Optimization of on-off dampers for reducing collision of base-isolated buildings with retaining walls

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Excessive deformation of a building's isolation layer in the event of a huge earthquake may cause the layer to collide against retaining walls.

Conventional passive dampers increase the response acceleration during design earthquakes and lower the performance of the seismic isolation structure.
Proposed on-off dampers

Conventional oil damper

- The on-off damper has an elongated hole at the support joint.
- The design involves a simple modification of the shape of the pin support in existing oil dampers.
- The on-off damper actuates when

\[
\begin{align*}
l_{ri} &\leq 0 & \text{or} & & l_{li} &\leq 0 \\
V &> 0 & & & V &< 0
\end{align*}
\]

Proposed on-off damper
How on-off damper actuates

Level 2, JMAKobe (Design large earthquake)

Level 3C, Tp2 pulse wave (Extreme earthquake)
Shaking Table Test

We conducted an experiment using a shaking table to confirm the effect of the on-off damper. The test specimen is a four-story model with a base isolation layer.
Plan of shaking test

The similarity ratio of the length between test model and real building was 1:4.

Correspondence between test specimen and real building

Real building

- Total mass: 6720(t)
- 12(kN/m²)
- 80m (20story)
- 16.5m

Model

- Total mass: 420(t)
- 4.1m
- 1/4
- 1/200

Isolator: Push-pull spring
Initial damper: MR damper
Additional damper: On-off damper
Moat wall: Air cylinder
**Initial Damper**: Damper set to an isolation layer initially.

**Additional Damper**: Damper added to measure against huge earthquakes.

**Moat Wall**: Air cylinders are used alternately.

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- **Initial damper**
  - MR damper was set to simulate a bilinear hysteresis of an oil damper with a valve relief.

- **Additional Damper**
  - Two on-off dampers are used as additional dampers.
  - The oil damper has linear viscous damping performance.

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![Graph](image)
Behavior of dampers and air cylinder

**Force-velocity relation of MR damper**
- No additional dampers
- With on-off dampers
- East damper
- West damper
- Standard value

**Force-displacement relation of Air cylinder**
- Average of loading force
- Average of unloading force
- Test value of loading force
- Test value of unloading force
Time history waveforms of input accelerations

Level-2 Observed Earthquakes
• El Centro 1940 NS, Hachinohe 1968 NS, JMA Kobe 1995 NS \((V_{max} = 50\ \text{cm/s})\)

Huge Earthquakes in excess of Level-2 (Level-3C)
• Estimated pulse waveforms of earthquakes that are predicted to occur along Uemachi fault in Osaka, Japan. The periods are \(T_p=1,2,3\text{(s)}\)

![Graph of Level 2 Observed earthquakes and Level 3C Pulse waves]
Influence of initial clearance length

| Test cases |
|-----------------|--------------------------------------------------|
| **Input accelerations** | El Centro, Hachinohe, JMA Kobe, Tp1, Tp2, Tp3 pulse waves |
| **Combinations of initial clearance lengths** $(l_1, l_2)$ (mm) | $(l_1, l_2) = (0, 0), (0, 5), \ldots, (30, 30)$, No additional dampers |
| **Damping coefficient $c$ (kN·s/m)** | $c = 1.96 : dp2$ |
| **Output-force of air cylinder (kN)** | 1.0 |
| **Distance between test specimen and air cylinder $L_w$ (mm)** | 100 |
Definition of Response ratio

Response ratio = \frac{\text{Maximum response with on-off dampers}}{\text{Maximum response without on-off dampers}}

If \text{Response ratio} < 1.0, then the response decreased (get better).
If \text{Response ratio} > 1.0, then the response increased (get worse).
Response ratios of absolute acceleration in response to level-2 observed earthquakes.
Response ratios of relative story displacement in response to level-2 observed earthquakes.
Response ratios of absolute acceleration in response to level-3C pulse waves.

Response ratios

\[ (0,0), \quad (10,15), \quad (30,30) \]
\[ (5,10), \quad (15,15) \]
\[ (5,25), \quad (20,25) \]
Response ratios of relative story displacement in response to level-3C pulse waves.
Numerical analysis model that simulate the shaking test.

Modeling of on-off damper

\[
\begin{align*}
l_{li} &= l_{l(i-1)} - u_i \\
l_{ri} &= l_{r(i-1)} + u_i \\
u_i &= x_i - x_{i-1}
\end{align*}
\]

\( l_{li}, l_{ri} \): Left and right clearance of the hole at the \( i \)-th step.

\( x_i \): Relative displacement of the isolation layer.

**Actuation condition**

\[
\begin{align*}
l_{li} &\leq 0 \quad \text{and} \quad \frac{u_i}{\Delta t} > 0 \quad (\dot{x}_{1i} > 0) \\
l_{ri} &\leq 0 \quad \text{and} \quad \frac{u_i}{\Delta t} < 0 \quad (\dot{x}_{1i} < 0)
\end{align*}
\]

Before transfer to next step, correct as follows,

- If \( l_{li} < 0 \), then \( l_{li} = 0, \; l_{ri} = 2L \)
- If \( l_{ri} < 0 \), then \( l_{li} = 2L, \; l_{ri} = 0 \).

