Proposal of a New Type of Rigid-frame Viaduct
Insusceptible to a Reverse Fault

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In some cases, it is impossible to avoid building a linear structure, including those built for the railways, near a fault. This study evaluates the behavior of rigid frame viaducts against vertical surface fault displacements initiated by a reverse fault, in order to propose a viaduct structure that could resist this type of fault displacement. Three types of viaduct were examined: two with an existing long track record in service, and a new type, proposed in this study. Results obtained confirmed the effectiveness of the proposed viaduct design, i.e. a one-span extension viaduct, against vertical surface fault displacements.

Keywords: surface fault displacement, railway rigid-frame viaduct, spread foundation, one-span, extension type

1. Introduction

In the 1999 Kocaeli earthquake in Turkey and the 1999 Jiji earthquake in Taiwan, civil structures were severely damaged by surface fault displacements, reminding us of the tremendous force they can have [1], [2]. Although surface fault displacements cause severe damage to structures, predicting the degree of ground surface dislocation is almost impossible. The Jiji earthquake in Taiwan caused a displacement measuring 10 m. This kind of large surface fault displacement is not unique to Taiwan, and has been observed in Japan as well. In the 1891 Nobi earthquake, the record shows a maximum horizontal displacement of 8.0 m and a maximum vertical displacement of 4.0 m. The 2016 Kumamot Earthquake, in which there was no major damage to civil engineering structures, saw a horizontal surface fault displacement of around 2.0 m initiated by a strike-slip fault [3]. Therefore, in Japan, where a number of inland active faults are known to exist, structures need to be protected from surface fault displacement by applying appropriate measures. Accordingly, civil engineering structures should ideally be constructed where the effect of surface fault displacements is small [4].

Linear railway structures however, must unavoidably be built above or near faults because of the linearity of routes. Reflecting this, the Design Standards for Railway Structures and Commentary (on Seismic Design) (hereafter referred to as “the Seismic Standards”) [5] cover surface fault displacement as an earthquake-associated event and discuss easy-to-restore embankments and bridges with widened seats [6] for structures being built above faults.

There have been a number of studies on structural damage caused by surface fault displacement, many of which looked at the structural safety of bridges in the event of surface fault displacement initiated by a strike-slip fault, and often discussing the relationship between the scale of the surface fault displacement and the damage to the foundations, guidelines on structural protection measures against surface fault displacement and other relevant topics [6]-[10]. While fault ruptures are either strike slips or vertical slips, only few studies have focused on vertical slips, leaving much to be clarified as to how structures behave when subjected to surface fault displacement initiated by a vertical slip.

Consequently, this study examines how rigid-frame viaducts, which are a widely-used railway structure, behave in response to vertical surface fault displacements initiated by a vertical slip, and proposes a type of viaduct that is highly resistant to surface fault displacement. When subjected to vertical surface fault displacement, rigid-frame viaducts and other similar structures can suffer horizontal member deformation, affecting for example upper and underground beams, possibly leading to the collapse of the entire structure.

In order to examine their behavior, three different types of rigid-frame viaduct were modeled. The models were put through a static push-over analysis in which surface fault displacement was input to observe the behavior of the models. Two of the three rigid-frame viaducts modeled are commonly used on the railways: one with and the other without underground beams. The third type was based on a design made specially for the study: a one-span extension rigid-frame viaduct considered to be better adapted for surface fault displacement. The static push-over analysis aimed to evaluate the behavior of each model of rigid-frame viaduct when subjected to a surface fault displacement. Therefore, only surface fault displacement was investigated, and the influence of inertial force was not taken into consideration. The impact of inertial forces on structures is generally reflected in aseismic design and can therefore be mitigated primarily by rearranging reinforcement bars in the members, reducing significantly the probability of collapse.
2. Analysis conditions

2.1 Rigid-frame viaducts for analysis

Based on the specifications of a single-level, 5-span reinforced concrete rigid-frame viaduct shown in Fig. 1, the following three types of rigid-frame viaduct were created for analysis with the number of spans and the presence or absence of underground beams as the parameters. These models are outlined in Fig. 2 [11].

