

Great East Japan Earthquake, JR East Mitigation Successes, and Lessons for California High-Speed Rail



MTI Report 12-37



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REPORT 12-37

GREAT EAST JAPAN EARTHQUAKE, JR EAST MITIGATION SUCCESSES, AND LESSONS FOR CALIFORNIA HIGH-SPEED RAIL

Frances L. Edwards, M.U.P., Ph.D., CEM
Daniel C. Goodrich, M.P.A., CEM, MEP
Dr. rer. nat. Margaret Hellweg
Jennifer A. Strauss, Ph.D.
Martin Eskijian, P.E.
Omar Jaradat, Ph.D.

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16. Abstract <p>California and Japan both experience frequent seismic activity, which is often damaging to infrastructure. Seismologists have developed systems for detecting and analyzing earthquakes in real-time. JR East has developed systems to mitigate the damage to their facilities and personnel, including an early earthquake detection system, retrofitting of existing facilities for seismic safety, development of more seismically resistant designs for new facilities, and earthquake response training and exercises for staff members. These systems demonstrated their value in the Great East Japan Earthquake of 2011 and have been further developed based on that experience. Researchers in California are developing an earthquake early warning system for the state, and the private sector has seismic sensors in place. These technologies could contribute to the safety of the California High-Speed Rail Authority's developing system, which could emulate the best practices demonstrated in Japan in the construction of the Los Angeles-to-San Jose segment.</p>			
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To order this publication, please contact:

Mineta Transportation Institute
College of Business
San José State University
San José, CA 95192-0219

Tel: (408) 924-7560
Fax: (408) 924-7565
Email: mineta-institute@sjsu.edu

transweb.sjsu.edu

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EXECUTIVE SUMMARY

Earthquakes are a reality in both Japan and California. Seismically active areas lie near and under high-speed rail systems in Japan and along the proposed route for the California High-Speed Rail Authority's (CHSRA) developing system. Japanese high-speed lines have withstood significant earthquakes without a single loss of life. Their experiences are instructive for California as it develops its system.

The report begins with an explanation of seismology and the study of earthquakes in various parts of the world. It provides a brief explanation of plate tectonics and the types of seismic waves. Next, it describes how earthquake monitoring technology has developed, and how early warning of approaching earthquakes is now possible using algorithms to evaluate data collected by seismometers and accelerometers.

The report then describes the history of the threefold aspects of seismic mitigation on the East Japan Railway (JR East), beginning with a study of the development of Japan's earthquake early warning system. It next reviews the recent seismic history of Japan and the JR East infrastructure retrofits that followed each significant earthquake from 1978 through 2011. Finally, it evaluates the planning and training involved in preparing JR East staff to assist passengers and staff in time of disaster.

Next, it describes the Great East Japan Earthquake on March 11, 2011, and its impact on JR East facilities. What began as a M 9.0 earthquake off the coast of Tohoku became a tsunami disaster because the earthquake was under the ocean. It disturbed the seabed and generated a tsunami wave that rose to 12 meters (39 feet), devastating many cities along the coast. The "triple disaster" was created when the tsunami wave overwhelmed the tsunami walls and flooded the nuclear power plant at Fukushima.

The impact of the triple disaster on the JR East infrastructure provides many lessons about the value of various types of mitigation for the CHSRA system. The next section evaluates the value of earthquake early warning systems, including the systems currently in use in California and their possible application to high-speed rail facilities. Real-time earthquake engineering (RTEE) and real-time seismology (RTS) are described, and their relationship to a high-speed rail earthquake early warning system is explained. Public policy and government activities in the development of warning systems are also discussed.

Seismic retrofitting of rail infrastructure in Japan is evaluated for its applicability to the California high-speed rail system. Lessons are drawn regarding the types of retrofitting that may be beneficial and the differences in California's geology that may drive the development of different engineering solutions for seismic threats.

The JR East earthquake early warning system stops the train, prompting a response by the passengers and staff. Staff training in Japan was largely responsible for the subsequent lifesaving activities that moved passengers and staff out of harm's way. The types of training and exercise activities used in Japan are evaluated for applicability to California rail systems.

The report concludes that the lessons learned from the experiences of JR East in the 2011 Great East Japan Earthquake can inform decisions to be made by the CHSRA as it develops its route, designs its infrastructure and selects its train sets. The training lessons are equally valuable.

The report uses literature review, case study, and interviews with researchers and practitioners as approaches to understanding the history and current state of the EEW development and application to infrastructure, including high-speed rail. Articles indexed in scholarly databases and newspaper archives formed the basis for much of the literature review. In addition, the JR East system provided reports rarely available to Western researchers on EEW system performance, seismic resistance/resilience research related to columns, piers and bridges, and staff training. The authors conducted extensive EEW research through the Berkeley Seismic Laboratory, and structural engineering research on seismic resistance through private engineering activities, both of which are documented in sections of this report.

I. INTRODUCTION

In March 2011, the Tohoku region of Japan suffered a triple disaster: the largest earthquake in recent Japanese history at moment magnitude (M_w) 9.0;¹ a catastrophic tsunami; and flooding of the Fukushima Nuclear Power Plant, which led to the release of radioactive materials.² Two rail systems operated by the East Japan Railway Company (JR East) served the disaster area: the country's renowned high-speed Tohoku Shinkansen and a coastal rail line connecting the region's farmers and fishermen to the markets of metropolitan Tokyo. While the government's mitigation and preparedness measures successfully minimized the impact of the shaking, flooding from the tsunami overwhelmed both mitigation measures and community preparedness activities and led to the catastrophic failure of the nuclear power plant reactor.³

Among all the destruction, one success stood out: the JR East system's mitigation measures, which include an earthquake early warning system, infrastructure retrofits, and staff training. Although the tsunami damaged most of the coastal rail line and washed five unoccupied trains off the tracks,⁴ its flooding did not extend inland to the high-speed rail line,⁵ which suffered no loss of life or rolling stock and, considering the size of the earthquake, experienced relatively little damage.⁶ This success was due to a combination of robust mitigation and preparedness activities, including automatic train system braking and electrical shut-off, triggered by the early earthquake detection system (EEDS); retrofit of the viaducts, bridge piers, tunnels, station buildings, and other facilities to withstand seismic shaking; and training of railway staff to direct passengers in post-earthquake evacuation and sheltering.⁷

As California develops a new high-speed rail system, it needs to consider adopting seismic mitigation measures with proven return on investment. The Japanese experience may help to inform those investments.

II. THE SCIENCE OF EARTHQUAKES

In the mid-twentieth century, scientists determined that Earth is made up of more than a dozen separate tectonic plates that move against each other on a sea of molten material. According to this theory, new crust is created at vents along the sea floor, and old crust is recycled in deep-sea trenches.⁸ As the plates move, they may become stuck beneath Earth's surface. When the pressure has built up sufficiently, the subterranean rock breaks, causing an earthquake. This break in the crust is called a fault.⁹ The place in the earth where the rock begins to break is called the earthquake hypocenter, or focus, while the point on the earth's surface directly above the focus is called the epicenter.¹⁰ The greater the magnitude of the earthquake, the larger the area of the fault that ruptures, the greater the shift between the sides of the fault, and the longer the earthquake's duration. Seismic waves travel away from the rupturing fault in all directions, and large earthquakes can be felt hundreds of miles away. Seismologists have recognized that earthquakes generate four different types of waves. Each travels at a different speed and can cause different types of damage.

PLATE TECTONICS

Seismic studies have led to the recognition of four types of tectonic plate boundaries: divergent boundaries where new crust is created and the plates pull away from each other; convergent boundaries where crust is destroyed as one plate is subducted, or dives beneath another; transform boundaries where plates move horizontally past each other and crust is neither created nor destroyed; and plate boundary zones – broad belts in which boundaries are not well defined and the effects of plate interaction are unclear.¹¹ The Mid-Atlantic Ridge, which extends from the Arctic past South America almost to Antarctica, is an example of a divergent boundary. It accounts for the separation of the Americas from Europe and Africa. Iceland, which straddles the ridge, is being built by volcanic activity along the ridge, with the island divided between the Eurasian and North American plates. The region that includes the northern coasts of California, Oregon, and Washington, and their adjacent sea floor, is an example of a convergent boundary, or subduction zone, where the Juan De Fuca Plate is subducting under the North American Plate and sinking into the mantle.¹² The San Andreas Fault system in California is made up of transform faults with slow horizontal movement of about 35 mm (1.38 inches) per year.

Another type of fault is the blind thrust fault. Unlike plate boundary faults, blind thrust faults have no surface expression, making them difficult to map. When these faults shift, one side “moves upward over the other,”¹³ producing more vertical movements. This type of faulting was the cause of the February 9, 1971 Sylmar, California, earthquake (M 6.6) that caused collapses at two hospitals and the deaths of 65 people.¹⁴ Rupture on a nearby blind thrust fault was the cause of California's most costly earthquake, the January 17, 1994 Northridge Earthquake (M 6.7) with 61 deaths and \$15 billion in damage.¹⁵

Tsunamis are commonly the result of undersea subduction zone earthquakes, which cause sudden vertical movement of the seafloor. This movement generates ocean waves that can travel at an average speed of 750 km per hour (466 mph) – roughly the speed of a commercial jet plane. When the wave encounters shallower water, as at the coastline,

it slows and the wave amplitude increases. Sometimes the trough of the wave arrives first. Then, the first sign of tsunami will be an unusually low water level, like an extremely low tide, in which the water quickly recedes and is then followed by inundation of coastal areas. The inundation can take the appearance of an extremely high tide, a series of breaking waves, or a bore (wall of water). The initial wave trough or crest may be followed by a series of wave trains that return within a few minutes to several hours after the earthquake.¹⁶ In 1965, the International Tsunami Information Center was established in Hawaii to issue tsunami warnings for the Pacific nations. Over time, its equipment has improved, and it now receives data from seismic sensors, buoy-based measuring systems, and tide gauges throughout the Pacific basin and in Hawaii.¹⁷

On December 26, 2004, a M 9.1 earthquake occurred beneath the sea floor, offshore of Banda Ache, Indonesia, with a rupture length of about 1200 km (745 miles).¹⁸ This earthquake generated a tsunami that swept through the entire Indian Ocean, killing more than 280,000 people in 11 nations. At that time, there was no tsunami warning system in the Indian Ocean,¹⁹ but this event prompted UNESCO to create the Indian Ocean Tsunami Warning System, which began operation in June of 2006.²⁰

SEISMIC WAVES

Seismic waves are created by a fault rupture, an explosion, or other movements of the earth. Like waves in a pond, they spread out through the earth in all directions from the source. Body waves, which travel through the earth's interior, are either "primary" or "secondary." Primary, or P-waves, arrive first and are compressional waves. P-waves travel through rock near the earth's surface at about 6 km/s and also through the earth's liquid core. Secondary, or S-waves, travel at about half the speed of the P-waves and exhibit movement transverse (side-to-side) to the direction the waves are propagating, and thus are unable to traverse the earth's liquid core. P-waves travel more quickly, so they arrive at seismic sensors in advance of S-waves.²¹

In addition to body waves, a seismic source, such as an earthquake, also produces surface waves – seismic waves that move only the ground near the earth's surface. These waves appear only at some distance from the epicenter. There are two types of surface waves, each traveling at a different speed and producing a different kind of ground movement. Love waves, which travel at 2–6 km/second (1.24-3.73 miles/second),²² arrive first and cause purely horizontal, side-to-side motion. Rayleigh waves, which produce most of the shaking that humans feel,²³ travel at 1–5 km/second (.62-3.1 miles/second)²⁴ and therefore arrive later. Rayleigh waves produce a rolling motion much like that of ocean waves, leading some observers to describe it as the ground "rippling."

Most of the damage to buildings and infrastructure is caused by the shaking from S-waves and surface waves.²⁵ Buildings are designed to withstand the vertical force of gravity and are relatively insensitive to P-waves. Before lessons about shaking effects were learned from recent earthquakes, little effort was made to protect buildings from horizontal forces, thus, during moderate earthquakes, structures were susceptible to damage by shaking from S-waves and Love waves.²⁶

Seismic waves generally propagate uniformly away from their source; however, seismic waves propagate at different speeds through the earth due to its layered composition. When seismic waves hit a boundary, such as the one between the earth's mantle and crust, they may be reflected causing them to hit the surface at the same location and at the same time as other waves arriving directly from the quake. This is known as the Moho effect,²⁷ and it causes increased amplitudes of ground motion (or shaking), usually about 100 km (62 miles) from the epicenter.²⁸ Such a 'focusing' effect was observed during the Loma Prieta earthquake, an earthquake with magnitude 6.9, which struck the San Francisco Bay Area on the evening of October 17, 1989, at 5:04 pm local time. That event's epicenter was approximately 35 km (22 miles) southwest of San Jose, California, but did the greatest damage in Oakland, 65 km north-northeast of San Jose, where the Interstate 880 Cypress Viaduct and a section of the upper tier of the San Francisco-Oakland Bay Bridge collapsed,²⁹ and in San Francisco, 65 km (40 miles) northwest of San Jose, where soft story homes pancaked in the Marina District, and elevated sections of Interstate 280 were damaged.³⁰ Surface shaking at frequencies that affect buildings and structures usually results from shallow earthquakes rather than deeper ones.³¹

Since earthquakes can vary greatly in size, they are described using a logarithmic scale called a magnitude scale (M). Each unit of an earthquake's magnitude indicates a change by a factor of ten; thus, a M 4.0 earthquake is ten times larger than a M 3.0 quake. The first magnitude scale for California earthquakes, now called the local or Richter magnitude, was defined in 1935 by Charles Richter and Beno Gutenberg. The scale measured the amplitude from an earthquake recorded by a standard seismograph invented by Wood and Anderson. For an earthquake at a distance of 100 km (60 miles) from the seismograph, a M 3.0 earthquake would register with an amplitude of 1 mm (0.04 in) while an earthquake with M 4.0 would show an amplitude of 10 mm (0.4 in). The Wood-Anderson seismograph has several limitations, among them the fact that the paper is only 30 cm (~12 in) across, so the local or Richter magnitude scale is reliable only for earthquakes with magnitudes up to about M 6. Since the development of the Richter magnitude, gains have been made in both our understanding of the physics of earthquakes and in the instrumentation for recording them. It is now known that an earthquake record with an amplitude 10 times greater than another releases approximately 32 times more energy. For example, a M 4.0 earthquake releases 32 times more energy than a M 3.0 earthquake and a M 9.0 earthquake releases 32 times more energy than a M 8.0. Based on the physical understanding of earthquakes, seismologists now prefer to use the moment magnitude scale to all other types of historically defined magnitudes, particularly for larger earthquakes. Moment magnitude, usually represented as M_w , describes the moment released in a quake, which increases with the area of the rupture zone and the amount of offset and scales approximately with the energy. For example, the rupture of the M 9.1 earthquake in the Indian Ocean on December 26, 2004 covered 199,947 square km (77,200 square miles). The moment can be determined by estimating the size of the rupture zone from the locations of aftershocks, or it can be modeled from seismic or GPS recordings³² of the earthquake. GPS recordings can also be used to monitor the direction and rate of drift of the tectonic plates after a rupture, and also to monitor elevation changes that may have occurred during the earthquake.³³

