TEPCO issued a confirmatory result on May 6, 2011 [13].The nuclear reactors, despite having been designed with many ways to protect from cooling water system failure, failed because automatic backup systems and instruments were not properly maintained and reactor operators were not properly trained in case of emergency. In addition, the plant's safety system should have automatically shut down the reactors in case of a loss of coolant. That it did not produce steam is critical for the nuclear plant, because the steam is produced to run the turbine to generate electricity, it removes excess intense heat that the reactor water carries as well, and there was no emergency automatic start of the feed water pump to provide needed water to cool the reactor, the most likely cause leading to meltdown.

Even by the end of March, 2011 TEPCO and The Nuclear and Industrial Safety Agency still held critical safety data from the public. This is because the politically powerful TEPCO and the nuclear industry of Japan did not have a plan of action in place before the accident to reduce or stand safe in case of an earthquake such as in this accident. Nuclear power companies and the Japanese government failed to learn from similar experiences in the past, even the Japanese Prime Minister's Office's own nuclear disaster manuals were never made available to local official after the accident on March 11, 2011[14].

3. What is the estimated magnitude of the Earthquake at Honshu Island?

We believe that what happened on the ocean floor near Honshu Island took place along a subduction fault zone, where the Pacific and the Philippine plates were pushing in, colliding and sub ducted [15] beneath Japan's continent in the east of the Eurasian plate. The subduction followed by the fault displacement enlarged by a vertical slip of the plates in 'sudden choke off seawater', resulting in the tsunami 'earthquake wave' from that the foci at about 32 km deep below the ocean floor. Therefore, the estimated fault size about 32 km deep below the ocean floor and at about 150 km long along on the ocean floor. It is clear the earthquake occurred at a known fault on the ocean floor, travelled from the epicentre, and effected the greater Eastern region of Japan [16], including Fukushima, Miyagi, Iwate, Ibaraki, Chiba Prefectures, Tokyo, and the region's major cities, towns, villages, and Honshu Island shore.

We can get some fairly good idea about the magnitude of the earthquake, which is controlled by the size of the fault, using the well-known Moment Magnitude Equation [17],

which is given by,

$$M = \frac{2}{3}\left[\log\left(M_0\right) - 16.05\right] \quad (3.1)$$

Where,

M_0 is the seismic moment in the above Equation, defined by,

$$M_0 = D\ A\ G\ (\text{dyne cm}) \quad (3.2)$$

Where,

A= area of running fault length and depth

D= Rate of slip in years

G= Shear modulus of rocks

We can get a fairly accurate estimation about the magnitude and intensity of the ocean floor earthquake from this well-known fault around Honshu Island with the approximate data available. We assume that the subduction fault zone on the ocean floor is about 150 km long and 32 km deep, and the slip rate about 18m/year [18]. We assume an Earthquake recurrence interval of 6 years as a short interval. We assume approximately the shear modulus of rocks as $G = \frac{3x10^{11}dyne}{cm^2}$

Then, we need to obtain the seismic moment M_0 in the Equation (3.2)

$$M_0 = (1800 \text{ x } 6)\ (15 \text{ x } 10^6)\ (3.2\text{x}10^6)\ (3\text{x}10^{11})$$

$$M_0 = 10{,}800(4.8\text{x}10^{13})\ (3\text{x}10^{11}) = 1.55\text{x}10^{29}$$

Using Equation Moment Magnitude Equation (3.1), we have,

$$M = \frac{2}{3}\ [\log\ (1.55\text{x } 10^{29} - 16.05]$$

$$M = 0.66[29.19 - 16.05] = 8.67 \sim 9$$

$M \sim 9.0$

Therefore, an estimated an earthquake magnitude about 9.0. This is indeed occurred from the fault on the ocean floor about Honshu Island.

In combination with the reasons given above, we see increasing earthquakes occurring in relatively shorter periods, thereby costing large numbers of human lives, properties, and causing devastating damage to existing civil structures, road, railways, bridges, ports, airports, power lines such as electricity, gas, water sewage, telecommunication lines [19] and nuclear power plants added with the additional damage caused by the tsunami. However, Japan had developed and implemented a resilient earthquake-resistant building planning and building code, which included the retro-fitting of wood and previously built buildings. These buildings were be able to withstand a major earthquake such as that of March 11, and survive even with minor damage in or near the earthquake zone.

