Exposition of Revision of Seismic Design Guideline for Overhead Contact Systems

Yuichi KONDO
Contact Line Structures Laboratory, Power Supply Technology Division

In Japan, in order to prevent supports (referred to poles and portal structure etc.) in overhead contact systems from collapsing at the time of an earthquake, we design them according to the Seismic Design Guideline for Overhead Contact Systems and Commentary (hereafter referred to as the OCS Guideline).

We revised the OCS Guideline in 2013 to evaluate seismic performance of supports more precisely. The paper shows the process of revising OCS Guideline until now and details of the latest revision of the OCS Guideline.

Key words: earthquake, railway structure, Overhead Contact System, seismic design, supports

1. Introduction

Japan is one of countries affected by earthquakes frequently. We need to design railway structures adequately so that earthquakes of higher magnitude do not cause serious damage to them, such as destruction of viaducts and collapse of supports (referred to poles and portal structure etc.) in overhead contact systems. International Electrotechnical Commission (IEC) does not describe any seismic design methods of supports in overhead contact systems. Incidentally, in Japan, we established the Seismic Design Guideline for Overhead Contact Systems and Commentary (hereafter referred to as the OCS Guideline) in 1982 [1] and the Design Standard for Railway Structures of Seismic Design and Commentary (hereafter referred to as the Seismic Standard) in 1999 [2]. We design supports according to the OCS Guideline and railway structures according to the Seismic Standard including civil engineering structures.

The Seismic Standard, revised in 2012, additionally includes new design ground motion and a method of inputting waves into overhead contact systems and station buildings on civil engineering structures when estimating their dynamic behavior [3]. In order to maintain consistency with the Seismic Standard, we revised the OCS Guideline in 2013 [4]. The paper shows the process of revising OCS Guideline until now and details of the latest revision of the OCS Guideline.

2. Establishment and revision of OCS Guideline

2.1 Establishment of the OCS Guideline

In the past we had designed supports used in overhead contact systems mainly to resist wind pressure. However, in the 1978 MIY-AGI-KEN-OKI Earthquake, many concrete supports in overhead contact systems, which were installed under construction of Tohoku Shinkansen line, were damaged. Therefore, in 1982 we established the OCS Guideline that describes the design method for preventing collapse of the supports by an earthquake. In 1978, supports on earth structures were hardly damaged, and most of the damaged supports were on viaducts. Thus, the OCS Guideline describes the design method in consideration of the effect of the dynamic behavior between supports and civil engineering structures.

2.2 Revision of the OCS Guideline in the past

The 1995 Great Hanshin-Awaji Prefecture Earthquake seriously damaged civil engineering structures. Therefore, the seismic design method for civil engineering structures has been modified and the seismic force to which civil engineering structures are subjected has been substantially modified. Since we designed supports on civil engineering structures using this force basically, the OCS Guideline was also modified in 1997 [5].

2.3 Latest revision of the OCS Guideline

In 2012, the Seismic Standard was revised accordingly since the international standers were changed to performance regulations. In consideration of the ground motion and damage at the 2011 Great East Japan Earthquake, the Seismic Standard additionally included new design ground motion and a method of inputting waves into overhead contact systems and station buildings on civil engineering structures when estimating their dynamic behavior. In order to maintain consistency with the Seismic Standard, we revised the OCS Guideline in 2013. The revised OCS Guideline included new knowledge to make more precise evaluation of seismic performances.

3. Outline of the seismic design method of supports in overhead contact systems

According to the analysis of the damage in the past earthquakes, we found that many supports were damaged in case they resonated with civil engineering structures at the time of the earthquakes. Therefore, we have to design supports in consideration of the vibration property of both supports and civil engineering structures.

There are methods using a unified model and a separated model as the seismic design method of supports on civil engineering structures. Figure 1 shows a concept of the unified model and the separated model. In case of the unified model based on the consideration of unifying supports and civil engineering structures, we evaluate the response acceleration of supports to the ground motion. However, it is difficult and complex to evaluate the response acceleration of supports. On the other hand, the separated model is easy to evaluate...
the response acceleration of supports but cannot evaluate the dynamic behavior between supports and civil engineering structures. Therefore, we compensate the effect of the dynamic behavior to adopt the separated model.

4. Details of latest revision of the OCS Guideline

The OCS Guideline describes the seismic design method of supports on viaducts and those on the earth structures. Since the seismic design method of supports on viaducts was mainly revised in 2013, we show it as an example and explain the details of revision of the OCS Guideline.

