Research and Development Trends regarding Countermeasures to Prevent "Earthquake-related Events"

Yoshitaka MURONO
Center for Railway Earthquake Engineering Research

It is well known that the most important countermeasure to earthquakes is to prevent shaking caused by strong ground motion. Consequently, the Center for Railway Earthquake Engineering Research is involved in extensive research and development, encompassing early earthquake warning, seismic reinforcement and earthquake data provision. Recently however, damage caused by fault induced surface deformation, tsunamis and multiple earthquakes, including aftershocks, has been reported. These phenomena are said to be "earthquake-related events." Since the characteristics of many "earthquake-related events" are still unknown, no seismic design methods have been established yet in response to them, while it is necessary to minimize damage through seismic structural planning. This paper therefore describes the work that has been done and achievements made, to minimize seismic damage due to earthquake-related events.

**Keywords:** earthquake-related events, surface fault displacement, aftershock, remaining strength, re-liquefaction

1. Introduction

Over recent years, it has become clear that damage is occurring which differs from that caused by what is called strong motions, or shakes, for example, (i) damage due to surface fault displacement, (ii) girder drifting or pier collapse due to tsunamis, and (iii) progressive damage caused by multiple earthquakes including aftershocks. In the case of (i), fault displacement occurring in the bedrock may occasionally appear on the ground surface through the sedimentary layer (surface fault displacement), and there have been reports of structures that have suffered direct damage from such displacement. Well-known examples of this, are the collapse of road bridges and dams that occurred during the Chi-Chi Earthquake in Taiwan and the buckling of railway tracks in the Kocaeli Earthquake in Turkey, both of which occurred in 1999. In Japan, examples include the Tanna tunnel in the 1930 Kita-Izu Earthquake, and traces of surface fault displacement were seen in the 2016 Kumamoto Earthquake although there was no direct damage on railway structures. Examples of (ii), are still fresh in our memory with the massive destruction wreaked in the 2011 off the Pacific Coast of Tohoku Earthquake. As for (iii), the moment magnitude of the main shock in the 2011 off the Pacific Coast of Tohoku Earthquake was 9, while aftershocks reaching about M 7 occurred five times in the following month, leading to a spread of damage to catenary poles and RC piers. In the 2016 Kumamoto Earthquake, an earthquake about seismic intensity 7 occurred twice (foreshock and main shock), resulting in the widespread collapse of dwellings and other buildings. These events are defined as “earthquake-related events” in the Design Standards for Railway Structures (Seismic Design Standard) (hereinafter “Seismic Design Standard”) [1].

Despite the fact that earthquake-related events have been recognized as possible hazards, there are few studies into their consequences, and so it is difficult to verify the performance that would be required, taking current technological levels into account. For this reason, although not subject to direct investigations under Seismic Design Standards, it is considered necessary to minimize their impact as far as possible at the stage of seismic structural planning [1].

2. Study on surface fault displacement

2.1 Surface fault displacement

In order to develop anti-quake measures, it is necessary to know what surface fault displacement should be assumed on the ground surface, and across what range.

Surface fault displacements occurring during past inland active fault earthquakes were investigated; as a result, it was revealed that if the moment magnitude is about Mw 7.0, the surface fault displacement is about 1 m on average, and if it is about Mw 7.5, the displacement may exceed 3 m.

RTRI the extended the evaluation method so that the sedimentary layer could be considered for crustal deformation evaluation by the discrepancy elasticity theory. It was revealed that applying this method made it possible to obtain a trend roughly matching past records. It was also revealed that even for earthquakes of the same scale, the shallower the fault depth, the larger the maximum amount of displacement, and the narrower the impact range. Figure 1 shows the results of applying this method to the foreshock of the Kumamoto Earthquake that occurred on April 14, 2016. The distribution of the resulting surface fault displacement, which adequately expresses the trend obtained by GPS, demonstrated the effectiveness of the surface fault displacement evaluation using the proposed method. The current analysis technique cannot, without difficulty, predict surface fault displacement etc. with the accuracy required for performance verification. Therefore, anti-quake countermeasures need be taken by making the most of the
fault position and the displacement direction, the latter of which can be specified to some extent.

