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DEVELOPMENT OF THE DEAD WEIGHT COMPENSATION SYSTEM TO IMPROVE THE ANTI-CATASTROPHE PERFORMANCE OF A VIADUCT

A. Toyooka(1), H. Nunokawa(2), Y. Murono(3)

(1) Railway Technical Research Institute, Japan, toyooka.akihiro.58@rtri.or.jp
(2) Railway Technical Research Institute, Japan, nunokawa.hirokazu.82@rtri.or.jp
(3) Railway Technical Research Institute, Japan, murono.yoshitaka.51@rtri.or.jp

Abstract

The recent great earthquakes in Japan have reminded us that unanticipated earthquake and damage might take place that is beyond the estimation of current seismic design. Nevertheless, structure should be robust enough to prevent the catastrophic consequences even under unexpected great motions. This property is referred to as "anti-catastrophe" in the seismic designed standard for Japanese railway. However, only a few methods have found to realize the anti-catastrophe that is ready to be applicable to the real structures.

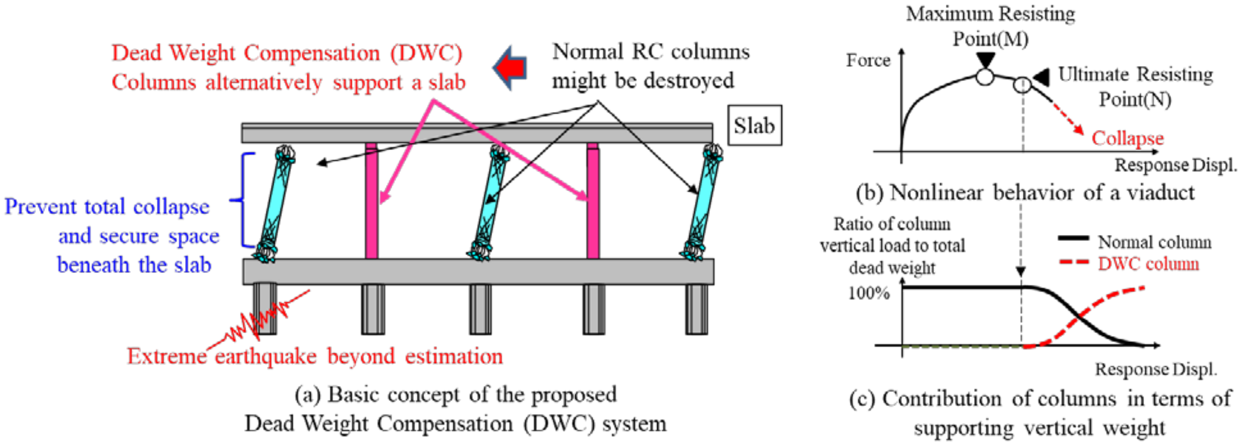
In order to overcome such a problem, this paper proposed a new "Dead Weight Compensation system," or DWC system that is intended to be installed to a viaduct. In the system, supplemental DWC columns are installed in between columns of viaduct. In case the unexpected strong motion takes place that is enough to destroy the viaduct, DWC columns would successfully support the falling slab and prevent the total collapse. In addition, top of the DWC columns are isolated from the slab to keep them intact under ordinal earthquakes.

The viaduct model was manufactured and excited using a large-scale shake table. The model consisted of eight reinforced concrete (RC) columns, four of which were equipped with DWC columns. The maximum acceleration of an earthquake motion was gradually increased until the RC columns were severely damaged. It was observed that the DWC columns have kept supporting the slab and prevented the collapse. It consequently followed that the proposed device be one of the promising countermeasures to realize the anti-catastrophe properties.

