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PAGES 33–40

Active Faults and Nuclear Power Plants

PAGES 33–34

The destruction of the Fukushima Daiichi Nuclear Power Plant (NPP) following the March 2011 Tohoku earthquake and tsunami brought into sharp focus the susceptibility of NPPs to natural hazards. This is not a new issue—seismic hazard has affected the development of plants in the United States, and volcanic hazard was among the reasons for not commissioning the Bataan NPP in the Philippines [*Connor et al.*, 2009].

A closer look at two NPPs, the Tsuruga NPP in Japan and the Diablo Canyon NPP in California, sheds light on issues important to regulators of the nuclear industry in different countries. Both NPPs are situated close to active faults in these tectonically active regions. The methods of assessing risk and the specific issues arising at the Tsuruga NPP in particular highlight the complex choices faced by a country that is trying to balance risk mitigation and energy needs in the wake of a nuclear disaster.

Status of NPPs in Japan

The Tohoku earthquake and tsunami gave Japan a rude awakening with respect to its assessment of, and preparedness for, high-impact natural events. As a direct result of the event, most of Japan's 50 NPPs are currently closed. After routine closures for planned maintenance outages, the government restricted the restart of these plants until they could successfully pass "stress tests," which were subsequently replaced by new safety criteria issued in July 2013 by Japan's new Nuclear Regulatory Authority (NRA).

Some restarts are blocked because NRA is concerned about the proximity of NPPs to active faults. The NRA's definition of what constitutes an active fault and how it intends to apply new draft regulations on ground stability are thus pivotal, determining whether the plant's operations should cease or continue. The approach that the regulator and the NPP operator take could significantly affect the future of Japan's major energy infrastructure.

The Tsuruga NPP: Hazards Posed by a Bedrock Fault

Tsuruga is a historic port in a large bay on the eastern coast of the Sea of Japan in Honshu. Two major nuclear complexes are located on the peninsula that forms the western side of the bay. One of these, the Tsuruga NPP, has two reactor units, one of which is the oldest functional nuclear power station in the country. The site lies in a valley that extends southeastward to form Urasoko Bay, a small local extension of the main bay (Figure 1).

The eastern side of the valley and Urasoko Bay are the scarp slope of a major active fault—the Urasoko fault, whose length has been mapped at about 10 kilometers but could possibly extend significantly farther to the south and north. Trenching evidence suggests that this fault has moved repeatedly in the late Pleistocene (between 120,000 and 130,000 years ago). The foundations of both reactor units lie about 200 meters to the west of the fault. The Urasoko fault was not considered to be active when the nuclear power plant was sited in the 1970s, but it has appeared on subsequent updates of Japan's active fault map since 1991 as either "active" or "possibly active."

However, it is not the Urasoko fault itself that has been causing problems over the past year for the Japan Atomic Power Company (JAPC), the operators of Tsuruga NPP. An inspection by experts commissioned by the NRA concluded that a bedrock fault (called the "D-1 fault") that was already known to lie in the granitic rocks that lay directly beneath the base mat of the Unit 2 reactor might be connected to the Urasoko fault and might move in sympathy with it—and thus should be defined as active. According to NRA's regulations, an active fault beneath critical facilities means that they should not be operated. Although this criterion was originally

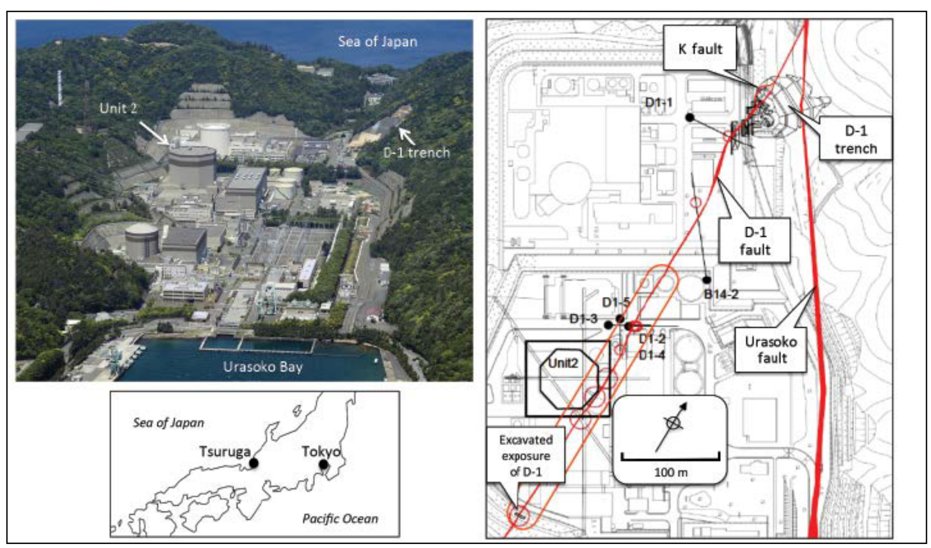

Fig. 1. (top left) The Tsuruga Nuclear Power Plant (NPP), looking to the northwest and (bottom left) its location in Japan. (right) Map of the Tsuruga NPP. The upthrown side of the active Urasoko fault forms the prominent scarp to the right of the complex. Note the size of one of the trenches (D-1 trench), excavated to expose the Urasoko and D-1 faults. The K fault is a small feature exposed in the D-1 trench. Unit 2 is the reactor under which the D-1 fault passes. Borehole positions are shown as black dots, and the orange lozenge and circles indicate locations where D-1 was evaluated prior to D-1 trench excavation.