The optimization of the initial clearance lengths
Configuration of optimization strategy

\[ \text{Objective function } F(l) = \alpha_2 \sum R_{2ij} + \alpha_3 \sum R_{3Cij} \]

Find \( l = l_1, l_2 \)

To minimize \( F(l) \)

subject to \( 0 \leq l \leq 30 \)

\( \alpha \): Weighted coefficient.

\( R_{ij} \): Response ratio of the \( i \)-th story for the \( j \)-th earthquake.

<p>| Weighted coefficients to multiply the maximum responses for each earthquake level |
|---------------------------------|---------------------------------|-----------------|-----------------|</p>
<table>
<thead>
<tr>
<th>Reproduction period (year)</th>
<th>Probability of exceedance (%)</th>
<th>Weighted coefficient</th>
</tr>
</thead>
<tbody>
<tr>
<td>Level 2</td>
<td>500</td>
<td>5.8</td>
</tr>
<tr>
<td>Level 3</td>
<td>1000</td>
<td>3.0</td>
</tr>
</tbody>
</table>
In case of

\[ F_1 = \alpha_2 \sum_{i=1}^{4} \left( R_{i(El)} + R_{i(Kb)} \right) + \alpha_3 \sum_{i=1}^{4} \left( R_{i(Tp2)} + R_{i(Tp3)} \right) \]

Objective function values calculated from test results

<table>
<thead>
<tr>
<th>( F_{1acc} )</th>
<th>( l_1 )</th>
<th>( l_2 )</th>
<th>( F_{1dsp} )</th>
<th>( l_1 )</th>
<th>( l_2 )</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0</td>
<td>5</td>
<td>10</td>
<td>15</td>
<td>20</td>
</tr>
<tr>
<td>8.19</td>
<td>8.52</td>
<td>8.28</td>
<td>7.83</td>
<td>7.43</td>
<td>7.75</td>
</tr>
<tr>
<td>8.95</td>
<td>8.47</td>
<td>8.73</td>
<td>8.49</td>
<td>8.37</td>
<td>8.19</td>
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<tr>
<td>8.16</td>
<td>7.72</td>
<td>7.35</td>
<td>7.31</td>
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<td>8.16</td>
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<tr>
<td>sym.</td>
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<td>7.04</td>
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<tr>
<td>6.97</td>
<td>7.01</td>
<td>7.24</td>
<td>0</td>
<td>10</td>
<td>25</td>
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</table>

Optimization results

<table>
<thead>
<tr>
<th>Objective function</th>
<th>( F_{1acc} )</th>
<th>( F_{1dsp} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solution ((l_1, l_2))</td>
<td>(19.7 , 21.6)</td>
<td>(15.1 , 23.2)</td>
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<tr>
<td>Objective function value at solution</td>
<td>7.68</td>
<td>7.40</td>
</tr>
</tbody>
</table>
In case of \( F_2 = \alpha_2 \sum_{i=1}^{4} R_{i(El)} + \alpha_{3C} \sum_{i=1}^{4} R_{i(Tp2)} \)

Objective function values calculated from test results

<table>
<thead>
<tr>
<th>( F_{2\text{acc}} )</th>
<th>( l_2 )</th>
<th>( F_{2\text{dsp}} )</th>
<th>( l_2 )</th>
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</thead>
<tbody>
<tr>
<td>0</td>
<td>4.23</td>
<td>0</td>
<td>3.95</td>
</tr>
<tr>
<td>5</td>
<td>4.68</td>
<td>5</td>
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<td>3.75</td>
<td>30</td>
<td>3.62</td>
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</table>

Optimization results

<table>
<thead>
<tr>
<th>Objective function</th>
<th>( F_{2\text{acc}} )</th>
<th>( F_{2\text{dsp}} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solution ((l_1, l_2))</td>
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<td>(28.5, 28.5)</td>
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<tr>
<td>Objective function value at solution</td>
<td>3.93</td>
<td>3.84</td>
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</tbody>
</table>
In case of

\[ F_3 = \alpha_2 \sum_{i=1}^{4} R_{i(Kb)} + \alpha_3C \sum_{i=1}^{4} R_{i(Tp2)} \]

Objective function values calculated from test results

<table>
<thead>
<tr>
<th>( F_{3\text{acc}} )</th>
<th>( l_2 )</th>
<th>( F_{3\text{dsp}} )</th>
<th>( l_2 )</th>
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<tbody>
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<td>10</td>
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<tr>
<td>0</td>
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<td>3.98</td>
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<tr>
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<tr>
<td>30</td>
<td></td>
<td>3.51</td>
<td></td>
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Optimization results

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<th>( F_{3\text{dsp}} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solution ((l_1, l_2))</td>
<td>(13.5, 29.6)</td>
<td>(14.0, 14.0)</td>
</tr>
<tr>
<td>Objective function value at solution</td>
<td>3.88</td>
<td>3.76</td>
</tr>
</tbody>
</table>
Conclusions

• An optimization approach for the initial clearance length of on-off dampers in base-isolated buildings is proposed.

• Solutions of optimization were compared with results obtained from shaking table tests with 28 combinations of initial clearance lengths.

• The solutions from the optimization accord well with the test results in cases where the objective functions are calculated by the sum of the response ratios.

This optimization method allows us to determine the initial clearance length of on-off dampers uniquely without analyzing by trial and error.