2.2 Examining behavior of and countermeasures for structures in the case of vertical faults

The behavior of rigid-frame viaducts was investigated in the case of vertical faults. The objects of the investigation were two conventional four-span rigid-frame viaduct without underground beams (conventional structure ①), a four-span rigid-frame viaduct with underground beams (conventional structure ②), and a single-span rigid-frame viaduct proposed by RTRI [2].

As an example, Fig. 2 shows the whole deformation of the conventional structure ① and the single-span rigid-frame viaduct, while Fig. 3 is a graph showing the bending moments of the upper beams. The fault displacement was applied to the end of each rigid-frame viaduct: indicated by the arrows in Fig. 2. Figure 3 demonstrates that the conventional structure exhibits a twisting behavior and its beams are subject to a large force. This trend is more noticeable (disadvantageous) for the rigid-frame viaduct without underground beams. On the other hand, since the proposed structure deforms rigidly, it is understood that no large force acts on the beams.

This suggests that underground beams significantly affect the behavior of the rigid-frame viaduct, and that in the absence of underground beams, upper beams are seriously damaged even by a small fault displacement. Installing underground beams is therefore clearly desirable. Overhang viaducts without girders are effective in terms of eliminating the risk of falling girders. In addition, it was found that the single-span rigid-frame viaduct was overwhelmingly more advantageous than the rigid-frame viaduct with multiple spans. These findings suggest therefore that if a rigid-frame viaduct is selected for a location with a vertical fault, the single-span overhang type rigid-frame viaduct is the most advantageous structural form. Note that would be the optimal choice in view of fault displacements but not so in terms of operations and maintenance or performance against strong ground motion.

2.3 Countermeasures against horizontal faults

In the case of horizontal faults, in addition to the above and through experiments and numerical analyses, it was revealed that structural behavior varied greatly depending on the angle of intersection with the fault [3]. It is important to take this point into account for seismic structural planning.

As shown in Fig. 4, if the intersection angle is 90° or less, the horizontal displacement of the active fault would force piers apart at the fault line as the boundary. In this case, the girders crossing the fault do not come into contact with any other adjacent girders, and deformation is concentrated only on the span crossing the fault. The scope
of the countermeasures against fault displacement needs only to target the spans across the fault. If the angle of intersection is over 90°, deformation is compressed along the viaduct with the fault as the boundary. In this case, the girder crossing the fault comes into contact with the adjacent girders, and the behavior of the structure crossing the fault propagates to adjacent bridges, resulting in damage spreading to multiple spans. The impact of the fault displacement on the structure therefore spreads, which means that the scope of the countermeasure against fault deviation has to be extended as well. Risk can be drastically mitigated by ensuring that the angle of intersection is within 90° as much as possible during linear programming, and by narrowing the angle and the range of countermeasures during structural planning.

3. Aftershock

When considering a massive earthquake, there is a strong possibility that damage will be compounded by aftershocks, even if damage by the main shock is slight. This should be borne in mind when developing anti-quake measures for railway facilities, in preparation for a massive earthquake. Studies conducted at RTRI therefore factor in aftershock occurrence models and ground and structural behavior evaluations.

3.1 Aftershock occurrence model

Data on the magnitude and timing of aftershocks is important for the seismic design of structures. Therefore, a model was statistically constructed using past earthquake data on timing and magnitude of aftershocks that occurred following the main shock [4]. The model revealed that the maximum aftershock was smaller by about 1 in magnitude than the main shock.

Next, the expected number of earthquakes was calculated for each hour and each scale of magnitude. Figure 5, for example, shows the relationship between time elapsed after the main shock and the scale of the aftershock of an inland active fault. From these results, it is assumed that, for example, an aftershock whose difference in magnitude with the main shock is about -1 occurs once or so every several hours (within 10 hours) after the main shock. Over 100 hours (about 4 days) following the main shock, one more aftershock occurs in the case of inland active fault induced earthquakes. This aftershock occurrence interval model can be used to simulate the time series of the seismic motion group. Figure 6 shows an example of this. The

![Fig. 5 Aftershock occurrence model (inland active fault)](image)

![Fig. 6 Example of evaluation of the seismic motion group from the main shock to each aftershock)](image)

statistical Green’s function method was used for simulation of each individual seismic motion.

