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WhiteCap System

STRUCTURAL ANALYSIS REPORTS

Buehler & Buehler Associates
Structural Engineers, Inc.

Y.H. Chai, Ph.D. and K.M. Romstad, Ph.D.
University of California, Davis

MBAK Code Design
Code Review, Civil/Structural Engineering

Compiled April 27, 1995

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WhiteCap System
STRUCTURAL ANALYSIS REPORTS

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Roof Science Corporation
April 27, 1995
STRUCTURAL ENGINEERING REPORT

CoolRoof (WhiteCap) SYSTEM

Buehler & Buehler Associates
Structural Engineers, Inc.

February 13, 1992
We have completed an engineering investigation of the CoolRoof System as applicable to typical building construction in the Sacramento Valley. The purpose of this investigation is to provide structural engineering recommendations regarding structural modifications to typical building construction required by CoolRoof. This report presents the results of our investigation.

Our scope of work included the following:

- Background research on long term roof deflections.
- Vertical calculations on roof structures using CoolRoof.
- Comparisons to similar roof construction.
- Lateral calculations on building systems using CoolRoof.
- Comparisons to typical lateral systems of buildings using similar construction
- Cost analysis of additional structure required by CoolRoof.
- Preparation of this report.

Based upon a review of the CoolRoof brochure and conversations with David Springer of Davis Energy Group, Inc., it is our understanding the CoolRoof system is comprised of insulation panels supported by a 3-1/2 inch layer of water contained by a single ply membrane. The weight of these components is understood to be 22 pounds per square foot. ¹

A 20 psf live load was assumed as the base design. It may be questioned whether it is necessary to require the roof structure to resist a live load in addition to the weight of the CoolRoof system. The construction loading will be applied prior to the placement of the CoolRoof system. Once the system is in place, any additional water is removed by the self leveling drainage system. If a live load is required considering that the floating panels can sustain foot traffic loading, a reduced live load of 0 to 10 psf may be reasonable.

¹ The CoolRoof system weight includes 0.5 psf panel, 18.2 psf water, 0.5 membrane, and 2.8 psf allowance for an additional 1/2 inch of water.
This lower roof live load will need to be reviewed and accepted by each local jurisdiction before the roof framing is designed. We have shown the affects of the 0 live load condition and the 20 psf live load condition.

We have assumed a typical building size, shape and structural layout as the basis for this report. It should be noted that for this typical building, some elements of the structure were governed by the smallest or lightest member available rather than the actual stress levels. For other building geometries or structural system layouts, a savings may be realized which is not reflected in this report. This savings however is highly variable and beyond the scope of this investigation.

**VERTICAL ANALYSIS**

We considered four different loading conditions representing possible combinations of live and dead load.

A. **COOLROOF WITH LIVE LOAD**

<table>
<thead>
<tr>
<th></th>
<th>Panelized</th>
<th>TJI</th>
<th>Metal Deck</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dead Load</td>
<td>34 psf</td>
<td>34 psf</td>
<td>38 psf</td>
</tr>
<tr>
<td>Live Load</td>
<td>20 psf</td>
<td>20 psf</td>
<td>20 psf</td>
</tr>
</tbody>
</table>

B. **COOLROOF WITHOUT LIVE LOAD**

<table>
<thead>
<tr>
<th></th>
<th>Panelized</th>
<th>TJI</th>
<th>Metal Deck</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dead Load</td>
<td>34 psf</td>
<td>34 psf</td>
<td>38 psf</td>
</tr>
<tr>
<td>Live Load</td>
<td>0 psf</td>
<td>0 psf</td>
<td>0 psf</td>
</tr>
</tbody>
</table>

C. **COOLROOF WITH NO LIVE LOAD AND 2' WATER DEPTH**

<table>
<thead>
<tr>
<th></th>
<th>Panelized</th>
<th>TJI</th>
<th>Metal Deck</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dead Load</td>
<td>27 psf</td>
<td>27 psf</td>
<td>31 psf</td>
</tr>
<tr>
<td>Live Load</td>
<td>0 psf</td>
<td>0 psf</td>
<td>0 psf</td>
</tr>
</tbody>
</table>

D. **TYPICAL: (LIVE LOADS ARE REDUCIBLE)**

<table>
<thead>
<tr>
<th></th>
<th>Panelized</th>
<th>TJI</th>
<th>Metal Deck</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dead Load</td>
<td>15 psf</td>
<td>16 psf</td>
<td>21 psf</td>
</tr>
<tr>
<td>Live Load</td>
<td>20 psf</td>
<td>20 psf</td>
<td>20 psf</td>
</tr>
</tbody>
</table>

1. Blocking is required at unsupported plywood edges for lateral loading.
2. Load duration factor of 15% considered.
3. As the area tributary to an element (beam, column etc.) increases, the probability that it will ever receive the maximum live load decreases. Therefore, the live loads can be reduced on major elements of the structure to account for this probability.
The following listing represents the structure required for the three types of construction and the four loading conditions.

### A. PANELIZED CONSTRUCTION

<table>
<thead>
<tr>
<th></th>
<th>CoolRoof With Live Load</th>
<th>CoolRoof W/O Live Load</th>
<th>CoolRoof W/O Live Load &amp; 2&quot; Water Depth</th>
<th>Typical</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plywood</td>
<td>5/8&quot; CDX</td>
<td>5/8&quot; CDX</td>
<td>1/2&quot; CDX&lt;sub&gt;2&lt;/sub&gt;</td>
<td>1/2&quot; CDX</td>
</tr>
<tr>
<td>Joists</td>
<td>2 x 6 #1</td>
<td>2 x 6 #2</td>
<td>2 x 6 #2&lt;sub&gt;2&lt;/sub&gt;</td>
<td>2 x 6 #2</td>
</tr>
<tr>
<td>Purlins</td>
<td>30&quot; TJI 65 or 3-1/8&quot; x 15&quot; glulam beam</td>
<td>28&quot; TJI 55E or 3-1/8&quot; x 12&quot; glulam beam</td>
<td>22&quot; TJI 55E or 4 x 12 #1</td>
<td>22&quot; TJI 55E or 4 x 14 #1</td>
</tr>
<tr>
<td>Girders</td>
<td>6-3/4&quot; x 34-1/2&quot;</td>
<td>6-3/4&quot; x 28-1/2&quot;</td>
<td>6-3/4&quot; x 22-1/2&quot;</td>
<td>6-3/4&quot; x 24&quot;</td>
</tr>
<tr>
<td>Columns</td>
<td>TS 4 x 4 x 3/8</td>
<td>TS 4 x 4 x 1/4</td>
<td>TS 4 x 4 x 3/16</td>
<td>TS 4 x 4 x 1/4</td>
</tr>
<tr>
<td>Footings</td>
<td>5' sq. x 1' deep</td>
<td>4' sq. x 1' deep</td>
<td>4' sq. x 1' deep</td>
<td>4' sq. x 1' deep</td>
</tr>
</tbody>
</table>

