Economic Application of Post-Tensioning
In Korean Residential Building

- Alternative Application of Post-Tensioned Floor System –
  (RC Slab vs. PT Slab vs. PT Void Slab)

2012. 5. 8

DAELIM Industrial Co., Ltd.
ADAPT Corporation

2012 PTI Convention
[Part 1] Post-Tension Design Proposal in Korea

1) Residential Buildings in Korea
2) Economic Application of Post-Tensioning
3) Sustainable Application of Post-Tensioning
   (Post-Tensioned Void Slab)

[Part 2] Evaluation of Alternative PT Floor System

1) Post-Tensioned Void Slab Design Method
2) Alternative Application of Post-Tensioning
3) Evaluation of Economic Efficiency
4) Evaluation of Structural Performance
[Part 1] Post-Tension Design Proposal in Korea

DAELIM
Jang Keun Yoon / Manager/ Korean P.E
1) Residential Buildings in Korea
**Residential Buildings in Korea**

- **Typical Residential Buildings**

**DAELIM Apartment**

- **Location**: Kimpo, Gyeonggi-do
- **Occupancy**: Residential Apartment
- **Gross Area**: 198,456m²
- **No of Block**: 14 Apartments
- **Bldg Story**: 20~30F
- **Bldg Height**: 60~90m
- **Lateral Resist**: Shear Wall System
- **Floor Type**: RC Flat Plate
- **Architect**: Haeahn Architecture
- **Construction**: DAELIM Co., Ltd
- **Const’ Period**: Jan 2010 ~ July 2012
Residential Buildings in Korea

**Apartment Complex**

- *Chunan Project* (11 Block, 2011~2013)
- *Sindang Project* (13 Block, 2009~2011)
- *Buchun Project* (8 Block, 2009~2011)
- *Dangjin Project* (10 Block, 2008~2010)
- *Osan Project* (19 Block, 2008~2010)

More than 100 Projects
(Daliem, since 1998)
Residential Buildings in Korea

Recent Change of the Structural System

[Past] RC Shear Wall System

[Present] RC Column System

Why Column Type?

1) Flexible → Easy to Renovate
2) Sustainable → Long Life House
3) Eco-friendly → Reduce CO₂ Emission
4) Serviceable → Reduce Noise Transmission

< Prototype Building >
Residential Buildings in Korea

- **Increase of the Floor Span**

  - [Present] Short Span (5~6m)
  - [Future] Long Span (9~10m)

  - Remove Interior Column

- Why Long Span Floor?

  1. Provide Open Space with Fewer Columns
  2. Improve Constructability
  3. Save Construction Time
  4. Reduce Concrete Volume (Reduce CO₂)

- Why Long Span Floor?

  - 210 mm (8 ¼ in) SLAB

- Why Long Span Floor?

  - 210 mm (8 ¼ in) SLAB

- Why Long Span Floor?

  - 210 mm (8 ¼ in) SLAB

- Why Long Span Floor?

  - 210 mm (8 ¼ in) SLAB

- Why Long Span Floor?

  - 210 mm (8 ¼ in) SLAB

Wooden Floor Cover

- THK 45mm : Cement Mortar (Heating Coil)
- THK 45mm : Lightweight Aerated Concrete (Insulation)
- THK 20mm : Cushioning material (Soundproof)
- THK 210mm : RC SLAB

< Standard Floor, Korean MLTMA >

* MLTMA : Ministry of Land, Transport and Maritime Affairs
Residential Buildings in Korea

- **Post-Tensioning Solution**

  1. **Reduced Floor Height**
     - Maintain Typical 2.8m Height

  2. **Longer Span**
     - 210mm PT Flat Plate → \( L = 9.5m \) \((L/45)\)

  3. **Lesser Weight**
     - Reduce \( CO_2 \) Emission
     - Improve Seismic Performance

  4. **Improved Durability**
     - Reduce Crack & Deflection

  5. **Saving Material & Money**
     - Reduce Concrete and Rebar Quantity

< Post-Tensioned Slab System >
2) Economic Application of Post-Tensioning
[CASE STUDY] Typical 20F Residential Building

* Completed by DAELIM in 2011

< Typical Floor of Apartment >

< RC Column Plan >
[ALT 1] Reinforced Concrete SLAB
(Thk = 210mm, Span = 6.0m)