Japan has the third largest number of nuclear power plant after the U.S.A. and France [20] to generate its electricity. Also, Japan's electricity production rests in the hands of the politically powerful four major Electric Power Companies [21].

Therefore, in case of an earthquake, the Japanese government's special concern should be especially focused on nuclear power plants' ability to withstand and reduce the hazards of strong ground motion from an earthquake.

The nuclear power plants use uranium oxide as fuel to generate electricity. That is why there is special concern if it is located within an earthquake zone, as it poses a serious threat and danger to the public and the environment. If the nuclear reactor building collapses, then radiation leaks and spreads when nuclear radioactive particles leak out from a damaged nuclear plant, or its water cooling system discharges radioactive materials into an uncontrolled environment because of these plants. The radiation, as a thick cloud of gases leaking out from a nuclear plant, has far most damaging effects on its immediate surroundings and on all living beings, the environment, and the atmosphere nearby. The escaped radioactive water particles will contaminate the entire habitat and ecology nearby, and destroy the environment. Furthermore, all atmospheric activity will carry and spread the radioactive particles by wind across the whole of Japan and even the whole world.

That is why the prime focus should be on to enforcing Japan's existing laws on the nuclear power industry, and hold them accountable for their failure to maintain and plan a safe plant in case of any accidents at the nuclear sites. It is known that the Japanese nuclear industry has a long history of falsifying data when it comes to safety breaches within its facilities, and the failure of Japanese political leadership, even in the March 11, 2011 earthquake, when it downplayed the danger to public safety [22].

Even though Japan has what is known as a Disaster Management Council, chaired by the Prime Minister, it established in March 2005 an Earthquake Disaster Management Program and a ready use officially published Manual is available to local Prefecture Governments and Municipalities. This program set out goals for disaster mitigation and strategies for housing and public facilities earthquake resistant and tsunami countermeasures [23]. However, Prime Minister Office directed the program ineffectively and did not even make the Manual available to Prefecture Governments and Municipalities that also have their own Disaster Management Councils that formulate and promote local disaster management plans [24].

However, time after time repetitive earthquake and tsunami experiences have shown that there are delays and lapses in getting readily available disaster Manual to the local level committees and Japan's citizens harmed in treble ways by earthquakes, tsunamis, and radiation. There is a heavy bureaucracy and this caused a breakdown in communication between the Prime Minister's office and the Prefecture Governments and Municipalities after the earthquake that damaged nuclear reactors and the plant's systems. I recommend that Japan's Disaster Management Program be turned over to one of the other ministries. This will avoid chaos at the first step. The Ministry in charge would manage and coordinate all aspects of the earthquake and tsunami in Japan with a dedicated and highly selective customer service oriented staff to assist the public in the field, as well as insure the enforcement of Japan's laws.

In the U.S. a National Earthquake Hazards Reduction Program (NEHRP) was proposed by President Jimmy Carter Administration 1977. Thereafter, U.S. Congress passed the National Earthquake Hazards Reduction Act in 1977 with a specific goal to reduce losses from earthquakes [25]. The prime agency of NEHRP is the Federal Emergency Management Agency (FEMA) with the responsibility of earthquake implementation, an outreach arm directly in contact with public in case of a national disaster in the U.S.A.

I believe that Japan needs to abolish the Central Disaster Management Council, and turn over its duties to a designated ministry to plan and manage the Earthquake Disaster Management Reduction Program, with a new name added (tsunami), to be called the Japan National Earthquake and Tsunami Hazards Reduction and Management (JNETHRM) program. A single Disaster ministry, similar to the one in the U.S., with a dedicated staff, is the solution to the chaos and confusion. In case of an earthquake, tsunami, or other natural disaster, the designated ministry will deploy its dedicated personnel to the disaster region to actively control and manage the disaster at the location with all its functions and care. This ministry should rigorously monitor and coordinate affairs afterwards, to reduce the losses due to earthquakes, tsunami, and other natural disasters.

Today, on the earth, rapid population growth around the world, Japan faces more frequent and repetitive occurrences of the same nature; more earthquakes and tsunami occurrences on its territory. However, the Japan Government has been reluctant consistently and rapidly to manage, coordinate, and respond to disasters at this magnitude to the public in all scope.

