Development of Dead Weight Compensation Device for Improving Anti-catastrophe Performance of Viaducts

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Railway structures may be severely damaged if the intensity of an earthquake is beyond the design motion. Even in this situation, significant loss of life and long-term suspension of train operations could be avoided if complete collapse of the structure is prevented. This capacity is referred to as “anti-catastrophe” in Japanese design standards. In order to achieve this capacity, a new “dead weight compensation” device is proposed. The dynamic loading tests are conducted using a shaking table, on which a viaduct model with the device is mounted. It was confirmed that the proposed device was capable of preventing total collapse of the specimen under extreme motion.

Keywords: dead weight compensation system, anti-catastrophe performance, shake table tests

1. Introduction

Resilience engineering has been recognized as a marked paradigm shift from ordinary safety engineering and reliability engineering to mitigate unwanted outcomes, injuries, and losses due to uncertainties [1, 2]. Resilience is defined as the intrinsic ability of a system to adjust its functioning prior to, during, or following changes and disturbances, so that it can sustain required operations under both expected and unexpected conditions.

In earthquake engineering, design codes have been repeatedly revised in the light of results from structural damage surveys and ground motion records observed during and after several devastating earthquake events [3]. In order to possibly end such endless revision of seismic codes based on unexpected damage and mitigating actions, a paradigm shift built on the concept of resilience engineering is necessary [4, 5, 6]. In this study, it is primarily admitted that the devastating damage of structures could occur due to unexpectedly large ground motion despite possessing sophisticated knowledge from historical earthquake events relevant to seismic design. Even in this situation, however, reducing human casualties as well as keeping work places clear for quick recovery is possible if total collapse of a structure can be securely prevented.

In order to achieve the performance, authors have proposed a new “Dead Weight Compensation system,” (hereafter, DWC) for a viaduct as shown in Fig. 1(a)[4]. This paper describes the fundamental concept underlying the proposed system and large-scale verification tests using shaking table.

2. Concept of the proposed DWC system

This section briefly describes the design concept behind the DWC device: to adapt the DWC for use on real structures, a reinforced-concrete (RC) rigid frame viaduct was selected as a target structure, given the large number of viaducts in use for both railways and road structures. Figure 1(b) shows the typical nonlinear behavior of a viaduct. In general, such viaducts are designed against designated design motions to ensure that damage of the structure is sufficiently small enough to allow rapid repair after earthquake. Verifications are made by confirming that the response displacement of a structure is restrained below the maximum resisting level (Point (M) in Fig. 1(b)). A structure would still be safe enough to avoid total collapse, even if the response slightly exceeds maximum resisting displacement.

However, a structure gradually or rapidly loses its resistance capacity and goes into total collapse if the induced earthquake exceeds the predetermined design level and vertical columns are severely damaged. The DWC was intended to be effective in such circumstances to prevent total collapse. Figure 1(a) shows an overview of the proposed DWC system. As shown in the figure, supplemental columns are installed in parallel with normal columns. This DWC column prevents the total collapse of a viaduct by holding the vertical weight of the slab even if normal columns are fully destroyed. Figure 1(c) shows schematically the desirable distribution of the vertical weight of the slab to both ordinal and DWC columns. As illustrated in the figure, the DWC column would gradually replace the vertical support function of the normal column, in line with damage to normal columns.

In order to achieve this type of performance, the DWC column should be designed to be strong enough to endure the vertical dead weight of the slab. In addition, resisting forces against the horizontal inertial force of the slab need to be suppressed to a significantly small extent to prevent unexpected damage of the DWC column that might result in the loss of the vertical support function. In order to sat-
isfy these conflicting demands, sliding material with a low friction should be employed between the top of the DWC column and the slab.

3. Experimental verification

3.1 Test setup

The effectiveness of the proposed device was investigated through shaking table tests. In the series of tests, a viaduct model shown in Fig. 2 was constructed on the table and excited repeatedly until it came to a complete collapse. The proposed DWC columns were also employed as specimens as illustrated in Fig. 2. The effectiveness of the proposed system was confirmed by checking whether the DWC column successfully supported the slab and prevented the total collapse in the case of strong motion.

