ANALYTICAL STUDY ON BEHAVIOR OF RESTRAINING DEVICES INSTALLED IN BETWEEN CONSTRUCTION JOINTS OF PLAIN CONCRETE PIERS

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ABSTRACT

In Japan, plain concrete piers with no reinforcing bars built years ago for railway bridges are still in use. In an earthquake, these piers can suffer horizontal through cracking and resultant large residual displacement at the construction joint. As an aseismic countermeasure for plain concrete piers with construction joints, we developed a method for restraining excessive horizontal displacement that consists of a steel bar fixed in the lower concrete body below the construction joint and a gap between the steel bar and the upper concrete body above the construction joint. In developing the method, dynamic analysis techniques were considered desirable for evaluating the forces acting on the steel bars. However, only a limited number of proposed dynamic analytical models were capable of accurately evaluating the behavior of the upper concrete body above the construction joint. Given the above, sway-rocking models incorporating springs for simulating joint slipping, springs representing steel bars and springs for simulating joint rotation were used to evaluate the forces acting on the steel bars. Firstly, attempts were made using a sway-rocking model to simulate the results of shaking table tests of scaled plain concrete piers without steel bars. It was found that the proposed model demonstrated acceptable levels of reproducibility of the residual displacement observed in the tests. Secondly, response analysis was conducted on real plain concrete piers without steel bars and those with steel bars. It was found that the steel bars were effective in reducing horizontal displacement at the construction joint. Finally, an examination was made as to whether a difference in the size of the gap between the steel bar and the upper concrete body and/or the use of buffering material could have any influence on the forces working on the steel bar. It was found that increasing the bar-to-body gap contributed only slightly, while installing buffering material around the steel bar contributed greatly to the reduction of forces acting on the steel bar.

Keywords: Plain Concrete Piers; Construction Joint; Restraining Devices; Sway-rocking Model

1. INTRODUCTION

In Japan, plain concrete piers with no reinforcing bars built years ago for railway bridges are still in use and many of them are still in a healthy state. Typical damage of plain concrete piers in the past earthquakes includes horizontal through cracking at the construction joint and concrete flaking below the construction joint (Sugisaki et al. 2007, Kyushu kougyoudaigaku saigaichousadan 2004 etc.), as shown in Figure 1. The resultant large displacement of the construction joints might require major repair after the earthquake. Piers are seismically reinforced generally by means of reinforced concrete lining, but this increases the cross-sectional area of a pier. This might prevents river water from flowing smoothly and, in many cases, is opposed by river administrators from the viewpoint of disaster prevention. Given the above, a restraining devices using steel bars for aseismic effects that do not involve any increase in the pier’s cross-sectional area has been proposed. In the restraining method, each

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steel bar is fixed in the lower concrete body below the construction joint, while a gap is maintained between the upper concrete body above the joint and each steel bar to prevent excessive horizontal displacement. To grasp the behavior of plain concrete piers with broken construction joints during an earthquake and verify the effect of aseismic measures, shaking table tests were conducted using reduced-size models of plain concrete piers (Sakaoka et al. 2017). In the series of tests, the slipping and rocking behavior was measured, and it was confirmed that steel bars are effective for reducing displacement. Application of the restraining method to real piers requires the evaluation of forces applied to the steel bars. One possible solution is a static analysis technique whereby horizontal seismic factors are used for application to the upper concrete body above the construction joint and inertial forces are applied statically to the steel bars. However, static analysis techniques cannot evaluate the friction at the construction joints or the energy absorption due to yielding of the steel bars. It is therefore rational to use dynamic analysis techniques to evaluate the forces applied to the steel bars.

On a plain concrete pier with through cracking at the construction joint, the upper concrete body above the joint can be regarded as a rigid body. Kaneko et al. conducted a study on the seismic response of rigid bodies and presented experimental/analytical considerations on overturning limits and displacement of rigid bodies (Kaneko et al. 1996, Kaneko et al. 1997). In the development process of our restraining method, the forces applied to the steel bars had to be evaluated in addition to the overturning and slipping behavior of a rigid body. This made it necessary to create a model capable of representing all of these phenomena.

