How Japan's Bullet Trains Survived the 2011 Great Tohoku Earthquake

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Abstract: This paper assesses the consequences of the March 2011 Great Tohoku Earthquake in Japan in terms of the performance of the earthquake countermeasures deployed on Shinkansen, the Japanese high speed railway network (also known as the 'Bullet Train') so far. The survival of the Shinkansen trains is markedly an example of how technology made the difference.

Keywords: High-speed Rail, Shinkansen, Earthquake, 3/11, Japan

1. INTRODUCTION

Japan's triple disaster - the 9.0 earthquake centered in Tohoku, the massive accompanying tsunami and the Fukushima nuclear accident - that rocked Japan on March 11, 2011 (now known widely as '3/11') is the biggest crisis that Japan has faced since World War II ended in 1945. Among all devastating events caused by 3/11 the nation's railway infrastructure was badly damaged and its network function was crippled, but it was a great comfort that nobody among the railway passengers and crew members on board was hurt and none of the Shinkansen trains exposed to the quake was derailed except one with no passengers.

2. EARTQUAKE AND JAPAN

The Japanese archipelago derives its origin primarily from several large oceanic tectonic movements as a result of the subduction of the Philippine Sea Plate beneath the continental Eurasian Plate and Okinawa Plate to the south, and subduction of the Pacific Plate under the North American Plate to the north. These plates mash and grind together and cause elastic displacements between the plates at a rate of 4 ~ 8 cm/year. The displacements progress until they ultimately bounce and release vast amounts of energy triggering earthquakes. Minor tremors occur on a nearly daily basis. Deadly quakes are a tragic part of the nation's past.

The anniversary of the Great Kanto Earthquake of 1923, for example, which killed more than 100,000 people around Tokyo, is now national Disaster Prevention Day. The most recent major quakes include the 2011 Great Tohoku Earthquake and tsunami, the 2004 Chuetsu Earthquake and the Great Hanshin Earthquake of 1995.

When it comes to building and operating a high-speed railway, you'd be hard-pressed to find a place to do it in a thornier part of the earth than Japan.

3. EARTHQUAKE SAFEGUARDS ON THE TOHOKU SHINKANSEN BEFORE 3/11

Starting with the Tokaido Shinkansen (515 km) in 1964, the Shinkansen network has expanded to currently consist of some 2,400 km of lines with maximum speeds of 240–320 km/h. The network presently connects most major cities on the islands of Honshu and Kyushu, with construction of a link to the northern island of Hokkaido underway.

The Tohoku Shinkansen, which connects Tokyo to Sendai, Morioka, Aomori and other major cities through the rather sparsely populated Tohoku region of Honshu in a route length of 674 km, making it Japan's longest Shinkansen line. The line is operated by East Japan Railway Company (JR East). The company had executed various earthquake-proof measures to the line prior to 3/11 based on previous experiences of disasters and accidents.

3.1 Viaduct Reinforcement

The structure of the Tohoku Shinkansen is comprised of continuous double-track viaducts, not of embankments as most conventional railway lines in Japan do except for tunnels in mountainous parts of the line. In Japan, earthquake-resistant construction standards were introduced in full-scale shortly after the Great Kanto Earthquake of 1923 and also have been revised successively up to today based on the lessons learnt from past damage cases. Especially in response to the Great Hanshin Earthquake of 1995, which destroyed many railway viaducts and revealed the fragile nature of the conventional reinforced concrete viaduct columns against horizontal displacement caused by earthquake shear force, the country's rail operators rapidly took actions of anti-seismic reinforcement of viaduct columns.

JR East had already completed the reinforcement works on the most vulnerable viaducts within its areas before the 2004 Chuetsu Earthquake. In this earthquake case, a Joetsu Shinkansen train running at a speed of some 200km/h was derailed due to the strong quake

Figure 1. Viaduct Column Reinforcement

motion but made a successful 'soft landing' without deviating and flipping from the roadbed. Nobody on board was killed nor injured thanks to the the anti-seismic reinforcement which had been justly completed to the viaduct on which the train was derailed. It was quite possible that the derailment would be more devastating if the reinforcement had not been completed.

Learning lessons from the 2004 Chuetsu earthquake, JR East accelerated the progress of the anti-seismic reinforcement of the viaducts of the Tohoku Shinkansen, which is believed to be exposed to higher seismic hazard than those of the Joetsu Shinkansen, and completed it by 2008.