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. The resilience is defined as the intrinsic ability of a system to adjust its functioning prior to, during, or following changes and disturbances [1, 2], so that it can sustain required operations under both expected and unexpected conditions. In earthquake engineering, design codes have repeatedly been revised in accordance with the results of reconnaissance of structural damages and ground motion records observed in several devastating earthquake events [3]. To have a possible end to such endless revision of seismic codes based on unexpected damages and mitigating actions, a paradigm shift relying on the concept of resilience engineering is necessary[4,5] . In this study, it is primarily admitted that the devastating damage of structures could occur due to unexpected large ground motions despite possessing sophisticated knowledge from historical earthquake events pertinent to the seismic design. In this situation, however, reducing human casualties as well as keeping working places clear for quick recovery is possible if total collapse of structure is securely prevented. In order to attain the concept, a new "Dead Weight Compensation system," or DWC system shown in Fig. 1(a) was proposed in this research that is intended to be installed to a viaduct. In this paper, fundamental concept of the proposed system as well as large-scale verification tests using shake table are described.



(a) Basic concept of the proposed Dead Weight Compensation (DWC) system

(b) Nonlinear behavior of a viaduct

(c) Contribution of columns in terms of supporting vertical weight

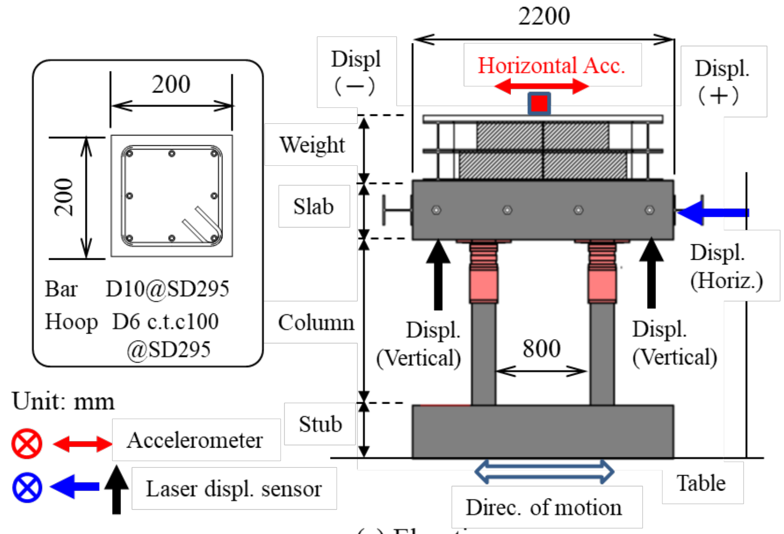
Fig.1 – Schematic of the proposed Dead Weight Compensation system

2. Concept of the Proposed DWC system

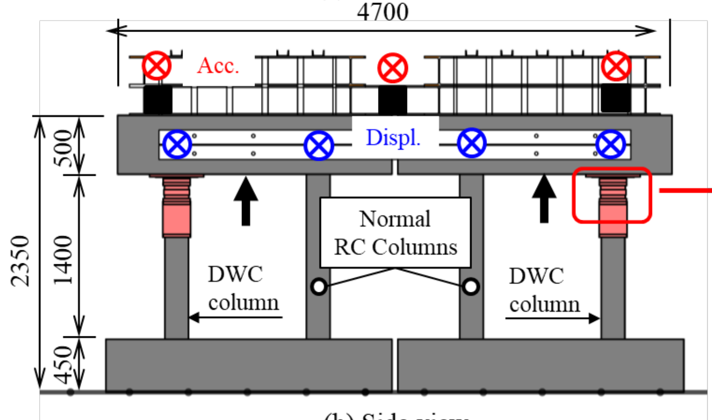
The design concept of the DWC device is summarized. In developing a new device to be applicable to the real structures, a reinforced-concrete (RC) rigid frame viaduct was selected as a target structure, since there are numerous number of viaducts in use for both railway and road structures. Fig. 1(b) shows a typical nonlinear behavior of a viaduct. In general, such a viaduct is designed so that structure would be resilient enough to enable rapid repair under designated design motions. It would be verified by confirming that response displacement of a structure is restrained below the maximum resisting level (Point M in Fig. 1(b)). Even if the response slightly exceeds maximum resisting displacement, a structure would be still safe enough to avoid a total collapse.