- Con’c : 57m³ (21MPa)
- Rebar : 5.25tonf

Interior Columns : 4EA
Exterior Columns : 3EA

< Rebar Layout >

< MIDAS ADS Model >
[ALT 2] Reinforced Concrete SLAB
(Thk = 250mm, Span = 7.9m)

Remove Interior Columns (4EA)

- Con’c : 68m³ (21MPa)
- Rebar : 6.35tonf

< Rebar Layout >

< MIDAS ADS Model >
[ALT 3] Post-Tensioned SLAB  
(Thk = 210mm, Span = 8.3m)

- **Concrete**: 57m³ (30MPa)
- **Rebar**: 2.93tonf
- **Tendon**: 0.73tonf

Remove Interior Column (4EA)
Remove Exterior Column (2EA)

< Tendon Layout >

< MIDAS ADS Model >
Economic Application of Post-Tensioning

[ALT 3] Post-Tensioned SLAB
(Thk = 210mm, Span = 8.3m)

Δmax = 16.0mm < L/480 = 17.3mm → O.K
### Tendon & Rebar Price Ratio in Many Countries

**[unit : USD]**

<table>
<thead>
<tr>
<th>Region</th>
<th>Tendon</th>
<th>Rebar</th>
<th>Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Swiss</td>
<td>11,100</td>
<td>1,550</td>
<td>7.2</td>
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<tr>
<td>Korea</td>
<td>4,550</td>
<td>890</td>
<td>5.1</td>
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<tr>
<td>Middle East</td>
<td>3,805</td>
<td>800</td>
<td>4.8</td>
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<tr>
<td>Spain</td>
<td>5,472</td>
<td>1,176</td>
<td>4.7</td>
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<tr>
<td>Vietnam</td>
<td>3,300</td>
<td>850</td>
<td>3.9</td>
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<tr>
<td>Hong Kong</td>
<td>4,260</td>
<td>1,160</td>
<td>3.7</td>
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<tr>
<td>Malaysia</td>
<td>3,333</td>
<td>1,167</td>
<td>2.9</td>
</tr>
<tr>
<td>Singapore</td>
<td>3,499</td>
<td>1,229</td>
<td>2.8</td>
</tr>
<tr>
<td>USA</td>
<td>3,800</td>
<td>1,350</td>
<td>2.8</td>
</tr>
<tr>
<td>Thailand</td>
<td>2,667</td>
<td>1,000</td>
<td>2.7</td>
</tr>
</tbody>
</table>

*Price include Material & Labor Costs (per ton)*

#### Cost of Rebar vs. Tendon

![Graph showing cost comparison between Tendon and Rebar in various countries]
Construction Cost Comparison in USA Market

- Tendon: 3,800 USD → 2.8 Times
- Rebar: 1,350 USD

<table>
<thead>
<tr>
<th>Structural Member &amp; Material</th>
<th>Slab System</th>
</tr>
</thead>
<tbody>
<tr>
<td>Slab</td>
<td></td>
</tr>
<tr>
<td>Concrete</td>
<td>2228 m³</td>
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<tr>
<td>Form</td>
<td>10800 m²</td>
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<tr>
<td>Rebar</td>
<td>210 tonf</td>
</tr>
<tr>
<td>Tendon</td>
<td></td>
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<tr>
<td>Column</td>
<td></td>
</tr>
<tr>
<td>Concrete</td>
<td>281 m³</td>
</tr>
<tr>
<td>Form</td>
<td>1921 m²</td>
</tr>
<tr>
<td>Rebar</td>
<td>65 tonf</td>
</tr>
<tr>
<td>Exterior Wall</td>
<td></td>
</tr>
<tr>
<td>Concrete</td>
<td>1128 m³</td>
</tr>
<tr>
<td>Form</td>
<td>11923 m²</td>
</tr>
<tr>
<td>Rebar</td>
<td>65 tonf</td>
</tr>
<tr>
<td>Interior Wall</td>
<td></td>
</tr>
<tr>
<td>Concrete</td>
<td>313 m³</td>
</tr>
<tr>
<td>Form</td>
<td>4640 m²</td>
</tr>
<tr>
<td>Rebar</td>
<td>19 tonf</td>
</tr>
</tbody>
</table>

< Material Quantity for 20F Building >
### Economic Application of Post-Tensioning

