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Behavior of Rigid-Frame Viaduct as Affected by Fault-Induced Ground Deformation

A. Hino[(1)], Y. Murono[(2)]

[(1)] *Researcher, Center for Railway Earthquake Engineering Research, Railway Technical Research Institute, hino.atsushi.44@rtri.or.jp*
[(2)] *Director, Center for Railway Earthquake Engineering Research, Railway Technical Research Institute, murono@rtri.or.jp*

Abstract

The 1999 Kocaeli earthquake in Turkey and the 1999 Chi-Chi earthquake in Taiwan indicated the horror of surface fault displacement. Regarding the surface fault displacement, its value is difficult to predict and it can inflict devastating damage to structures. Therefore, the structures should ideally be designed and built in ways that provide protection from damage by surface fault displacement. However, for linear structures such as railway structures, it may be impossible to avoid building directly above a fault. In those cases, it is necessary to consider the impact of surface fault displacement which is taken as an earthquake-associated event, in addition to the actions considered in a general seismic design.

While many studies have covered the behavior of bridges when impacted by surface fault displacement, far fewer such studies have been conducted on rigid-frame viaducts, with the result that the behavior of these viaducts has been unclear. Therefore, this study looks at how rigid-frame viaducts would behave when impacted by surface fault displacement and, based on the findings, effective countermeasures are proposed.

In our study, static nonlinear analysis was conducted on rigid-frame viaduct models composed of lumped beam-spring elements in which the viaducts were subjected to surface fault displacement to clarify the relationship between various magnitudes of displacement input and the models' stress resultants and deformation. It was found that the impact of surface fault displacement can be reduced by simplifying the structure subjected to displacement; here, "simplifying" means reducing the number of spans and integrating the foundations. By simplifying a viaduct, its collapse can be better controlled upon surface fault displacement.

Keywords: Surface Fault Displacement, Rigid-Flame Viaduct, Static Nonlinear Analysis, Spread Foundation

1. Introduction

Surface fault displacement is known to inflict massive damage to civil engineering structures as exemplified by the 1999 Kocaeli earthquake in Turkey and the 1999 Chi-Chi earthquake in Taiwan[1][2][3]. Surface fault displacement is unique in that its magnitude at the ground surface level is difficult to predict and it can inflict massive damage to structures. In the Chi-Chi earthquake, surface fault displacement of up to 10 m was recorded[2][3]. In Japan, the largest displacements observed since the Meiji era are 8.0 m in the horizontal direction and 4.0 m in the vertical direction, both caused by the 1891 Nobi earthquake, and major surface fault displacements average 2.6 m in the horizontal direction and 1.7 m in the vertical direction[4].

Engineering concepts that have been proposed to mitigate damage caused by surface fault displacement to civil engineering structures include "avoid," "follow" and "absorb" displacement; the options to be taken depend on the degree of difficulty in coping with displacement. [5]. In the case of railway structures designed for tracks that are linear, it is often difficult to avoid displacement and some structures need to be built above or near a fault. Therefore, seismic designing must take into account how to follow or absorb surface fault displacement in the event of an earthquake. The design standards for railway structures and commentary (on seismic design) [4]. specify easy-to-restore embankments and bridges with widened girder seats[6]. for structures being built above a fault. both of these measures belong to the "follow displacement" concept. Currently, most of those railway structures that can be affected by surface fault displacement are designed based on these concepts.

In Japan, many studies have covered the safety of bridges when they are impacted by surface fault displacement, discussing the correlation between the magnitude of displacement and the damage done to the foundations as well as design approaches for mitigating structural damage[5] [7] [8] [9] [10]. With this background, the present study looked at how rigid-frame viaducts, which are widely used as bridges, and spread foundations, which are a widely used type of foundation although not well studied, would behave when impacted by surface fault displacement. Rigid-frame viaducts are one of the most widely used types of railway viaducts; they have a higher degree of indeterminacy than bridges and, compared with girder viaducts, are harder to construct but more cost-effective[11].

In our study, static nonlinear analysis was conducted on three types of rigid-frame viaducts subjected to surface fault displacement and their behavior was confirmed. The three types of models used were a rigid-frame viaduct with underground beams, a rigid-frame viaduct without underground beams and a single-span, overhang rigid-frame viaduct considered to withstand surface fault displacement more effectively than the other two. The analysis aimed to grasp the magnitude of impact on the viaducts from surface fault displacement and did not consider the impact of associated inertial force. The impact of inertial force has usually been considered in seismic designing, and it has been found that structural failure from inertial force can be effectively prevented by appropriately arranging reinforcing bars. In an actual earthquake, however, it is considered that structures are subjected to surface fault displacement and surface-vibration-caused inertial force at almost the same time. Thus, structural behavior in this particular situation must be clarified in a future study.