3.2 Seismic Early Warning System

A seismic early warning system (SEWS) is a system of seismometers, communication, computers, and alarms that is devised for regional notification of a substantial earthquake while it is in progress. The Tohoku Shinkansen is protected by a SEWS, which includes two sets of seismometers: one set is deployed along the line (wayside system), while the other comprises seismometers placed along the eastern and western coasts of Honshu (coastal system). The coastal system is designed to protect the train against earthquakes with origin in the highly active offshore subduction zone. The system causes trains to automatically stop when it detects a potentially destructive seismic vibration.

As the initial setting of the SEWS, which was inaugurated in 1982, the system picked up the peak ground acceleration of the S-wave of an earthquake and triggered braking of trains when the ground acceleration exceeds a preset limit. The new SEWS, which JR East launched in 1998, improved its warning performance by supplementing sensors that pick up the faster-moving and less destructive P-waves produced by an earthquake and transmits a warning to trains before the destructive S-waves and surface waves arrive, giving greater temporal margin for recipient trains to braking.

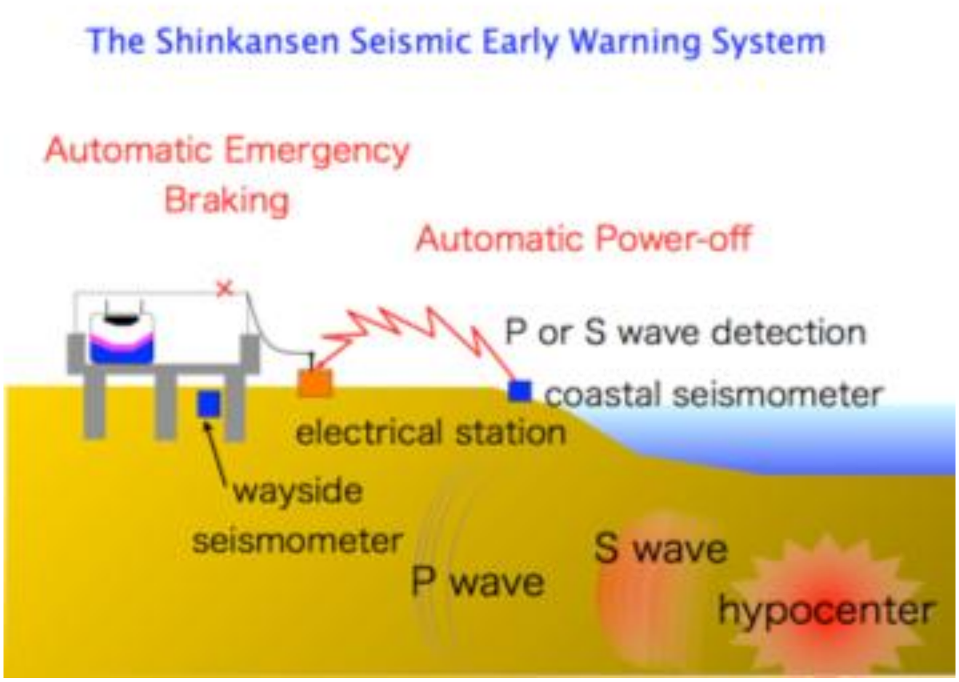

Figure 2. The Composition and Mechanism of SEWS

3.3 Anti-straying Wheel Guide Mechanism

Based on the lessons learned from the derailment case in the 2004 Chuetsu Earthquake, JR East started to install the newly developed anti-straying wheel guide mechanism to all Shinkansen cars in 2006 and completed it in 2008.

Figure 3. The Anti-straying Wheel Guide Mechanism

4. EARTHQUAKE AFTERMATH

The ginormous earthquake that struck the Pacific Coast of East Japan on March 11, 2011 claimed the lives of over 15,000 people and threw the country's infrastructure including rail network into complete chaos.

Seeing pictures from the earthquake and the tsunami it is hard to believe that not one passenger or crew members died on any of the numerous trains in operation throughout the country that day, especially as Japan's rail network - including all the conventional lines as well as that of the high-speed bullet train, Shinkansen.