Japan's regulating body, the Nuclear and Industrial Safety Agency, is ineffective in supervising the powerful nuclear industry that most of the time does not concern itself with the safety of the public, and provides little or no information to it. More rigor, closer monitoring and earthquake drills are necessary to prepare for earthquakes and the likelihood of damage to nuclear plants. Practice, practice, and more practice only makes for the necessary preparedness and safety of nuclear plants.

The monitoring of nuclear plants appears to be of major concern especially within minutes of an earthquake strike, to see if, for example, cracks have appeared in the wall of the reactor building or if any loss of coolant is due to cracks in the piping system. If the piping system is damaged, the flow of cooling water to the reactor core no longer cools the reactor very hot reactor core. Normally at this point the emergency cooling system would have automatically shut down the reactor, but because of malfunction, instruments were giving erroneous readings, and the reactor continued to operate without coolant. The reactor's fuel rods overheated to meltdown, triggered by an uncontrolled chain reaction. An even worse scenario could have happened, if a number of reactor explosions had blown off the reactor roof, sending a plume of radioactive particles and dust into the atmosphere. Then, atmospheric activity would have spread these radioactive particles and dust thousands of miles away to all parts of the world from its original location. The radioactive pollution would eventually have altered the earth's ecosystems with catastrophic and other complications might escalate leading to short- and long-term effects in many other critical parts of the world.

4. Not Being Prepared for Earthquakes, Tsunami, and Radiation

Globally speaking, we witness time and time again that earthquake occurrences are on the rise because the earth's tectonic plates are moving faster in a much shorter time frame than before, due to reasons stated above. The local parts of tectonic plate movement results in small earthquakes, yet its effect is that of a big earthquake.

The tsunami reached Honshu and Japan's continental shore as high waves, swamping whatever it found in its way, including humans, property, infrastructure, and even causing destruction to the environment. In addition to human casualties, there were and are direct and indirect economic losses as well.

We believe that the public was at the mercy of the inefficient functioning of the Japan Government, its Ministries and Agencies, and from the lack of leadership at the top. Numerous nearly identical experiences have not taught the Japan Government to deal effectively with natural disaster preparedness; and its organizations are still lagging. Citizens are dying because the government failed to take necessary safety measures or effectively control hazards at earthquake locations, and afterwards withheld radiation level data from public[26].

5. Scope of Failures at Nuclear Power Plants. What Can Be Done?

Japan's energy is in the hands of the powerful nuclear power industry, especially TEPCO [27]. Because of the lack of vigorous supervision and enforcement by Japan's Nuclear and Industrial Safety Agency as its regulator, TEPCO appears to have no contingency or preplanning in place in case of an accident at this scale. How can we manage and control the immediate after effects of an accident, or even predict a coming earthquake and take necessary steps to minimize the hazards? There appears to be no earthquake practice drill programs in existence or plans to simulate actual earthquakes at nuclear plants to know what to do or how to respond in case the nuclear plant's system or systems malfunction. The commercial electric power companies have had a free ride, while nuclear plants are operating without thorough checks for structures, equipment, reactor cores, piping and cooling systems and subsystems for safe operation under earthquake conditions, and an automatic shutdown system in case of an earthquake emergency. Without the response plan outlined above, to be used by power companies in the case of an actual earthquake, there will be no more than confusion and disarray in the use of plant resources, and it may result in the chaos of a massive amount of radiation leakage from a power plant, posing an enormous danger to the public and the environment at an un presented level. We can say it once again: this accident is yet another warning to Japan that it must be prepared to minimize the risk of such natural disasters to her own citizens.

Meanwhile, scientist and engineers are still continuing to stabilize the situation at the Fukushima Daiichi Nuclear Power Plant. TEPCO stated that it may take an additional six to nine months to stabilize and get the crises under control. In the meantime, the cooling of the fuel rods and the accumulation of radioactive water is of major concern [28]. TEPCO' nuclear scientist and engineers did a splendid job to contain the major scale of this disaster in short time., however the residual effects will last for years to come.