2. Conditions for the analysis

2.1 Setting types of 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 existence or otherwise of underground beams as the parameters. These models are outlined in Fig.2[12].

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

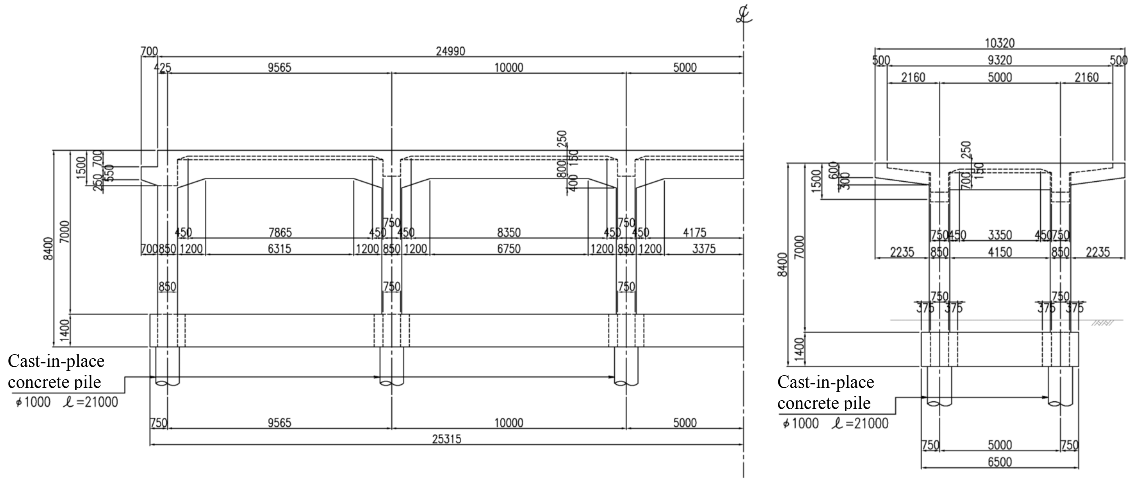
Type 1 and Type 2, both widely used types of rigid-frame viaduct, have Gerber girders at both ends. Type 3, devised especially for our analysis, has fewer spans to reduce the stress resultants and overhanging ends to eliminate the risk of bridge girder fall.

The reference viaduct shown in Fig.1 used 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

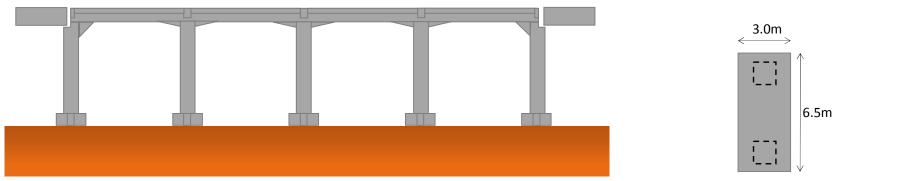
The magnitude of surface fault displacement is a function of many variables including the scale and depth of the fault and the thickness of the alluvium, and must be set carefully when used for seismic designing of structures[4]. In our analysis, the magnitude of surface fault displacement to be applied to the models was set to 3.0 m for the following reasons: data on surface fault displacement observed in the past in Japan[13] showed that in earthquakes of around Mw 7.5, displacement exceeding 3.0 m was measured only at around 30% of the observation sites while displacement exceeded 10 m at some of the other sites; and that in earthquakes of around Mw 7.0, displacement reached 3.0 m only at several percent of the observation sites.

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



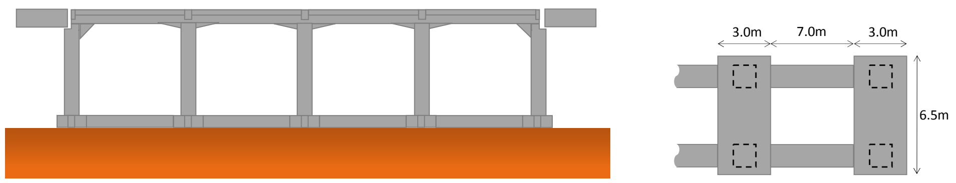
(a) Longitudinal view (b) Lateral view (center)