On the day of the quake, at 2:47 PM, a seismometer at Cape Kinkazan in Miyagi Prefecture 50 kilometers from the tracks detected ground acceleration of 120 gals, which is the benchmark for stopping train operations. (This was S-wave detection. Later investigation made it clear that the P-wave detection failed due to an unusually slow oscillation growth pattern attributed to the exceedingly gigantic magnitude of the earthquake.) The emergency brakes were then automatically applied to all 33 trains on the tracks to slow down. The seismometer at Sendai Station recorded the biggest tremors. The railway operator found that the first tremor occurred 9 to 12 seconds after 2 trains near Sendai slammed on the brakes. The strongest tremor came one minute and 10 seconds later. Only one train, running under test without passengers, derailed that day, but thanks to the above-mentioned anti-straying wheel guide mechanism, without falling from the roadbed .

The SEWS and reinforcement works couldn't, however, save the railways from avoiding any damage whatsoever. Viaduct columns escaped from collapsing proving the effectiveness of the reinforcement works. But tracks were displaced and electrification masts were broken, leaning or cracked in many places.

In spite of these damages, Shinkansen trains re-started operations only 49 days after the earthquake. Around 8,500 engineers worked round the clock - repairing viaducts, bridges, tunnels, tracks, points, electrification masts and train stations - in order for the service to resume in time for the spring holiday season at the beginning of May. One reason for the early recovery was obviously that the damage in the structures was limited because of strengthening measures based on former earthquakes.

Figure 4: Physical Damages on the Shinkansen Structures

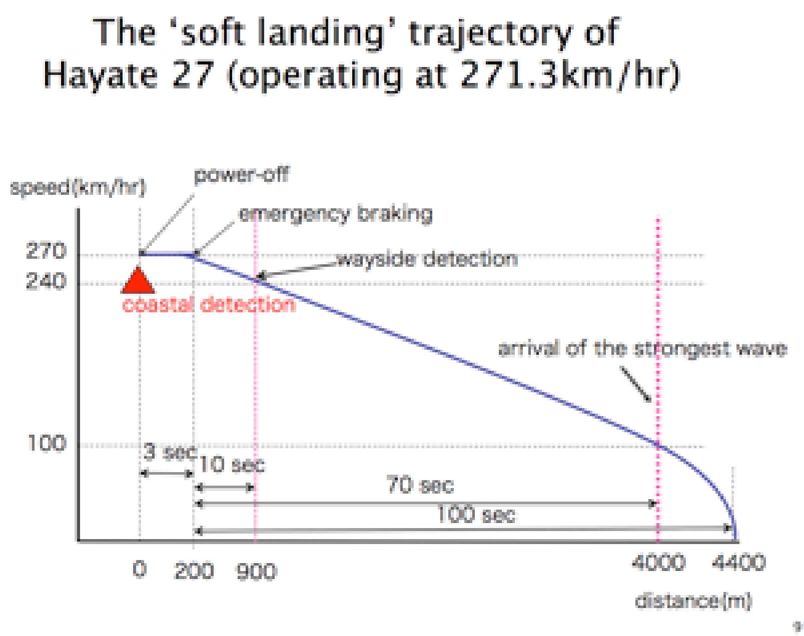

Figure 5: The Braking Trajectory of a Shikansen Train

5. CONCLUSION

Shinkansen has long been synonymous with safety. And the system has actually been improved and evolved constantly its quality and reliability. The fact that Shinkansen survived all earthquakes in Japan so far including the three major ones : the Great Hanshin of 1995, the Chuetsu of

2004 and the 2011 Great Tohoku probably raised society's feeling of trust on the seismic safety of Shinkansen. But experiencing no fatal accidents is merely a cold comfort from the view point of railway operators.

Actually, although we would presumably be allowed to say that Shinkansen's anti-seismic measures worked properly to save lives this time, they are in fact not inherently designed to cope with all outlying events outside the realm of regular expectations like the 3/11 tsunami, as was not the Fukushima nuclear power plant.

In a circumstance where successive 3/11 like or even more devastating disasters are expected to occur in other regions of Japan in the near future, railway operators in Japan are more willing to pay for additional anti-seismic measures than ever. If forced to give the examples of the gain side of the consequences of the Great Tohoku Earthquake, I would not hesitate to point it out to be the significant improvement of the railway operator's budgetary, industrial, scientific, psychological, political and what so ever preparedness against future devastating earthquakes in Japan.