#### Construction Cost Comparison in Korean Market

**Tendon**: $4,550 USD → 5.1 Times

**Rebar**: $890 USD

<table>
<thead>
<tr>
<th>Structural Member &amp; Material</th>
<th>Slab System</th>
<th>Slab</th>
<th>Column</th>
<th>Ext. Wall</th>
<th>Int. Wall</th>
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</thead>
<tbody>
<tr>
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<td>2282 m³</td>
<td>2717 m³</td>
<td>2282 m³</td>
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<tr>
<td>Form</td>
<td>10800 m²</td>
<td>10800 m²</td>
<td>10800 m²</td>
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<td></td>
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<tr>
<td>Rebar</td>
<td>210 tonf</td>
<td>254 tonf</td>
<td>117 tonf</td>
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<tr>
<td>Tendon</td>
<td></td>
<td></td>
<td>29 tonf</td>
<td></td>
<td></td>
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<tr>
<td>Concrete</td>
<td>281 m³</td>
<td>532 m³</td>
<td>433 m³</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Form</td>
<td>1921 m²</td>
<td>3382 m²</td>
<td>2787 m²</td>
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<tr>
<td>Rebar</td>
<td>65 tonf</td>
<td>72 tonf</td>
<td>59 tonf</td>
<td></td>
<td></td>
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<tr>
<td>Exterior Wall</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Concrete</td>
<td>1128 m³</td>
<td>1102 m³</td>
<td>1010 m³</td>
<td></td>
<td></td>
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<tr>
<td>Form</td>
<td>11923 m²</td>
<td>11657 m²</td>
<td>10658 m²</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rebar</td>
<td>65 tonf</td>
<td>64 tonf</td>
<td>79 tonf</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Interior Wall</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Concrete</td>
<td>313 m³</td>
<td>271 m³</td>
<td>389 m³</td>
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<tr>
<td>Form</td>
<td>4640 m²</td>
<td>4045 m²</td>
<td>5752 m²</td>
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<tr>
<td>Rebar</td>
<td>19 tonf</td>
<td>16 tonf</td>
<td>21 tonf</td>
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<td></td>
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</table>

< Material Quantity for 20F Building >
SUMMARY

1) Slight increase in construction cost by Post-Tensioning in Korean market can be negligible. (+0.8%)

2) [ALT 3] Post-Tensioned Slab can be good alternative floor system for Residential Buildings in Korea.
   - Provide more open span with longer span 8.3m
   - Maintain the same slab depth 210mm with conventional design [ALT 1]
   - Maintain the same floor height 2.8m with conventional design [ALT 1]

3) In the future, it seems like that increasing demand for Post-Tensioning can lower the tendon price, thereby Post-Tensioning can be more competitive in Korea.
3) Sustainable Application of Post-Tensioning
Sustainable Application of Post-Tensioning

- **Void Slab System**

![Diagram of void slab system](image)

*Image by Cobiax*

### Benefits

**Weight Reduction**
- Lighter than Solid Slab
- Reduce Floor-to-Floor Height
- Reduce Load Acting On Foundation

**Sustainability**
- Save Building Material (Concrete & Rebar)
- Reduce CO₂ Emission
- Use of Recycled Material (Plastic Ball)

### Weakness

- **Span Length Limitation (Bubble Deck)**

<table>
<thead>
<tr>
<th>Type</th>
<th>SLAB Thk</th>
<th>Bubble</th>
<th>Span</th>
</tr>
</thead>
<tbody>
<tr>
<td>BD 230</td>
<td>230mm</td>
<td>Φ180</td>
<td>5 - 8.1m</td>
</tr>
<tr>
<td>BD 280</td>
<td>280mm</td>
<td>Φ225</td>
<td>7 - 10.1m</td>
</tr>
<tr>
<td>BD 340</td>
<td>340mm</td>
<td>Φ270</td>
<td>9 - 12.5m</td>
</tr>
</tbody>
</table>
- **Post-Tensioned Slab + Void Slab**

  - **Post-Tensioned Slab**
    - Slimmer (Long Span)
    - 210mm PT Flat Plate $\rightarrow$ L=9.5m (L/45)

  - **Void Slab**
    - Lighter (Less Weight)
    - 210mm Void Slab $\rightarrow$ L=6.5m (L/30)

---

**Post-Tensioned Void Slab System**

*Sustainable Green Technology*
How to model & analyze PT Void Slab?