Fig.1 — General views of the structure used as the basis for developing the three analytical models



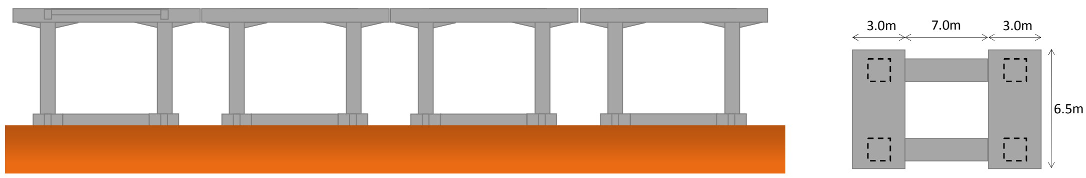
(a-1) General view of viaduct (a-2) Top view of foundations

(a) Type 1: Viaduct without underground beams



(b-1) General view of viaduct (b-2) Top view of foundations

(b) Type 2: Viaduct with underground beams



(c-1) General view of viaduct (c-2) Top view of foundations

(c) Type 3: Single-span viaduct

Fig.2 — Rigid-frame viaducts for analysis

3. Static nonlinear analysis of the impact of surface fault displacement

3.1 Analytical models and methods

Two- and three-dimensional static nonlinear analyses were conducted on the three different types of rigid-frame viaduct. The two-dimensional analysis considered geometric nonlinearity.

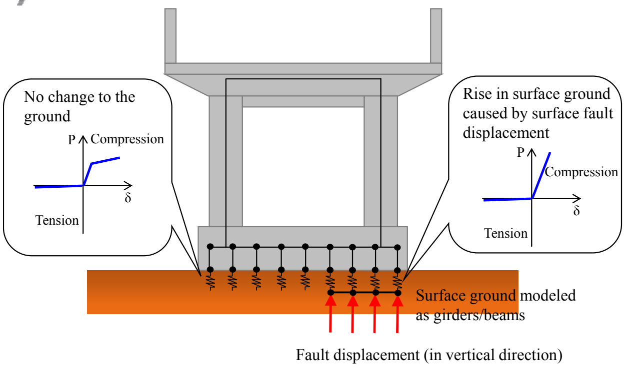


Fig.3 — Analytical modeling

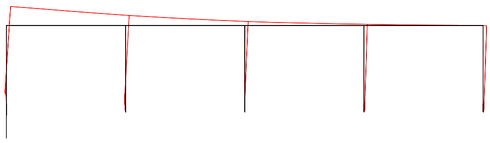
Table 1 — Cases of surface fault displacement input

(a) Lateral input

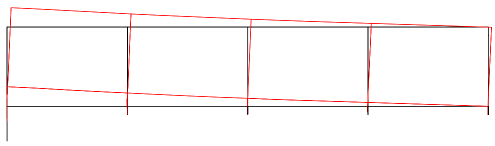
	Fault displacement input width (m)
CaseC1	0
CaseC2	0.8
CaseC3	1.7
CaseC4	2.5
CaseC5	3.3
CaseC6	4.1
CaseC7	4.9
CaseC8	5.7
CaseC9	6.5

(b) Longitudinal input

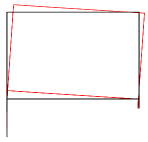
	Fault displacement input width (m)
CaseL1	0
CaseL2	10
CaseL3	20
CaseL4	30
CaseL5	40



(a) Type 1 Case L1: Max. displacement 3.020 m



(b) Type 2 Case L1: Max. displacement 3.002 m



(c) Type 3 Case L1: Max. displacement 3.499 m

Fig.4 — Maximum displacements in two-dimensional analysis

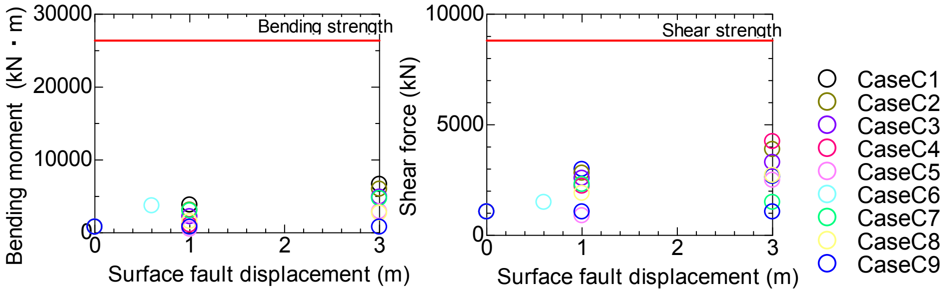
The analytical models were composed of beam-spring elements arranged in both the longitudinal and lateral directions of the viaduct. The columns and beams were modeled as linear members, while the foundations and ground were modeled as nonlinear, interacting springs. These springs were modeled as bilinear springs representing the resistance of the ground under the footings in the vertical and horizontal (shearing) directions. The spring constant and upper limit for these springs were calculated according to the design standards for railway structures and commentary (on foundations) [14].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 that are 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 can lead to underestimation of the stress resultants of columns and beams.