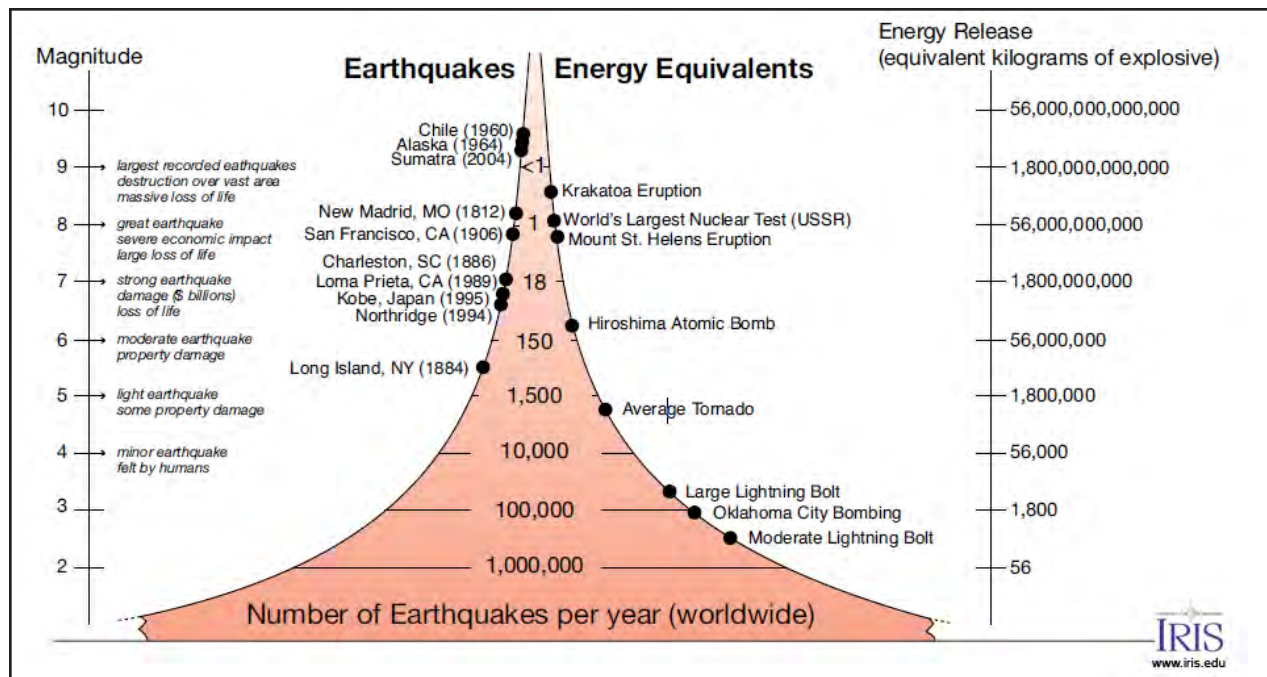


Figure 1. Comparison of the Moment Magnitude and Corresponding Energy Release of Large Earthquakes and Other High-energy Phenomena

Source: Incorporated Research Institutions for Seismology.

Since moment magnitude is defined as the measure of the total moment released during a rupture, an earthquake has a single moment magnitude. However, local shaking intensity, which is reported on a 12-level Modified Mercalli scale, is a useful measure for understanding the impact of an earthquake. The intensity is different at various locations, depending on distance from the fault and the geology and surface conditions at the site. The shaking intensity is a parameter determined for each point in the region and describes specific observed impacts (Table 1).³⁴

Table 1. Modified Mercalli Intensity Scale

Intensity	Effect on People and Property
I	Rarely felt by people except in special circumstances
II	Felt by a few at rest, especially on upper floors of buildings
III	Felt by people indoors and on upper floors; vibrations similar to a passing truck
IV	Felt indoors and sometimes outdoors, cars rock, dishes, windows and doors disturbed, walls make cracking sound
V	Felt by everyone, dishes and windows may break, unstable objects may overturn, pendulum clocks may stop
VI	Felt by all, heavy furniture moves, plaster may fall, slight damage
VII	Damage negligible in buildings of good design and construction; slight to moderate in well-built ordinary structures; considerable damage in poorly built or badly designed structures; some chimneys broken.
VIII	Damage slight in specially designed structures; considerable damage in ordinary substantial buildings with partial collapse. Damage great in poorly built structures. Fall of chimneys, factory stacks, columns, monuments, walls. Heavy furniture overturned.
IX	Damage considerable in specially designed structures; well-designed frame structures thrown out of plumb. Damage great in substantial buildings, with partial collapse. Buildings shifted off foundations.
X	Some well-built wooden structures destroyed; most masonry and frame structures destroyed with foundations. Rails bent.
XI	Few, if any (masonry) structures remain standing. Bridges destroyed. Rails bent greatly.
XII	Damage total. Lines of sight and level are distorted. Objects thrown into the air.

Source: USGS, 2013c.

Scientists at the United States Geological Survey's (USGS) National Earthquake Information Center (NEIC) have asked the public to join them in collecting information about earthquakes. The "Did You Feel It?" website allows anyone to register how much shaking they felt for a specific event. The information is sometimes added to the "Shake Map," which shows intensity and extent of shaking. These observations contribute information to guide the Federal Emergency Management Agency's (FEMA's) response to disaster events.³⁵

Earthquakes are a daily threat in Japan, which sits at the junction of four tectonic plates: the Eurasian Plate, the North American Plate, the Philippine Plate and the Pacific Plate. During the twentieth century, Japan had 13 significant earthquakes, resulting in more than 150,000 deaths and the collapse of "hundreds of thousands of buildings."³⁶ For example, on September 1, 1923, the Great Kanto Earthquake (M 7.9) caused a fire and a 12 m (39-foot) tsunami; these two combined events killed 143,000 people.³⁷ They destroyed large sections of both Tokyo, Japan's capital, and Yokohama, its trade center with the Western nations. The earthquake's shaking lasted for 14 seconds; the resulting tsunami wave was 6 m (20 feet) high when it washed over Kamakura on the Honshu coast. The shaking led to fires throughout Tokyo that burned for two days. About half of the buildings were destroyed because the broken water mains meant the fire department had nothing with which to douse them. Yokohama, built on mud flats, had wholesale building collapses and fires that destroyed most of the city.³⁸

Table 2 shows the most significant Japanese earthquakes of the twentieth century.

Table 2. Significant Japanese Earthquakes of the Twentieth Century

Name	Date	Moment Magnitude	Deaths
Kanto Plain (Tokyo)	9/1/23	7.9	143,000
Tango	3/7/27	7.6	3,020
Sanriku	3/2/33	8.4	2,990
Tottori	9/10/43	7.4	1,190
Tonankai	12/7/44	8.1	1,223
Mikawa	1/12/45	7.1	1,961
Nankaido	12/20/46	8.1	1,330
Fukui	6/28/48	7.3	3,769
Hokkaido	3/4/52	8.1	31
Niigata	6/16/64	7.5	26
Off East Coast of Honshu	5/16/68	8.2	47
Miyagi	6/12/78	7.4	27
Kobe	1/17/95	7.2	5,502

Note: There were also many earthquakes with magnitude greater than 7.0 along the coast of Honshu that caused no fatalities.

Source: USGS, 2013b; Nakamura and Saita, 2007b.

III. MONITORING EARTHQUAKES

The earliest mention of a seismic sensor comes from ancient China, where Chang Heng developed the first seismoscope in 132 A.D. European interest in seismoscopes increased in the late 1700s due to a series of earthquakes around the Mediterranean Sea. These primitive instruments were pendulum systems, which could etch recordings, but provided no time information. Early attempts at incorporating temporal information involved basins of mercury, such as those in use by Cavalli in 1784 and Mallet in 1851. Seismographs, which provide a written record, in one form or another, of shaking as a function of time, were invented in the late 1800s. The earliest seismographs employed pendulums and were built in Italy by Filippo Cecchi in 1875. Soon after, large advances in damping and recording resulted in improved instrumentation, developed by Milne, Ewing, Gray, Omori, and Wiechert. The seismometers in use today have digital output and record relative motion with respect to the earth as a function of time.³⁹

The concept of an earthquake early warning system appears to have originated with Dr. J.D. Cooper of San Francisco. On November 3, 1868, he wrote a letter to the editor of the San Francisco Daily Evening Bulletin suggesting the development of an automatic electricity-based sensor system, using the city's existing telegraph lines to warn the public of an impending earthquake through the use of an alarm bell to be triggered by electric current over the telegraph wires.⁴⁰ He was interested in protecting the population of San Francisco from earthquake damage following the 1868 earthquake on the Hayward fault. Although the technology of the time did not permit the development of the envisioned telegraph-based system,⁴¹ the first seismic network in the Western Hemisphere was installed by UC Berkeley, with one station on the Berkeley campus and another at the Mt. Hamilton Observatory. The first strong-motion seismograph was developed in Japan (1953), more than 80 years after Dr. Cooper's proposal paved the way for modern earthquake early warning systems. Japan's development of an earthquake early warning system will be discussed in the next section, which focuses on JR East's seismic mitigation project.

The next improvement in earthquake monitoring came when the United States and Russia (then the Union of Soviet Socialist Republics) concluded the Test Ban Treaty of 1963, which "prohibits nuclear weapons tests 'or any other nuclear explosion' in the atmosphere, in outer space, and under water. While not banning tests underground, the Treaty does prohibit nuclear explosions in this environment if they cause 'radioactive debris to be present outside the territorial limits of the State under whose jurisdiction or control' the explosions were conducted." Verification of the cessation of testing required the installation of sensors, which could distinguish between earthquakes and nuclear tests, to monitor treaty compliance. This required that seismic events smaller than M 4.75 would have to be monitored globally. For this purpose, the Worldwide Standardized Seismographic Network (WWSSN) was created in 1963. In addition to improving monitoring for nuclear tests, the new seismic network allowed "seismologists to map precisely the zones of earthquake concentration worldwide." The network included 75 stations in 40 countries, and 20 US states.⁴²

The National Earthquake Information Center (NEIC) started in 1966 in Rockville, Maryland, as part of the National Ocean Survey, an agency of the Department of Commerce. In 1972, it was moved to Boulder, Colorado, and became part of the USGS. In 1974, it moved

to a more resilient location,⁴³ its current home in Golden, Colorado, against the Rocky Mountains with a lower seismic hazard than other areas in the west. It has three missions:

- Identify and characterize earthquakes around the world using a network of 2,000 sensors,⁴⁴ and rapidly disseminate this information;
- Maintain a database of seismic activity based on national and global networks using internet and satellite acquired data;
- Conduct research to improve the understanding of earthquakes to better mitigate risks to humans.⁴⁵

The focus of NEIC is to collect and disseminate information to scientists, first responders, Red Cross, USAID and other government agencies, the media, and the public. The seismic networks from which the NEIC collects information are worldwide, based on international agreements for data sharing.⁴⁶

In 1984, the Global Seismographic Network (GSN) was established. This partnership between the USGS, the National Science Foundation, and the Incorporated Research Institutions for Seismology (IRIS) provides a permanent digital network of global instruments for monitoring and research. Currently, the GSN includes over 150 modern seismic stations around the globe.

In 1997, Congress authorized the development of a “real-time seismic warning system” for the United States. In the summer of 2000, strong-motion instruments for the Advanced National Seismic System (ANSS) were installed in San Francisco, Salt Lake City and Seattle, followed by more than 100 additional instruments in other locations over the next 2 years.

California developed a strong-motion instrumentation program (SB 1374) following the 1971 Sylmar earthquake. Additional funding (SB 593) was provided after the Whittier Narrows Earthquake of 1987. The goal was to collect data on building performance during earthquake-induced shaking to enable engineers to design structures that are more resistant to earthquakes. “Accelerographs” were installed in 650 locations representing various types of soil, and “earthquake monitoring devices” were installed in 170 buildings (including hospitals and essential services buildings), 20 dams and 60 bridges. The California Strong Motion Instrumentation Program (CSMIP) is based at the California Geological Survey (CGS). It uses real-time telemetry as well as dial-up modems and at a few sites, still, the collection of paper records, to aggregate data after an earthquake. For example, data collected on shaking near the fault during the Northridge Earthquake was used to improve the Uniform Building Code for structures in near-fault zones, and to guide the development of more earthquake resistant design.⁴⁷

In 2000, the California Integrated Seismic Network (CISN) was formed as one of eight regional networks making up the ANSS. The network includes the USGS offices in Menlo Park and Pasadena; California Institute of Technology’s (Caltech) Seismological Laboratory; University of California at Berkeley (Berkeley) Seismological Laboratory; the California

Geological Survey; and the Governor's Office of Emergency Services (CalOES) to monitor earthquakes. The CISN provides earthquake information as well as dedicated software for receiving and viewing earthquake information: CISN Display and ShakeCast. CISN Display provides software-based, rapid maps of earthquake information for emergency response, including ShakeMap, special reports, and links to external products, such as HAZUS, which overlays information on community infrastructure and construction.⁴⁸ ShakeCast distributes ShakeMaps and includes post-earthquake automatic notification to users about the event and its relationship to their infrastructure. For example, the California Department of Transportation (Caltrans) uses ShakeCast to help engineers select which overpasses and bridges should be inspected first after an earthquake.⁴⁹

The USGS National Earthquake Information Center (NEIC) has recently developed PAGER (Prompt Assessment of Global Earthquakes Response) to provide a rapid estimation of possible fatalities and economic losses due to an event. This has greatly added to the available information for post-event hazard analysis and response. The suite of available earthquake information products was rounded out by the addition of the USGS Earthquake Notification System. Using email, text messaging and Twitter, this alert service sends post-event notification of earthquakes that occur in areas specified by the subscriber, anywhere in the world. The notices, which include the location, magnitude, and depth of the earthquake, are currently received by more than 350,000 subscribers.⁵⁰

In 2006, the USGS supported Phase I of the development and testing of real-time algorithms for earthquake early warning (EEW) in the state of California in partnership with Berkeley and Caltech, the Southern California Earthquake Center and the Federal Technical Institute in Zurich, Switzerland. The "proof of concept" earthquake for the system was the magnitude 5.4 Alum Rock earthquake on October 30, 2007, at 8:04 pm local time. This was the first moderate sized earthquake detected by the system and it highlighted the efficacy of early warning alerts. The earthquake's epicenter was near San Jose, and the system sent a warning to the scientists 5 seconds before peak shaking was felt in San Francisco. Phase II of the project began in 2009 with the implementation of an end-to-end test or "demonstration" system, which integrated the previously tested methods into a single prototype warning system.⁵¹ This end-to-end test prototype system, ShakeAlert, became fully operational in 2011 based on data from 400 seismic sensors throughout the state operated by the CISN and its partners. Alerts are sent out in real-time to beta users running the UserDisplay. The beta users include scientists, emergency managers, and the Bay Area Rapid Transit system (BART), among others. The UserDisplay is a Java applet that runs on a computer desktop. It provides information on the magnitude, location, estimated shaking intensity at the user's configured location, and a countdown of the time until the S-wave arrival at that location. Phase III commenced in January of 2012 with the addition of a \$6 million grant from the Gordon and Betty Moore Foundation awarded to the partners: the USGS, Caltech, Berkeley, and the University of Washington. This grant enabled the expansion of the California demonstration system into a prototype for the entire West Coast.⁵²

Many algorithm improvements, speed enhancements, and UserDisplay updates were implemented during the ongoing Phase III. One of ShakeAlert's three algorithms, ElarmS, now only requires 100 ms of P-wave data to start the calculations. As a result, when the

recent La Habra earthquake struck on March 28, 2014, scientists only 30 km (18.64 miles) from the epicenter in Pasadena received 4 seconds of warning before the arrival of the shaking from the S-wave. BART, like the Shinkansen in Japan, is poised to mitigate hazards by using EEW. Trains automatically decelerate once an alert from ShakeAlert is received. “Within 24 seconds we can get the train to a complete stop.”⁵³ During the past few years, several small earthquakes ($\sim M 3$), which occurred close to the epicenter of the 1989 Loma Prieta rupture, were detected by ShakeAlert. “[A]lerts were provided around 20 seconds before peak ground motion arrived in San Francisco, Oakland and Berkeley – illustrating what would be possible in a repeat of the devastating 1989 quake.”⁵⁴ Thus, ample time would be available to slow or stop most trains in the areas where BART operates, and prevent catastrophic derailments.