### B. TJI CONSTRUCTION

<table>
<thead>
<tr>
<th></th>
<th>CoolRoof With Live Load</th>
<th>CoolRoof W/O Live Load</th>
<th>CoolRoof W/O Live Load &amp; 2&quot; Water Depth</th>
<th>Typical</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plywood</td>
<td>1/2&quot; CDX</td>
<td>1/2&quot; CDX</td>
<td>1/2&quot; CDX&lt;sub&gt;2&lt;/sub&gt;</td>
<td>1/2&quot; CDX</td>
</tr>
<tr>
<td>Joists</td>
<td>14&quot; TJI 35x</td>
<td>12&quot; TJI 35x</td>
<td>12&quot; TJI 35x&lt;sub&gt;2&lt;/sub&gt;</td>
<td>12&quot; TJI 35x</td>
</tr>
<tr>
<td>Girders</td>
<td>6-3/4&quot; x 34-1/2&quot;</td>
<td>6-3/4&quot; x 28-1/2&quot;</td>
<td>6-3/4&quot; x 22-1/2&quot;</td>
<td>6-3/4&quot; x 24&quot;</td>
</tr>
<tr>
<td>Columns</td>
<td>TS 5 x 5 x 1/4</td>
<td>TS 4 x 4 x 1/4</td>
<td>TS 4 x 4 x 3/16</td>
<td>TS 4 x 4 x 1/4</td>
</tr>
<tr>
<td>Footings</td>
<td>5' sq. x 1' deep</td>
<td>4' sq. x 1' deep</td>
<td>4' sq. x 1' deep</td>
<td>4' sq. x 1' deep</td>
</tr>
</tbody>
</table>
## C. METAL DECK CONSTRUCTION

<table>
<thead>
<tr>
<th></th>
<th>CoolRoof With Live Load</th>
<th>CoolRoof W/O Live Load</th>
<th>CoolRoof W/O Live Load &amp; 2’ Water Depth</th>
<th>Typical Live Load &amp; 2’ Water Depth</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rigid Ins.</td>
<td>2”</td>
<td>2”</td>
<td>2”</td>
<td>2”</td>
</tr>
<tr>
<td>Metal Deck</td>
<td>1-1/2” x 20 ga.</td>
<td>1-1/2” x 22 ga.</td>
<td>1-1/2” x 22 ga.</td>
<td>1-1/2” x 22 ga.</td>
</tr>
<tr>
<td>Beams</td>
<td>W12 x 16</td>
<td>W12 x 14</td>
<td>W10 x 12</td>
<td>W10 x 12</td>
</tr>
<tr>
<td>Girders</td>
<td>W21 x 62</td>
<td>W21 x 50</td>
<td>W18 x 40</td>
<td>W21 x 44</td>
</tr>
<tr>
<td>Columns</td>
<td>TS 5 x 5 x 1/4</td>
<td>TS 4 x 4 x 3/8</td>
<td>TS 4 x 4 x 3/16</td>
<td>TS 4 x 4 x 1/4</td>
</tr>
<tr>
<td>Footings</td>
<td>5’ sq. x 1’ deep</td>
<td>4’ sq. x 1’ deep</td>
<td>4’ sq. x 1’ deep</td>
<td>4’ sq. x 1’ deep</td>
</tr>
</tbody>
</table>

### LATERAL ANALYSIS

The three lateral systems evaluated are wood shear walls, concrete block or concrete tilt-up walls and steel brace frames with the following layout:

<table>
<thead>
<tr>
<th>Wood Shear Walls</th>
<th>Concrete Block or Tilt-up</th>
<th>Braced Frames</th>
</tr>
</thead>
<tbody>
<tr>
<td>Building Layout</td>
<td>100’ square</td>
<td>100’ square</td>
</tr>
<tr>
<td>Elements Per Side</td>
<td>2</td>
<td>5 at CMU</td>
</tr>
<tr>
<td></td>
<td></td>
<td>10 at Tilt-up</td>
</tr>
<tr>
<td>Length of Element</td>
<td>15’</td>
<td>6’ at CMU</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3’ at Tilt-up</td>
</tr>
<tr>
<td>Height of Element</td>
<td>15’</td>
<td>15’</td>
</tr>
</tbody>
</table>

1. 1/2” gypsum board may be used in lieu of the rigid insulation yielding a $.60/sq. ft. savings.

2. Indicates condition where minimum size governs for span indicated. A savings may be realized for other spans.
The following listing represents the different structural elements for various systems assuming that the number and size of the resisting elements remain constant.

### A. WOOD SHEAR WALLS

<table>
<thead>
<tr>
<th>Element</th>
<th>CoolRoof with 3-1/2&quot; water depth</th>
<th>CoolRoof with 2&quot; water depth</th>
<th>Typical</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sheathing</td>
<td>1/2&quot; CDX with 10d @ 3&quot;cc each side</td>
<td>1/2&quot; CDX with 6d 6&quot;cc each side</td>
<td>1/2&quot; CDX with 10d @ 4&quot;cc one side</td>
</tr>
<tr>
<td>Framing</td>
<td>2 x 6 studs with 3 x 6 at panel edges</td>
<td>2 x 6 studs thruout</td>
<td>2 x 6 studs thruout</td>
</tr>
<tr>
<td>Anchor Bolting</td>
<td>3/4&quot; dia. at 16&quot;cc</td>
<td>5/8&quot; dia. at 16&quot;cc</td>
<td>5/8&quot; dia. at 16&quot;cc</td>
</tr>
<tr>
<td>Holdowns</td>
<td>HD - 20A</td>
<td>HD - 7A</td>
<td>HD - 5A</td>
</tr>
<tr>
<td>Add'l Footing</td>
<td>3' sq 1' deep at each end</td>
<td>2' sq. x 1' deep at each end</td>
<td>None</td>
</tr>
</tbody>
</table>

### B. CONCRETE BLOCK WALLS

<table>
<thead>
<tr>
<th>Element</th>
<th>CoolRoof with 3-1/2&quot; water depth</th>
<th>CoolRoof with 2&quot; water depth</th>
<th>Typical</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wall</td>
<td>8&quot; block solid grouted</td>
<td>8&quot; block solid grouted</td>
<td>8&quot; block solid grouted</td>
</tr>
<tr>
<td>Typical Reinforcing</td>
<td>#5 at 16&quot;cc each way</td>
<td>#5 at 16&quot;cc each way</td>
<td>#5 at 16&quot;cc each way</td>
</tr>
<tr>
<td>Jamb Reinforcing</td>
<td>3 - #7</td>
<td>3 - #6</td>
<td>2 - #7</td>
</tr>
<tr>
<td>Footing</td>
<td>Typical continuous</td>
<td>Typical continuous</td>
<td>Typ. continuous</td>
</tr>
</tbody>
</table>