Given the above, in developing the restraining method, dynamic analysis techniques were employed to evaluate the effect of steel bars in plain concrete piers with construction joints using sway-rocking models incorporating springs for simulating joint slipping, springs representing steel bars and springs for simulating joint rotation. Firstly, we used a sway-rocking model to simulate the results of shaking table tests on reduced-size models of plain concrete piers without steel bars. We then conducted a response analysis on real plain concrete piers without steel bars and those with steel bars to find out whether the steel bars would be effective in reducing horizontal displacement at the construction joint. Finally, we examined whether a difference in the size of the gap between the steel bar and the upper concrete body and/or the use of buffering material could have any influence on forces working on the steel bar.

2. OUTLINE OF THE RESTRAINING METHOD

The restraining method is outlined below including its purposes. Figure 2 shows a general representation of the method (Sakaoka et al. 2017).

- The shape of the pier stays unchanged to prevent any impact in the downstream of the river.
- The steel bar type restraining devices are installed at construction joints, which have been shown by past disasters to be weak points, to restrain both displacement during an earthquake and residual displacement following an earthquake.
- The steel bar type restraining devices are a set of steel bars installed across the construction joints, with the bottom of the bars fixed onto the lower concrete body below the joint. A gap is maintained between the restraining devices and the upper concrete body above the construction joint.
joint to allow a certain degree of rocking and slipping at the joint to minimize the response to the foundation.

3. PROCEDURES OF ANALYSIS

Analysis was conducted on the models of plain concrete piers with construction joints used for shaking table tests (Sakaoka et al. 2017) and on real plain concrete piers. Figure 3 shows general views of the analysis objects. Since the analysis focused on the behavior of the upper concrete body above the construction joint, and the bearing foundation was not modeled.

![Diagram of analysis objects](image)

Figure 3. General views of objects to be analysed

Figure 4 shows the flow of the analysis. Firstly, analysis was conducted on the reduced-size model of plain concrete piers without steel bars for response displacement of the upper concrete body above the construction joint. The results were compared with those of the shaking table tests to verify the reproducibility, or validity, of the proposed model. While it was found that rocking of the upper concrete body was damped, the damping effect remains to be clarified. Therefore, the settings for damping were also evaluated for validity in comparison with the results of the shaking table tests. Secondly, response analysis was conducted on real plain concrete piers without steel bars and those with steel bars to find

![Flowchart of analysis](image)

Figure 4. Flow of analysis
out whether the steel bars would be effective in reducing horizontal displacement at the construction joint. Steel bars were modeled as nonlinear springs to factor in their yield, and evaluation was made based on whether or not the residual displacement was within an allowable range. The allowable range for residual displacement was set based on vehicle running safety during an earthquake, restorability after an earthquake and other criteria. Lastly, evaluation was made on how forces acting on the steel bars could be reduced, focusing on such methods as securing a wide gap between the steel bar and the upper concrete body and surrounding the steel bar with buffering material.

4. ANALYSIS FOR REPRODUCING OF THE RESULTS OF SHAKING TABLE TESTS

4.1 Outline of the Analytical Model

Figures 5 and 6 show the outline of the proposed analytical model to reproduce results of shake table tests. The model used for the analysis was a single-mass sway-rocking model with a spring representing friction at the construction joint and a spring representing rocking resistance. Their details are described in 4.2 and 4.3, respectively.

![Figure 5. Outline of the analytical model (test specimen)](image)

4.2 Modeling of Construction Joint Friction

To ensure its stability, the analysis did not examine static friction, and construction joint friction was represented by a bilinear spring, which had sufficiently high rigidity until the upper limit \( \tau_f \) of kinetic friction was reached and sufficiently low rigidity after \( \tau_f \) was reached. The kinetic friction coefficient and cohesion of construction joints were determined by element tests (Sakaoka et al. 2017) on test pieces used in the shaking table tests. The analysis assumed full contact and did not consider changes in contact area of the construction joint during rocking. Table 1 shows key specifications of the spring representing construction joint friction. To ensure the stability of the analysis, damping is set to small value enough not to affect the response is set in the horizontal direction.