ShakeAlert’s UserDisplay (see Figure 2) shows a simulation of the Loma Prieta earthquake. The blue house is the User’s location, the red dot is the epicenter, and the yellow and red circles are the P-wave and S-wave fronts, respectively. It displays the calculated 23 s until the S-wave reaches the User’s location, the expected moderate shaking intensity V, and the estimated magnitude of 6.9.

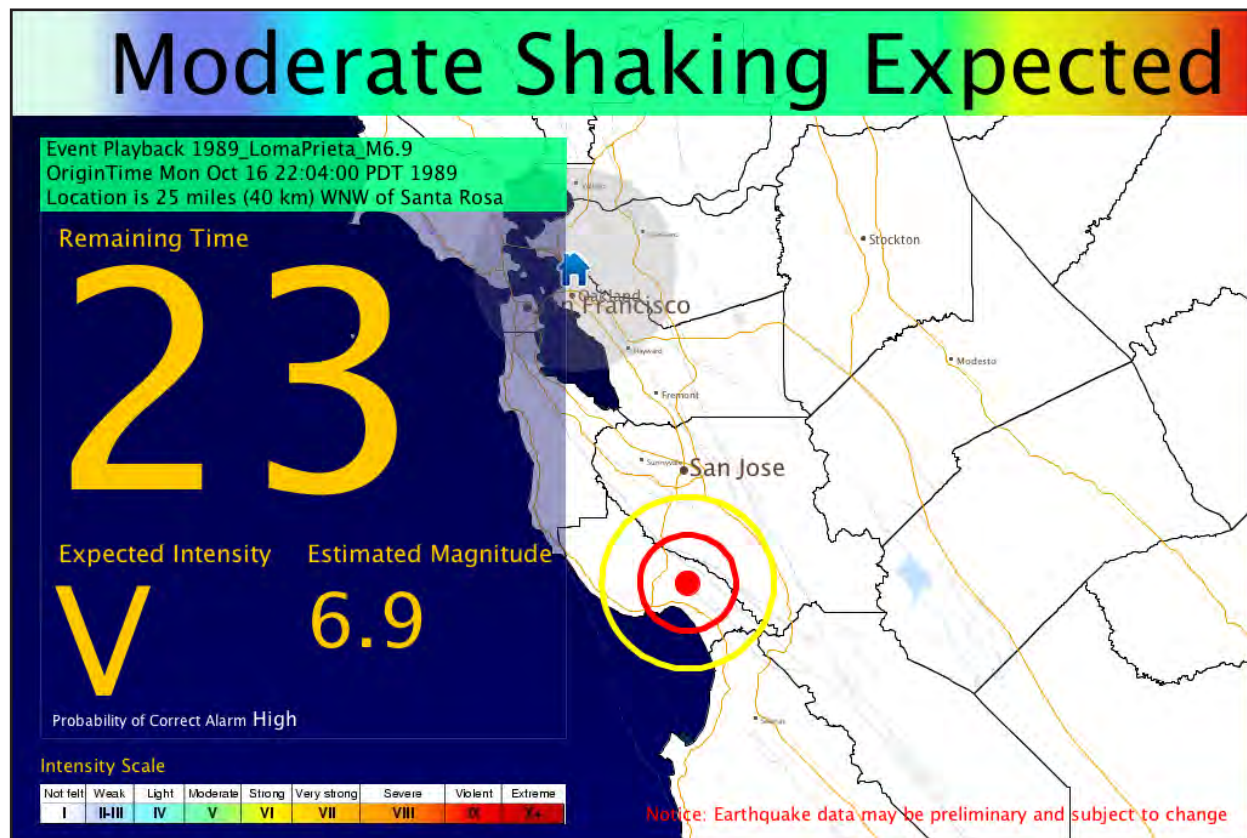


Figure 2. ShakeAlert’s User Display

Source: ShakeAlert Earthquake Early Warning, 2012.

Recently ShakeAlert developers have begun to incorporate GPS data to measure the gross movement of the earth’s plates as the rupture unfolds. The satellites are part of the U.S Department of Defense’s Nav Star System, which consists of 21 satellites orbiting 20,000 km (12,427 miles) above the earth. They transmit radio signals that are used in sets

of four to determine latitude, longitude and elevation.⁵⁵ In non-EEW applications, scientists use these stations to monitor the ongoing motion of the Pacific Plate and its surrounding continental plates along the Pacific Rim of Fire – the most seismically and volcanically active zone in the world.⁵⁶ For EEW, real-time analysis of plate motion allows for better magnitude estimations for the largest earthquakes, which is important for ensuring that all affected municipalities receive appropriate early warning.

Scientists would like to be able to forecast earthquakes far enough in advance to protect people and critical infrastructure, such as trains, and to interrupt dangerous activities that would be negatively impacted by shaking, such as surgery or hazardous materials mixing. The USGS has been studying the San Andreas Fault in Parkfield, California, “to monitor and analyze geophysical and geochemical effects before, during, and after the anticipated earthquake,”⁵⁷ and to develop appropriate communication methods and systems for response to their possible warnings of a coming earthquake. The experiment sought to capture the characteristic rupture, which occurs on the same portion of the fault, at approximately 22-year intervals. At the time of the initial experiment, scientists expected the next rupture to occur before 1993 but had to wait until 2004 to record the next event. The experiment is ongoing. As part of the National Earthquake Hazard Reduction Program, scientists continue to collect data on the fault to understand its behavior, which they hope will someday lead to the ability to better understand fault processes and – perhaps some day in the future – predict earthquakes.

In 2007 Dr. Elizabeth Cochran, now a seismologist with USGS, established the Quake Catcher Network (QCN) to broaden the range of earthquake data collection. She collaborates with Professor Jesse Lawrence of Stanford.⁵⁸ People are invited to voluntarily join the distributed computing network by purchasing a sensor for \$50, plugging it into the USB ports in their computers, and orienting it to North so that data describing the full movement of the earth at the site can be collected.⁵⁹ Ideally, the sensor would be attached to a concrete slab to best record the shaking. Users with mobile devices can also add the accelerometers – built into their devices to protect the hard drive – to the network. However, since they move they cannot be oriented for directionality, and each requires its own calibration. Since these devices may be carried on a person or in a vehicle, the ability to sense earthquake shaking may be limited by external motion. The data is communicated from the computer to Stanford’s server via the user’s existing Internet connection.

People in 67 countries are members of QCN.⁶⁰ Stanford’s servers analyze the shaking information from multiple sites to better understand the distribution of shaking intensities.⁶¹ This system helped to detect and warn of Chile’s M 8.8 earthquake in 2010, the M 6.3 earthquake in Christchurch, New Zealand, in 2011, and a M 4 earthquake near Berkeley in 2012.⁶² Dr. Cochran plans to add smartphones to the QCN to better serve poor countries and to harden the wireless connections in more developed nations.⁶³ A UNESCO report from 2014 estimates that 6 billion people, out of a worldwide population of 7 billion, have access to mobile phones.⁶⁴

While not as precise as the seismological accelerometers, QCN instruments provide supplementary information on ground motion at specific locations. They depend on private computers and Internet connections, which makes their use as an independent

early warning system for California impractical. However, their value is in gathering data from areas without one of the 400 CISON sensors. QCN sensors can also be used to blanket an area after an earthquake to collect data on aftershocks. For example, after the Christchurch earthquake in New Zealand, 180 of these sensors were deployed in the epicentral region.⁶⁵

IV. HISTORY OF JR EAST SEISMIC MITIGATION

East Japan Railway Company (JR East) was formed in April 1987 when the government-run Japan National Railroad (JNR) was separated into three companies: East Japan Railway Company (JR East), Central Japan Railway Company (JR Tokai), and West Japan Railway Company (JR West).⁶⁶ Today there are also JR Hokkaido, JR Kyushu, JR Shikoku, and JR Freight.⁶⁷ The new private system replaced the public system that was heavily in debt and suffered from deferred maintenance. To facilitate the privatization of the lines, the government assumed half of the debt.⁶⁸ As shown in Figure 3, JR East provides bullet train and conventional train services to Japanese communities from Tokyo to the northern end of Honshu. The company serves 16.5 million people each day on 7,510 km (4,660 miles) of track. Its 2013 net income was \$1,860,800,000, derived from the operation of conventional and high-speed (Shinkansen) rail lines, as well as 30 percent “from leasing restaurant and retail space in its stations and from managing shopping centers and office buildings on property that has been developed near its stations.”⁶⁹ The daily income from the railroad alone was estimated at \$430 million (4.5 billion yen) in 2011, of which \$11.5 million (1.2 billion yen) comes from bullet train services.⁷⁰



Figure 3. JR East Passenger Railway Lines

Source: Tanemura, 2012.

JR East uses its non-train revenue to support investments in safety. After the Great Hanshin-Awaji (Kobe) Earthquake in 1995, the Ministry of Transport and the Railroad Bureau ordered the railroads to retrofit their facilities to prevent a recurrence of the damage to the systems. By the time of the March 11, 2011 earthquake, JR East had completed all of the ministry's listed retrofits and mitigation activities.⁷¹

The JR East retrofits and mitigation fall into three categories. First is an earthquake early warning system to slow and stop the Shinkansen to prevent derailments at high-speeds. Second is improvement to infrastructure, including viaducts, piers and bridge connections, to reduce damage to them in earthquakes. Third is training staff in passenger safety and evacuation procedures, including annual drills. Each type will be discussed below.

HISTORY OF EARTHQUAKE EARLY WARNING SYSTEMS IN JAPAN

Dr. J.D. Cooper's vision of an earthquake early warning system became possible 80 years after his letter to the editor, when the first strong-motion seismograph was developed in Japan in 1953. A decade later, following the 1964 Niigata earthquake (M 7.5), the discussion of the need for an earthquake warning system for the Shinkansen, which was in the final stages of construction, was resurrected. Soon after, the 1965 earthquake in Shizuoka (M 6.1) caused some damage to the newly completed railway structures and a proto-earthquake warning system was put into place "with ordinary alarm seismometers and waveform recording seismometers."⁷² The sensors were placed at 20 to 25 km (12.4 to 15.5 miles) intervals along the track, and monitored the ground acceleration in real-time. The seismometers were set to alarm if the horizontal ground acceleration exceeded 40 Gals (1 Gal = 1 cm/s², or one thousandth the acceleration of gravity).⁷³ This level was chosen to avoid false alarms from small quakes and passing trains.

This on-site warning system served the rail lines well, but a true early warning system for Japan (such as that envisioned by Dr. Cooper in 1868) would require a coastline detection system, and public alerts. The Japan Meteorological Agency (JMA)⁷⁴ installed a coastline system that began operation in 1982, using a triggered S-wave detection system, similar to the onsite warning system used for the Shinkansen.⁷⁵ This "coastline detection system" sensed offshore fault activity (front-facing system) and relayed that information to the trains. Japan's earthquake warning system focused on protection of the Shinkansen trains. A similar triggered warning system was created by Mexico in 1991 to alert the citizens of Mexico City to expected shaking from earthquakes that occurred offshore of the southern and southwestern coastlines,⁷⁶ and later Istanbul implemented a system for the Bosphorus bridge.⁷⁷

The next phase of earthquake warning progress was the development of a P-wave detector that provided some warning time for protective measures before the arrival of the damaging seismic shaking (S-wave). P-wave detection methods provide earthquake early warning, because they do not require strong ground shaking to trigger, but can provide warning information based on the compressional P-wave alone. Called UrEDAS (Urgent Earthquake Detection and Alarm System) in Japan, the system could issue a warning three seconds after the P-wave was detected. The prototype front-facing P-wave detector began testing in 1984, and was operational for the Tokaido Shinkansen line in 1992. Its installation included

an automatic train control system, which cut off electricity to the trains and applied the brake. The same system was used for the Sanyo Shinkansen line in 1996. Installation of earthquake warning systems for the various Shinkansen routes is shown in Table 3.

Table 3. Shinkansen Routes and Earthquake Warning Systems

Name	Date in Service	Route	Length KM/Miles	Maximum Speed KMr./MPH	Earthquake Warning System	Date Installed
Tokaido	1964	Tokyo to Osaka	515/320	270/168	P-wave front alarm UrEDAS	1992
Sanyo	1972/75	Osaka to Hakata (Fukuoka)	554/344	300/186	P-wave front alarm UrEDAS	1996
Tohoku	1982/85 1991/2002	Tokyo to Morioka	593/368	275/171	Compact UrEDAS	1997-S-wave; 1998- P-wave
Joetsu	1982	Tokyo to Niigata	270/168	275/171	Compact UrEDAS	1998
Hokuriku	1997	Takasaki to Nagano	117/73	260/162	Compact UrEDAS	1998
Yamagata	1992/99	Fukushima-Shinjo	149/93	130/81		
Akita	1997	Morioka-Akita	127/79	130/81		

Source: Smith, 2003; Nakamura and Saita, 2007a.

The Great Hanshin-Awaji Earthquake, also known as the Kobe earthquake, of 1995 resulted in significant damage to the region's transportation infrastructure, including the railway system, discussed in more detail below. The UrEDAS and the onsite alarm system both issued alarms, but the UrEDAS warning "did not arrive at the target area due to transmission failure, ...showing the difficulty of controlling" messages to the trains from remote locations.⁷⁸ Because the Shinkansen is closed each day from midnight to 6:00 a.m. for maintenance, no Shinkansens were affected by the 5:46 a.m. earthquake. However, regular trains were operating.