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intended to apply when a new NPP is being sited, NRA will now apply it to the relicensing of existing facilities.

What Do Japanese Officials Define as an Active Fault?

Tsuruga is only one of several NPPs and other nuclear facilities in Japan that are threatened with closure as a consequence. Others include the Higashidori, Mihama, and Shika NPPs as well as the prototype fast breeder reactor, Monju. A suspect fault at the Ohi plant (about 100 kilometers west of Tsuruga) has been investigated and, in September 2013, was found to be inactive by NRA.

The definition of what NRA considers active thus becomes critical. The question also arises of what the appropriate response should be to ensure plant safety in the situation where active faulting is found to occur near an existing plant: Is it to close the plant, or should officials assess the risk and consider how it could be mitigated before making a decision? JAPC and other NPP operators are currently struggling to avoid closures, with the decision depending on the criterion of whether or not an active fault is present below their facility.

Many countries have definitions of active fault that have been established for various hazard and civil engineering purposes and that vary significantly. Japan's NRA uses a definition based on paleoseismological evidence of movement during the late Pleistocene. Where there are no young, overlying sediments that can be examined to determine whether or not movement has occurred over this period, NRA instructs investigators to look for evidence of movement over the past 400,000 years. Whether evidence of movement over this longer period would be judged to indicate that a fault is active for the purposes of the regulations has not yet been clarified.

A Quest for More Paleoseismological Evidence

Faced with the conclusion of NRA's expert geoscientists, JAPC began a major program to gather additional paleoseismological evidence [*Japan Atomic Power Company,* 2013]. The work was completed in mid-2013 and involved excavating deep trenches, some of which required massive support to shore up trench walls cut on the scarp slope of the Urasoko fault, exposing both it and several traces of the D-1 fault in the granitic basement formations.

Work focused on identifying the stratigraphy and characterizing the chronology of the overlying sediment layers of the Quaternary (roughly the past 2.6 million years)—a mixture of terrestrial and marine margin sediments draped over the basement rocks. Nine Quaternary layers provided evidence of periodic movement of the Urasoko fault. The critical dating evidence came from tephrochronology (dating based on volcanic ash that can be linked chemically to specific eruptions in the Quaternary). Tephra bands and distributed tephra phenocryst fragments occur in several of the Quaternary layers uncovered by the trench; these layers were correlated with tephra that had already been dated in sediments from terrestrial, lake, and marine boreholes in the region around Tsuruga. JAPC's scientific team integrated data on geochemical similarities between tephra phenocrysts, palynology, and a limited amount of carbon-14 dating to develop a chronologic history of fault motion bounded by dated volcanic events [*Japan Atomic Power Company,* 2013].

Assessing Seismic Hazards to the Tsuruga NPP

Trenching exposed more fault structures than were known about from the original foundation works of the Tsuruga NPP. The NRA experts considered that one of these, the K fault, was also active and could extend beneath reactor Unit 2. Further studies were carried out by JAPC to see whether this could be the case.

New evidence for the age of the last movement of both the D-1 and the K faults came from several deep exposures in the trenches that allowed plotting of the extent of upward fault penetration into the sediment layers. By seeing which layers had been penetrated and the geometry of the penetrations, it was possible to conclude when the latest movement had occurred.

For both features, there was no evidence of movement in the late Pleistocene. D-1, which had been known about since Unit 2 was under construction, appeared to be considerably older than this, and the K fault was seen to trend toward a termination well before it approached Unit 2. Results also suggest that neither the K nor the D-1 fault has moved in sympathy with the Urasoko fault, at least during the most recent Urasoko fault events.

At the end of the investigations, an independent team of geoscientists (including some of this article's authors) assessed the evidence and concluded that JAPC was justified in saying that there was no evidence of active structures below the reactor units [*Berryman et al.,* 2013]. A recommendation was made to both JAPC and NRA to open a constructive dialogue to consider how best to manage decisions on the future of the Tsuruga site. While NRA is assessing these results and making further visits to examine the site, the Tsuruga NPP remains closed.

Tsuruga NPP as a Case Study for Risk Analysis

The independent experts evaluating the Tsuruga NPP also concluded that critical decisions should not be based simply on whether features are defined as active or not.

Certainly, for situations like Tsuruga, proximity to a known major active fault means that seismic hazard has to be taken very seriously. All NPPs undergo periodic seismic hazard analysis to evaluate the impact of ground motion on structures, systems, and components (fragility analysis), with potential peak ground acceleration being used as the measure for classic probabilistic seismic hazard analysis (PSHA). The international standard approach of probabilistic risk analysis (PRA), used almost universally for NPPs worldwide, is one of the few areas where Japan's science and engineering community use probabilistic techniques, with PSHA being the only part of PRA that is recognized by Japan's nuclear regulators.