- **Concrete Reduction**
  \[ \frac{V}{V_e} = 77\% (-23\%) \]

- **Stiffness Reduction**
  \[ \frac{I}{I_e} = 91\% (-9\%) \]

**Equivalent Slab Modeling Method**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Void Slab</th>
<th>Equivalent Slab</th>
</tr>
</thead>
<tbody>
<tr>
<td>Concrete Strength</td>
<td>( f'c )</td>
<td>( f'c )</td>
</tr>
<tr>
<td>Width</td>
<td>( b )</td>
<td>( b )</td>
</tr>
<tr>
<td>Depth</td>
<td>( h )</td>
<td>( h )</td>
</tr>
<tr>
<td>Section</td>
<td>( A )</td>
<td>( A_e )</td>
</tr>
<tr>
<td>Volume</td>
<td>( V )</td>
<td>( V_e )</td>
</tr>
<tr>
<td>Moment of Inertia</td>
<td>( I )</td>
<td>( I_e )</td>
</tr>
<tr>
<td>Unit Weight</td>
<td>( W )</td>
<td>( W_e = \frac{V}{V_e} W )</td>
</tr>
<tr>
<td>Modulus of Elasticity</td>
<td>( E )</td>
<td>( E_e = \frac{I}{I_e} E )</td>
</tr>
</tbody>
</table>

Reduction Property:

- Concrete Reduction
  \[ \frac{V}{V_e} = 77\% (-23\%) \]
- Stiffness Reduction
  \[ \frac{I}{I_e} = 91\% (-9\%) \]
Sustainable Application of Post-Tensioning

[Ref.] Free Vibration Test of Void Slab (Dr. Kyoung-Kyu Choi, Soongsil Univ, Korea)

< Slab Section with Ellipsoid Ball >

< Isometric Ellipsoid Ball >
[Ref.] Free Vibration Test of Void Slab  
(Dr. Kyoung-Kyu Choi, Soongsil Univ, Korea)

<table>
<thead>
<tr>
<th>Slab Thick (mm)</th>
<th>Plastic Ball (mm)</th>
<th>Concrete Reduction</th>
<th>Damping Ratio</th>
<th>Frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td>210</td>
<td>Ellipsoid, $\Phi 170 \times H110$</td>
<td>-23 %</td>
<td>0.8 %</td>
<td>21.6 Hz</td>
</tr>
</tbody>
</table>

< Acceleration-Time History >

< Natural Frequency by FFT >

* FFT : Fast Fourier Transformation
- Verification (Test Result vs. Analysis Result)

<table>
<thead>
<tr>
<th></th>
<th>Void Slab</th>
<th>Solid Slab</th>
</tr>
</thead>
<tbody>
<tr>
<td>Isometric View</td>
<td><img src="image1" alt="Isometric View of Void Slab" /></td>
<td><img src="image2" alt="Isometric View of Solid Slab" /></td>
</tr>
<tr>
<td>Unit Weight (kN/m²)</td>
<td>( W_e = 1.85 ) (77%)</td>
<td>( W = 24 )</td>
</tr>
<tr>
<td>Modulus of Elasticity</td>
<td>( E_e = 27,099 ) (91%)</td>
<td>( E = 29,779 )</td>
</tr>
</tbody>
</table>

- Free Vibration Test Result: 21.6 Hz
- Free Vibration Analysis Result: 21.7 Hz

(Equivalent Slab Modeling Method)
[Part 2] Alternative Application of PT Floor System

ADAPT
Florian Aalami / President / Ph.D.
1) Post-Tensioned Void Slab Design Method
### Void Slab System with Plastic Ball