At the Fukushima Daiichi Nuclear power plant, even immediately after the accident it appears that no emergency evacuation plan was adopted, and about 45 percent of the 1,080 children in three Fukushima communities surveyed in late March tested positive for thyroid exposure to radiation, according to a recent announcement by the government [29]. Had the Japanese Government directed local officials to enforce an emergency evacuation from the area with rescue workers to guide evacuees away from radioactive plumes [30], this might have prevented serious exposure to radiation by local communities. It appears that no continuous radiation monitoring system was in place before and after the March 11, 2011 accident to measure the increasing levels of radiation in the environment; and additionally, the radiation levels of the water discharged from the plant is still unknown. There is no data available on the radiation exposure caused by the accident and distance it traveled in the environment. These are potential hazards to the public of the Fukushima community. In addition, it appears that the Japan Meteorological Agency's Tsunami Warnings and Advisories were not conveyed to the Honshu Island region, alerting Japan's mainland harbor populations to move to higher ground, or to evacuate harbor areas despite tsunami warnings issued by the Pacific Tsunami Warning Center (PTWC) and the West Cost and Alaska Warning Center (WCATWC) advisories, watches and warnings for all of the islands throughout the Pacific coastal regions [31], including Honshu Island.

The effects of earthquakes and tsunami damage can be realistically simulated, especially for nuclear power plant structures and their soil-structure interaction with the foundation sub surfaces in during an earthquake. For the simulation of a building, one can take into account the building's foundation, soil, and materials structure.

The simulation provides important information about reactor building responses to an earthquake and tsunami, for example. It may reveal important structural information in 3-D, showing micro molecular dynamics and the dislocation of crystals, including its likely behavior during an earthquake. After a data analysis of the structure's materials and crystals when dislocated, plus other behavior, it would know if fail further during any earthquakes. Then a replacement of the partial or the whole structure would be possible; or, if the entire structure simulated to fail, the entire nuclear plant would be shut down, and engineers could rebuild the structure with materials determined to be able to withstand high seismic or vertical motions of the ground and still survive. Therefore, to understand, interpret, and implement a simulation provides results that can prevent more catastrophic disasters, save human life, property, and the environment. The simulation can be accomplished by the K-super computer computational power (8.2x1015 flop per sec [8.2 petaflops per sec]), which can simulate the earthquake and tsunami effect on infrastructures, civil structures, and nuclear power plants. This conference's conclusion would provide such foundation, so that future generations could benefit from the hazard reduction of earthquakes and tsunami, and live in peace without terror from these natural disasters.

6. Conclusion

In conclusion, once Japan builds an effective earthquake and tsunami hazard reduction system, then the safe operation of nuclear power plants will be possible. The damage to living beings caused by radiation includes cancer, health complications, and other long term damages. These would be avoided. Otherwise, unless structurally safe nuclear power plants are designed and retrofitted to stand up to any type of natural disasters, the public, its infrastructures, its civil structures and its nuclear power plants will continue to be threatened by unnecessary risks.

As more powerful computers are becoming available, like the powerful K-computer with its unparalleled computational speed, it will be possible to consider an alternative design method of building based on simulation. In simulation it is possible to use strong ground motion distribution for the purpose of design, and it serves to predict the earthquake and tsunami hazards which possible earthquake and tsunami disasters will be estimated, so that resultant estimate can be use in planning such natural disaster mitigation against itself. Also, it helps great deal to simulate earthquake events to provide more detailed picture and lesson based on simulation and probability based and deterministic base approach. This conference would provide such required and necessary knowledge how to benefit of the result of a simulation. By simulation, nuclear power plants would not have to be built, with material and cost savings, thereafter nuclear power plants would be built to stand strong earthquake, resistant to ground motion, after analysis and study of simulation results.

However, there are difficulties with numerical simulations in the simple shape that a cube requires; enormous amounts of computer memory are needed for even a short period of time when using the particular numerical methods of the Finite Difference Method (FDM), the Finite Element Method (FEM), the Boundary Element Method, and the Finite Volume Method (FVM) to solve an earthquake problem with spatial and temporal resolution. The smaller mesh size requires a very large computer memory and speed becomes essential. The other difficulty is to know how accurate modeling is possible without any real data. The area simulation experts at this meeting will be able to address further issues, while we do not.

In conclusion, we believe that, if nuclear power plants are safely designed with the help of simulation results, it is safe to operate nuclear reactors for electric power generation, even if an earthquake triggers a tsunami.

Compliance with ethical standards

Disclosure of conflict of interest

In this article one author have contributed in the manuscript, and there is no the conflict of interest.

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