As shown in Fig. 2, the rigid frame model consisted of a total of eight reinforced concrete columns, a slab and a foundation. The size of the slab was 2200 mm in width, 4700 mm in depth and 500 mm in height, and was supported by four normal RC columns. The size of each column was 200 mm in width, 200 mm in depth and 1400 mm in height, with reinforcing bars of 8-D10 (SD295). This specimen was designed to be approximately 1/4 of a real railway viaduct. The DWC columns were allocated at each corner of the slab. The dead weight on the slab was added by loading it with a stack of steel blocks. Consequently, the section stress on each normal column was 1.72 N/mm². According to a preliminary static analysis, the yielding coefficient and maximum resistance displacement of the viaduct were 0.4 and 34.1 mm, respectively.

3.2 The DWC column and device

Figure 3 shows the details of the DWC column. The specifications of the DWC column were identical to that of those of a normal column to ensure resistance against vertical load. On the top of DWC column, Teflon was attached to the concrete column. In addition, a steel plate was attached to the bottom of the slab. The horizontal reaction force between the DWC column and the slab was restricted to a small extent due to the small friction coefficient between Teflon and steel plate (approximately 0.1). The DWC column will not be severely damaged due to the horizontal inertial force from the slab even after the vertical weight of the slab was completely induced to the DWC columns.

3.3 Measurement and excitation

Measurements were made of the absolute accelerations of the slab and table as well as relative displacement between the slab and table in the horizontal and vertical directions. Moreover, multi-directional load cells were embedded in-between columns and the DWC device to measure reacting forces with respect to the vertical and horizontal directions. See Fig. 2 for the distribution of sensors.

The specimen was excited in a transverse direction using a Level-2 Spectrum I acceleration for a G3 soil condition. This waveform is a general surface motion in good soil conditions caused by an inter-plate earthquake designated in the Japanese railway design standard. This motion was selected because of its long duration time, and the repetitive motions could be induced in the viaduct model. The time scale of the waveform was compressed to 1/2 of the original earthquake to meet the law of similarity.

In the series of tests, maximum acceleration of the waveform was increased gradually from 100 gal (No.1) to 1300 gal (No.13). After test No.13, moderated acceleration (800 gal) were induced assuming the aftershock. All test conditions carried out are shown in Table 1.
4. Test results and discussions

4.1 Damage of the specimen

Figure 4(a) is a snapshot of the specimen after completion of all tests. Figure 4(b) and 4(c) compare the bottoms of piers with respect to the normal RC column and the DWC column. Figures 4(a) and 4(b) show that the normal columns were severely damaged and inclined due to the buckling of reinforcing bars and crash of core-concrete. Nevertheless, the specimen did not collapse completely because the vertical weight of the slab was supported by the supplemental DWC columns. In addition, as can be observed in Fig. 4(c), the DWC column was almost intact since the sliding device at the top of the column moderated the horizontal forces from the slab.

Table 1 Test condition

| TestNo. | Max.Acc. | TestNo. | Max.Acc. |
|---------|----------|---------|----------|
| 1       | 100 gal  | 9       | 1100 gal-1 |
| 2       | 200 gal  | 10      | 1100 gal-2 |
| 3       | 300 gal  | 11      | 1100 gal-3 |
| 4       | 400 gal  | 12      | 1100 gal-4 |
| 5       | 500 gal  | 13      | 1300 gal  |
| 6       | 600 gal  | 14      | 800 gal-1 |
| 7       | 800 gal  | 15      | 800 gal-2 |
| 8       | 1000 gal |         |          |
4.2 Behavior of the specimen and columns

Figure 5 illustrates the hysteretic relationship between inertial forces and the horizontal displacement of the slab. The displacement of the slab is relative to the shaking table. An inertial force is given by multiplying measured acceleration of the slab by its weight. It was found that the resisting force decreased to almost half of maximum force after test No.11 was completed, due to damage to the normal columns. Nevertheless, the specimen underwent several motions since the DWC columns took over the vertical support of the slab and prevented the total collapse of the specimen. As seen in the figure, the hysteretic relationship after test No.11 test shows a friction-type behavior due to the sliding between the Teflon and the slab.

Figure 6 shows the relationship between the horizontal and vertical displacements of the slab. The negative value of the vertical axis indicates the settlement of the slabs. Figure 6 also shows that the slab was lifted and detached from the DWC column during test No.1 through to test No.10, due to the extrusion of the reinforcing bars. After test No.11, however, the slab settled because of buckling in reinforcing bars. Nevertheless, the DWC columns successfully supported the vertical weight of the slab and restrained the settlement of slab down to -3 mm despite the increase in horizontal displacement.