Type 1: Single-level, 4-span rigid-frame viaduct without underground beams
Type 2: Single-level, 4-span rigid-frame viaduct with underground beams
Type 3: Single-level, single-span rigid-frame viaduct with underground beams

Type 1 and Type 2, are both widely used rigid-frame viaduct types and have Gerber girders at both ends. Type 3, designed especially for this analysis, had fewer spans to reduce the stress resultants and overhanging ends to eliminate the risk of bridge girders falling.

The reference viaduct shown in Fig. 1 had pile foundations. Therefore, spread foundations of sandy soil with an N value of 30 were used for the analytical models. The footings were designed to be 3.0 m long in the longitudinal direction of the viaduct, 6.5 m long in the lateral direction of the viaduct and 2.0 m in thickness to satisfy the stability requirements for foundations during an earthquake.

2.2 Surface fault displacement used for the analysis

The magnitude of a surface fault displacement is a function of many variables including the scale and depth of the fault and the thickness of the alluvium, and must be set carefully when used for the seismic design of structures [4]. In this analysis, the magnitude of surface fault displacement to be applied to the models was set to 3.0 m for the following reasons: data on surface fault displacement observed in the past in Japan [12] showed that in earthquakes of around Mw 7.5, displacement exceeding 3.0 m was measured only in around 30% of the observation sites although displacement exceeding 10 m was measured in some locations; and, in the case of earthquakes of around Mw 7.0, displacement reached 3.0 m in only a small percentage of the observation sites.

The selected displacement of 3.0 m was sufficiently higher than the average vertical value of the observed displacement. In addition, the analysis focused only on vertical components of surface fault displacement because the spread foundations used for the models were considered less likely to be affected by horizontal components compared to pile foundations.

2.3 Analytical models and methods

Two-dimensional static nonlinear analyses were conducted on the three different types of rigid-frame viaduct. The two-dimensional analysis was conducted in consideration of geometric nonlinearity. The analytical models were composed of beam-spring elements arranged in both the longitudinal and lateral directions of the viaduct. The columns and beams were modeled as linear members, while the foundations and ground were modeled as nonlinear, interacting springs. These springs were modeled as bilinear springs representing the resistance of the ground under
the footings in the vertical and horizontal (shearing) directions. The spring constant and upper limit of these springs were calculated according to the design standards for railway structures and commentary (on foundations) [13]. As shown in Fig. 3, the vertical springs on the bottom of the footings were modeled as linear springs without considering the upper limit in the locations of displacement input (or the locations pushed up by the ground). This was because the springs representing the ground resistance, while meeting the design standards for railway structures and commentary (on foundations), were not designed to consider surface fault displacement, with the possible result that on the secondary gradient (3% of the initial gradient) past the upper limit, the increase in load would be minimal compared with the increase in displacement, which could lead to the underestimation of the stress resultants of columns and beams.

3. Evaluation of behavior by static push-over analysis

3.1 Analysis cases

In the static push-over analysis of the models, input locations for the surface fault displacement were considered to be a parameter. The displacement input locations used in the analysis are shown in Table 1. In nine cases, displacement was input across the viaduct. In five cases, displacement was input along the viaduct. As shown in Fig. 4, the ground displacement was input over the widths listed in Table 1. An examination of the viaduct’s behavior using inputs across the viaduct was only carried out on Type 2 because the difference between the three viaducts was so small that the same examination on the other two types became redundant.

3.2 Results of the calculation of response values

Static push-over analyses were conducted on the models according to the cases in Table 1. The results were collated to clarify the relationship between the surface fault displacement and the rotation angle of the footings, and the relationship between the surface fault displacement and the section forces of the members. The case resulting in the greatest section force per type of displacement input along the viaduct, is shown below for each parameter. Members such as footings and upper beams were considered linear and the impact of their non-linearity was ignored. Therefore, to roughly represent their section forces, their design bending yield strengths and design shear strengths are also shown together with the results.

3.2.1 Rotation angle of the footings

Figure 5 (a) shows the relationship between the surface fault displacement input across the viaduct and the rotation angle of the footings. The relationship indicates that, when the surface fault displacement was input over more than half the width of the footings (Case C6 and up), the footings did not rotate while the viaduct was lifted by the displacement.

Figure 5 (b) shows the relationship between the surface fault displacement input along the viaduct and the rotation angle of the footings, for Type 1, Type 2 and Type 3 respectively. The relationship shows that there is no significant difference in rotation angle between Type 1 and Type 2 and that the rotation angle of Type 3 is about three times that of the other types. This is because Type 3 is shorter than the other two types. Considering that the rotation angle limit specified in the footings standards is 0.03 rad, the rotation angles observed in the analysis were significantly large.