On the contrary, a structure gradually or rapidly loses its resisting capacity and goes to a total collapse if the induced earthquake exceeds the predetermined design level and vertical columns are severely damaged. The proposed device was intended to take effect under such a circumstance and prevent the total collapse. Fig. 1(a) shows the overview of the proposed DWC system. As shown in the figure, supplemental "Dead Weight Compensation“ 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.

Fig 1(c) shows schematic of the desirable distribution of the vertical weight of slab to both ordinal and DWC columns. As illustrated, the DWC column would gradually replace the function with respect to the vertical support of normal column. It should be also noted that the DWC column supports almost no vertical weight if



(a) Elevation



(b) Side view

Fig.2 – Test setup

Table 1 – Test condition

TestNo.	Max.Acc.	TestNo.	Max.Acc.
1	100gal	9	1100gal-1
2	200gal	10	1100gal-2
3	300gal	11	1100gal-3
4	400gal	12	1100gal-4
5	500gal	13	1300gal
6	600gal	14	800gal-1
7	800gal	15	800gal-2
8	1000gal		

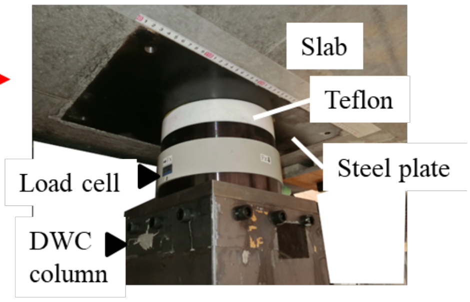


Fig.3 – Head of a DWC column

the response is below the maximum resisting level. This consideration is needed so as not for the supplemental DWC columns to disturb the behavior expected by an ordinal seismic design and avoid unexpected damage of the structure and DWC columns.

3. Experimental Verification

3.1 Test Setup

The effectiveness of proposed device was investigated by a shake table test. 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 in the specimen 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 under strong motions.

As shown in Fig.2, a rigid frame model consisted of total eight reinforced concrete columns, slab and foundation. The size of a slab was W2000 mm x D4700 mm x H500 mm, and they were supported by four normal RC columns. The size of a column was W200 mm x D200 mm x H1400 mm with reinforcing bars of 8-D10 (SD295). This specimen was designed so that it would be approximately 1/4 of real railway viaduct. The DWC columns were allocated at each corner of the slab. The dead weight on the slab was given by mounting a bunch of steel blocks on the slab. Consequently, section stress on each normal column was

1.72N/mm^2. According to the preliminary static analysis, yielding coefficient and maximum resisting displacement of the viaduct were 0.4 and 34.1 mm, respectively.

3.2 The DWC Column and Device

Fig.3 shows the detail of the DWC column. The specification of the DWC column was identical to that of the normal column shown in previous section, excepts that a Teflon device was embedded on top of the DWC column. In addition, the steel plate was attached to the bottom of slab. The horizontal reacting force between the DWC column and the slab was restricted to the small extent due to the small friction coefficient between a Teflon and a steel plate (approximately 0.1). It followed that 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 is totally induced to DWC columns.

3.3 Measurement and Excitation

For data acquisitions, absolute accelerations of slab and table as well as relative displacement between slab and table in horizontal and vertical directions were mainly measured. In addition, multi-directional load cells were embedded in-between columns and DWC device to measure reacting forces with respect to vertical and horizontal directions. See Fig.2 for 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 a good soil condition due to an inter-plate earthquake designated in the Japanese railway design standard. This motion was selected because of its long duration time, by which the repetitive motions would be induced to the viaduct model. The time scale of the waveform was compressed to 1/2 of the original one to meet the law of similarity.