![Figure 6. Analytical model (test specimen)](image)
Table 1. Key specifications of the spring representing construction joint friction.

<table>
<thead>
<tr>
<th>Item</th>
<th>Value</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weight of upper side of construction joint ( W ) [kN]</td>
<td>28.72</td>
<td></td>
</tr>
<tr>
<td>Kinetic friction coefficient on construction joint ( \mu )</td>
<td>0.61</td>
<td>Element test results</td>
</tr>
<tr>
<td>Cohesion on construction joint ( c ) [kN/m^2]</td>
<td>0</td>
<td>Element test results</td>
</tr>
<tr>
<td>First gradient of friction spring ( K_1 ) [kN/m]</td>
<td>( 1.00 \times 10^4 )</td>
<td></td>
</tr>
<tr>
<td>Maximum friction force ( \tau_f ) [kN]</td>
<td>17.52</td>
<td></td>
</tr>
<tr>
<td>Second gradient of friction spring ( K_2 ) [kN/m]</td>
<td>( 1.00 \times 10^{-3} )</td>
<td></td>
</tr>
<tr>
<td>Damping coefficient of horizontal dashpot ( C ) [kN-s/m]</td>
<td>( 1.00 \times 10^{-9} )</td>
<td></td>
</tr>
</tbody>
</table>

4.3 Modeling of Rocking

The upper concrete body above the construction joint resists rocking. Therefore, the rocking model was designed to incorporate a rotation spring to represent rocking resistance. The rocking resistance spring was modeled partly based on the study of Mutou (1966) as shown in Figure 7, which has sufficiently high rotational rigidity before being lifted, and declining rotational rigidity after being lifted until reaching the overturning limit. On the analytical model, the lower concrete body below the construction joint was represented by a horizontal plane. Key specifications of the rocking resistance spring designed for the analysis are shown in Figure 8.

The damping constant \( h_r \) of rocking at the construction joint was set to 0.03, a value considered capable of sufficiently reducing the response rotational angle and not exerting excessive impact on the response. The constant was then converted to a damping coefficient \( c_r \) (kN/(rad/s)) in an equation of motion for a single-degree-of-freedom system for the rotational direction and was set to 6.732 kN/(rad/s). The validity of the selected damping constant was evaluated by comparing the results obtained with and without the constant.

4.4 Input Seismic Motion and Other Analysis Conditions

The analysis of test pieces used in the shaking table tests was conducted at integration intervals of 1/1000 s. Level-2 Spectrum II motion for G2 ground (diluvial stratum) described in Railway Technical Research Institute (2012) adjusted so that its maximum acceleration corresponds to 600, 700, 800, 1000, 1200gal, which are the same input waveforms that had been used in the experimental study (Sakaoka et al. 2017), are used as input motions for the analysis. Numerical calculations were made using the Newmark-\( \beta \) method (\( \beta = 1/4 \)). Integration interval is set to 1/1000 s.

4.5 Results of the Analysis and Remarks

For each input acceleration used, response displacement waveforms were compared between the experiment and analysis. Shown here are comparisons in the time range of 10 to 25 s where the displacement was significant. As shown in (a) to (c) in Figure 9, there is a high degree of agreement in the trend of response displacement between the experiment and analysis up to the input acceleration of
800 gal. On the other hand, with the input accelerations of 1000 and 1200 gal, the direction of residual displacement differs between the experiment and analysis. Possible reasons for this include the following:

- The surface conditions of the test pieces were not necessarily uniform across all test pieces.
- The proposed analytical model did not factor in static friction.
- Each test piece had gone through multiple sessions in the shaking table tests, rendering surfaces that differed from what was assumed for the analysis.
- In the shaking table tests, input acceleration of 1000 gal caused significant concrete flaking below the construction joint, while the proposed model was designed without factoring in the effect of such flaking.