The onsite combined S-wave and P-wave alarm system, known as the Compact UrEDAS, was developed soon after, with a goal to increase early warning times for the trains. The system combined a new estimation algorithm with a system that included a velocity meter, an accelerometer and a computer-processing unit.⁷⁹ The Compact UrEDAS was designed to "issue the alarm within one second of P-wave arrival."⁸⁰ In 1997, JR East installed 56 sets of the Compact UrEDAS for the Shinkansen lines, but with only the S-wave alarm actively used. In 1998, the system was adjusted to be an "along-the-railroad, onsite, P-wave detection system."⁸¹ By combining the P-wave and S-wave detectors, the Compact UrEDAS "achieves both rapidity and reliability."⁸² Since the Tokaido Line already had the UrEDAS system, the new Compact UrEDAS was installed on the Tohoku, Joetsu, and Nagano Shinkansen Lines, and eventually also on the Tokyo subway system (2001).⁸³

On May 26, 2003, the Sanriku-Minami (M 7.0) earthquake (also called Miyagiken-Oki) occurred in the northern part of Miyagi Prefecture. The Tohoku Shinkansen line received warning from the Coastline Compact UrEDAS front detection system using a P-wave alarm, which was issued within 3 seconds, and the alarm reached the line before the P-wave's arrival. "The on-site Compact UrEDAS then issued the P-wave alarm one second after P-wave detection. After that, the onsite Compact UrEDAS re-issued the ground motion triggered

alarm before the S-wave arrival.”⁸⁴ Only two trains, Yamabiko #59 and Hayate #26, were in high-speed operation in the warning area at the time. Yamabiko #59 received the early warning alert and came to a stop 3 km (1.9 miles) outside of the station and 10 km (6.2 miles) away from structures damaged by the earthquake. Hayate #26 was traveling outside of the warning area and ultimately received an alert 10 s after Yamabiko #59. Fortunately, the train did not cross into the area where the worst damage and track displacement occurred. It is estimated that due to the train’s high speed, passengers and operators may not have noticed the earthquake motion in the area, which exceeded 300 Gal. The warning system performed as expected, with the Coastline UrEDAS issuing the first P-wave alarm, followed by the three Compact UrEDAS sensors along the Shinkansen line.⁸⁵

On Sunday, October 23, 2004, the Niigata-ken Chuetsu earthquake (M 6.8) occurred at 5:56 p.m., with the hypocenter almost under the Shinkansen tracks. This reduced the available early warning time due to the proximity of the fault rupture.⁸⁶ The earthquake caused 35 deaths and 3,183 injuries. In addition, 6,000 buildings were damaged or destroyed and 1,300 landslides occurred.⁸⁷ It caused “the most extensive structural damage that JR East has suffered”⁸⁸ up to that time. Damage occurred at 86 locations on five conventional train lines, but the worst event was the first-ever derailment of a Shinkansen train, which occurred between Muikamachi and Nagaoka. While none of the 154 passengers was injured, eight of the ten cars derailed, and 900 meters (984 yards) of rail line were damaged. (The extent of the disruption to railway facilities will be discussed below.)

The P-wave sensor cut power to the train 3.9 seconds after the fault rupture began, which caused the brakes to be applied automatically. The driver also put on the emergency brake when he recognized the Compact UrEDAS alarm that states, “Emergency braking resulting from power disruption.”⁸⁹ “The S-wave hit the train 2.5 seconds after the alarm, and one second later strong shaking hit the train, which continued for about 5 seconds.”⁹⁰ Because the train was already slowing for a station stop, the 2.5 seconds warning from the alarm allowed for additional slowing and was enough to avoid a catastrophic derailment⁹¹ when the train encountered the section of track being displaced by the rupture, thus demonstrating the value of even a brief warning period.⁹² It took 66 days to restore Joetsu Shinkansen service and 65 days to restore service on the conventional lines.⁹³ Regardless of the relative success of the Compact UrEDAS warnings, JR East invested 1 billion yen (\$9.5 million) to upgrade its earthquake detection systems as part of its 2009-2013 Safety Vision program.⁹⁴

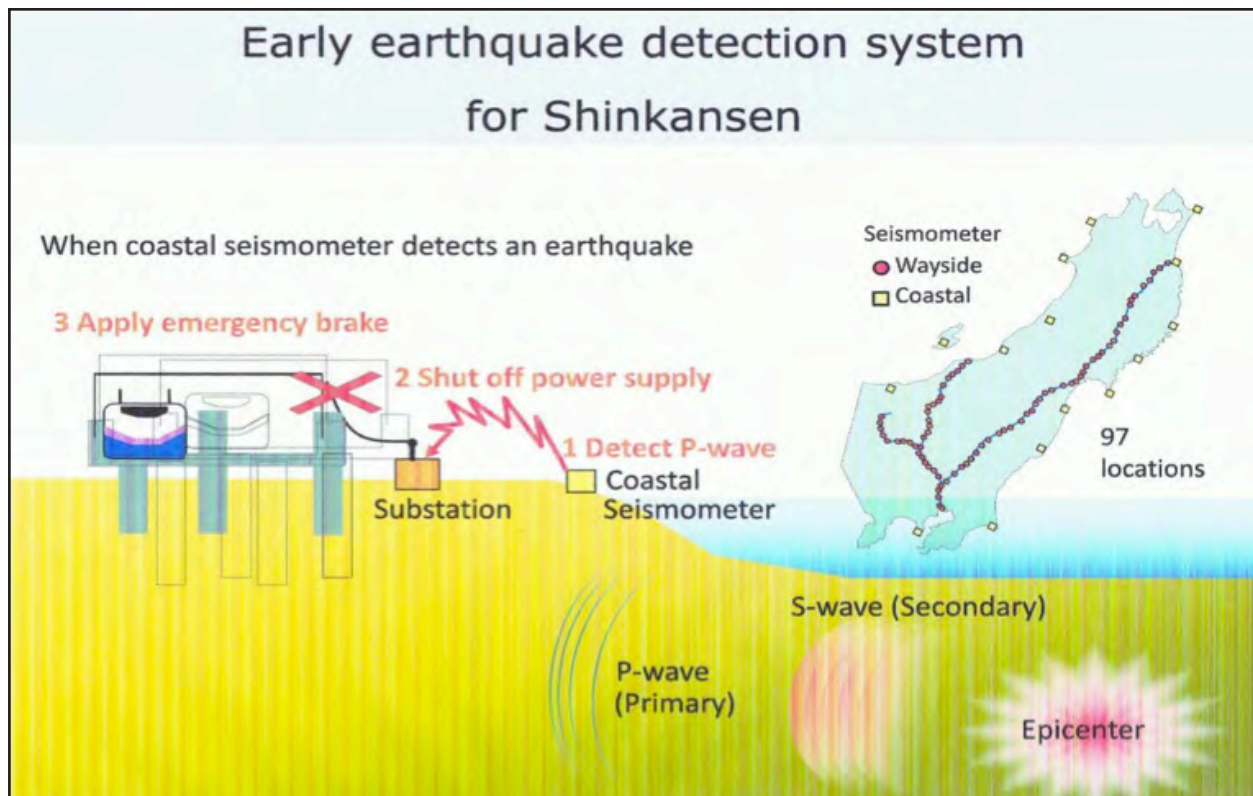


Figure 4. Early Earthquake Detection System for Shinkansen

Source: Hiraoka, 2011.

The Early Earthquake Detection System (EEDS), shown in Figure 4, was the result of this investment: “the fastest early warning system in the world to detect P-waves.”⁹⁵ When the earthquake occurred on March 11, 2011, there were 239 seismometers in the EEDS.⁹⁶ It shortened “the processing time for issuing the alarm and combined the functions of UrEDAS and Compact UrEDAS. ... After the P-wave detection, [EEDS] can issue the alarm within one second and estimate the earthquake parameters in one second.”⁹⁷ It integrates UrEDAS, Compact UrEDAS and AcCo functions, and has replaced the earlier sensor systems.⁹⁸ In the first second after the P-wave detection, it can “estimate the earthquake parameters ... can judge the dangerousness of the earthquake motion...and can output the information and alarm in real-time based on acceleration and RI [“real-time intensity”].”⁹⁹ “When the wayside seismometer detects P-waves, the system rapidly estimates the hypocenter and magnitude with a B-delta method.”¹⁰⁰ The system cuts the electricity to the overhead wire, and the ATC (automatic train control) unit aboard the train applies the emergency brake when the power is disrupted. To prevent false positives, four sensors must be triggered for the power to be cut.¹⁰¹

EEDS can be triggered either by the arrival of a P-wave, predicting the imminent arrival of a large-scale earthquake, or by “detecting an S-wave over a certain threshold.”¹⁰² The order to cut power can come from the coastline seismometers or the sensors along the Shinkansen lines. On March 11, 2011, a Shinkansen train running through the Sendai area was traveling at 270 km/h (168 mph) when the P-wave reached the sensor in 3 seconds. While the train traveled 225 m (246 yards), the power was cut and the emergency brakes

deployed. In 70 seconds, when the largest vibration occurred, the train had traveled 4 km (2.5 miles) total since the arrival of the P-wave, and had dropped its speed to 100 km/h (63 mph). Within the 100 seconds since the brake was applied, it had traveled a total of 4.4 km (2.7 miles) and stopped safely. This rapid deceleration prevented a derailment.¹⁰³

Regular trains also benefit from the earthquake early warning system. Their notification system combines the coastal array of the JMA EEW and the wayside (along-the-rail) EEDS system of JR East to sound an alarm. The train's driver then applies the emergency brake.¹⁰⁴

For local use in specific facilities, AcCo, a palmtop seismometer, was developed. It “can indicate not only acceleration, but also the world’s first real-time intensity.”¹⁰⁵ It is recommended for use in schools and factories. Because of its ease of use and portability, the AcCo earthquake detection system is used by the Tokyo fire department to detect aftershocks during post-earthquake rescue operations.¹⁰⁶ Its first practical use by the Tokyo Fire Department was in rescue operations after the 2005 Pakistan earthquake.¹⁰⁷ It has now been adopted in Japan, the Philippines and Taiwan, as well as by the Tokyo subway system.

RECENT SEISMIC HISTORY OF JAPAN AND RAIL SERVICE FACILITIES RETROFITS

Japan’s culture of rail safety and emergency preparedness starts with an assessment of the hazards that impact the area under study. The JR East Safety Research Laboratory assesses the JR East operating system for engineering standards applications, causes and results of accidents, collision prevention, derailment prevention, and human factors that influence the safe operation of the system.¹⁰⁸ Part of this effort is understanding the physical hazards to the JR East system, which is accomplished by mapping the known hazards to the lines.¹⁰⁹ Earthquake fault zones, tsunami impact zones, and landslide zones are examples of disasters with geological causes where mitigation may reduce loss of life and property. At JR East, they have also recognized the need to plan for “natural disasters caused by abnormal weather,”¹¹⁰ and for events caused by geography and climate.¹¹¹ Building on lessons from the past has been the laboratory’s strategy for enhancing safety. However, starting in 2009, they added “the maximum scale of damage of the events we can imagine,” which included a great earthquake in Tokyo¹¹² and coastal tsunamis.¹¹³ By 2013, the focus was on a “system to evaluate seismic impact by quantitatively evaluating risks to the whole railway system at time of earthquake.”¹¹⁴

1978 Miyagi Earthquake

On June 12, 1978, a M 7.7 earthquake occurred near Miyagi Prefecture, off the east coast of Japan. The earthquake was in a seismically active area that includes Sendai, Ofunato, Ishinomaki, Shiogama, and Fukushima – areas later severely damaged by the 2011 disaster. There were 27 deaths and 1,600 injuries. The National Land Agency estimated total losses to infrastructure at \$800 million.¹¹⁵ Of this, \$38.8 million was railway damage, including bridge piers and bridge abutments that settled and were damaged due to “liquefaction and inadequate footings.”¹¹⁶ The earthquake also caused shoe damage to reinforced concrete (RC) viaducts and piers.¹¹⁷

Train service was suspended after the earthquake, initially because of the loss of electric power¹¹⁸ and then to allow time for inspections. Service was restored “quite soon after repairs were made.”¹¹⁹ The new Shinkansen line extending to the northern tip of Honshu was under construction when the earthquake occurred. The elevated structures, which were built to 1971 design standards, were damaged at the bearing shoes and columns.¹²⁰ This was the first earthquake to cause “serious damage to railway concrete structures in Japan,” which led to a revision of the seismic design standards in 1983.¹²¹ While new structures benefitted from the design standard changes, the older railway structures were not all retrofitted. Restrainer cables and jackets were used to reinforce bridges, but RC (reinforced concrete) structures were reinforced only in areas near the expected Tokai Earthquake zone, and reinforced steel plating was used to upgrade the RC viaduct for the Shinkansen in Shizuoka, another seismically active area.¹²²

1995 Great Hanshin-Awaji (Kobe) Earthquake

On January 17, 1995, the Hanshin-Awaji earthquake (M 6.8) struck the southern coast of Honshu, causing 5,502 deaths, 36,896 injuries, and widespread shaking-related damage and multiple conflagrations.¹²³ Of the 13 significant earthquakes in Japan during the twentieth century, this was the second most deadly, the 1923 Kanto Earthquake being the first.¹²⁴ Estimated losses were \$100 billion, or 2.5% of Japan’s GDP.¹²⁵

Damage to transportation infrastructure was widespread. Researchers from the National Center for Earthquake Engineering Research (NCEER) in Buffalo, New York, noted “strong ground shaking was responsible for inflicting severe damage to the region’s built environment including...railways.”¹²⁶ One kilometer (.62 miles) of the Hanshin Expressway collapsed, along with 120 quays in the port. The number of destroyed buildings totaled 150,000, including most of the ancient traditional homes with heavy tile roofs designed to withstand the region’s frequent typhoons. Railways were also damaged, with only 30 percent of the tracks between Osaka and Kobe left intact. “Wooden supports collapsed inside supposedly solid concrete pilings under the tracks of the Shinkansen high-speed rail line, causing the entire line to shut down completely,”¹²⁷ but 80 percent of these tracks were restored to service within one month.



Figure 5. Train System Damage in the 1995 Great Hanshin-Awaji (Kobe) Earthquake

Source: JR East.