These results confirm that the proposed DWC device is an effective support for the vertical weight of a viaduct when its normal columns are severely damaged, thereby preventing the total collapse of the structure.

4.3 Effectiveness of the proposed DWC column

Figure 7 shows the vertical loads of all DWC columns as well as the residual vertical and horizontal displacements of the slab in the tests. The vertical loads and residual displacements were measured at the end of each test. In addition, the vertical loads of Fig. 7 are expressed as percentiles, a ratio of the vertical load supported by all DWC columns to the total weight of the slab. It was found that the vertical weight of the slab gradually shifted to the DWC columns after test No. 11, where there was a concurrent drastic increase in horizontal residual displacement. This suggests that the normal columns were severely damaged and lost their resistance capacity following test No. 11. It was noted, however, that the vertical residual displacement did not increase since the DWC columns supported the slab weight. It was also found from tests No.12...
through No.15 that the DWC columns kept supporting the slab stably and replaced the function of normal columns, thereby preventing the total collapse of the specimen.

It was also found from Fig. 7 (a) that approximately 20% of the total weight was induced to the damaged normal columns after all tests were finished. It follows that the residual supporting capacity of damaged normal columns could be taken into account in designing the DWC column, unless the normal columns were totally destroyed in extreme situations. According to the test, the amount of residual section stress capacity of the normal columns was 0.29 N/mm².

5. Conclusions

Railway structures may be severely damaged if the intensity of an earthquake is beyond the design motion. Even in this situation, significant loss of life and long-term suspension of train operations could be avoided if complete collapse of the structure is prevented. This capacity is referred to as “anti-catastrophe” in Japanese design standards.

In order to realize such a structure, this paper verified the efficacy of new “Dead Weight Compensation system,” that is intended to be installed on viaducts. In the system, supplemental DWC columns are installed in between the columns on a viaduct. In the case of unexpected motion taking place that is strong enough to destroy a viaduct, the DWC columns would successfully support the slab and prevent the total collapse of the normal columns.

A viaduct model was manufactured and excited using a large-scale shaking table. The model consisted of eight reinforced concrete (RC) columns, four of which were equipped with DWC columns. The maximum acceleration of the earthquake motion was gradually increased until the RC columns were severely damaged. It was verified through a series of tests that the DWC columns successfully underwent the vertical weight of slab and prevented the total collapse of the specimen. It consequently follows that the proposed DWC system has a potential as a promising countermeasure to realize structure with anti-catastrophe performance.

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References

[1] Bruenau M, Chang S E, Eguchi R T, Lee G C, O’Rourke T D, Reinhorn A M, Shinozuka M, Tierney K, Wallance W A, von Winterfeldt D, “A Framework to Quantitatively Assess and Enhance the Seismic Resilience of Communities,” Earthquake Spectra, Vol.19, No.4, pp.733-752, 2003.

[2] Hollangel E, Woods D D, Leveson N, Resilience Engineering – Concepts and Precepts, CRC Press, 2006.

[3] Ministry of Land, Infrastructure, Transport and Tourism (MLIT, supervised), and Railway Technical Research Institute (RTRI, compiled), Design Standard for Railway Structures and Commentary (Seismic Design), Maruzen, 2012 (in Japanese).

[4] Saitoh M, Murono Y, Motoyama H, Resilient Structural Systems for Earthquake Disaster Mitigation Using Collapse Direction Control Device, Proc. of the 4th International Symposium on Engineering, Energy and Environment, 8-10 November 2015, Thammasat University, Pattaya Campus, Thailand, 2015.

[5] Honda R, Akiyama M, Nozu A, Takahashi Y, Kataoka S, Murono Y, “Seismic Design for ‘Anti-Catastrophe’ – A Study on the Implementation as Design Codes–, Special Topics – Restoration and Recovery from the 2011 Great East Japan Earthquake,” Journal of JSCE, Vol. 5, pp.346-356, 2017.

[6] Cabinet Secretariat in Japan, Basic Act for National Resilience Contributing to Preventing and Mitigating Disasters for Developing Resilience in the Lives of the Citizenry, 2017.

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