1) **SLAF System, Korea**

2) **Cobiax, Switzerland**

3) **Bubble Deck, Denmark**

<table>
<thead>
<tr>
<th>Property</th>
<th>Void Slab</th>
<th>Property</th>
<th>Void Slab</th>
<th>Property</th>
<th>Void Slab</th>
</tr>
</thead>
<tbody>
<tr>
<td>Slab Depth</td>
<td>210mm</td>
<td>Slab Depth</td>
<td>210mm</td>
<td>Slab Depth</td>
<td>210mm</td>
</tr>
<tr>
<td>Plastic Ball</td>
<td>Φ170 x H110</td>
<td>Plastic Ball</td>
<td>Φ100</td>
<td>Plastic Ball</td>
<td>Φ100</td>
</tr>
<tr>
<td>Unit Weight</td>
<td>$W_e = 0.77 , W$</td>
<td>Unit Weight</td>
<td>$W_e = 0.85 , W$</td>
<td>Unit Weight</td>
<td>$W_e = 0.85 , W$</td>
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<td>Modulus of Elasticity</td>
<td>$E_e = 0.91 , E$</td>
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<td>$E_e = 0.95 , E$</td>
<td>Modulus of Elasticity</td>
<td>$E_e = 0.95 , E$</td>
</tr>
</tbody>
</table>

*Ellipsoid Ball*  
*Sphere Ball*  
*Sphere Ball*
Post-Tensioned Void Slab Design Method

- How to Analyze and Design the PT Void Slab?

[6 STEP] Post-Tensioned Void Slab Design

1. Void Slab Modeling
2. Design Load Input
3. Tendon Layout
4. Structural Analysis
5. Design Strip Modeling
6. Allowable Stress Check

Tendon

Void Slab
[STEP 1] Void Slab Modeling

[CASE 1] Ellipsoid Ball (Φ170 x H110)

- **Calculate Section Change**
  \[ A_e = 200 \times 210 = 42,000 \text{mm}^2 \]
  \[ A = A_e - 16,103 = 25,897 \text{mm}^2 \]

- **Calculate Volume Change**
  \[ V_e = 130 \times 130 \times 210 = 3,549,000 \text{mm}^3 \]
  \[ V = V_e - 523,599 = 3,025,401 \text{mm}^3 \]

- **Calculate Stiffness Change**
  \[ l_e = 130 \times 210^2 / 12 = 100,327,500 \text{mm}^3 \]
  \[ l = l_e - 4,908,739 = 95,418,761 \text{mm}^3 \]
[STEP 1] Void Slab Modeling

[CASE 1] Ellipsoid Ball (Φ170 x H110)

- Reduced Weight: $W_e = \frac{V}{V_e} \times W$
  
  \[ = 0.77 \times 2,400 \text{kgf/m}^3 = 1,848 \text{kgf/m}^3 \]

- Reduced Stiffness: $E_e = \frac{I}{I_e} \times E (= 8,500 \times 3 \sqrt{f_{ck} + 8})$
  
  \[ = 0.91 \times 28,577 \text{MPa} = 26,005 \text{MPa} \]
**Post-Tensioned Void Slab Design Method**

### [STEP 1] Void Slab Modeling

#### < Sphere Ball >

### [CASE 2] Sphere Ball (Φ100)

- **Isometric View**
- **Equivalent Slab Representation**

- **Calculate Section Change**
  \[
  A_e = 130 \times 210 = 27,300 \text{ mm}^2 \\
  A = A_e - 7,854 = 19,446 \text{ mm}^2
  \]

- **Calculate Volume Change**
  \[
  V_e = 200 \times 200 \times 210 = 8,400,000 \text{ mm}^3 \\
  V = V_e - 1,903,594 = 6,496,406 \text{ mm}^3
  \]

- **Calculate Stiffness Change**
  \[
  I_e = 200 \times 210^2 / 12 = 154,350,000 \text{ mm}^3 \\
  I = I_e - 13,841,884 = 140,508,116 \text{ mm}^3
  \]

<table>
<thead>
<tr>
<th>Calculation</th>
<th>Formula</th>
<th>Result</th>
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<tbody>
<tr>
<td>Section Change</td>
<td>[A = A_e - 7,854]</td>
<td>19,446 mm²</td>
</tr>
<tr>
<td>Volume Change</td>
<td>[V = V_e - 1,903,594]</td>
<td>6,496,406 mm³</td>
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<tr>
<td>Stiffness Change</td>
<td>[I = I_e - 13,841,884]</td>
<td>140,508,116 mm³</td>
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Post-Tensioned Void Slab Design Method

[STEP 1] Void Slab Modeling

< Sphere Ball >

[CASE 2] Sphere Ball (Φ100)

- Reduced Weight: \[ W_e = \frac{V}{V_e} \times W = 0.85 \times 2,400\text{kgf/m}^3 = 2,040\text{kgf/m}^3 \]