### C. TILT-UP CONCRETE WALLS

<table>
<thead>
<tr>
<th>Element</th>
<th>CoolRoof with 3-1/2&quot; water depth</th>
<th>CoolRoof with 2&quot; water depth</th>
<th>Typical</th>
</tr>
</thead>
<tbody>
<tr>
<td>Walls</td>
<td>6&quot; concrete</td>
<td>6&quot; concrete</td>
<td>6&quot; concrete</td>
</tr>
<tr>
<td>Typical Reinforcing</td>
<td>#5 at 12&quot;cc each way</td>
<td>#5 at 12&quot;cc each way</td>
<td>#5 at 12&quot;cc each way</td>
</tr>
</tbody>
</table>
Jamb Reinforcing: 2 - #6  2 - #5  2 - #5  
Footing: 3' x 7' x 1' deep  3' x 6' x 1' deep  3' x 6' x 1' deep  

D. BRACE FRAMES: CHEVRON TYPE

Brace Beams: W21 x 62  W21 x 50  W21 x 44  
Brace Columns: TS 5 x 5 x 1/4  TS 4 x 4 x 3/8  TS 4 x 4 x 1/4  
Brace Diagonals: TS 6 x 6 x 1/4  TS 6 x 6 x 1/4  TS 6 x 6 x 1/4  
Diagonal Weld: 40" of 1/4" fillet each end  32" of 1/4" fillet each end  20" of 1/4" fillet each end  
Footing: 9' sq. x 3' deep  7'-6" sq. x 3' deep  6' sq. x 3' deep  

COST ANALYSIS

The additional costs denoted below were acquired from the 1991 edition of Means Building Construction Cost Data and are based on square footage of building area. The base costs were obtained from estimates of standard construction for the combinations listed below. The depths indicated represent the water depth associated with different CoolRoof water thicknesses.

PANELIZED ROOF SYSTEM:

<table>
<thead>
<tr>
<th>Plywood Walls</th>
<th>Concrete Block Walls</th>
<th>Tilt-Up Walls</th>
</tr>
</thead>
<tbody>
<tr>
<td>Base Cost/sq.ft.</td>
<td>$30 - $56</td>
<td>$38 - $64</td>
</tr>
<tr>
<td>Differential Cost to Vertical System</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3-1/2&quot; Depth with Live Load</td>
<td>+$.84/sq. ft.</td>
<td>+$.84/sq. ft.</td>
</tr>
<tr>
<td>3-1/2&quot; Depth without Live Load</td>
<td>+$.18/sq. ft.</td>
<td>+$.18/sq. ft.</td>
</tr>
<tr>
<td>2&quot; Depth without Live Load</td>
<td>-$.08/sq. ft.</td>
<td>-$.08/sq. ft.</td>
</tr>
</tbody>
</table>
## Additional Cost to Lateral System

<table>
<thead>
<tr>
<th>Depth</th>
<th>Plywood Walls</th>
<th>Concrete Block Walls</th>
<th>Tilt-Up Walls</th>
</tr>
</thead>
<tbody>
<tr>
<td>3-1/2&quot;</td>
<td>$0.79/sq. ft.</td>
<td>No change</td>
<td>No change</td>
</tr>
<tr>
<td>2&quot;</td>
<td>$0.35/sq. ft.</td>
<td>No change</td>
<td>No change</td>
</tr>
</tbody>
</table>

## TJII Roof System:

<table>
<thead>
<tr>
<th>Depth</th>
<th>Plywood Walls</th>
<th>Concrete Block Walls</th>
<th>Tilt-Up Walls</th>
<th>Base Cost/sq. ft.</th>
<th>Differential Cost to Vertical System</th>
</tr>
</thead>
<tbody>
<tr>
<td>3-1/2&quot; with Live Load</td>
<td>+$0.62/sq. ft.</td>
<td>+$0.62/sq. ft.</td>
<td>+$0.62/sq. ft.</td>
<td>$32 - $58</td>
<td>+$0.62/sq. ft.</td>
</tr>
<tr>
<td>3-1/2&quot; without Live Load</td>
<td>+$0.05/sq. ft.</td>
<td>+$0.05/sq. ft.</td>
<td>+$0.05/sq. ft.</td>
<td>$37 - $59</td>
<td>+$0.05/sq. ft.</td>
</tr>
<tr>
<td>2&quot; without Live Load</td>
<td>-$0.12/sq. ft.</td>
<td>-$0.12/sq. ft.</td>
<td>-$0.12/sq. ft.</td>
<td>$41 - $65</td>
<td>-$0.12/sq. ft.</td>
</tr>
</tbody>
</table>

## Additional Cost to Lateral System

<table>
<thead>
<tr>
<th>Depth</th>
<th>Plywood Walls</th>
<th>Concrete Block Walls</th>
<th>Tilt-Up Walls</th>
</tr>
</thead>
<tbody>
<tr>
<td>3-1/2&quot;</td>
<td>$0.94/sq. ft.</td>
<td>No change</td>
<td>No change</td>
</tr>
<tr>
<td>2&quot;</td>
<td>$0.35/sq. ft.</td>
<td>No change</td>
<td>No change</td>
</tr>
</tbody>
</table>

## Metal Deck Roof System:

<table>
<thead>
<tr>
<th>Depth</th>
<th>Concrete Block</th>
<th>Tilt-Up</th>
<th>Brace Frames</th>
<th>Base Cost/sq. ft.</th>
<th>Differential Cost to Vertical System</th>
</tr>
</thead>
<tbody>
<tr>
<td>3-1/2&quot;</td>
<td>$43 - $72</td>
<td>$41 - $70</td>
<td>$47 - $74</td>
<td>$43 - $72</td>
<td>+$0.05/sq. ft.</td>
</tr>
<tr>
<td>2&quot;</td>
<td>$41 - $70</td>
<td>$47 - $74</td>
<td></td>
<td>+$0.05/sq. ft.</td>
<td></td>
</tr>
</tbody>
</table>
3-1/2" Depth with Live Load
+$1.30/sq. ft. +$1.30/sq. ft. +$1.30/sq. ft.

3-1/2" Depth without Live Load
+$0.32/sq. ft. +$0.32/sq. ft. +$0.32/sq. ft.

2" Depth without Live Load
-$0.29/sq. ft. -$0.29/sq. ft. -$0.29/sq. ft.

Additional Cost to Lateral System

3-1/2" Depth  No change  No change  $1.13/sq. ft.
2" Depth  No change  No change  $0.32/sq. ft.

The additional costs above were generated by the following factors:

A. Increase due to additional vertical loads.
B. Increase due to additional lateral loads on wall or brace elements.
C. Decrease due to reduced supplemental framing required by fewer and/or lighter mechanical units on roof.
D. Decrease due to flat construction without warps, crickets, etc.
E. Decrease due to reduced wall and column heights generated by flat roof construction.