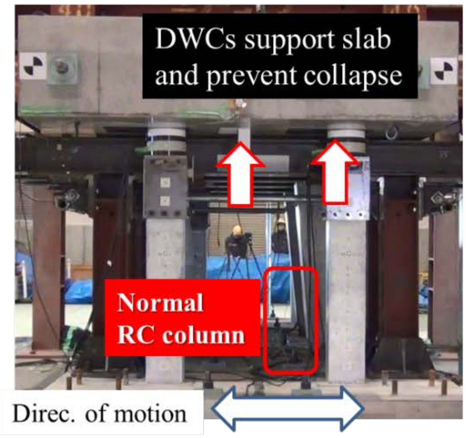
In the series of tests, maximum acceleration of the waveform was gradually increased from 100 gal (No.1) to 1300gal (No.13). After test No.13, moderated acceleration (800gal) were induced assuming the aftershock. All test conditions carried out are shown in Table 1.

3.4 Test Results and Discussions

Fig. 4(a) illustrates the snapshot of the specimen after all tests finished. Figs. 4(b) and 4(c) show comparison of bottom of piers with respect to the normal RC column and the DWC column. As shown in Figs. 4(a) and 4(b), normal columns were severely damaged and inclined due to the buckling of reinforce bars and crash of core-concrete. Nevertheless, the total collapse of the specimen did not take place since vertical weight of the slab was supported by supplemental DWC columns. In addition, as observed in Fig.4(c), only few damage was found in the DWC column since the sliding device on top of the column moderated a horizontal inertial force of the slab.

Fig.5 shows the vertical loads of all DWC columns as well as residual vertical and horizontal displacements of slab according to the tests. The vertical loads and residual displacements were measured at the end of each test. In Fig.5, vertical load are expressed in a percentile, ratio of vertical load supported by all DWC columns to the total weight of a slab. It is found that DWC columns begun supporting the slab at and after test No. 11, where the horizontal residual displacement was drastically increased accordingly. It implies that normal columns were severely damaged and lost their resisting capacity after No.11. It is, however, noted that the vertical residual displacement was not increased since the DWC columns supported the slab weight. It is also found that the DWC columns kept supporting the slab stably as an alternative to normal columns, and prevent the total collapse (tests No.12-No.15).

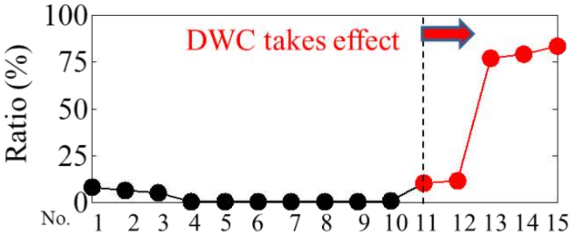
Fig.6 illustrates the hysteretic relations between inertial force and horizontal displacement of slab. The displacement of the slab is measured relative to the shake table. It is found that nonlinear behavior changed from a typical hysteresis of a RC viaduct to a friction-type loop after test No.11. It consequently follows that sliding between slab and Teflon on top of DWC column dominated the total nonlinear behavior.



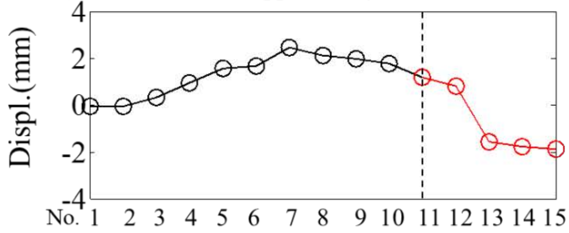
(a) Condition of the specimen after test No.15

(b) Bottom of normal column (c) Bottom of DWC column

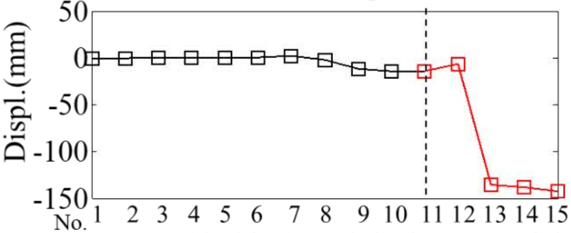
Fig.4 – General view of the specimen after tests