On each of the models, analysis was conducted for a number of cases while varying the magnitude of surface fault displacement input as shown in Table 1. In the lateral input analysis of displacement, the 6.5-m-long footings were divided into eight segments and the input width was increased stepwise by around 0.8 m starting from one end of the footings for a total of nine cases. In the longitudinal input analysis of displacement, the input width was increased stepwise by the intercolumn distance for a total of five cases.

For each step, the models were subjected to displacement of 0.25 mm 12000 times for a total displacement of 3.0 m.

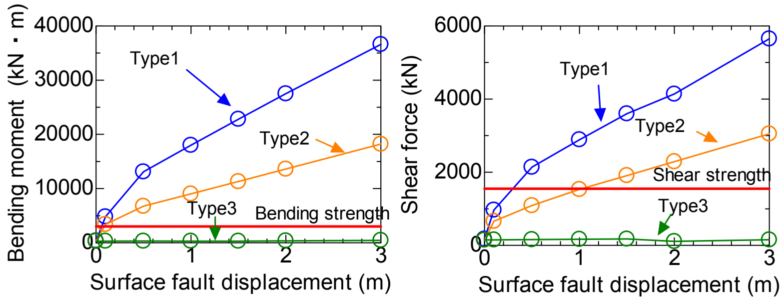
3.2 Two-dimensional analysis

Two-dimensional analysis was conducted on the models to grasp the relationship between the surface fault displacement, the stress resultants of the columns and beams and the rotation angle of the foundations.



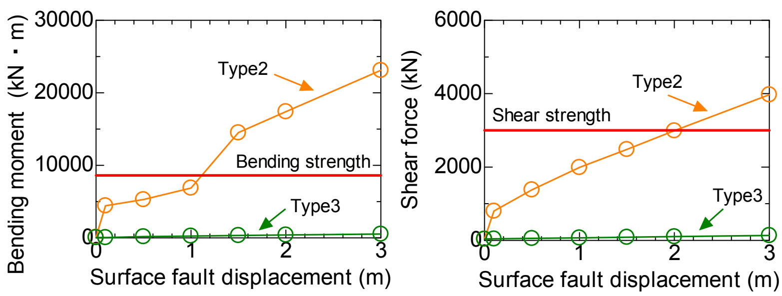
(a) Bending moment (b) Shear force

Fig.5—Distribution of stress resultants of the footings (in the lateral input analysis)



(a) Bending moment (b) Shear force

Fig.6—Distribution of stress resultants of the upper beams (in the longitudinal input analysis)



(a) Bending moment (b) Shear force

Fig.7—Distribution of stress resultants of the underground beams (in the longitudinal input analysis)

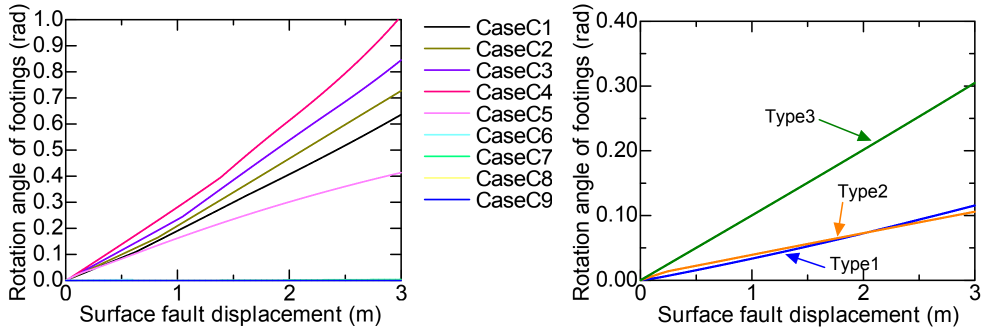
Fig.4 shows examples of the models' displacement when subjected to longitudinal input only at the end of the model (Case L1).