The problems that JAPC has had to address concerning the presence of smaller faults in the vicinity suggest that it would be useful to extend classical PSHA in circumstances where a facility lies so close to known active features. Despite the clear geological findings on the inactivity of the D-1 and K faults that appear to answer the regulator's specific requirement, it is possible that there might be secondary fault displacement in the damage zone of the Urasoko fault during some future movement episodes. Geoscientists recognize that the processes controlling when secondary fault rupture occurs in relation to primary fault rupture need more study. Here is where paleoseismic studies similar to those done for the Tsuruga NPP can shed light on such processes.

In addition, officials thus might find useful seismic hazard analyses that are extended to include an assessment of the possibility and impacts of secondary fault displacement beneath the facilities. Even though the features beneath Tsuruga appear inactive using NRA's definition, a probabilistic fault displacement hazard analysis (PFDHA) has been suggested to explore "what-if" scenarios, where features such as the D-1 fault do move, incorporating expert, evidence-based judgments on the likelihood of movement and possible magnitudes of displacement.

A Hemisphere Away: Lessons From Hazard Assessments at Diablo Canyon NPP

The Diablo Canyon NPP in central coastal California was constructed in the late 1960s, with seismic analyses at the site having evolved continually since then.

In the early 1970s, the Hosgri fault zone was discovered 5 kilometers offshore from the plant, leading to a reevaluation of hazard that required assessment criteria and surveying methods to be developed. In contrast to the deterministic approach being taken today by the Japanese regulator, probabilistic approaches were being developed and applied in the late 1980s, and there has been a history of regulator-operator dialogue, with an agreed-upon program of seismic hazard assessment updating. The work at Diablo Canyon motivated the U.S. Nuclear Regulatory Commission (NRC) to move toward more probabilistic approaches since the late 1990s.

On the basis of recommendations by the U.S. Geological Survey, NRC specified that a magnitude 7.5 earthquake should be postulated to occur anywhere along the Hosgri fault zone, including the point closest to the plant. The design ground motion spectrum for this fault zone was anchored to a peak acceleration of 0.75 times the acceleration of gravity (g). The Diablo Canyon NPP was strengthened for the postulated Hosgri event, and the operating license was granted in 1984.

The license included a condition, based on a recommendation by the NRC's Advisory Committee on Reactor Safeguards, that the plant owner develop and implement a program to reevaluate the seismic design bases regularly. The owner, the Pacific Gas and Electric Company (PG&E), implemented a "Long-Term Seismic Program," which uses the latest techniques and data to perform periodic seismic reevaluations to assess whether the range of seismic behavior that the nuclear power plant is designed to withstand continues to be appropriate.

The active involvement of experts, including the NRC staff and its consultants, the U.S. Geological Survey, the Pacific Earthquake Engineering Research Center, the Southern California Earthquake Center, academia, and private consulting firms, together with state-of-the-art geoscientific investigations, has resulted in a comprehensive technical program for periodic hazard assessment at the Diablo Canyon NPP. Both NRC and PG&E stress open communication as the program evolves. Frequent independent reviews by a consulting board and peer reviewers have contributed to this open approach and mutual trust.

The Long-Term Seismic Program continues today, and the activities have allowed PG&E to anticipate and respond to new seismic safety issues and concerns as they arise. For example, it was possible to test and verify the results of the program's ground-motion evaluation by using new data from the well-recorded 17 October 1989 Loma Prieta earthquake, as well as other relevant earthquakes in California and elsewhere. This ability has provided increased confidence that earthquakes occurring in central California are not likely to produce surprising or conflicting data.

The Search for the Best Approach

As countries grapple with how to meet their energy needs while ensuring public safety, a question arises: Which approach to this particular problem—setting an age window for the last known movement of a fault or evaluating the probability that the fault will actually move while still ensuring that the structure is designed to handle the movement—works best to meet both objectives?

Closing down plants that are perceived to be at hazard based on blanket criteria is an easily understood approach in that it completely removes a specific type of hazard to the public, but it also impacts key local and national infrastructure, which presents other hazards. Because the approach does not evaluate and consider the quantitative risks associated with particular NPPs, it could be highly conservative on a case-by-case basis.

To tackle this problem, an approach such as that taken at Diablo Canyon could provide a useful model for the current reevaluation of seismic and active fault hazards in Japan. Using information from combined fragility analyses and PFDHA and establishing long-term seismic evaluation programs, it would be possible to make risk-informed decisions about how to manage Japan's nuclear power facilities that are currently under threat of permanent closure owing to potential active fault hazards. Of course, this approach requires the time and resources of operators and regulators to ensure comprehensive evaluations, plus a difficult decision on whether to complete the evaluation of fault-related hazards and risks before a plant reopens or to reopen the nuclear power plant and initiate the analyses simultaneously.

In the meantime, the clock is still running at Japan's out-of-action NPPs. Whatever choices are made, improved dialogue between scientists, regulators, and NPP operators, as well as the public and its decision makers, will ensure that the best information gets to those who need it.

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