The decreases noted above were estimated using the typical building described herein and ranged from $0.30 to $0.55/sq. ft. These values are highly variable and care should be taken in extrapolating to other projects.

The totals above are combinations of all these effects on the building as they relate to individual types.

RECOMMENDATIONS

Special design considerations should be given to the support elements for the CoolRoof system. Deflections and/or cambers should be investigated for long term loading. The design stress level should correspond to the appropriate dead loads. Roof live loads may be reduced or eliminated but further research into local jurisdiction or model code acceptance is needed. Also, further analysis should be considered on determining the type of movement of a flat water mass subject to lateral loads. While we have assumed a fixed mass for the CoolRoof system, there may be either increased loads due to sloshing effects or decreased loads due to dampening effects.
CONCLUSION

The additional costs generated by the extra weight of the CoolRoof system can be summarized as follows: as the initial weight of the building increases, the additional cost decreases.
REPORT ON SEISMIC DESIGN
OF BUILDINGS INCORPORATED
WITH COOL STORAGE ROOF SYSTEM
by
Y.H. Chai, Ph.D. and K.M. Romstad, Ph.D.

Prepared For:
Davis Energy Group, Inc.

April 28, 1994
1. Introduction

This report investigates the seismic design of buildings incorporated with Cool Storage Roof (CSR) system developed by the Davis Energy Group Inc. The CSR system is designed to provide a cost-effective cooling system for commercial buildings. The basic component of the CSR system consists of 3 to 4 inches of water stored over the roof area of the structure and thermally insulated with 3 inch thick polystyrene insulation panels. A schematic diagram of the CSR system is shown in Figure 1.

The objectives of this investigation are:

• to determine the dynamic characteristics of the water in the CSR system

• to study the interaction of the water in the CSR system with the structure particularly for low-rise buildings.

Figure 1: Cool Storage Roof System Developed by Davis Energy Group Inc.
2. Dynamic Characteristics of Water Tank Under Lateral Load

The traditional approach for characterizing the dynamic properties of a water tank with a free water surface uses two equivalent masses and one equivalent stiffness, as shown in Figure 2. The equivalent mass $M_{wo}$ represents a portion of the water that is assumed to be rigidly attached to the tank while $M_{wl}$ and $K_w$ represent a mass and equivalent stiffness which model the vibratory motion in the water.

For a rectangular tank of length $2L_w$ and water height of $h_w$ shown in Figure 2, the equivalent masses and spring stiffness are given by [ref. 1]:

\[
M_{wo} = \frac{\text{tanh} \, 1.7 \frac{L_w}{h_w}}{1.7 \frac{L_w}{h_w}} M_w
\]  

(1)

\[
M_{wl} = \frac{0.83 \text{tanh} \, 1.6 \frac{h_w}{L_w}}{1.6 \frac{h_w}{L_w}} M_w
\]  

(2)

\[
K_w = \frac{3gM_w^2 h_w}{M_w L_w^2}
\]  

(3)

where $M_w$ = total mass of the water; $g$ = gravitational constant. It should be noted that the two equivalent masses given by Eqs. 1 and 2 do not add up to the total mass of the water.

The characteristics of water contained in the CSR system will first be studied using Eqs. 1 to 3. A water height of $h_w = 3$ inches and a tank length of $2L_w = 60$ ft (i.e. $L_w/h_w = 120$) is assumed. The two equivalent masses according to Eqs. 1 and 2 are computed to be:

\[
M_{wo} = 0.0049 M_w
\]  

(4)

\[
M_{wl} = 0.83 M_w
\]  

(5)
It can be seen from these results that the water contained in the CSR system behaves in such a way that only a very small mass of the water participates as a rigid mass with the structural tank while about 83% of the total mass acts in vibratory (sloshing) mode. By substituting the total mass of the water (per ft width of the tank) as $M_w = 0.0291$ kip.s²/ft, the two equivalent masses are $M_{wo} = 1.424 \times 10^{-4}$ kip.s²/ft and $M_{w1} = 2.415 \times 10^{-4}$ kip.s²/ft, and the equivalent spring stiffness from Eq. 3 is $K_w = 5.378 \times 10^{-4}$ kip/ft. Thus the fundamental (sloshing) period of the water in the assumed CSR system becomes:

$$T_w = 2\pi \sqrt{\frac{M_{w1}}{K_w}} = 42.1\ sec$$

(6)
The vibratory period of the water in the CSR system is very long compared to the predominant periods of the ground motion (typically ranging from 0.2 sec to 1.0 sec) in an earthquake. Therefore the sloshing mode of the water is unlikely to be excited during a seismic event and would not affect the seismic design of the buildings. Even with a shorter tank length of $2L_w = 20$ ft and a deeper water of 4 inches, the vibratory period of the water which reduces to $T_w = 12.2$ sec is still very long compared to the predominant periods of the ground motion.

3. Structural Design of Example Building

To illustrate the non-participating nature of the water in a CSR system for seismic design of buildings, a numerical example with structural properties representative of low-rise office building is chosen. The selected structure is a rectangular building with a width of 60 ft, length of 120 ft and height of 18 ft, with layout shown in Figure 3. A parapet wall of 2.5 ft is provided at the roof level. The lateral load is assumed to be resisted entirely by the reinforced concrete shear walls.

![Diagram of Example Building](image_url)
The following design data are assumed for the structure:

The dead load assumed for the roof (without water) is 75 lb/sq. ft.

- Weight of the roof (without water): \( W_{\text{roof}} = 0.075 \times 120 \times 60 = 540 \) kips
- Half-story height for walls: \( W_{\text{wall}} = 9 \times 10 \times 20 \times 6 / 12 \times 0.15 = 135 \) kips
- Half-story height for columns: \( W_{\text{col}} = 9 \times 16 \times 16 / 144 \times 12 \times 0.15 = 28.8 \) kips
- Parapet Wall (2.5' x 4" thick): \( W_{\text{parapet}} = 2.5 \times (120 \times 2 + 60 \times 2) \times 4 / 12 \times 1.5 = 45 \) kips
- Total Weight of Roof (without water) \( W_{\text{total}} = 540 + 135 + 45 + 28.8 = 748.8 \) kips

For 20' long x 6" thick wall, gross moment of inertia is \( I_g = 20^3 \times 6 / 12 / 12 = 333.3 \) ft\(^3\)

Total wall area: \( A_g = 10 \times 20 \times 6 / 12 = 100 \) ft\(^2\)

Total column area: \( A_c = 12 \times 16 \times 16 / 144 = 21.33 \) ft\(^2\)

Concrete compressive strength \( f'_c = 4000 \) psi.