- Reduced Stiffness: \[ E_e = \frac{E}{E_c} = 0.95 \times 28,577\text{MPa} = 27,148\text{MPa} \]
### Design Load for Residential Building in Korea

<table>
<thead>
<tr>
<th>Room, Kitchen</th>
<th>Load</th>
<th>Material</th>
<th>THK</th>
<th>Floor Load</th>
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<tbody>
<tr>
<td>SDL</td>
<td>Partition Wall</td>
<td>-</td>
<td>1.5 ( \text{kN/m}^2 )</td>
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</tr>
<tr>
<td></td>
<td>Mortar</td>
<td>45mm</td>
<td>0.945 ( \text{kN/m}^2 )</td>
<td></td>
</tr>
<tr>
<td></td>
<td>ALC*</td>
<td>45mm</td>
<td>0.293 ( \text{kN/m}^2 )</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Sound Proof</td>
<td>20mm</td>
<td>0.04 ( \text{kN/m}^2 )</td>
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<tr>
<td>SW*</td>
<td>Equivalent Slab</td>
<td>210mm</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Toilet</td>
<td>SDL</td>
<td>Partition Wall</td>
<td>-</td>
<td>1.5 ( \text{kN/m}^2 )</td>
</tr>
<tr>
<td></td>
<td>Mortar</td>
<td>40mm</td>
<td>0.84 ( \text{kN/m}^2 )</td>
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<td>SW*</td>
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<td>LL</td>
<td></td>
<td>2.0 ( \text{kN/m}^2 )</td>
<td></td>
</tr>
<tr>
<td>Balcony</td>
<td>SDL</td>
<td>Mortar</td>
<td>110mm</td>
<td>2.31 ( \text{kN/m}^2 )</td>
</tr>
<tr>
<td></td>
<td>SW*</td>
<td>Equivalent Slab</td>
<td>210mm</td>
<td></td>
</tr>
<tr>
<td></td>
<td>LL</td>
<td></td>
<td>3.0 ( \text{kN/m}^2 )</td>
<td></td>
</tr>
<tr>
<td>ELEV. Hall</td>
<td>SDL</td>
<td>Terrazzo Finish</td>
<td>25mm</td>
<td>0.675 ( \text{kN/m}^2 )</td>
</tr>
<tr>
<td></td>
<td>Mortar</td>
<td>30mm</td>
<td>0.63 ( \text{kN/m}^2 )</td>
<td></td>
</tr>
<tr>
<td></td>
<td>SW*</td>
<td>Equivalent Slab</td>
<td>180mm</td>
<td></td>
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<tr>
<td></td>
<td>LL</td>
<td></td>
<td>3.0 ( \text{kN/m}^2 )</td>
<td></td>
</tr>
</tbody>
</table>

* SW (Self Weight) is automatically calculated by software

---

**Step 2**  
**Design Load Input**

- Wooden Floor Cover
  - THK 45mm: Cement Mortar / Panel Heating
  - THK 45mm: Lightweight Aerated Concrete
  - THK 20mm: Cushioning material (Sound Insulation)
  - THK 210mm: Equivalent SLAB

< Floor Section >
Post-Tensioned Void Slab Design Method

[STEP 3] Tendon Layout

Tendon

< Void Slab >

< Tendon Layout >

< Banded Tendon for Column Strip >
Post-Tensioned Void Slab Design Method

STEP 4: Structural Analysis

- Tendon
- Void Slab

< FEM Analysis >

\[ \delta_{\text{max}} = 10.3 \text{mm} < \frac{L}{480} \]

< Long-term Deflection >
Post-Tensioned Void Slab Design Method

[STEP 5] Design Strip Modeling

Support Line 1

Tendon

< Void Slab >

< Moment Diagram - Design Strip 1 >
Post-Tensioned Void Slab Design Method

**[STEP 6] Allowable Stress Check**

- **Tendon**
- **Support Line 1**
- **Void Slab**

**Stress Diagrams**
- Project General Case: Load Case 1 (Total Load)
  - 1.00 x Self-weight + 1.00 x Dead load + 1.00 x Live load + 1.00 x Processing

- **Tensile Stress Positive**

- **Bottom Stress - Design Strip 1**
  - $f_{M/2} = 1.81 + 0.72 = 2.53 \text{MPa}$