(1) Stress resultants of horizontal members

Horizontal members were examined for the relationship between surface fault displacement and stress resultants. Horizontal members specifically refer to the footings in the lateral input analysis of displacement and the upper and underground beams in the longitudinal input analysis of displacement.

Fig.5 shows the surface fault displacement and the stress resultants of the footings in the lateral input analysis of displacement. The figure also shows the flexural yield strength Myd and shear strength Vyd to indicate the limit. As shown in Fig.5, the stress resultants of the footings did not exceed the flexural yield strength or the shear strength with a surface fault displacement of 3.0 m regardless of where the displacement was applied.

Fig.6 shows the surface fault displacement and the upper beams' stress resultants for Type 1, Type 2 and Type 3 in the longitudinal input analysis of displacement. The figure also shows the flexural yield strength Myd and shear strength Vyd of the upper beams to indicate the limit. The stress resultant values for each type shown in Fig.6 are the maximum values obtained from among the various cases with different input locations as detailed



(a) Lateral input analysis (b) Longitudinal input analysis

Fig.8－Distribution of rotation angle of the footings

in Table 1. As shown in the figure, with Type 1 and Type 2, the bending moment exceeded the bending strength even with a small displacement. The shear force followed a similar pattern, exceeding the shear strength at a displacement of around 0.3 m with Type 1 and at a displacement of around 1.0 m with Type 2. With Type 3, the stress resultants were much smaller than those of Type 1 and Type 2, staying below the bending strength and the shear strength even at a displacement of 3.0 m.

Fig.7 shows the surface fault displacement and the underground beams' stress resultants for Type 2 and Type 3 in the longitudinal input analysis of displacement. The figure also shows the flexural yield strength Myd and shear strength Vyd of the underground beams to indicate the limit. The stress resultant values for each type shown in Fig.7 are the maximum values obtained from among the various cases with different input locations as detailed in Table 1. As shown in the figure, with Type 2, the bending moment exceeded the bending strength when surface fault displacement exceeded 1.0 m while the shear force exceeded the shear strength when displacement exceeded 2.0 m. With Type 3, as with the upper beams, both the bending moment and shear force remained at a minimum, never exceeding the limit.

The above results indicate the possibility that footings meeting the current seismic standards for the arrangement of reinforcing bars would not be damaged when impacted by surface fault displacement of 3.0 m. On the other hand, the results indicate that upper and underground beams like those in Type 1 and Type 2 would be unlikely to avoid damage from displacement just by the arrangement of reinforcing bars. It was also indicated that single-span, rigid-frame viaducts like the one in Type 3 would generate minimal stress resultants and therefore would highly likely avoid damage from displacement.

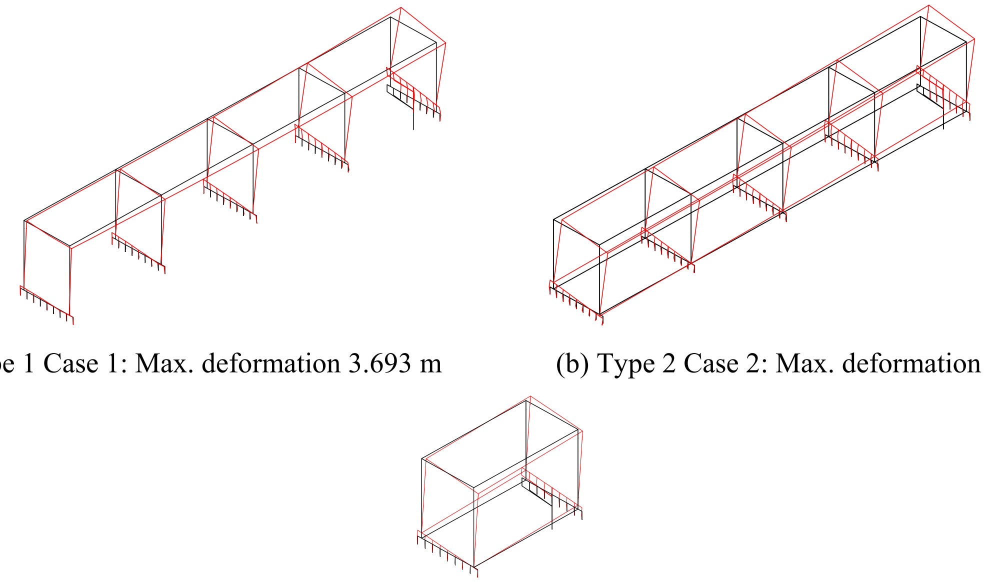
(2) Response of the foundations

The foundations' response to surface fault displacement input was examined by looking at the magnitude of displacement and the rotation angle of the footings for each input location.