Average axial stress ratio for wall \( \frac{W_{\text{total}}}{f'_c (A_g + A_c)} = \frac{748.8}{4/(100+21.33)/144} = 0.011 \) ksi

From [ref 2 - page 376], the wall effective moment of inertia is estimated by:

\[
I_e = \left[ \frac{14.5}{f'_y} + \frac{W_{\text{total}}}{f'_c (A_g + A_c)} \right] I_g
\]

where \( f'_y \) = yield strength of the reinforcement in ksi. The effective moment of inertia is:

\( I_e = (14.5/60 + 0.011) \times 333.3 = 84.21 \) ft\(^4\) = 1.746\(\times 10^6\) in\(^4\). Using the ACI expression for the modulus of elasticity for concrete \( E_c = 57000 \) (\( f'_y \)^0.5 = 57000(4000)^0.5 = 3605 ksi), the lateral stiffness of wall is given by:

\[
K_{\text{wall}} = \frac{1}{h^2 + \frac{1.2h}{3E_c I_e \frac{G_c A_e}{G_e A_e}}}
\]

Substituting \( h = 216" \) (or 18'), \( E_c = 3605 \) ksi, \( G_c = 0.4E_c = 0.4 \times 3605 = 1442 \) ksi, and \( A_e = 0.5 \times 6 \times 20 \times 12 = 720 \) in\(^2\) (as recommended in Ref. 2) into Eq. 8, gives \( K_{\text{wall}} = 1277 \) kip/in. The lateral stiffness of the structure (in the short direction) is \( K_s = 4 \times 1277 = 5106 \) kip/in.

Hence the fundamental period of the structure is given by:

\[
T_s = 2\pi \sqrt{\frac{W_{\text{total}}}{g K_s}} = 2\pi \sqrt{\frac{748.8}{386.4 \times 5106}} = 0.122 \text{ sec}
\]

This structural period is small compared to the vibratory period of the water in CSR system.
4. Interaction of Water with Buildings

The interaction between the water in the CSR system and example building will be studied using the two degree-of-freedom model shown in Figure 4. The first degree-of-freedom corresponds to that of the water tank and the second degree-of-freedom corresponds to that of the structure at the roof level.

Since the characteristics of the water tank and structure are distinctly different, the first mode of vibration for the combined system will correspond to the vibratory period of the water system i.e $T_1 = 42.1$ sec, and the second mode will correspond to the fundamental period of the structure i.e. $T_2 = 0.122$ sec. The two mode shapes are given by:

$$\{\phi_1\} = \begin{bmatrix} 1 \\ 0 \end{bmatrix} ; \quad \{\phi_2\} = \begin{bmatrix} 0 \\ 1 \end{bmatrix}$$

and the mass matrix for the combined system (after multiplying $M_w$ by the length of building) can be written as:

$$[M] = \begin{bmatrix} 2.898 & 0 \\ 0 & 23.26 \end{bmatrix} \frac{kip \cdot s^2}{ft}$$

![Diagram of Two-Degree-of-Freedom Model for Building and CSR System](image)
The modal masses for the two modes are:

\[ M_1^* = \{\phi_1\}^T[M]\{\phi_1\} = 2.898 \frac{kip \cdot s^2}{ft} \]

\[ M_2^* = \{\phi_2\}^T[M]\{\phi_2\} = 23.26 \frac{kip \cdot s^2}{ft} \]

and the modal participation factors are:

\[ L_1 = \{\phi_1\}^T[M]\{1\} = 2.898 \frac{kip \cdot s^2}{ft} \quad ; \quad L_2 = \{\phi_2\}^T[M]\{1\} = 23.26 \frac{kip \cdot s^2}{ft} \]

To estimate the seismic design base shear force, the provisions in UBC 91 [ref. 3] are followed. The elastic base shear force for the \( i \)th mode can be written as:

\[ V_{ei} = Z.I.C_i \frac{L_i^2}{M_i} g \]

where \( Z \) = seismic zone factor; \( I \) = importance factor; and \( C_i \) = seismic coefficient for the \( i \)th mode which is given by:

\[ C_i = \frac{1.25 S}{T_i^{23}} \leq 2.75 \]

where \( S \) = soil condition factor, and \( T_i \) = period of the structure. For the example building, \( Z = 0.4, I = 1.0 \) and \( S=1.0 \) are assumed.

The seismic coefficient for the first mode of vibration is:

\[ C_1 = \frac{1.25}{42.1^{23}} = 0.1033 < 2.75 \]

giving the elastic base shear force as:

\[ V_{el} = 0.4 \times 0.1033 \times 2.898 \times 32.2 = 3.83 \text{ kips} \]
The distribution of inertial force for the first mode is given by:

\[
\{f_1^1\} = [M] \{\phi_1\} \frac{L_1}{M_1} V_{e1}
\]

\[
= \begin{bmatrix} 3.83 \\ 0 \end{bmatrix} \text{ kips}
\]

The seismic coefficient for the second mode is given by:

\[
C_2 = \frac{1.25}{0.078^{2/3}} = 6.847 > 2.75
\]

Using the limiting value of seismic coefficient \( C_2 = 2.75 \), the elastic base shear force for the second mode is:

\[
V_{e2} = 0.4 \times 2.75 \times 23.26 \times 32.2 = 823.9 \text{ kips}
\]

Thus the distribution of inertial force for the second mode is:

\[
\{f_2^2\} = [M] \{\phi_2\} \frac{L_2}{M_2} V_{e2}
\]

\[
= \begin{bmatrix} 0 \\ 823.9 \end{bmatrix} \text{ kips}
\]

The SRSS (square root of the sum of the square) is used to estimate the total base shear force:

\[
V_e' = \sqrt{3.83^2 + 823.9^2} = 823.9 \text{ kips}
\]

It can be seen that the total base shear force for the combined system is essentially the same as the base shear force for the structure alone i.e.

\[
V_e' = V_{e2}
\]

Thus the seismic design of the buildings can be assumed to be unaffected by the presence of water in the Cool Storage Roof System.
Although a large variation of dead load is possible for various designs, the typical fundamental period of a single-story building lies in the range of 0.03 to 0.2 sec. For the example building, a smaller dead load of 20 lb/sq. ft (instead of the assumed 75 lb/sq. ft) would reduce the fundamental period of the structure to about 0.08 sec. Assuming the same lateral stiffness for the structure, the smaller period actually increases the separation between the periods of the structure and the water in the CSR system. Thus an even smaller interaction between the structure and the water in the CSR system would occur and seismic design involving a lighter roof construction is not expected to be affected by the water in the CSR system.

5. Influence of Insulation Panels on Seismic Response

The application of Cool Storage Roof system requires the use of an insulation layer for reflecting the solar radiation imparted on the roof structure. The insulation layers are fabricated from 2 ft by 8 ft polystyrene panels having nominal thickness of 3 inches and are interconnected by tongue and groove joints. The relatively small rigidity of the polystyrene panels and the inherent flexibility of the connecting joints means that the insulation layers are very flexible in its out-of-plane deformation and are therefore unlikely to provide any significant restraint against the sloshing mode of the water. Thus the water in the CSR system will behave essentially as a shallow water tank with a free water surface.