The results obtained with zero damping constant $h_r$ of rocking show continuing vibration even after the input acceleration became significantly small. On the other hand, the results obtained with a damping constant of rocking of 0.03 show that the vibration subsided as the input acceleration decreased. This indicates that allotting a damping constant leads to results that are closer to reality. Analyses were also conducted with a damping constant of 0.05, from which it was confirmed that there was no significant difference in the trend of rotational angle between a constant of 0.05 and that of 0.03. It was also found that there were only small differences in the response displacement between sessions conducted with damping and those without it. Considering this, the following remarks refer to the results obtained with a damping constant $h_r$ of rocking of 0.03.

Figure 10 shows a comparison between the experiment and analysis with regard to the peak response displacement of the center of gravity at around 12.4 s for different input accelerations. Figure 11 shows

![Figure 9. Comparison of response displacement waveforms for different input accelerations between the experiment and analysis](image-url)
a similar comparison of the residual displacement. The residual displacement is the average value over a period of one second from the end of the test. The data for input accelerations of 1000 and 1200 gal is presented only for reference purposes due to that the condition of the test pieces after the shaking differed from what was assumed for the analysis as described earlier. Figure 10 of the peak displacement shows that the trends of the results of the analysis and the experimental results agree. Figure 10 also shows that the results of the analysis put that of the experiment on the safe side, since it is safer to evaluate the response displacement largely to some extent when examining running safety of trains and restorability of structures. Figure 11 of the residual displacement shows acceptable levels of reproducibility of the analytical model. The absolute residual displacement shows acceptable levels of agreement between the experiment and analysis even with input accelerations of 1000 and 1200 gal, apart from the direction. With the above, the proposed analytical model can be considered capable of roughly reproducing the slipping and rocking behavior of plain concrete piers with construction joints.

![Figure 10. Displacement of the center of gravity at around 12.4 s](image1)

![Figure 11. Residual displacement](image2)

![Figure 12. Outline of the analytical model (real pier with and without steel bar)](image3)

5. RESPONSE ANALYSIS ON REAL PLAIN CONCRETE PIERS

5.1 Outline of the Analytical Model

The analytical model is basically the same as the one shown in Figure 5 that was used in the analysis for
reproducibility of the results of shaking table tests, but has an additional spring to represent a steel bar. Figure 12 shows the outline of the model to compose the analytical model shown in Figure 13. The analysis, which factored in the yield of a steel bar, was aimed at confirming that residual displacement was within an allowable range. While the allowable range for residual displacement is set based on vehicle running safety during an earthquake, restorability after an earthquake and other criteria, it was set to 20 mm in the analysis.

### 5.2 Modeling of Construction Joint Friction

The modeling was based on the same concept that was used for the analysis for reproducibility of the results of shaking table tests. Table 2 shows key specifications of the spring representing construction joint friction. The kinetic friction coefficient and cohesion of construction joints were determined by element tests (Sakaoka et al. 2017) on test pieces that were modeled after the construction joints of real piers.

<table>
<thead>
<tr>
<th>Item</th>
<th>Value</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weight of upper side of construction joint $W$ [kN]</td>
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</tr>
<tr>
<td>Kinetic friction coefficient on construction joint $\mu$</td>
<td>0.89</td>
<td>Element test results</td>
</tr>
<tr>
<td>Cohesion on construction joint $c$ [kN/m²]</td>
<td>2.3</td>
<td>Element test results</td>
</tr>
<tr>
<td>First gradient of friction spring $K_1$ [kN/m]</td>
<td>$7.89 \times 10^5$</td>
<td>$1.0 \times 10^5 \times 2266.9/28.72$</td>
</tr>
<tr>
<td>Maximum friction force $\tau_f$ [kN]</td>
<td>2043.82</td>
<td></td>
</tr>
<tr>
<td>Second gradient of friction spring $K_2$ [kN/m]</td>
<td>$1.0 \times 10^{-3}$</td>
<td></td>
</tr>
<tr>
<td>Damping coefficient of horizontal dashpot $C$ [kN-s/m]</td>
<td>$1.0 \times 10^{-9}$</td>
<td></td>
</tr>
</tbody>
</table>