- **Average Prestress only - Design Strip 1**
  - $f_{P/A} = -0.72 \text{MPa}$
Post-Tensioned Void Slab Design Method

[STEP 6] Allowable Stress Check

Geometry of Solid Section Modeled in ADAPT

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Width (mm)</td>
<td>4,650</td>
</tr>
<tr>
<td>Depth (mm)</td>
<td>210</td>
</tr>
<tr>
<td>Asolid (mm²)</td>
<td>976,500</td>
</tr>
<tr>
<td>Isolid (mm⁴)</td>
<td>3,588,637,500</td>
</tr>
</tbody>
</table>

Geometry of Equivalent Void Section used to Check Stresses

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Radius 1 of Void (mm)</td>
<td>30</td>
</tr>
<tr>
<td>Radius 2 of Void (mm)</td>
<td>55</td>
</tr>
<tr>
<td>Height of Void (mm)</td>
<td>110</td>
</tr>
<tr>
<td># of Voids in section</td>
<td>17</td>
</tr>
<tr>
<td>A of Each Void (mm²)</td>
<td>16,103</td>
</tr>
<tr>
<td>Avoid (mm²)</td>
<td>702,744</td>
</tr>
<tr>
<td>I of Each Void (mm⁴)</td>
<td>13,841,884</td>
</tr>
<tr>
<td>Ivoid</td>
<td>3,353,325,471</td>
</tr>
</tbody>
</table>

Conversion Parameters

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Avoid/Asolid (A/Ae)</td>
<td>0.72</td>
</tr>
<tr>
<td>Ivoid/Isolid (I/Ie)</td>
<td>0.93</td>
</tr>
</tbody>
</table>
**Allowable Stress Check**

\[
\sigma = \frac{A_e}{A} \times \frac{f_{p/k}}{I} \pm \frac{I_e}{I} \times f_{m/z} < \text{Allowable Stress}
\]

Where, \( \frac{A_e}{A} = \frac{1}{0.72} = 1.39 \)
\( \frac{I_e}{I} = \frac{1}{0.93} = 1.07 \)

\[
\sigma = 1.39 \times (-0.72) + 1.07 \times (1.81 + 0.72) = 1.71 \text{MPa}
\]

Allowable Stress = \( 0.9 \times 0.5 \sqrt{f_{ck}} = 2.46 \text{MPa} \)

\[
\therefore \sigma = 1.71 \text{MPa} < 2.46 \text{MPa} \rightarrow \text{O.K}
\]

\(< \text{Ellipsoid Ball} > \)
2) Alternative Application of Post-Tensioning
Alternative Application of Post-Tensioning

[CASE STUDY] Tower Type Residential Building

< Typical Floor Plan >

Max. Span 9m
[ALT 1] Reinforced Concrete Slab (250mm)

**Design Information**

- **DESIGN CODE**
  - KBC 2009 (Ref. ACI 318-05)
- **MATERIAL**
  - Con’c : $f_{ck} = 21\text{MPa}$
  - Rebar : $f_{y} = 400\text{MPa}$
- **Cover to Rebar**
  - Rebar : 20mm
- **Mesh Reinforcement**
  - Top D10@200
  - Bot D13@250
- **Add Rebar**
  - Top & Bot D13

< Typical Floor - Rebar Layout >

- **Added Rebar**
  - A: D13x2000
  - B: D13x3000
  - C: D13x4000
  - D: D13x5000
[ALT 2] Post-Tensioned Slab (210mm)

**Design Information**

- **DESIGN CODE**
  - KBC 2009 (Ref. ACI 318-05)
- **MATERIAL**
  - $f_{ck} = 30$MPa
  - $f_y = 400$MPa
  - $f_{pu} = 1,860$MPa
- **Cover to Rebar/Tendon**
  - Rebar : 20mm
  - Tendon : 27mm
- **Prestressing Tendon**
  - Unbonded Mono-Strand Tendon
  - $\Phi 12.7$mm (99mm²)

*Typical Floor - Tendon Layout*
**Design Information**

- **DESIGN CODE**
  - KBC 2009 (Ref. ACI 318-05)

- **MATERIAL**
  - Conc’c : $f_{ck} = 30$MPa
  - Rebar : $f_y = 400$MPa
  - Tendon : $f_{pu} = 1,860$MPa