Fig8 (a) shows the surface fault displacement and the footings' rotation angle from the lateral input analysis. As indicated here, a viaduct could easily be pushed up when more than half the length of the footings receives displacement input like in Case C6. Where a rigid-frame viaduct would not be pushed up, a maximum rotation of 1.0 rad could be expected with a displacement input of 3.0 m.

Fig8 (b) shows the maximum surface fault displacement and maximum rotation angle of the footings for Type 1, Type 2 and Type 3 from the longitudinal input analysis of displacement (Case L1 to L5). As shown in the figure, the rotation angle of Type 1 and that of Type 2 are nearly the same with the maximum being around 0.1 rad. The maximum rotation angle of Type 3 is around 0.3 rad, about three times the angle for Type 1 and Type 2.

In the analysis, surface fault displacement input of 3.0 m caused the foundations to rotate 0.1 to 0.3 rad, which is fairly large. The rotation angle of Type 3 is much larger than that of Type 1 and Type 2, which can be explained as follows: Type 1 and Type 2 are 4-span structures while Type 3 is a single-span structure, and this difference in longitudinal distance caused Type 3 to rotate at a much larger angle than the other models. The rotation angles measured in the analysis are extremely large considering that 0.03 rad is the maximum permissible rotation angle for foundations in the design standards for railway structures and commentary [14].



(a) Type 1 Case 1: Max. deformation 3.693 m

(b) Type 2 Case 2: Max. deformation 3.421 m

(c) Type 3 Case 3: Max. deformation 4.114 m

Fig.9 — Examples of maximum deformation from three-dimensional analysis

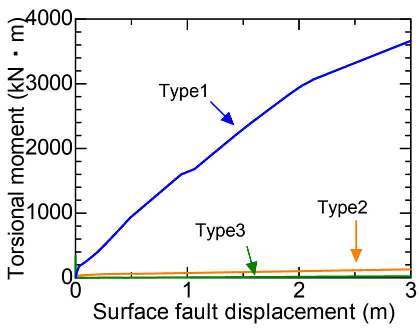


Fig.10 — Relationship between surface fault displacement and upper girder's torsional moment (in the longitudinal input analysis)

3.3 Three-dimensional response analysis

Three-dimensional analysis was conducted on the models to clarify the relationship between surface fault displacement and the torsional moment of the upper beams. Fig.9 shows examples of the longitudinal deformation of each model in Case L1.

(1) Torsional moment of the upper beams

The upper beams were examined for the relationship between surface fault displacement and torsional moment. Fig.10 shows the relationship between surface fault displacement and the upper beams' torsional moment for Type 1, Type 2 and Type 3 from the longitudinal input analysis. The figure also shows the maximum torsional moment for each type resulting from the various displacement input locations as summarized in Table 1. As shown in Fig.10, Type 1 generated a much greater torsional moment than the other models. This indicates that underground beams like those in Type 2 and Type 3 help greatly reduce the torsional moment of upper beams.

4. Summary

Two- and three-dimensional static nonlinear analyses were conducted on three types of rigid-frame viaducts subjected to surface fault displacement and their behavior was observed. The three types of models used were a rigid-frame viaduct with underground beams, a rigid-frame viaduct without underground beams and a single-span, overhanging rigid-frame viaduct considered to withstand surface fault displacement more effectively than the other two.

From the analyses, the following was found. The footings were affected more greatly by surface fault displacement than the upper and underground beams. Type 2 with underground beams was less damaged than Type 1 without underground beams by surface fault displacement. Type 3, the single-span model, was much less damaged than the other models, except for the foundations, which were more greatly deformed than the other models.

While the foundations of Type 3 would be substantially deformed by surface fault displacement, its members could be made to sustain less damage, or “absorb” damage, through relatively minor modifications such as rearranging the reinforcing bars. The foundations could be considered capable of “following” displacement if their deformation was accepted on the condition that the viaduct’s members were not damaged. Reducing the damage to members helps prevent the worst scenario where the destruction of beams and other members leads to the destruction of tracks, causing trains to fall. Capable of “following” or even “absorbing” displacement, Type 3 could be an effective countermeasure against surface fault displacement.

Our future study will include such subjects as the impact of inertia force and input modes of surface fault displacement.

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