The RC viaducts in the Kobe area experienced shear failure to “beams and bridges that hold up the railway tracks.”¹²⁸ This led to the retrofitting of RC structures, first in high-density areas, setting a priority for areas with high probability of fault rupture.¹²⁹ RC pillars were reinforced with steel winding, limiting shear failures.¹³⁰

Early Twenty-first Century Earthquakes

The 2003 Sanriku-Minami earthquake (M 7.0) occurred in the northern part of Miyagi Prefecture. The on-site detector observed “acceleration along the Shinkansen line of 300-600 Gal.”¹³¹ The earthquake led to a major landslide.¹³² The shaking damage to the Shinkansen’s RC viaducts led to retrofitting of structures on all rail lines, regardless of previous priority.¹³³

The first of two significant earthquakes in the west coast region of Japan occurred one year later. The M 6.8 October 23, 2004 Niigata Chuetsu Earthquake, which caused the first ever derailment of a Shinkansen train,¹³⁴ was followed by the M 6.6 Niigata Chuetsu-oki Earthquake on July 16, 2007.¹³⁵ Damage to the Shinkansen lines included ground settlement, bent rails, tilted poles and damaged signals.¹³⁶ As described above, the Joetsu Shinkansen derailed, causing service interruption for 66 days.¹³⁷

These earthquakes highlighted both the importance of the retrofits that were already underway,¹³⁸ and the difficulty of conducting the construction work. Often shops were under the railway viaducts, requiring relocations before retrofits.¹³⁹ Several methods were used to get around these limitations. Steel jackets were applied to RC viaducts; alternate materials jackets (fiberglass, plastics), rib-bar and rib plate, and dampers and braces were among the methods used for RC members.¹⁴⁰ By the time of the 2011 Great East Japan Earthquake, these Shinkansen retrofits were mostly completed.¹⁴¹

The trains and tracks were also retrofitted to prevent “deviation and derailment.” The 2013 Safety Vision program emphasized the installation of “L-shaped car guides, countermeasures against rail rollover, seismic reinforcement of elevated bridges.”¹⁴² Structural retrofits were already underway before the Niigata Chuetsu derailment.¹⁴³ Three techniques have been used across the Japanese railway system. JR East uses L-shaped guides that have been attached to the train-car axle boxes to prevent derailed trains from overturning. On JR Tokai lines, anti-derailing guards prevent most derailments, while a “post derailment stopper” attached to the bogie reduces the chance of rollover. On JR West and JR Kyushu a safety guide fitting grasps the rails to prevent rollover.¹⁴⁴

JR EAST STAFF TRAINING AND EXERCISES FOR EARTHQUAKES AND TSUNAMIS

The third aspect of the JR East seismic safety system is the training and exercising of its staff for earthquake and tsunami events. JR East has developed maps of the geological-based threats to the system, including “hazard maps for all the local segments of the line along the seacoast.”¹⁴⁵ The system then created a manual for both train crews and the staff members at stations on how to respond to anticipated disasters, including ensuring passenger safety.

Staff members on both the Shinkansen and conventional lines are given training in managing passengers during disasters. The training is comprehensive and is administered not only to the train crews and station staff, but also to staff from the maintenance and repair offices and rolling stock inspectors.¹⁴⁶



Figure 6. JR East Passenger Evacuation on March 11, 2011

Source: JR East.

September 1, 1923, was the day the Great Kanto Earthquake struck. Since 1960, September 1 of each year has been commemorated as Disaster Prevention Day,¹⁴⁷ and the JR East staff members have a training session followed by an exercise. The training focuses on four areas:

- Confirmation and update of disaster control task forces at the headquarters and in each branch of JR East
- Review of the emergency organization and its functionality
- Confirmation of the safety of the employees and their families
- Provision of first aid, firefighting, and evacuation training at every workplace

The training is followed by an exercise on the trains in which staff members practice assembling escape ladders (for disembarking when the train is not at a station), managing a calm and safe evacuation of passengers, and movement of passengers to a safe shelter area.¹⁴⁸

Because many of the lines are near the coast, tsunami response training is included in the earthquake safety classes. JR East began by establishing tsunami preparedness zones along its lines and creating maps of areas likely to be inundated and the locations of evacuation centers operated by local governments. Using the localized hazard maps they developed a response manual for train crews and station staff members.¹⁴⁹ Since the most likely source of a tsunami is a subsea earthquake off the eastern coast, training in map and manual usage is integrated into the annual event. In a real emergency, JR East dispatchers will generally advise train crews of the need to evacuate,¹⁵⁰ but the crews may also evacuate at their discretion. In tsunami-prone areas, the training includes the following information:

- Assess the local damage, contact dispatch for evacuation guidance, or use your discretion if you cannot contact dispatch
- Lead an orderly and calm evacuation and see to passenger needs
- Have passengers and local bystanders assist the evacuees to shelter
- Get to high ground as soon as possible
- Do not return to the train until the threat of tsunami is past, or until the official tsunami warning is cancelled¹⁵¹

In an earthquake, the passengers may not know why the train is stopping, as passengers inside a moving train are unlikely to sense the seismic shaking. Therefore, the train crew begins the response by making an announcement about the earthquake, and, if appropriate, the tsunami warning.¹⁵²

Pre-event guidance is also provided to passengers through posters and signage. For example, evacuation route signs are posted in railroad stations along the coastline.¹⁵³ Posters may also be found in waiting rooms at stations and in train cars. Instructions on the posters are as follows:

- Remain calm and follow the instructions of the train crew
- Assist the train crew with assembling the escape ladders and help other passengers to disembark
- After leaving the train, follow the signs to the tsunami evacuation center



Figure 7. JR East Station Evacuation Map

JR East has been practicing for earthquakes since the 1995 Hanshin-Awaji earthquake. This investment of time and effort was rewarded in the Great East Japan Earthquake of 2011 (discussed in the next section). Although the quake and ensuing tsunami caused 15,891 confirmed deaths and washed five coastal trains off the tracks, including a 36-ton diesel car, which came to rest 250 meters (273 yards) inland and 15 meters (49 feet) above its previous location, not a single life was lost among the train passengers or crew.¹⁵⁴

V. GREAT EAST JAPAN EARTHQUAKE

On March 11, 2011 at 2:46 p.m. local time, a M 9.0 earthquake occurred about 70 km (43.5 miles) off the east coast of Japan beneath the floor of the Pacific Ocean, where the Pacific Plate is subducting under the North American Plate, setting off a cascading triple disaster (described in Table 4). The JMA's upgraded \$600 million earthquake early warning system (EEW), in operation since October 2007,¹⁵⁵ informed residents of the impending shaking via mobile phones, computer screens, TV, and radio. The immediate shaking was felt over hundreds of square kilometers, with buildings in Tokyo swaying. Residents of Tokyo received 30 or more seconds of warning through text messages sent to mobile phones, factories received emails to stop production,¹⁵⁶ and people near the earthquake received 5 to 10 seconds' warning.¹⁵⁷ When sensors detect a P-wave the computer calculates its size and sends out the appropriate warnings. On March 11, 2011, that process took 8.6 seconds, providing valuable warning time.¹⁵⁸

Table 4. Great East Japan Earthquake Facts

Origin time:	March 11, 2011, 2:46 p.m., Local Time
Magnitude	M 9.0
Tsunami height	9.3 meters (over 31 feet)
Major damage	Fukushima Power Plant inundated, lost power, led to radioactive material leaks
Casualties	18,000 people dead or missing
Damage area	500 km ² (193 square miles) damage to Tohoku area
Damage cost	16.9 trillion yen in damage (US \$188 billion) = 3% GDP or 18% annual government budget
Global effects	Balance of trade impact limited, as area accounts for only 2.5% of Japanese economy

Source: Kanno, 2013.

Because the earthquake occurred at a relatively shallow depth, the seismic disturbance along the sea floor created a tsunami that drove into the northeast coast with a run-up of almost 38 m (124 feet). It devastated coastal communities, ports, and transportation systems, including the coastline trains and tracks of JR East. At one point, four trains were unaccounted for.¹⁵⁹ The Shinkansen was too far inland to be reached by the tsunami.¹⁶⁰ The third disaster was the tsunami's inundation of the Fukushima Daiichi power plant, which sustained damage to the reactors.

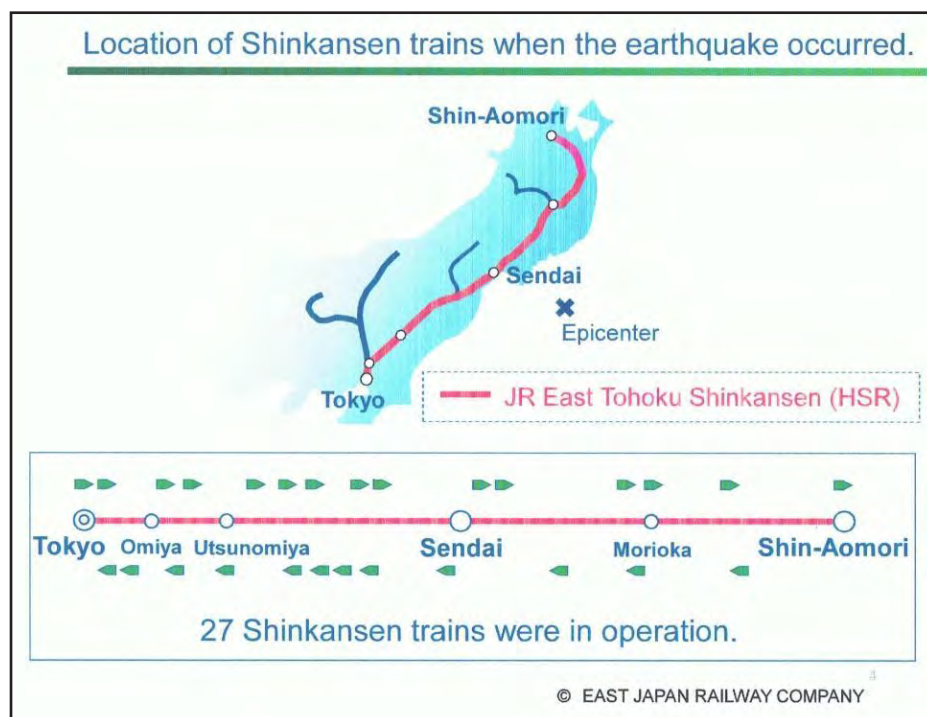
Over 130 aftershocks occurred the same day, with more than 400 greater than M 5 by May 5, 2011. More than 15,000 people were killed, over 5,000 were injured, and over 8,000 are still unaccounted for. Evacuations along the coast and near Fukushima's damaged nuclear plant displaced over 100,000 people. Damage exceeded \$300 billion.¹⁶¹

Table 5. Comparison between the Great East Japan Earthquake and the Hanshin-Awaji (Kobe) Earthquake

	Great East Japan Earthquake (2011)	Hanshin-Awaji (Kobe) Earthquake (1995)
Magnitude	9.0	7.3
Area flooded by tsunami	561 km ² (216 square miles)	no tsunami
Number of missing and dead	About 20,000	6,434
Number of evacuees (Maximum)	About 480,000 within Iwate, Miyagi and Fukushima Prefectures	About 317,000
Completely and partially destroyed houses	About 300,000	About 249,000
Damage	About 16.9 trillion yen (1.05 trillion Yuan)	About 9.6 trillion yen (599 billion Yuan)

Source: General Affairs and Planning Bureau, Sendai City, 2011.

JR East had 27 trains operating on the Tohoku Shinkansen Line when the earthquake occurred. The EEDS performed as designed. The Shinkansen's EEDS includes 97 locations in the JR East territory, including 15 coastal (front-facing) sensors belonging to the JMA's EEW, and over 80 wayside sensors placed at 20 to 25 km (12.43 to 15.54 mile) intervals. When the P-wave hit the first coastal sensor, the sensor transmitted a signal to the substation, and the electricity to the rail line in the disaster area was cut off. Within three seconds, the power supply was cut, and within three more seconds, the brakes for the trains in the area were automatically applied.¹⁶² The trains slowed from 275 kilometers per hour (171 mph) to just over 70 kilometers per hour (43.5 mph) by the time the S-wave and the surface waves hit the line. As a result, no high-speed trains derailed.¹⁶³

**Figure 8. Location of Shinkansen Trains when the Earthquake Occurred**

Source: Kanno, 2013.

Following the Kobe Earthquake and the 2004 Shinkansen derailment, JR East took some new mitigation measures to prevent derailments. L-shaped rail car guides were installed. Viaducts were retrofitted to prevent shear failure, so damage was limited to some bending,¹⁶⁴ which allowed rapid repair and restoration of service. Retrofits to the bridges, viaducts and tunnels provided additional seismic resistance, so there was no major destruction to the infrastructure. More than 1,000 sites did require repairs, but by April 29, 2011, the Tohoku Shinkansen service was fully restored, with repairs on the stretch from Sendai to Ichinoseki, which sustained the highest level of shaking, completed last.¹⁶⁵

Conventional rail lines in the earthquake area sustained damage due to shaking at approximately 4,400 sites. Fortunately, JR East had acquired earthquake insurance in 2005 after the Chuetsu derailment (2004), which covered 71 billion yen in earthquake-related damages.¹⁶⁶

Unfortunately, because the conventional trains ran along the coast serving isolated villages, seven train lines suffered severe damage from the tsunami as well. These include the Senseki Line, Ishinomaki Line, and Joban Line, which lost a total of 27 stations.¹⁶⁷ Reporters described photos of the post-tsunami damage as showing “trains tossed around like discarded toys.”¹⁶⁸ Five passenger trains were swept away by the 38 m (124-foot) run-up of the tsunami wave, but no lives were lost, thanks to rapid evacuation of passengers and crew following the earthquake.¹⁶⁹ By April 27, most of the JR East conventional lines had been restored, however 325 km (202 miles) of rail line along the coast was still out of service.¹⁷⁰ These coastal routes were also within the exclusion zone for the Fukushima Nuclear Power Plant’s ongoing disaster, so it is difficult to evaluate the full extent of the damage. Early estimates suggested that the damage would exceed the 164-billion-yen losses from the 1995 Great Hanshin-Awaji earthquake.¹⁷¹ Some routes may be realigned once the government’s regional recovery plan is clear.

Table 6. Damage to Tohoku Shinkansen from March 11, 2011 Earthquake

Major Damage	Number of Locations (approximate)
Damage to electric poles	540
Broken overhead lines	470
Damage to concrete piers	100
Damage to tracks	20
Damage to transformer units	10
Damage to noise barriers	10
Damage to the ceiling board at stations	5
Gap in beams	2
Damage to bridge bearings	10
Damage to tracks in tunnels	2
Total damage sites	1,200

Note: 550 additional sites were damaged in the continuing aftershocks.

Source: Hiraoka, 2011.

Table 7. Damage to JR East Conventional Lines from March 11, 2011 Earthquake

Major Damage	Number of Locations (approximate)
Damage to tracks	2,200
Damage to electric poles	1,150
Lost crushed stone ballast	220
Damage to platforms	220
Damage to embankments	170
Damage to signals	130
Damage to concrete piers	120
Damage to station buildings	80
Damage to tunnels	30
Damage to transformer units	30
Other	50
Total damage sites	4,400

Source: Hiraoka, 2011.

Table 8. Damage to JR East Conventional Lines from March 11, 2011 Tsunami

Major Damage	Number of Locations (approximate)
Lost stations	23
Lost/submerged tracks (60 km/37.3 miles)	65
Lost/submerged bridges	101
Damage to tracks	210
Damage to electric poles	950
Lost crushed stone ballast	80
Damage to platforms	40
Damage to embankment	50
Damage to signals	80
Damage to concrete piers	30
Damage to station buildings	25
Broken overhead lines	10
Others	20
Total damage sites	1,680

Source: Hiraoka, 2011.