6. Conclusions

The period of vibration for Cool Storage Roof System is found to be very long compared to the predominant period of the ground motion in an earthquake. Consequently, the seismic design of building is unaffected by the presence of water in the Cool Storage Roof System. Because of the flexibility in the insulation panels and their connecting joints, the insulation panels are considered not to affect the vibratory characteristics of the water in the CSR system. However, auxiliary components of the CSR systems (e.g. pump, pipes etc) will need to be considered as seismically reactive mass when designing the building.

References


REVIEW COMMUNICATIONS
CHAI & ROMSTAD
WhiteCap
SEISMIC DESIGN REPORT

Chai & Romstad Letter, February 6, 1995
Buehler & Buehler Associates Letter, January 9, 1995
MBAK Code Design Letter, December 20, 1994
Feb 6, 1995

Mr. Jerry Best  
Roof Science Corporation  
123 C Street, Davis, CA 95616  

Re: Report on Seismic Design of Buildings Incorporated with Cool Storage Roof System  

Dear Mr. Best,  

We have read the comments by the two reviewers (MBAK and Buehler & Buehler) on our study of your Cool Storage Roof (CSR) System. Our responses to their comments are as follows:  

- **Review by MBAK - Letter of December 20, 1994**  

1. Our study uses a simple model originally proposed by G. Housner for calculating the fundamental period of water in a rectangular tank. The approach uses an equivalent system of two masses; one rigidly attached to the tank and the other connected by linear spring. The rigidly attached mass $M_{wo}$ and vibratory mass $M_{w1}$ are given by Eqn. 1 and 2 of our Report. For subsequent discussion, the two masses are added to give the following Eqn.:  

   $\frac{M_{wo} + M_{w1}}{M_w} = \frac{\tanh 1.7 \frac{L_w}{h_w}}{1.7 \frac{L_w}{h_w}} + \frac{0.83 \tanh 1.6 \frac{h_w}{L_w}}{1.6 \frac{h_w}{L_w}}$  

   (a)  

The right-hand-side of Eqn. (a) is plotted in Figure 1 as a function of the aspect ratio of the contained water, $\frac{L_w}{h_w}$, where $L_w$ = half the length of the tank; and $h_w$ = height of water. It can be seen from Figure 1 that the sum of the rigidly attached mass and vibratory mass do not add up to the total mass of water for a wide range of water aspect ratios. For a shallow water tank, the sum of equivalent masses approaches asymptotically to a value of about 83% of the total water mass. The lack of convergence to total water mass is inherent in the simple model. Despite the deficiency, the calculated fundamental period agrees well with that calculated from an equation derived differently by Fujuno and Sun ("Vibration Control by Multiple Tuned Liquid Dampers", ASCE Structural Journal, Vol. 119, No.12, Dec. 1993, page 3482-3502):
The substitution of \( h_w = 3 \text{ in.} \) and \( L_w = 360 \text{ in.} \) and \( g = 386.2 \text{ in/s/s} \) into Eqn. (b) gives a fundamental period of \( T_w = 42.3 \text{ sec} \) which is very close to that obtained from the Housner's model. For practical design, however, we suggest the use of a mass \( M_{w_1} \) as rigidly attached to the building as given by Eqn. (c) below. In our example, that becomes 17% of the total water mass instead of the mass calculated from Eqn. 1 of the Housner's model. Such an approach would lead to a conservative design for the building and is justified by the lack of experimental data on the dynamic characteristics of such system.

\[
M_{w_0} = (1 - \frac{0.83 \tanh 1.6 \frac{h_w}{L_w}}{1.6 \frac{h_w}{L_w}}) M_w \quad (c)
\]

2. The non-participatory nature of the water in the CSR system as a result of a large separation of the fundamental periods of water and building can also be expected in irregular buildings. Since the water is shallow relative to the plan dimensions of the building, the sloshing periods of the water will not be very sensitive to the shape of the building. For example, Reference 1 of our Report gives the following Eqns. for approximating the fundamental periods of shallow water tanks:

For rectangular tank:

\[
T_w \approx 1.25 \frac{L_w}{\sqrt{h_w}} \quad (d)
\]

and for cylindrical tank:

\[
T_w \approx 1.07 \frac{R}{\sqrt{h_w}} \quad (e)
\]

where \( R = \text{radius of the cylindrical tank} \). It should be noted that Eqns. (d) and (e) are unit-specific and requires meters for \( L_w, h_w \) and \( R \). Although Eqn. (d) and (e) give a 17% difference in the fundamental periods between a rectangular and cylindrical tank, the smaller period in a cylindrical tank is still significantly larger than the fundamental period of the building. Thus one can expect the water in the CSR system to remain non-participatory in irregular buildings.
Figure 1: Sum of water masses versus Length/Depth Ratio of Rectangular Tank

Figure 2: Variation of Fundamental Period of Water in Rectangular Tank
3. Obstruction of water movement by vertical projections required for the normal operation of CSR system (e.g. piping or mechanical devices) is expected during the lateral response of the building during an earthquake. However, in order to significantly reduce the fundamental period of the water to within the practical period range of the building, the obstruction has to be severe. Figure 2 shows the variation of the fundamental period of water in a rectangular tank as a function of the dimensions of the tank. It can be seen from Figure 2 that for the period to be in the region of the building period, the length of the tank had to be extremely small. Unless the obstruction caused by the vertical projections in the CSR system approaches that of two very closely-spaced walls, which is not expected in this case, we do not believe the reduction of fundamental period of water by vertical projections would be significant.

4. The influence of water on building design should be treated as a separate load case in addition to all other load cases required for a complete design. In the load case where water is considered to be present, the weight of the water can be included as contributing to a stabilizing moment against overturning. In case of rupture in the roof membrane, the design of the structure simply reverts back to the design of the structure assuming no water is present for gravity or lateral forces.

- **Review by Buehler and Buehler - Letter of Jan 9, 1995**

1. We are in agreement with the reviewer that the unaccounted mass in Housner’s model should be treated as a mass rigidly attached to the building. For the example in our report, the unaccounted mass is 17% of the total water mass. A short discussion of this issue has been addressed in our response to MBAK on previous pages.

2. The second question raised by reviewer is related to gravity load design which was studied earlier by B&B independent of ours. Our prime objective was to address the seismic issues related to use of CSR system in low-rise building. We have not considered gravity load design which obviously is important for the overall design of the building. We are therefore unable to comment on the use of additional live load for roof design.

If you have further questions or comments, please do not hesitate to call us.