### 5.3 Modeling of Steel Bar

Key specifications of the steel bar spring are shown in Table 3. The initial gradients and yield load of the steel bar spring were set based on the application of the yield stress obtained through the steel tensile test (Sakaoka et al. 2017) and the model shown in Figure 14 where a concentrated load was applied to the top end of the steel bar. Nonlinearity of the steel bar spring was modeled as a slip model shown in Figure 15 as plastic deformation of the steel bar was factored in on the hysteresis loop. The gap was set to 14 mm, which is the stagger limit with a maximum speed of 130 km/h, chosen from among the unequal displacements of tracks caused by earthquakes (Railway Technical Research Institute 2006).

### 5.4 Modeling of Rocking

The modeling was based on the same concept that was used for the analysis for reproducibility of the results of shaking table tests. Key specifications of the rocking resistance spring designed for the analysis are shown in Figure 16. The constant $h_i$ for the damping of rocking at the construction joint was set to 0.03 based on the analysis for reproducibility of the results of shaking table tests. The constant was then converted to a damping coefficient $c_r$ (kN/(rad/s)) in an equation of motion for a single-degree-of-freedom system for the rotational direction and was set to 3504 kN/(rad/s).
Table 3. Key specifications of the steel bar spring.

<table>
<thead>
<tr>
<th>Item</th>
<th>Value</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diameter of steel bar Φ [m]</td>
<td>0.22</td>
<td></td>
</tr>
<tr>
<td>Length of steel bar l [m]</td>
<td>0.35</td>
<td></td>
</tr>
<tr>
<td>First gradient of steel bar spring $K_1$ [kN/m]</td>
<td>$1.00 \times 10^{-4}$</td>
<td></td>
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<tr>
<td>Gap size [mm]</td>
<td>14</td>
<td></td>
</tr>
<tr>
<td>Second gradient of steel bar spring $K_2$ [kN/m]</td>
<td>$1.61 \times 10^6$</td>
<td></td>
</tr>
<tr>
<td>Spring force at the second break point $P_y$ [kN]</td>
<td>1385</td>
<td>Calculated from tensile test results of steel bars</td>
</tr>
<tr>
<td>Third gradient of steel bar spring $K_3$ [kN/m]</td>
<td>$1.00 \times 10^{-4}$</td>
<td></td>
</tr>
<tr>
<td>Number of steel bars</td>
<td>1, 2, 5</td>
<td></td>
</tr>
</tbody>
</table>

5.5 Input Seismic Motion and Other Analysis Conditions

The analysis of real piers was conducted at integration intervals of 1/10000 s. Level-2 spectrum II motion for G2 ground described in Railway Technical Research Institute (2012) was used as input motion for the analysis. Numerical calculations were made using the Newmark-β method ($\beta = 1/4$).

5.6 Results of the Analysis

Figure 17 and Figure 18 show the time history of the displacement of the concrete body at the center of gravity and that of a steel bar at the top end, for each of the following cases: with no steel bars, one steel bar, two steel bars and five steel bars of 220 mm in diameter. Figure 19 shows the hysteresis of the various numbers of steel bars. Figure 17 shows that with two steel bars of 220 mm in diameter installed, displacement stayed within the limit of 20 mm. Figure 19 shows that elastic design of the bar requires five steel bars of 220 mm in diameter and that designing can be rationalized by permitting the yield of steel bars. The maximum displacement of the center of gravity of the upper concrete body above the construction joint tends to be greater when steel bars are installed. This could be because the collision between the steel bars and upper concrete body helped promote rotation.

Figure 15. Slip spring

Figure 16. Key specifications of the rocking resistance spring

Figure 17. Time history of displacement of the upper concrete body’s center of gravity
6. MEASURES TO REDUCE FORCES ACTING ON STEEL BARS

As described in Section 5, residual displacement stayed within the limit when two steel bars of 220 mm in diameter were installed. On the other hand, it is desirable to use steel bars with a diameter as small as possible to improve construction efficiency. This led to the evaluation of the following measures to mitigate forces acting on the steel bars.