Power posed another problem for service restoration. JR East has its own power plants that serve the Shinkansen, but the conventional trains get power from the public grid. Since the Fukushima Nuclear Power Plant was out of service, the supply of power was curtailed. Other nuclear plants were taken offline for inspection after the earthquake, resulting in a 40 percent reduction in available electricity.¹⁷² This led to rolling blackouts that also affected train service. After negotiations, the power companies agreed to give the trains priority, but, in exchange, train service was reduced to conserve power consumption. This also did not resolve the problem of service to gates and signals at grade crossings, which are tied to the local power grids and subject to the same rolling blackouts as other town services. Rolling blackouts ended and full rail service was restored on April 8, 2011.¹⁷³

Railroad staff in stations and on rolling stock had been trained to assist passengers with orderly exit from the train to safe locations, and the planning and training paid off: all passengers and crew were safely evacuated from the stopped Shinkansen trains.¹⁷⁴

VI. JR EAST'S MITIGATION SUCCESSES: LESSONS FOR CALIFORNIA

The California High-speed Rail Authority is building a rail system to link Los Angeles to San Jose through the Central Valley, with extensions to San Francisco and Sacramento. Since the route will cross the San Andreas Fault and other faults, as shown on the map, earthquake damage mitigation measures must be a critical component of system's design and development. In addition, if mitigation measures are not applied, shaking from regional large earthquakes generated by these faults will affect and may derail trains anywhere in the system. The experience of JR East in the triple disaster on March 11, 2011, offers practical examples of effective disaster countermeasures.

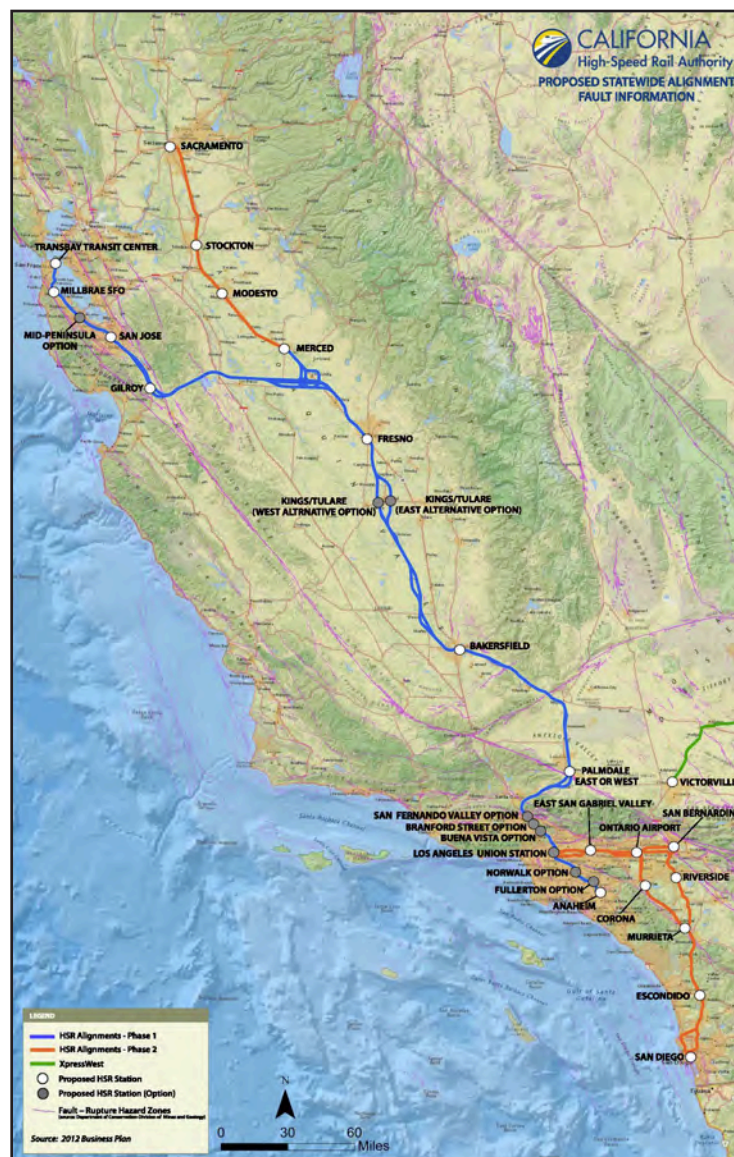


Figure 9. CHSRA Route Map and Earthquake Fault Zone Map

Source: California High-Speed Rail Authority.

EARTHQUAKE EARLY WARNING SYSTEMS

Japan's greatest earthquakes nucleate on the subduction zone off its east coast, where the Pacific plate dives beneath the North American plate. Oregon and Washington share a similar hazard, with the Cascadia Subduction Zone off their western shores. While lightly populated, northernmost California also abuts the Cascadia subduction zone; the heavily populated areas around the San Francisco Bay and Los Angeles are more directly threatened by the San Andreas Fault system – a transform fault that is capable of ruptures of long duration that can generate great earthquakes with magnitudes of 8.0 and above and high-intensity shaking.¹⁷⁵ The Alfred E. Alquist Seismic Safety Commission issued a report on its visit to Japan following the Niigata Chuetsu earthquake, which suggested that “The State should make a detailed and interdisciplinary evaluation of Japan’s Earthquake Early Warning System, track its progress on how effectively it provides warnings to the public in Japan, and then evaluate the feasibility of implementation in California.”¹⁷⁶ The success of the system in Japan’s largest earthquake demonstrates the effectiveness of both the JMA EEW public warning system (RTS) and the JR East EEDS (RTEE) Shinkansen protection system.

In a 2010 paper, Bose and Heaton of Caltech noted that most EEW systems in operation today use an algorithm with “a fixed time window of a couple of seconds of the seismic P-wave for a rapid estimate of the earthquake magnitude.”¹⁷⁷ Application of this algorithm triggers the alarm used by JR East to shut off power to trains and apply the brake. Seismologists are dissatisfied with this approach because it does not characterize the length of the fault rupture, which is an important predictor of the ultimate size of the earthquake and associated duration of the shaking. The importance of this information was seen in the 2011 Great East Japan earthquake. The forecasted magnitude saturated at M 8.0, yet the actual magnitude was M 9.0. The duration and intensity of the shaking and the size of the impacted area are all critical factors for response and recovery operations. As Bose and Heaton state, “The decision on [how] the EEW system [should be designed] is clearly user specific, and depends on (1) the vulnerability of the considered facility, and (2) the costs of the case of over- or under-estimated ground shaking.”¹⁷⁸

RTEE AND RTS

Based on their experience, the Japanese have separated their earthquake warning systems into two categories: real-time seismology (RTS) and real-time earthquake engineering (RTEE), each with a distinct application. Nakamura and Saita suggest that RTS is needed to give the public and first responders information on “rational action after the earthquake has terminated” while RTEE “is necessary for immediate response after the earthquake occurrence or earthquake motion arrival.”¹⁷⁹ They further differentiate the quality of information that is needed for each application, with RTS focusing on “highly accurate but not immediate information,”¹⁸⁰ while RTEE needs a rapid alarm and intervention¹⁸¹ to prevent secondary disasters, such as train derailments.

The Japanese therefore have two systems for earthquake monitoring. The large network operated by the JMA EEW collects data over a wide area to enable complete characterization of the seismic event while offering warning to the public and information for

emergency responders for post-quake countermeasures. Furthermore, RTS is essential for developing a greater understanding of the parameters of seismic events, which leads to more rapid seismic detection, leading in turn to further enhancements of the RTEE system. For RTEE, JR East operates its own EEDS, with along-the-railroad sensors to ensure rapid engagement of the electricity shut-off and braking of Shinkansen trains to prevent derailments. Nakamura and Saita (2007b) generalize the requirements of RTEE systems, listing six essential characteristics: They must be “fully automated,” “quick and reliable,” “small and cheap,” “independent of other systems,” “easy to connect to network,” and, for the alarm, accuracy is desirable but not essential.¹⁸² The Japan California High Speed Rail Consortium has published a document entitled “Shinkansen Technology for California High-Speed Rail,” highlighting aspects of Japan’s high-speed rail experience that can be applied in California. It recommends development of an Early Earthquake Detection System “where large earthquakes may be expected.”¹⁸³

RTS systems are in use in countries with active seismic hazards, including Turkey, Mexico, Italy, Romania, Taiwan, and as a demonstration system in the United States.¹⁸⁴ The American system, a joint RTS and RTEE system called CISEN ShakeAlert is operated through the collaboration of several organizations having both academic and seismological expertise, including UC Berkeley, Caltech, and USGS, with the recent addition of the University of Washington. Their efforts are focused on furthering the scientific understanding of earthquakes and accurately estimating their magnitude, location, and level of damage.

Commercial RTEE systems are also being developed in the United States, by Seismic Warning Systems (SWS) of Scotts Valley, California, among others. SWS products have been installed at 12 locations¹⁸⁵ in the Southern California desert area adjacent to the active San Jacinto Fault and along other faults of the San Andreas system. Coachella Valley communities have experienced several earthquakes over the past century, including the M 6.6 Painted Hills earthquake in 1986 that caused damage in Palm Springs. Firefighters responding to calls had to begin their rescue operations by finding a way to open the doors of their fire stations. Today, seismic sensors installed by SWS at each of the stations ensure that its doors will open and that the firefighters are notified to expect shaking of Modified Mercalli Intensity 5 or greater. A unit is also installed in the Paso Robles fire department, where it provided a 10-second warning before the M 6.5 San Simeon Earthquake struck in 2003.¹⁸⁶

SWS installations, which are site-specific, cost \$25,000 per unit¹⁸⁷ and are based on the deployment of two sensors at the user’s site. When the sensors detect the arrival of a P-wave that portends significant shaking, they activate an alarm, which may include audible warnings and flashing lights, as well as automatically opening garage doors or interrupting industrial activities at the site. The alarm at SunLine Transit in Palm Springs, for example, triggers the dispatch center to issue a warning to bus drivers of impending shaking so they can safely stop their vehicles.¹⁸⁸



Figure 10. SWS QuakeGuard at SunLine Transit

Source: Frances Edwards.



Figure 11. SWS P-wave Sensor and Internet line at SunLine Transit

Source: Frances Edwards.

Another SWS' product QuakeGuard 300, has been installed at 40 locations other than fire stations in California, including "the Department of Energy's Lawrence Berkeley National Laboratory, NASA's Dryden Flight Research Center and the day care center at Cisco's California headquarters."¹⁸⁹ The company is proposing to network local sensors for a quicker response time at locations farther from the earthquake's hypocenter because the networked electronic message would travel faster than the P-waves to more distant locations.¹⁹⁰ They also plan to provide a \$1,200-per-year subscription service for schools and a \$2,500-per-year subscription service for hospitals.¹⁹¹

As mentioned earlier, the CISON ShakeAlert statewide demonstration early warning system includes both RTS and RTEE capabilities. The project is currently in Phase III, and involves the USGS, the California Office of Emergency Services, UC Berkeley, Caltech, the University of Washington, and more than 20 individual corporations and public emergency management organizations in the State of California. ShakeAlert uses the statewide CISON network as a backbone and will issue alerts to the public, government, and private sector organizations with no subscription fee required. One of the early adopters is the Bay Area Rapid Transit system (BART), which now automatically slows and stops its trains when alerted by ShakeAlert. Google has integrated ShakeAlert into its emergency operations center. San Francisco Department of Emergency Management is working with city agencies to facilitate integration of alerts, in particular with the San Francisco Fire Department (to open the fire station equipment bay doors), the Police Department, and with Public Works to enable workers on projects near heavy machinery to take safe action. San Francisco hospitals, data centers, hazmat facilities, and local airports are also developing automated procedures based on ShakeAlert warnings. These actions can be tailored to particular uses.

More sensors will be needed to provide adequate monitoring for the 1,288-km (800-mile) route of CHSRA and nearby regions with earthquake hazards. In California an EEDS would have to be aligned with California's fault lines, most of which are not off the coast, with the accelerometers placed to detect fault movement at the earliest possible instant. In addition, some sensors must be more broadly distributed to detect earthquake sources from more broadly spread or unknown faults, such as those that ruptured in the Sylmar (1971), Coalinga (1983) and Northridge (1994) earthquakes. The ShakeAlert early warning system, based on the stations of the CISON, has demonstrated the capabilities of such a system in both densely and less densely instrumented regions. In earthquakes that occurred in the Greater Los Angeles area in the Spring of 2014, alerts were produced within 4.5 seconds of the quakes' nucleation. More recently, in the August 2014 M 6.0 South Napa earthquake, ShakeAlert produced alerts in 5.2 seconds, allowing actions 5 seconds before the S-wave arrived in Berkeley, 8 seconds before the shaking hit the BART operations center, and 9 seconds before the waves reached the San Francisco Department of Emergency Management. BART trains would have automatically begun braking based on the alert, however BART operates only from 4:00 a.m. to midnight on weekdays and 6:00 a.m. to midnight on Sundays, so it was not in operation at 3:20 a.m. on the Sunday when the quake occurred. Studies exist to determine optimum spacing and technical specifications for new stations for a California EEDS.¹⁹² Determining the best locations for that equipment, to protect CHSRA from earthquakes on the San Andreas and other faults in California will require additional studies of fault and shaking hazards as they impact the CHSRA and will depend in detail on the exact location of the tracks throughout the proposed route.