Sincerely

Y. H. Chai, Ph.D.
1441 Farragut Circle
Davis, CA 95616

Karl M. Romstad, Ph.D.
621 Buchanan Street
Davis, CA 95616
January 9, 1995

Mr. Dick Bourne  
Davis Energy Group  
123 C Street  
Davis, CA 95616

Dear Dick:

We have reviewed the study by Professors Romstad and Chai regarding the seismic effect for the white cap system on a theoretical building system. We have also read the letter by MBAK Code Design to the City of Davis Building Department and have the following comments.

The Romstad/Chai study leaves unaccounted a percentage of the total mass of the water. We concur with MBAK that further effort should be performed to determine how much participation the transitional layer has on the "rigidly attached" portion of the water mass. Until such work is performed we recommend using all of the transitional layer as additive to the "rigidly attached" portion of the water mass. While this is obviously a conservative approach, we believe that it is more important for this particular project to move forward than stagnate over a 20% increase in the overall roof lateral load. The increase in building cost will probably be insignificant.

The other issue to be considered regards the classification of the water weight as dead or live load. We have reviewed a number of possible loading scenarios and believe that there is merit to considering the water weight as live load in lieu of the conventional live load. Most of this concept is based on the buoyancy theory whereby any transitory load on the roof panels dissipates an equivalent weight in water ballast. Therefore, the net effect on the structure is insignificant. Since this point of view sees the water as neither dead nor live load but something in between, it will be difficult to gain immediate approval. For that reason we recommend for this particular project that the standard live load be used in addition to the water weight. While this is again the most conservative approach we feel that anything less would raise doubts and therefore slow the project permit process. Our recommendation is based in part on our review of the framing system designed by The Phillips Group and have found that with some minor modifications the additional roof weight could be handled at very little additional cost.
In conclusion, we recommend based on Romstad/Chai's study that 17% of the water mass be used in the lateral design of the building. Additional 15 psf of vertical dead load should be added to the original roof loads. Both of these additions are fairly minor and the cost impact relative to the original design should be minimal. If you have any further questions or comments please do not hesitate to call.

Very truly yours,

Eric A. Fuller
BUEHLER & BUEHLER ASSOCIATES
Structural Engineers, Inc.
December 20, 1994

City of Davis Building Department
Attention: Lorin Gardner, Building Official
23 Russell Boulevard
Davis, California 95616

RE: "COOL STORAGE" ROOF SYSTEM
MBAK PROJECT NO. 94-027-131/A
R1


Lorin:

We have reviewed the above referenced study and have the following comments concerning the application of the study's conclusions. It is important to understand at this time our office has only verbal descriptions of the building intending to utilize this study's concepts; any conclusions as to the applicability of this study to a specific building should be reviewed and confirmed through the authors of the study.

The main conclusion of the study is the water contained within the roof system is non-participatory insofar as seismic lateral load contribution to the building structure is concerned [RE Study: Section 4, page 10, Section 6, page 10]. This conclusion is based on the large difference in fundamental periods of the water and the structure; the fundamental period of the structure is much shorter than that of the contained water on the roof. Therefore, the majority of the water mass is not "excited" by the vibration of the structure below due to induced seismic motion.

We have the following comments concerning the conclusions of the report:

1. Section 2 (page 2) of the Study differentiates between water in the roof system which is part of the vibratory model, and water which is assumed to be "rigidly attached" to the "tank" (the "tank" in this study represents an open surface water tank and is intended to model the Cool Storage roof system). The term $M_{w1}$ represents the portion of the water which is dynamically involved; that term is calculated to be $0.83M_w$, where $M_w$ is the total mass of the water. In other words, 83% of the total water mass is not attached to the tank (roof) and, according to the Study, does not contribute to the seismic lateral load of the building. The portion of the water which is rigidly attached to the tank, defined as $M_{w0}$, is calculated to be $0.0049M_w$, or less than 1% of the total water mass.

(cont'd)
There appears to be about 16% of the water mass involved in a transitory fluid layer, not rigidly attached nor dynamically separated from the structure. The conclusion of the Study does not address this part of the water model. It would be prudent for the design engineer to either include this portion of the water mass in the seismic lateral load calculation or confirm with the authors what fraction of this water mass might be included in determining the seismic load to the building and why.

2. The building structure in the Study which was analyzed and compared to the water model was a very regular, rectangular low rise (18' high) structure with lateral load resisting elements evenly proportioned around the perimeter of the building [RE Study: page 4]. We understand the structure proposed to incorporate this design Study is irregular in plan by definition [UBC 2333(e)3]. The water tank model assumed in the Study does not consider any plan irregularities. What impact a reentrant corner building plan would have on the Study's conclusions is not addressed. We recommend the authors of the Study be consulted as to the applicability of the Study to an irregular building plan.

3. The Study models the water-roof interface as a smooth continuous surface with no irregularities [RE Study: page 1]. In the actual building construction, vertical projections arising from the roof surface (pipes, mechanical equipment, vents, etc.) would create local areas of direct structure-water interface where the sloshing of water would be initiated directly by the structure. In these situations the fundamental frequency of the free water mass (now estimated in the 10-45 second region) would begin to approach the structure's fundamental frequency because of a direct pushing of the water mass by portions of the structure. No provisions in the Study have accounted for these local disturbances in an otherwise assumed flat smooth roof surface.

4. Using the weight of the water to favorably resist overturning moments in any of the lateral load resisting elements should be critically reviewed. The possibility of a rupture in the roof membrane during a seismic event and the likely recurrence of the seismic event (i.e. aftershock) would preclude the use of the dead load of water to contribute to the lateral stability of the building, including dead load resisting moment contribution. This aspect of seismic design is not discussed in the Study, but is a crucial element to the lateral design of the structure.

The referenced Study addresses an issue which significantly lowers the static lateral load for seismic design in buildings using this roof system. The UBC does not specifically define "dead loads," and a mandate to absolutely use the full dead weight of water on a roof in seismic design is not present in the Uniform Building Code or other related documents (ASCE 7-88, e.g.). The theory put forth in the referenced Study is based on fundamental dynamic theory and seems to properly relate, in an ideal sense, the interaction of the structure with the water held on the roof. However, it is beyond our knowledge of the development of the static lateral force design procedure as defined in UBC 2334(h) to state with certainty that a portion of a building dead load can be neglected due to its dynamic properties.
As in any use of a study, it is important the application of the study’s recommendations be consistent with the assumptions made in that study. It would be appropriate to confirm with the authors, on a case by case basis, the seismic design criteria which is selected by the building’s structural design engineer. Approval of this design technique would be made under the guidance of sections 105 and 2303(b) of the 1991 Uniform Building Code.

Please let me know if you have any questions.

Sincerely,

MBAK Code Design

Douglas S. Krug, C.E.
STRUCTURAL DESIGN METHODOLOGY
FOR BUILDINGS WITH THE WhiteCap ROOFING SYSTEM

Buehler & Buehler Associates
Structural Engineers, Inc.