3.2.2 Section force of the footings

Figure 6 shows the relationship between the surface fault displacement input across the viaduct and the section force of the footings. The relationship shows that the section force of the footings in response to a surface fault displacement input of not more than 3 m did not exceed the design bending yield strength or the design shear strength.

3.2.3 Section force of the upper beams

Figure 7 shows the relationship between the surface fault displacement input along the viaduct and the section force of the upper beams, for Type 1, Type 2 and Type 3 re-
respectively. On both Type 1 and Type 2, the bending moment exceeded the design bending yield strength even with minimal surface fault displacement input. As for shear force, Type 1 and Type 2 exceeded the design shear strength with a displacement input of around 0.3 m and around 1.0 m respectively. The section force of Type 3 was smaller than for the other viaducts, staying below the design bending yield and shear strengths even with a displacement input of 3.0 m. On both Type 1 and Type 2, the maximum bending moment was observed when the surface fault displacement was input to the end of the viaduct (Case L1). The greater bending moments at the upper beams were due to the beams being far away from the point where the vertical force was initiated by application of the surface fault displacement.
3.2.4 Section force of the underground beams

Figure 8 shows the relationship between the surface fault displacement input along the viaduct and the section force of the underground beams, for both Type 2 and Type 3. With Type 2, the bending moment exceeded the design bending yield strength with a surface fault displacement input of around 1.0 m and the shear force exceeded the design shear strength with a surface fault displacement input of around 2.0 m. With Type 3, as is the case with the upper beams, the section force was smaller than for Type 2 and did not exceed either the design bending yield strength or the design shear strength even with a surface fault displacement input of 3.0 m. With Type 2, the maximum bending moment was observed when surface fault displacement was input to the end of the viaduct (Case L1). As is the case with the upper beams, the greater bending moments on the underground beams were due to the beams being far away from the point where vertical force was initiated by application of the surface fault displacement. The section force of the underground beams was roughly the same as that of the upper beams. On the other hand, the design bending yield and shear strengths of the underground beams were greater than those of the upper beams, resulting in those values exceeding those of the upper beams with greater surface fault displacement inputs.

3.3 Concluding sessions of behavioral analysis

To conclude the behavioral analysis, Fig. 9 shows a multiple-span Type 2 viaduct where the surface fault displacement input was applied to the ends of the underground beams (Case L1), another Type 2 for which surface fault displacement was input over half its length (Case L3), and one-span Type 3 on which surface fault displacement was input, along with the resultant behaviors. The multiple-span Type 1 without underground beams was omitted from Fig. 9 as there was no clear difference in behavior between Type 1 and the other two types (Type 2 and Type 3) with underground beams.

When surface fault displacement acts on the end of the multiple-span, rigid-frame viaduct, the weight of the structure counteracts the displacement force trying to lift the structure and only the columns at the end of the viaduct and the area around them are lifted, while the displacement input is still relatively small (Fig. 9 (a)). As the displacement grows, the area that is lifted expands and eventually the entire structure is supported only by the columns at both ends. When the multi-span, long viaduct is in such a state, the bending moment of the upper beams is greatly while the rotation angle of the footings is small.

When surface fault displacement acts on the structure over half of its length, the structure starts being lifted, with the end of the displacement as the center of the lift. As the displacement grows, the entire structure is lifted as shown on the left side of Fig. 9 (e) and rotates about the end of the displacement as shown in Fig. 9 (f).

As the one-span, rigid-frame viaduct is shorter and weighs less than the multiple-span viaduct, it starts lifting with even a slight surface fault displacement and rotates slowly. As the viaduct weighs far less and is far shorter than the other types, the section force of its horizontal members is far smaller than the other types.

4. Conclusion

To clarify how rigid-frame viaducts behave in response to vertical surface fault displacement, two-dimensional static push-over analyses were conducted on three types of rigid-frame viaducts: the first with underground beams, the second without underground beams and a third type especially
The above findings suggest that the one-span, rigid-frame viaduct devised for the analysis (Type 3) sustains far less damage than the multiple-span, rigid-frame viaducts.

Further studies will need to be done on the impact of inertial forces as well as on the modes of surface fault displacement input.

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