4.1 Procedure of the seismic design method of supports on viaducts

Figure 2 shows the procedure of the seismic design method of a support on a viaduct. In this case, we assume that design parameters of the viaduct were evaluated when the viaduct was designed. First, we evaluate the response wave of the crown of the viaduct to the ground motion. Second, we input this wave into the foundation of the support and evaluate the response acceleration of the support. Third, we evaluate the maximum moment of the support generated by this acceleration. Last, we compare the maximum moment of the support with its limit moment to evaluate the safety.

4.2 Ground motion to be considered

In the Seismic Standard, the design ground motion consists of L1 earthquake ground motion and L2 earthquake ground motion. L1 earthquake ground motion means the ground motion having a high possibility of occurrence, among those expected to occur at that place, judging from the relationship between the recurrence intervals of earthquake ground motion and the design working life of the viaduct concerned. L2 earthquake ground motion means the ground motion having an intensity of the maximum scale among those expected to occur at that place. In the OCS Guideline, the target is that supports in overhead contact systems do not cause destruction or collapse so that serious troubles for train run do not occur. Therefore, the ground motion to be considered is L2 earthquake ground motion and the procedures are explained.
motion for the seismic design of supports in the OCS Guideline.

L2 earthquake ground motion consists of spectra I and II. Spectrum I is assumed to be a subduction-zone earthquake and spectrum II is assumed as an inland active-fault earthquake. The acceleration wave of spectrum I keeps for a longer duration than that of spectrum II. On the other hand, the acceleration wave of spectrum II has higher amplitude than that of spectrum I. Therefore, in the past OCS Guideline, only spectrum II had been used. However, on account of the structural characteristic of supports, we found that the duration of the ground motion affects the response acceleration of supports when resonating with civil engineering structures. Therefore, in the latest OCS Guideline, we determine to use both spectra I and II.

Furthermore, in consideration of the characteristic of the ground motion and the damage at the 2011 Great East Japan Earthquake, in the Seismic Standard, we set two types of motion as L2 earthquake ground motion. One is the general ground motion that is the modification of the past design ground motion. The other is the additional ground motion in which a shorter period is predominant. In order to maintain consistency with the new design ground motion, in the latest OCS Guideline, we also determined the ground motion should be considered.

4.3 Methods of compensating the natural period of supports

As mentioned above, we design supports in consideration of vibration properties of both supports and civil engineering structures. A natural period is one of the vibration properties. In the past OCS Guideline, the natural period of a support such as a single pole was calculated assuming that it was the first natural period of a cantilever. Equation (1) shows the calculation.

\[
T_p = \frac{1}{f_p},\quad f_p = \frac{1}{2\pi} \left( \frac{1.875 EI}{L^2} \right) \sqrt{\frac{E}{\rho}}
\]

where,
- \( T_p \): Natural period of a support (s)
- \( f_p \): Natural frequency of a support (Hz)
- \( L \): Length of a support (m)
- \( EI \): Flexural rigidity of a support (Nm²)
- \( \rho \): Mass per unit length of a support (kg/m)

However, the mass of overhead wires and metal fittings attached to the pole may have an effect on the natural period of the pole. Figure 3 shows the example of calculations considering the effect. The natural frequency of the pole with wires and fittings is smaller than that of the pole without them. In case of a steel pipe pole, its natural frequency is much smaller, since it is lightweight.

Figure 4 shows the relation between load-point displacement and bending moment of a concrete pole. They are not in linear if the concrete pole is subjected to a load more than the allowable load of concrete. As the flexural rigidity of the concrete pole decreases, we need to consider the effect of it on the natural period of the pole.

The latest OCS Guideline describes compensation coefficients in order to compensate the natural period of a support in consideration of the mass of objects attached to the support and, in case of concrete supports, the flexural rigidity of supports as well.

4.4 Evaluation of response acceleration

4.4.1 Horizontal response acceleration

As same in the past OCS Guideline, we evaluate the horizontal response acceleration of a support using both the response acceleration spectrum and the ratio of between the equivalent natural period of a viaduct \( T_{eq} \) and the natural period of a support \( T_p \). The latest OCS Guideline describes the new response acceleration spectrum according to combination of the ground classifications and support classifications. The ground classifications have five categories according to the characteristic of the ground. Supports are classified into two categories depending on their material, that is, concrete and steel. Figure 5 shows the example of the response acceleration spectrum.