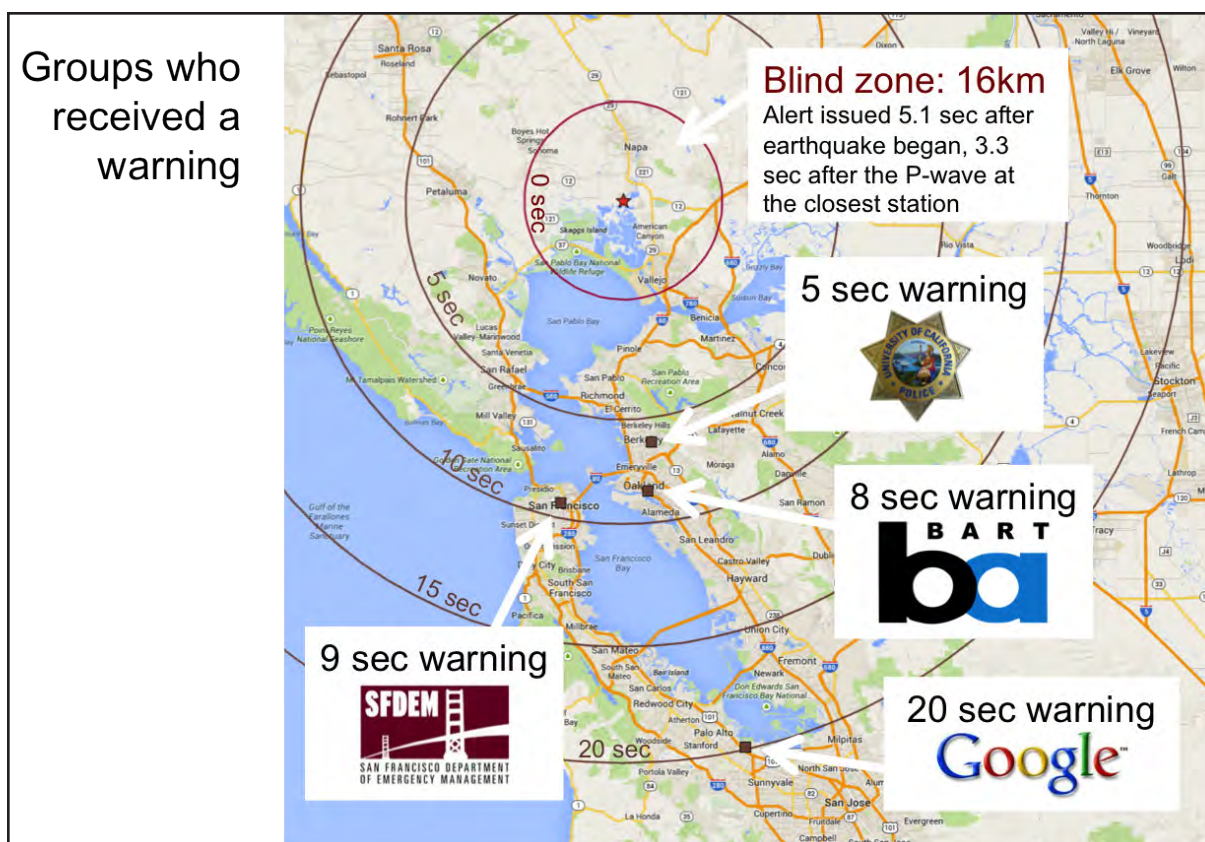


Figure 12. Warning Contours for Real-time ShakeAlert Performance During the 2014 Napa Earthquake

Note: System and telemetry upgrades as proposed for the full public system - would have resulted in a faster alert time, and a significant reduction in the diameter of the 0-sec. warning zone.

Public Policy and Government Activities

In 2013 California State Senator Alex Padilla sponsored a bill “to create a statewide early warning system for earthquakes...(using) technology to outrun shock waves (and) ... using existing communications infrastructure.”¹⁹³ This legislation provides support for the development of the ShakeAlert system, relying on the Governor’s Office of Emergency Services to identify funding sources by 2016.¹⁹⁴

Local governments have also taken some initiative to develop EEW capability. According to a report to the Seismic Safety Commission on September 12, 2012, the standalone earthquake warning systems installed in the Coachella Valley starting in 2000 could be considered an RTEE.¹⁹⁵ In 2009 the Coachella Valley Association of Governments (CVAG) partnered with the Coachella Valley Emergency Managers’ Association, three school districts, and SWS to propose the Coachella Valley Regional Earthquake Warning System (CREWS). Warnings are to be based on existing sensors and those to be installed at additional proposed locations. When the system is built, alerts could be issued to 136 sites, including fire stations, schools and public safety communication centers. The Riverside County Operational Area has also applied for a \$1.5 million FEMA grant but has not yet received funding as of this writing.¹⁹⁶

Neighboring Imperial County used this model to apply for FEMA funds to create a similar regional earthquake warning system called Imperial County Regional Earthquake Warning System (ICREWS), which will partner with the neighboring CREWS.¹⁹⁷ On April 4, 2010, the M 7.2 El Mayor-Cucapah Earthquake in Baja California caused “a seismic movement on multiple faults extending throughout the Salton Trough. The triggered surface movements were at distances up to 172 km (107 miles) from the epicenter.”¹⁹⁸ The earthquake caused the strongest shaking in the Imperial Valley since 1892, resulting in liquefaction and permanent ground deformation, leading to long-term damage to fields.¹⁹⁹

Damaged buildings and infrastructure included irrigation canals, schools, and downtown business buildings. The schools in Calexico were closed for 17 days for structural evaluation and repairs. The downtown business district was closed for 10 days, impacting even businesses in structurally sound buildings, while leaking gas mains were repaired. The water and wastewater facilities were damaged, reducing domestic water supplies by 50 percent for several weeks. Roadways, bridge approaches, rail lines, embankments, water tanks, and pipelines were damaged, disrupting rail and road traffic.²⁰⁰ Fire Station 1 in Calexico was damaged by the shaking. Fire Chief Pete Mercado reported that it took the fire station’s three-person staff 15 minutes to open the damaged bay doors and move the fire engine. Meanwhile they were receiving service calls for gas leaks, power outages, and structure fires.²⁰¹

The Imperial County Operational Area, with help from CVAG, successfully applied for a \$225,000 hazard mitigation grant under FEMA’s DR 1911, the El Mayor-Cucapah earthquake event, to fund the ICREWS. On April 25, 2014, Imperial County awarded a \$250,000 contract to SWS to install sensors and warning devices to “deploy and maintain this, the nation’s first regional earthquake warning system. ... ICREWS ... initial partners include Imperial Co. Fire; Imperial Co. Sheriff’s Office; Cities of Brawley, El Centro, and Calexico Fire and Police Dispatch Centers; Calipatria Fire; El Centro Medical Center; and Pioneers Memorial Hospital.”²⁰² The ICREWS system will place P-wave monitors at 6-to-12-km (3.7-to-7.5-mile) intervals along selected faults. Notifications will issue audible alerts, open fire station doors, turn on lights, and display warnings on monitors in public safety and utility dispatch centers. User locations can add activities, such as starting emergency generators or executing system shutdowns.²⁰³

SEISMIC RETROFITTING OF INFRASTRUCTURE

JR East also achieved success with its modifications to infrastructure design to accommodate large earthquakes. These may also be relevant to the proposed California high-speed rail system. First, the Japanese system will be presented, with discussion of the methodology and key details about the design of the cars, rails and the supporting viaducts. This is followed by a discussion of how the practices and issues of the Japanese system might apply to a similar train system currently proposed for California. This review is based on documents and reports provided by JR East and referenced here.

Methodology to Establish Operating Limits and Displacement Probability for Each Viaduct

The paper by Shimamura and Yamamura²⁰⁴ explains the methodology used to brake and shut down the high-speed Shinkansen trains, which can reach speeds up to 350 km/h (217 mph).

The steps described in this paper do not explain all of the details but do describe the general methodology. This level of information is insufficient to duplicate the system, but it does provide some guidance that could be implemented in California. The following steps led to the evaluation of aspects of the seismic mitigation measures.

First the investigators developed a ground motion attenuation relationship characteristic of the area. In the US, ground motion attenuation relationships are now called ground motion prediction equations, or GMPE. They estimate the decrease in maximum ground motion as the site's distance from the causative fault increases. The maximum expected ground motion is, in addition, based on the magnitude of the quake, the type of faulting and the type of ground at the site. GMPE are used to estimate shaking at the site of the infrastructure. For bridges/abutments it is important also to estimate both the longitudinal (track parallel) and lateral (track perpendicular) response. A GMPE from Japan may not be relevant to California, but a number of GMPE exist for the Western US and California. The Japanese GMPE uses a constant of $h = 0.20$. The SI (Spectral velocity integrated between 0.1 and 2.5 seconds) value was used as an index to evaluate the seismic demand. Values of SI were calculated for various earthquakes, resulting in SI ranging from 10 to 100.

Next, typical viaducts (overhead bridge/type supports for the high-speed rail) were selected for evaluation. Static nonlinear analyses were performed for each of these representative viaducts. Two orthogonal directions, parallel and perpendicular to the tracks, were analyzed in order to establish the capacity of each of these typical viaducts. Displacement limits for four levels of damage were calculated. Time-history analyses were then performed, with input time histories matching the 19 values of SI, and target displacements were established. Damage probability/fragility was then determined for each viaduct, for four levels of damage/displacement.

The stable operation of the cars was then inserted into the analysis, with some assumptions about operating vibration frequencies, and the running stability established of 70 mm. With operating car displacement limits established, the maximum horizontal displacement of the difference between cars (operating) and viaduct (seismic) was established. A logarithmic displacement probability was then computed, for each of 19 SI values. Using the fragility curves, SI values, and the stopping distances, a level of damage is assigned for each viaduct. The methodology not only provides the logic to quickly slow down the trains, it also provides logic for inspection/repair and serves to reduce post-event downtime.

Because Japanese conditions are different from California conditions, numerous variables must be considered to evaluate the information for possible California application. All of these variables are specific to the location where the HSR is built and the specific types of equipment purchased.

Table 9. Variables Needed for Seismic Damage Assessment

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- Performance values of capacity for various levels of damage
 - Running stability of cars (70 mm or other value)
 - Operating speed (normal and braking)
 - Braking performance
 - Earthquake measurements/accelerometers (P- and S-waves)
 - Pre-determined capacity limits for various levels of damage
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Train Derailment Mitigation Methodology – Shinkansen JR Trains

Engineers for the JR East Shinkansen high-speed railway have taken measures to minimize the possibility of a derailment during an earthquake. Rollover prevention devices (called “sleeper plugs”) have been installed on tracks and L-shaped railcar guides added to trains. These devices work together to help keep trains from leaving the track. Expansion joints in tracks, which could allow the track to separate and potentially derail a train, have been removed. The company has also planned for thermal (longitudinal) expansion of rails and provided a means to safely accommodate it.

Structural Modifications and Ductility of Viaducts

A paper by Kobayashi, Mizuno, and Ishibashi²⁰⁵ outlines the damage and restoration of Shinkansen structures after the Great East Japan Earthquake. The earthquake damaged the reinforced concrete (RC) viaduct columns and reinforced concrete bridge piers; however, no collapse was observed. According to seismic performance, the failure modes of the RC viaduct were categorized as either of two types: shear failure or flexure failure. Due to the damage caused to JR East structures, JR East implemented a seismic rehabilitation program. The methodology behind seismic rehabilitation is to prevent shear failure of the RC viaduct columns, which could result in their collapse.

After the Great East Japan Earthquake, the columns were observed to have experienced only flexural damage. This damage was then categorized by the degree of damage of RC members and restorability as shown in Table 10. Seismic damage to RC viaducts was mainly found in the upper end of the columns. The RC columns did not suffer level-A damage and the percentages of BB, B, and C are around 0.1 percent, 0.1 percent, and 0.3 percent. The percentage represents the ratio of the number of damaged RC columns to the total number of RC columns. JR East implemented seismic rehabilitation to RC columns. Several options that were considered included steel plate jacketing, rib-bar and single-face methods.

Table 10. Seismic Damage Categories for Columns and Piers

Category	Description
A	Collapse of columns, fall of girders
BB	Significant deformation of longitudinal bar, widespread fall of cover concrete, settlement of railroad track
B	Some amount of deformation of longitudinal bar, widespread fall of cover concrete, no settlement of the railroad track
C	Cracks in cover concrete, partial fall of cover concrete

Damage to the RC railway bridge piers was also investigated. It was observed that the damage was located at the cutoff of the longitudinal reinforcing bars. There was no observation of shear failure; only partial fall of cover concrete and cracks occurring at the cutoff of rebar. The seismic damage level category of the RC bridge piers was determined in a manner similar to that used for the RC viaduct as shown in the table above. Review of the reports suggests that there was no damage in the bridge piers at levels A and BB. For levels B and C the percentage was about 0.1 percent and 0.2 percent (considering the number of damaged RC piers to total number of RC piers). The rehabilitation method used for most of the RC piers was RC jacketing.

JR East's restoration of the Shinkansen RC structures was performed quickly. The most rapid retrofit was completed in one day, and the longest was completed within 49 days of the earthquake. The restoration of RC viaducts and bridge piers took priority. The tasks were sequenced according to the damage level of the structural members.

Applicability of JR East Mitigation Measures in California

California follows two major structural codes relating to railway infrastructure: Seismic Design Criteria (SDC) published by Caltrans and a code published by the American Railway Engineering and Maintenance-of-Way Association (AREMA). The codes require that columns and piers be designed to experience ductile behavior through the use of a plastic hinge at the deck soffit or above the ground interface. The seismic criteria ensure ductile behavior by requiring no shear failures, no collapse, special reinforcement detailing, and capacity-protected design elements. Special reinforcement detailing and capacity-protected designs are both needed to ensure that the plastic behavior occurs at a specified location. Special reinforcement detailing requirements are established to increase ductility and reduce the possibility of shear failure. When creating capacity-protected design, actual material properties, rather than expected material properties, are used in combination with overstrength factors.

The code requirements will produce a behavior similar to what was observed in the columns and piers after the Great East Japan Earthquake. No shear failures were encountered, no damage occurred to the deck, and there was no failure that led to collapse. There was deformation of the longitudinal bar and fall of concrete cover, both of which are ductility failures.

The methodology of the JR East mitigation effort could be applicable to California's developing high-speed rail system with some modifications. Japan-specific caveats and many other issues would need to be resolved. For example, the attenuation relationships used by Japan would have to be replaced with those applicable to California, which already exist. However, the "h" factor, the depth to the hypocenter, may be another site-specific variable.

Comparisons of the experimental relationships to determine magnitude for Berkeley's ElarmS early warning algorithm has shown that a single relationship can be used for all of California and Japan.²⁰⁶ A variety of ground motion prediction equations to estimate the decrease in shaking with distance from an earthquake epicenter or fault rupture surface exist for small and large quakes that occur in the Western US.

The nonlinear pushover analyses in the two directions (transverse/longitudinal) could easily be performed, along with the various time-history analyses, to determine the 19 values of SI, and fragility curves could be developed for each of the viaducts. The running stability value of 70 mm is obviously dependent on the train system selected, and would have to be determined after the train system is selected.

Site-specific geotechnical information would also be relevant to this methodology, and although not mentioned, it is part of the nonlinear pushover and time-history analyses – and may increase or decrease the fragility of each viaduct. Variation between adjacent viaducts would also have to be considered, along with the separation distances. Possible differential settlement between adjacent viaducts may create another problem, not addressed by the JR East Shinkansen methodology. Also, any vertical acceleration and inertial effects are not treated in this methodology.

Rail and train specifics (e.g., allowable displacement of 70 mm) would depend on the final system design for both the rail and the cars. This would also include the “L-type” rail car guides that may be specific for the Japanese system.

The complete methodology is not described in sufficient detail to say that it could be replicated. Additional exchanges of information and system architecture would be required for the California system to use the same logic. However, the retrofitting strategies used in Japan can inform decisions and investments made during the initial construction of CHSRA infrastructure.

In addition to retrofitting structures such as piers, bridges, and viaducts, JR East and its railway partners in Japan also undertook anti-derailment and anti-rollover mitigation measures on the cars and rails, as noted above. This type of mitigation measure would have to be designed for the specific train sets and rail configurations. These techniques might each be useful for CHSRA, depending on the train equipment that is purchased for the system.