March 1995
Introduction
The WhiteCap system introduces new technology which builds on earlier water ballast concepts of the 70's and 80's. The system comprises 2 foot by 8 foot interlocking extruded foam sheets which float over a 3-inch layer of water. This layer of water is not closed as in early designs, but cools the building by absorbing heat during the day and then cooling the water by spraying it on the roof panels at night. The water filters through the foam sheets back into the water layer below, ready for another day's cooling load. Because the exposed roof surface floats, new concepts about loading need to be discussed and new design methodologies developed. We intend to show that no roof live load is required and that the lateral load of the water can be substantially reduced.

Vertical Loads
The WhiteCap system is located above the roof of a building; for that reason we will be discussing the system's effect on roof structure for vertical load. In general, the roof framing systems we will be considering may comprise wood, steel or concrete members, and will always be designed as totally flat.

Vertical loads on roofs are presently divided into two categories: dead and live. Dead load is weight which does not change over the life of the structure and generally includes the following:

1. The roofing system.
2. The roof structural system.
3. The ceiling system (including lighting).
4. Roof supported or suspended mechanical, electrical and plumbing.
Live loads are transient loads which occur for varying lengths of time, such as water ponding on the roof, stacked roofing materials stored during construction, or maintenance/fire personnel and their equipment.

The WhiteCap system load falls somewhere between the classic definitions of dead and live load. While the system imposes load constantly for the life of the structure, it also compensates for any additional load above and beyond its own imposed weight. This characteristic is due to the buoyant nature of the roof panels. When superimposed load is applied to the panels, they displace an equivalent amount of water which is carried off through drains which regulate the water level. The drainage of water to compensate for "conventional" live load yields no net effect on the framing system. Large concentrated loads such as construction loads or mechanical unit loads need to be considered in the same manner for the WhiteCap system as for conventional roofs. Construction loads are applied before the water is added and therefore the use of the WhiteCap system does not affect this load condition. Mechanical units are placed on curbs just as in conventional roofs and would require the same additional analysis and framing capacity as for a conventional roof. When considering the load due to rain there are very few differences between the WhiteCap system and conventional drainage systems. The water level is maintained right at the level of the drains due to the operation of the system itself. Therefore, additional rain water is immediately carried off through the standard storm drain system. When the standard drains do not have enough capacity to absorb the load of heavy rainfall, water will accumulate until the level of the overflow drains are reached. In the WhiteCap system this additional height is accurately set at \( \frac{1}{4} \) inch. The total water height during heavy rainfall would be 3½ inches to include water moving to the drains, and the corresponding weight would be 19½ pounds. This load is still below the typical 20 pound live load of conventional roofs. In summary, vertical superimposed loads are accommodated by buoyancy of the panels, precluding the application of conventional live load to the structural system. Also, rain on the roof triggers the drain system before the 20 psf design load is exceeded.

Additional areas of concern are structural member creep and differential settlement. Both wood and concrete are subject to creep, while steel (in the elastic range) is not. In order to compensate for the long term deflection additional camber can be added to members. The Uniform Building Code (UBC) standard method for wood roof members is to camber for one-and-one-half times the dead
load deflection. This standard would still be applicable on the WhiteCap system using the higher dead load of the total system. Differential settlement is a concern for any structural system. The WhiteCap system is especially susceptible to differential movement because the water depth would increase at the low spots thereby causing additional load at the very location the structure is subsiding due to vertical load. To address this concern, the WhiteCap system is equipped with depth indicators which are monitored every six months as part of a standard maintenance agreement between Roof Science Corporation and the building owner. Were differential settlement exceeding ½ inch to occur, the affected roof area would be releveled to eliminate the additional water.

Lateral Loads

Typical design lateral loads on building are categorized as wind or seismic. As far as wind is concerned, the application of WhiteCap system could actually reduce lateral loading. Wind loads are proportional to the vertical projected area; for a roof which is totally flat the vertical projection could be reduced as compared to a conventional low slope roof. Seismic loads, on the other hand, are based on building mass. The effect of WhiteCap on building mass and thus on seismic load has been addressed by the Chai/Romstad study of April 1994, and supplemental letter of February 6, 1995. The study develops a model based on the concept of a shallow water body with an open surface. The mathematical model concluded that the vast majority of the water mass could be neglected when deriving the seismic dead load of a building. The simplicity of the model used by Chai/Romstad, however, leaves unaccounted for approximately seventeen percent of the total water mass. For this reason, we have taken a conservative approach and considered the entire seventeen percent as seismically reactive dead load. The study considers further the effect of irregular shaped buildings, obstructions in the body of the free pond and extrapolation of the model to other combinations of building period versus water mass period. All of these variables were considered inconsequential to the validity of the model because of the large difference between the fundamental periods. We believe that the Chai/Romstad study is valid, and we recommend its findings as the basis for the seismic design of buildings using the WhiteCap system.

Recommendations

Our recommendations for the structural design of buildings utilizing WhiteCap incorporate the concepts noted above, and use the UBC as a basis for design. For vertical load, standard UBC
design dictates that a twenty pound roof live load be used in addition to the roof dead loads. The WhiteCap system with its buoyant roofing (which weighs slightly less than twenty pounds per square foot) should be considered as additional dead load for design of the structural members. However, we recommend that no live load be applied in addition to the standard roof dead load and twenty pound WhiteCap load. As discussed earlier, the water drains off as superimposed “live load” is added, thereby causing no net effect on the structure. For the specific case of wood framed roofs we further recommend that a load duration factor of 0.9 be used as mandated by the UBC for consideration of dead load alone. As for deflection, we recommend using the total load of the roof as the basis for deflection calculations. For wood and concrete structures, beams which are cambered should be based on 150 percent of the total load deflection to account for creep. Steel structures should be cambered using the actual dead load deflections as no creep need be accounted for in elastic steel design. Also, for foundation design we suggest that the design engineer use similar soil pressures on all foundation elements so that differential settlement is minimized, to help mitigate the special sensitivity of the WhiteCap system to differential settlement.

Lateral loads should be derived using the standard UBC static or dynamic provisions as applicable to the specific building. The roof dead load for determining mass should be based on the typical dead loads as discussed earlier, plus seventeen percent of the weight of the water. Considering the standard 3 inch depth, this equates to an additional 2.6 pounds per square foot. This recommendation is based on the conservative conclusion of the Chai/Romstad study that all water which is not totally free must be considered totally fixed. The recommendations above, in our opinion, will yield a structural design which will provide performance consistent with standard UBC designs. We further believe that structural systems incorporating WhiteCap will provide factors of safety equivalent to designs utilizing standard design concepts.

Conclusion
The use of new technology in building systems has historically been met with some resistance. However, through diligence and proper research new concepts have been integrated into the design vocabulary. We hope that this report will act as stepping stone toward the acceptance of WhiteCap within the architectural and engineering communities.
References