We evaluate the response acceleration of a support using the
response acceleration spectrum in consideration of an effect of horizontal response of the viaduct. However, we found that this evaluation by a separated model is smaller than that by a unified model. Since that by a unified model is more precise, the past design method by a separated model can be dangerous [6]. To evaluate the behavior of supports more adequately at the time of an earthquake, we should also consider the effects of the rotational response of viaducts (Fig. 6). Actually, we have confirmed that considering this effect, we have estimated the situation of damage more adequately at the 2011 Great East Japan Earthquake [6].

The latest Seismic Standard describes the method to evaluate the response acceleration in consideration of the effects of the rotational response of a viaduct. On the basis of this, we set the ratio of the rotational response to the horizontal response $k_\theta$ in the latest OCS Guideline as the compensation coefficient to compensate the response acceleration of a support to the horizontal response of viaducts.

Equation (2) shows how to compensate the horizontal response acceleration of a support.

$$A_{h}' = A_h \times (1 + k_\theta \times L) \quad (2)$$

where,

- $A_h$: Horizontal response acceleration of a support (m/s$^2$)
- $A_{h}'$: Compensated horizontal response acceleration of a support (m/s$^2$)
- $k_\theta$: The ratio of the rotational response to the horizontal response.

By installing this method of compensating, the evaluation by a separated model is almost equal to that by a unified model [6]. Therefore, the method by a separated model in consideration of the effects of rotational response is more precise. Furthermore, we are easy to apply this method since it is similar to the past method.

### 4.4.2 Vertical response acceleration

We set the vertical response acceleration of a support to a half of the maximum of the design ground acceleration according to the ground classification in order to maintain consistency with the Seismic Standard.

4.5 Evaluation of the maximum moment

The maximum moment of a support is the moment at the foundation of the support. Figure 7 shows the loads used in calculating the moment at the ground of a support. We calculate the moment generated by inertial force of the support, the overhead wires and objects attached to them. Assuming that response acceleration calculated in the previous section is acting at the center of gravity of the support, we calculate inertial force multiplying the mass of them by this acceleration. In this regard, we assume that masses of the overhead wires are a half of them since they are not rigidly attached to the support.

Equation (3) shows the calculation of the moment of a support at the foundation.

In order to evaluate safety, we check that this moment is smaller than the limit moment of the support. Otherwise, we should
change the support to the adequate one and evaluate the safety of it in the same way. The limit moment of supports is set at the double allowable bending moment, since the safety factor for breaking strength is greater than two [7].

\[
M = \begin{cases} 
A'g \sum mh + (1 + A_v) g \sum mr + (1 + \alpha) \sum ph & \text{(Perpendicular to the direction of the rail)} \\
A'g \sum mh & \text{(Parallel to the direction of the rail)} 
\end{cases}
\]  

(3)

where,

- $M$: Moment of a support at the foundation (the maximum moment of a support) (Nm)
- $A_v$: Vertical acceleration of a support (m/s$^2$)
- $\alpha$: Variability rate of the tension of overhead wires

\[M = \begin{cases} 
A'g \sum mh + (1 + A_v) g \sum mr + (1 + \alpha) \sum ph & \text{(Perpendicular to the direction of the rail)} \\
A'g \sum mh & \text{(Parallel to the direction of the rail)} 
\end{cases}\]

Fig. 7 Load related to the moment of supports at foundations of supports

| Table 1 Main detail of the latest revision of the OCS Guideline |
|---------------------------------------------------------------|
| Lists | The past OCS Guideline | The latest OCS Guideline |
|---|---|---|
| Ground motion to be considered | L2 earthquake ground motion Spectra II | L2 earthquake ground motion  
• General ground motion  
Spectra I, spectra II  
• Ground motion in which shorter period is predominant  
Spectra I, spectra II |
| The natural period of single pole | The calculation of the first natural period of a cantilever | Calculation of the first natural period of a cantilever compensating the following effect  
• The mass of overhead wires and metal fittings attached to the pole  
• The flexural rigidity of the concrete pole |
| Evaluation of response acceleration | In consideration of the only effect of the horizontal response of the viaduct | In consideration of the effect of the horizontal and rotational response of the viaduct |

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4.6 Conclusion of latest revision of the OCS Guideline

Table 1 shows main details of the latest revision of OCS Guideline. These revisions allow us to evaluate the seismic performance of supports more precisely.

5. Conclusion of this paper

In order to maintain consistency with the revised Seismic Standard, we revised the OCS Guideline. The latest OCS Guideline includes new knowledge and examples of the evaluation of seismic performance to design supports efficiently and more precisely. In order to operate Japanese railway more safely, we should keep improving the precision of evaluating seismic performance.

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Author

Yuichi KONDO
Assistant Senior Researcher, Contact Line Structures Laboratory, Power Supply Technology Division
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