3.2 Residual strength against aftershocks

This section evaluates the residual strength of structures against aftershocks. The residual seismic performance ratio, \( R \), is proposed as an index for evaluating the residual strength, and is defined as the ratio of \( PGA_1 \) to \( PGA_2 \), where \( PGA_1 \) is main shock acceleration, when a sound structure reaches the ultimate state due to the main shock, and \( PGA_2 \) is the acceleration of the aftershock, or second wave, when the structure damaged by the main shock reaches the ultimate state due to the aftershock.

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R = \frac{PGA_1}{PGA_2}
\]

An \( R \) value equal to or less than 1 indicates that the critical acceleration for aftershocks is small due to damage caused by the main shock.

For a specific seismic wave, the residual seismic performance ratio, \( R \), is calculated for a structure with various periods, and the residual performance ratio spectrum is created. Figure 7 shows an example of this for the Hyogoken Nanbu Earthquake (Kobe Marine Observatory waves). It shows the value for each response ductility, \( \mu \), for the main shock. The conditions for the structure include M (maximum resistance point) ductility \( \mu_{M}=4 \) and N (ultimate state point) ductility \( \mu_{N}=6 \). If M was not reached in the main shock, \( R = 1.0 \), which indicates that the damage will not spread even if aftershocks occur. It was found however, that if damage exceeded M (\( \mu > 4 \)) with the main shock, there was a strong possibility that damage would propagate with aftershocks. The residual performance ratio may be high in a structure with an equivalent natural
period of 1 second or more. This is because the structure has lengthened its period due to the damage caused by the main shock and has become insensitive to aftershocks (base isolation effect).

3.3 Re-liquefaction of ground due to aftershocks

The influence of aftershocks can have a big influence on liquefaction as well as spread of damage to a structure. In order to study problems like those described above, RTRI developed a method which factored in the permeability of pore water by modeling the ground using a strain-space multiple shear model [5] and adopting the u-p formulation [6] as the equation of motion and the balance equation of water flow [7].

A ground model was constructed referring to topographical information about the Takasu District of Urayasu City, where liquefaction actually occurred, and an analysis was conducted. The estimated base rock ground motion in the Urayasu District during the 2011 off the Pacific Coast of Tohoku Earthquake was entered into the ground model. Although its maximum acceleration was only about 100 gal, it was characterized by its duration lasting several hundred seconds. The maximum acceleration of the after-shock that occurred about 30 minutes after the main shock was about 45 gal, which was smaller than the main shock.

Figure 8 shows the time-history for the excess pore water pressure ratio obtained through the analysis. The excess pore water pressure increased at every depth during the main shock; especially at G.L. -6.4 m, the water pressure ratio was almost 1.0, which suggests the occurrence of significant liquefaction. In fact, since pore water gradually drains towards the ground surface after the main shock, the excess pore water pressure ratio tends to decrease over time. Water pressure, however, does not completely dissipate before the occurrence of the aftershock, and the water pressure ratio rises again during the aftershock, indicating re-liquefaction. This result qualitatively agrees with the actual case of Irifune Junior High School.

Figure 8 also shows the result of applying only the aftershock without considering the main shock: only a small increase in the excess pore water pressure ratio is demonstrated, because the maximum acceleration of the aftershocks was very small: about 45 gal. As such it was confirmed that liquefaction does not occur when there is only an aftershock and no first main shock. However, the possibility of liquefaction increases if an aftershock occurs while excess pore water pressure ratio stands at around 0.5, remaining after the main shock.

Even if the same shear stress is exerted, elastic shear work larger than before the main shock is accumulated. This seems to have led to a significant rise again in the excess pore water pressure ratio during the aftershock following the main shock. As a result, the total settlement (about 0.76 m) due to both the main shock and aftershock was 38% larger than the case with only the main shock (about 0.55 m).

4. Conclusions

This paper introduces the latest work on the impact of surface fault displacement and multiple earthquakes as earthquake-related events. Seismic design standards state that the effects of earthquake-related events shall be considered for seismic structural planning, without specifying performance or verification means, taking into account the current level of accuracy of evaluations and technological constraints. It can be said that, though there is still great concern about earthquakes and when they will happen, it is increasingly important to take into account earthquake-related events as well as conventional "shaking" caused by the main shock.

References


Author

Yoshitaka MURONO, Dr. Eng.
Director, Head of Center for Railway Earthquake Engineering Research
Research Areas: Earthquake Engineering

Fig. 8 Time-history of excess pore water pressure ratio