From FY 2013 through FY 2018, JR East has a new focus on “disaster-resilient railways.” This includes seismic reinforcement of “embankments, earth cuttings, arched elevated brick bridges and power poles, and measures to prevent the collapse of station platform ceilings and walls” in Tokyo, as well as continuing the “seismic reinforcement of elevated bridge columns and bridge piers ... station buildings with 3,000 or more passengers per day, Shinkansen power poles ... [and] increas[ing] the transmission speed of seismometer measurement data ... and emergency power sources for our communication network.”²⁰⁷

Restoration of rail lines with tsunami damage has progressed more slowly as JR East has worked with local communities to integrate with their local planning. In addition, the disabled Fukushima nuclear plant continues to block access to a 20-km (12.4-mile) exclusion zone. The result is that FY 2013 saw unusable rail lines reduced from 400km (249 miles) to 250 km (155 miles). Bus rapid transit (BRT) systems are substituting for the damaged rail routes.²⁰⁸

The success for JR East was that the trains had 70 seconds to slow down before the damaging “S” waves arrived; trains slowed from 270 km/hour (168 mph) to 100 km/hour (63 mph) and there was no derailment.²⁰⁹ The combination of operational, emergency braking logic and accelerometers to provide the “P” and “S” wave information served the Japanese system well, and their history of almost 50 years of continuous operation without a single fatality is commendable. JR East also provided a rapid assessment of damage, and this served to reduce downtime. The retrofitting of the system components and the installation of derailment and rollover deterrence limited the amount of damage to be repaired.

Applicability of JR East Staff Training Strategies to California HSR

Japan's long experience with earthquakes and tsunamis has led to a robust level of emergency preparedness in areas prone to seismic events. The M 7.3 Ansei-Edo earthquake in Japan on November 11, 1855, resulted in the deaths of 16,000 – 20,000 people in the capital city of Edo (now called Tokyo). Woodblock prints “displaying the destruction, and telling of the despair of the survivors”²¹⁰ circulated around the world. The M 7.9 Kanto Plain earthquake of September 1, 1923, and its resulting fire, killed 143,000 people.²¹¹ The Sendai area had experienced earthquakes, including the 1978 M 7.7 Miyagi earthquake,²¹² so the likelihood of seismic activity was well known.

Each year on September 1 Japan commemorates the anniversary of the Great Kanto Earthquake with Disaster Preparedness Day. JR East uses this anniversary to hold an annual emergency response drill for its employees and passengers.²¹³ All JR East employees are included: train crews, station employees and rail line workers. The Great East Japan earthquake's fatality-free outcome demonstrates the value of a high level of employee training and preparedness. In addition, posters and signs in trains and stations, some of which are permanent, are a reminder to passengers of safety precautions to take during and after shaking, including safe exiting from the train and assisting other passengers.

A new emphasis on passenger care in FY 2013 includes the development of more detailed tsunami guidance, better signage, and the addition of an annual March 11 training day focused on tsunami evacuations. Recognizing that stations may be shelters of last resort for stranded commuters or disaster victims, JR East is stocking its 30 largest stations with “drinking water, blankets, and first aid kits for children and the elderly.” In FY 2014 it will expand these preparations to 170 stations.²¹⁴

There is also a new emphasis on collaboration with local communities surrounding the stations. In addition to working on disaster preparedness, JR East is supporting community restoration through tourism. The program includes special offers to promote travel to restored tourist areas in the disaster region. The company also sponsors disaster tours to recovered areas and markets and fairs to promote the produce, products and crafts of the disaster area.²¹⁵

California commemorates the M 7.9 April 18, 1906 San Francisco earthquake²¹⁶ and fire with local ceremonies. Previously, April was designated as a statewide Earthquake Preparedness Month, sponsored by the Governor's Office of Emergency Services.²¹⁷

California HSR could adopt the JR East anniversary strategy for training its employees and raising awareness among riders. April could be the time when every employee receives emergency preparedness refresher training. An annual drill on the April 18 anniversary could include passengers, as JR East does. Although California HSR is unlikely to be affected by a tsunami, aftershocks can cause tremendous damage. The ability of passengers to safely and quickly exit the trains and move to safe shelter could save lives.

VII. CONCLUSION

The JR East experience in the Great East Japan Earthquake offers a series of useful lessons for the CHSRA as it develops its route, designs its infrastructure, and acquires its train sets. These lessons are depicted in Table 11. Collaboration with the California earthquake research community at USGS, UC Berkeley, Caltech and NASA's JPL, and the private sector could lead to the installation of useful RTS and critical RTEE earthquake early warning systems. The BART experience is also paving the way for CHSRA application of faster computers, and more effective algorithms, such as ElarmS. CHSRA, will also be able to make use of the statewide prototype EEW system, ShakeAlert. Engineers can benefit from the strategies used by JR East to design the HSR infrastructure to be resilient. Emergency managers can emulate the universal employee training and passenger awareness programs.

Table 11. Lessons Learned from JR East EEW Experiences

EARTHQUAKE EARLY WARNING SYSTEM	
<ul style="list-style-type: none"> • EEW prevents derailments • Automatic electricity shut-off and brake application are critical to success – seconds count • Location of sensors in relation to the fault determines the length of the warning period • Direct delivery of warnings to the public through mobile devices and computer screens enhances the value of EEW beyond the benefits of media-based notices • EEW can be used for immediate protective measures as well as for understanding the event to manage the response most effectively • Faster computers and more effective algorithms enhance the speed and accuracy of the EEW system 	
INFRASTRUCTURE RETROFIT	
<ul style="list-style-type: none"> • EEW's value depends on the resiliency of the built environment • Periodic re-evaluation of infrastructure resilience is critical • Timely retrofit of infrastructure elements enhances the likelihood of system resilience • Infrastructure owners must learn from each new seismic event and upgrade, retrofit and replace critical connectors and supports to enhance resiliency 	
TRAINING	
<ul style="list-style-type: none"> • Trained staff are essential to an appropriate response to the EEW alarm • Exercises with staff and public maintain awareness of the appropriate response to EEW alarms 	

CHSRA leadership must invest in seismic safety for the long-term resiliency of the system. JR East has operated for over fifty years without an earthquake-related casualty because it has learned from each seismic event and continued to invest in improved systems and strategies. There is no quick fix or perfect design for seismic safety, just a path of thoughtful investment and proactive initiatives. Seismic safety must be a core value for CHSRA in all phases of its operation, and the experience of JR East can be instructive in how best to invest time and money for success.

ABBREVIATIONS AND ACRONYMS

A.D.	Anno Domini (current era)
ANSS	Advanced National Seismic System
AREMA	American Railway Engineering and Maintenance-of-Way Association
ATC	Automatic Train Control
BART	Bay Area Rapid Transit (San Francisco Bay Area)
Berkeley	University of California at Berkeley
Caltech	California Institute of Technology
Caltrans	California Department of Transportation
CGS	California Geological Survey
CHSRA	California High-speed Rail Authority
CISN	California Integrated Seismic Network
Co.	County
CREWS	Coachella Regional Earthquake Warning System
CSMIP	California Strong-Motion Instrumentation Program
CVAG	Coachella Valley Association of Governments
DR	FEMA Disaster Declaration designation (numbered)
EEDS	Earthquake Early Detection System (JR East)
EEW	Earthquake Early Warning
FEMA	Federal Emergency Management Agency (US)
GDP	Gross Domestic Product
GMPE	Ground Motion Prediction Equations
GPS	Global Positioning System
GSN	Global Seismic Network
HAZUS	FEMA's Hazards US mapping system
ICREWS	Imperial County Regional Earthquake Warning System
IRIS	Incorporated Research Institutions for Seismology
JMA	Japan Meteorological Agency
JPL	NASA's Jet Propulsion Laboratory
JNR	Japan National Railroad
JR East	East Japan Railway Company
JR Tokai	Central Japan Railway Company
JR West	West Japan Railway Company
km	kilometer
m	meters
ms	milliseconds
M	Magnitude
mm	millimeters
MMI	Modified Mercalli Intensity
MPH/mph	miles per hour

M _w	Moment magnitude
MTI	Mineta Transportation Institute
NASA	National Aeronautic and Space Administration
NCEER	National Center for Earthquake Engineering Research
NEIC	National Earthquake Information Center
PAGER	Prompt Assessment of Global Earthquake Response
P-wave	Primary Wave
QCN	Quake Catcher Network
RC	Reinforced concrete
RTEE	Real-time earthquake engineering
RTS	Real-time seismology
SB	California State Senate bill
SDC	Seismic Design Criteria
SI	Spectral velocity Integrated
S-wave	Secondary wave
SWS	Seismic Warning Systems, Inc.
UC	University of California

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ABOUT THE AUTHORS

FRANCES L. EDWARDS, M.U.P., PH.D., CEM

Frances L. Edwards is Deputy Director of the National Transportation Safety and Security Center at Mineta Transportation Institute, professor of political science, and director of the MPA program at San Jose State University. Her most recent book is *Introduction to Transportation Security*, with Dan Goodrich, and her most recent journal article is “Effective Disaster Response in Cross Border Events” in the *Journal of Contingency and Crisis Management*. She is co-author of two books on terrorism response in the NATO Science Series and co-author of ten monographs for MTI. Her research in climate change adaptation, cultural competency in disasters, emergency management, and homeland security has led to more than twenty chapters in professional books and more than thirty published articles. She has consulted with NATO, the European Union, and government agencies in Japan and Turkey. She is a Fellow of the Foundation for Defense of Democracies and a 2012 Salzburg Fellow. In 2013 she was named a University Scholar at San Jose State University. She has over 20 years’ experience as a director of emergency services in California, including a term on the California Seismic Safety Commission. She is a Certified Emergency Manager and a Professional Continuity Practitioner.

DANIEL C. GOODRICH, M.P.A., CEM, MEP

Daniel C. Goodrich is a Research Associate with Mineta Transportation Institute at San Jose State University and a lecturer in the MTI MSTM and MPA programs. He is co-author with Frances Edwards of the new *Introduction to Transportation Security* textbook, and the recent *Exercise Handbook: What Transportation Security and Emergency Preparedness Leaders Need to Know to Improve Emergency Preparedness*, as well as six other publications for MTI, a chapter in the ICMA Emergency Management Green Book, and four other chapters in professional books. He has presented papers at professional conferences sponsored by the City of Tokyo, NATO, the European Union, and the Second Conference on Global Security and Democracy, as well as at conferences sponsored by FEMA and the American Society for Public Administration. He has worked with the European Union’s CAST project and the City of San Jose’s CERT and MMRS organizations. He is a Fellow of the Foundation for Defense of Democracies, and a San Jose State University Scholar. He has over twenty years’ experience in the fields of security and emergency management, including work with the US Marine Corps Security Forces, county public health emergency management, and Lockheed Martin Space Systems. He is a Certified Emergency Manager, a Professional Continuity Practitioner, and a Master Exercise Practitioner.

DR. RER. NAT. MARGARET HELLWEG

Margaret Hellweg has been the Operations Manager at the University of California Berkeley Seismological Laboratory (BSL) since 2005. She oversees activities that ensure that the BSL’s geophysical stations are collecting high-quality data, that the BSL can report on earthquakes in Northern California, and that researchers have rapid and reliable access to the data collected. After Dr. Hellweg received a B.A. in Physics from U.C. San Diego in 1973, she moved to Germany, where she completed her Diploma from the Universität

Göttingen (Masters), also in physics, with a thesis on light scattering from biological particles. She then moved into seismology and has worked in broadband seismology at the Bundesanstalt für Geowissenschaften und Rohstoffe, in strong-motion seismology at the United States Geological Survey in Menlo Park, and in volcano seismology for her doctoral theses at the Universität Stuttgart. Dr. Hellweg joined the BSL in 2001 doing postdoctoral work on regional moment tensors for nuclear monitoring.

JENNIFER STRAUSS, PH.D

Jennifer Strauss is the External Relations Officer, Berkeley Seismological Laboratory, serving as the head of the Earthquake Research Affiliate Program, which fosters interaction between academic researchers and external partners interested in earthquake information services, including earthquake early warning (EEW) and novel technologies for geophysical research. Working with industry affiliates, legislators, and scientists on bringing an EEW system to the State of California, she also routinely interfaces with emergency managers to create action plans and strategies for hazard mitigation in the small lead time provided by earthquake warnings. She joined the lab in November 2012 after spending three years in the French Alps. She is a physicist by training, with a research history in powder diffraction, x-ray crystallography, computer modeling, and ice sheet dynamics and radar altimetry studies on the West Antarctic Ice Sheet. She was a co-chair of the inaugural Postdoctoral Society of Argonne National Laboratory. She received a B.S. degree in physics from the University of Texas at Austin in 2001 and a Ph.D. from Stony Brook University in May 2007.

MARTIN L. ESKIJIAN, P.E., M. ASCE, D. P.E.

Martin Eskijian has over 40 years' experience as an engineer specializing in structural dynamics, reservoir engineering, and structural engineering/code development for marine oil and LNG terminals. Following the earthquakes in Kobe (1995) and Izmit, Turkey (1999), the earthquakes and tsunamis in Sumatra (2004) and Chile (2010); and, most recently, the triple disaster in Japan (2011), he participated in coastal/port damage surveys, with an emphasis on the behavior of port and harbor structures and transportation infrastructure. He worked for the California State Lands Commission for 27 years and became the leader of a group focused on marine oil terminals. He is responsible for Chapter 31F of the California Building Code "Marine Oil Terminals," commonly known as "MOTEMS." Currently, he is an "on-call" senior engineer at Moffatt & Nichol in Long Beach, CA. His professional honors include the Professional Achievement Award for Professional Engineers in California (1998); the C. Martin Duke Award (2011) from ASCE/TCLEE for his lifetime work in earthquake engineering for lifelines, and membership in the Russian Academy of Natural Sciences (RANS) (2012). He is a registered civil engineer in California, a registered petroleum engineer in Texas, and a Diplomat of ASCE/COPRI. He earned a B.S. in Civil Engineering, an M.S. in Applied Mechanics, an Engineer Degree in Civil Engineering, and an M.S. in Petroleum Engineering from the University of Southern California. He has taught graduate classes on the subject of marine structures at the University of Southern California and the University of California San Diego.

OMAR JARADAT, PH.D.

Omar Jaradat, Ph.D., PE is a registered civil engineer in California and Washington, with more than 25 years' experience in engineering, specializing in earthquake engineering, soil-structure interaction and non-linear structural analysis. Dr. Jaradat earned a BSc in Civil Engineering and an MSc in Structural Engineering from the University of Jordan, and a PhD in Earthquake Engineering from Washington State University. He is well versed in state-of-the-art analysis and design techniques, including linear and non-linear time-history analysis, spectral analysis and non-linear static pushover analysis, and has published and co-authored numerous papers in the field of in-elastic behavior of concrete columns, earthquake engineering and bridge, port, and harbor structures. Dr. Jaradat serves on several technical committees specializing in developing code standards for the analysis and design of earthquake resistant structures, including American Society of Civil Engineers (ASCE) and Coasts, Oceans, Ports, and Rivers Institute (COPRI). In addition, he has directed an experimental program at the University of California at San Diego to study seismic behavior of concrete decks supported by vertical piles systems.

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