1) Adjusting the gap between the steel bar and upper concrete body
2) Surrounding the steel bar with buffering material

6.1 Effect of a Gap between the Steel Bar and Concrete Body

Analysis was conducted on the gap between a steel bar and the concrete body and its impact on forces acting on the steel bar, with the gap used as a parameter. In the analysis, evaluation was made on the magnitude of collision force acting on a steel bar with a diameter of 220 mm and, in light of the method used, the steel bar’s yield was not factored in. Figure 20 shows the plotted relationship between the gap size and the maximum force acting on the steel bar. It is found that that greater gaps result in weaker maximum forces acting on the steel bar. That is to say, if the gap were to be restricted to respect the limit (20 mm in this analytical study) of residual displacement, having a greater gap would only have a small effect on reducing the force acting on the steel bar.
6.2 Effect of a Buffering Material

Analysis was conducted on how the force acting on the steel bar would be affected by installing buffering material around the steel bar. The steel bar surrounded by buffering material was modeled by a spring representing the stiffness of the steel bar connected in series to a spring representing the stiffness of the buffering material. Figure 21 shows the analytical model of the steel bar surrounded by buffering material. The buffering material was modeled by a linear member, the stiffness of which was assumed to be 1/100 of the first gradient of the steel bar. The single steel bar used in the analysis was 220 mm in diameter. A comparison was made between the response values obtained with and without the buffering material. The thickness of the buffering material was not factored in, while the bar-to-body gap was set to 14 mm.

![Analytical model of a steel bar surrounded by buffering material](image)

Figure 21. Analytical model of a steel bar surrounded by buffering material

Figure 22 and Figure 23 respectively show the time history of the displacement of the upper concrete body at the center of gravity and that of the steel bar’s top end. Figure 24 shows the relationship between the force of the steel bar spring and the displacement. These results show that the installation of buffering material resulted in smaller response values and also kept the steel bar intact. It consequently follows that steel bar parameters can be improved by installing buffering material.

![Time history of displacement of the upper concrete body at center of gravity](image)

Figure 22. Time history of displacement of the upper concrete body at center of gravity

![Time history of displacement of the steel bars at the top end](image)

Figure 23. Time history of displacement of the steel bars at the top end

![Hysteresis of steel bar spring](image)

Figure 24. Hysteresis of steel bar spring
7. CONCLUSIONS

To develop a restraining method for a plain concrete pier with a construction joint, steel bars inserted in the pier were evaluated in terms of the forces acting on them by means of dynamic analysis techniques using sway-rocking models incorporating a spring for simulating joint slipping, a spring representing a steel bar and a spring for simulating joint rotation. Firstly, attempts were made using a sway-rocking model to simulate the results of shaking table tests on reduced-size models of plain concrete piers without steel bars. Secondly, response analysis was conducted on real plain concrete piers without steel bars and those with steel bars to find out whether the steel bars would be effective in reducing horizontal displacement at the construction joint. Finally, an examination was made as to whether a difference in the size of the gap between the steel bar and the upper concrete body and/or the use of buffering material could have any influence on forces working on the steel bar. The results are outlined below.

1) To evaluate forces acting on movement-restraining steel bars installed in a plain concrete pier with a construction joint, dynamic analytical models were proposed that consider the slipping and rocking behavior of the upper concrete body above the construction joint. Analysis was conducted using a proposed model to reproduce the results of the shaking table tests on plain concrete piers without steel bars, which showed the validity of the proposed model.

2) Response analysis was conducted on real bridge piers with and without the steel bars. It was revealed that restrained response performance was achieved with fewer steel bars when the yield was factored in than when it was not.

3) Analysis was conducted on the gap between a steel bar and the upper concrete body, which indicated that if the gap were to be restricted to respect the limit of residual displacement, having a greater gap would only have a small effect on reducing the force acting on the steel bar.

4) Analysis was conducted on a steel bar surrounded by buffering material, which showed that the buffering material could reduce the forces acting on the steel bar.

8. REFERENCES