(a) Vertical load supported by all DWC columns



(b) Residual vertical displacement of slab



(c) Residual horizontal displacement of slab

Fig.5 – Vertical load distribution to DWC column and corresponding residual displacements

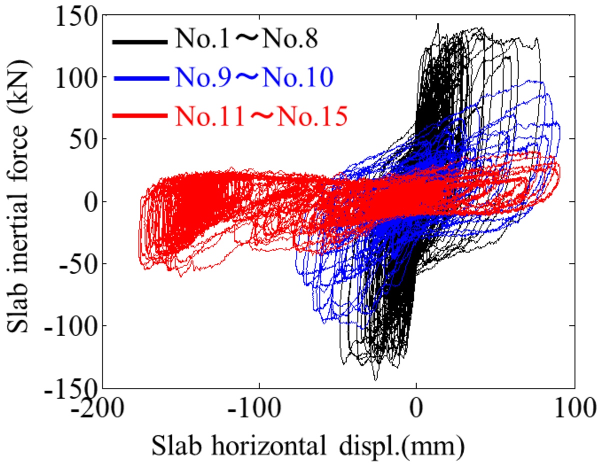


Fig.6 – Inertial force vs horizontal displ. of specimen

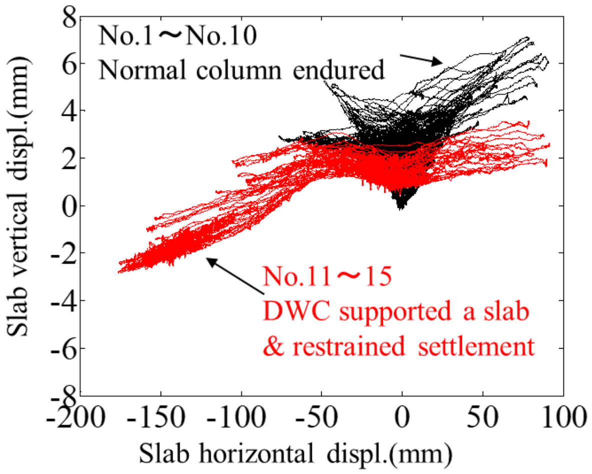


Fig.7 – Horizontal vs vertical displ. of specimen

Fig.7 shows the relation with regard to horizontal to vertical displacements. In the vertical axis, minus displacement indicates the settlement. As seen in Fig.7, DWC columns restrained a settlement of the slab down to -3mm regardless of the increase of horizontal displacement, say, damage of normal columns.

It was confirmed from aforementioned results that the proposed DWC device works effectively in terms of supporting a vertical weight of the viaduct after normal columns are severely damaged, by which the total collapse of the structure are prevented.

4. Conclusion

This paper proposed a new "Dead Weight Compensation system," or DWC system that is intended to be installed to a viaduct. In the system, supplemental DWC columns are installed in between columns of viaduct. In case the unexpected strong motion takes place that is enough to destroy the viaduct, DWC columns would successfully support the slab and prevent the total collapse.

The viaduct model was manufactured and excited using a large-scale shake table. The model consisted of eight reinforced concrete (RC) columns, four of which were equipped with DWC columns. The maximum acceleration of an earthquake motion was gradually increased until the RC columns were severely damaged. It was verified through series of tests that the DWC columns successfully undergone the vertical weight of slab and prevented the collapse under repetitive extreme motions. It consequently followed that the proposed device be one of the promising countermeasures to realize the anti-catastrophe properties.

5. Acknowledgements

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6. 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 (2003). A Framework to Quantitatively Assess and Enhance the Seismic Resilience of Communities. Earthquake Spectra, Vol.19, No.4, pp.733-752.

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

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

[4] Saitoh M, Murono Y, Motoyama H. (2015). 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.

[5] Honda R, Akiyama M, Nozu A, Takahashi Y, Kataoka S, Murono Y. (2017). 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.

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