- **Cover to Rebar/Tendon**
  - Rebar : 20mm
  - Tendon : 27mm

- **Prestressing Tendon**
  - Unbonded Mono-Strand Tendon
  - $\Phi 12.7$mm (99mm$^2$)

< Typical Floor - Rebar Layout >
Alternative Application of Post-Tensioning

[ALT 3] Post-Tensioned Void Slab (210mm)

**Design Information**

- **DESIGN CODE**
  - KBC 2009 (Ref. ACI 318-05)
- **MATERIAL**
  - Con’c : $f_{ck} = 30$MPa
  - Rebar : $f_y = 400$MPa
  - Tendon : $f_{pu} = 1,860$MPa
- **Cover to Rebar/Tendon**
  - Rebar : 20mm
  - Tendon : 27mm
- **Prestressing Tendon**
  - Unbonded Mono-Strand Tendon
  - Φ12.7mm (99mm²)

< Typical Floor - Tendon Layout >
[ALT 3] Post-Tensioned Void Slab (210mm)

**Design Information**

- **DESIGN CODE**
  - KBC 2009 (Ref. ACI 318-05)

- **MATERIAL**
  - Con’c : $f_{ck} = 30$MPa
  - Rebar : $f_y = 400$MPa
  - Tendon : $f_{pu} = 1,860$MPa

- **Cover to Rebar/Tendon**
  - Rebar : 20mm
  - Tendon : 27mm

- **Prestressing Tendon**
  - Unbonded Mono-Strand Tendon
  - Φ12.7mm (99mm²)

< Typical Floor - Rebar Layout >
3) Evaluation of Economic Efficiency
### Construction Cost Comparison in USA Market

#### Tendon: 3,800 USD → 2.8 Times
#### Rebar: 1,350 USD

<table>
<thead>
<tr>
<th>Slab Characteristic</th>
<th>Slab System</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>[ALT 1] RC Slab</td>
</tr>
<tr>
<td>Geometry</td>
<td></td>
</tr>
<tr>
<td>Slab Thickness (mm)</td>
<td>250</td>
</tr>
<tr>
<td>Slab Area (m²)</td>
<td>648.41</td>
</tr>
<tr>
<td>Concrete Volume (m³)</td>
<td>162.10</td>
</tr>
<tr>
<td></td>
<td><em>(CO₂ Reduction -16%)</em></td>
</tr>
<tr>
<td>Material Quantity*</td>
<td></td>
</tr>
<tr>
<td>Reinforcement (kgf)</td>
<td>11,727</td>
</tr>
<tr>
<td>PT Strand (kgf)</td>
<td>-</td>
</tr>
<tr>
<td>Economics (Unit Price)</td>
<td></td>
</tr>
<tr>
<td>Concrete (21MPa)</td>
<td>$ 47.6</td>
</tr>
<tr>
<td>Concrete (30MPa)</td>
<td>$ 54.8</td>
</tr>
<tr>
<td>Void Ball</td>
<td>$ 12.7</td>
</tr>
<tr>
<td>Form</td>
<td>$ 10.8</td>
</tr>
<tr>
<td>Rebar</td>
<td>$ 1,350</td>
</tr>
<tr>
<td>Tendon</td>
<td>$ 3,800</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td>Total Price (Korean Won)</td>
<td>$30,569</td>
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<td>Ratio</td>
<td>100%</td>
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<tr>
<td>Decrease</td>
<td>-17.8%</td>
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</table>

*Material Quantity Calculated for One Typical Floor*
## Evaluation of Economic Efficiency

### Construction Cost Comparison in Korean Market

- **Tendon**: $4,550 USD → 5.1 Times
- **Rebar**: $890 USD

<table>
<thead>
<tr>
<th>Slab Characteristic</th>
<th>Slab System</th>
<th>[ALT 1] RC Slab</th>
<th>[ALT 2] PT Slab</th>
<th>[ALT 3] PT Void Slab</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Geometry</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Slab Thickness (mm)</td>
<td></td>
<td>250</td>
<td>210</td>
<td>210</td>
</tr>
<tr>
<td>Slab Area (m²)</td>
<td></td>
<td>648.41</td>
<td>648.41</td>
<td>648.41</td>
</tr>
<tr>
<td>Concrete Volume (m³)</td>
<td></td>
<td>162.10</td>
<td>136.17</td>
<td>124.41</td>
</tr>
<tr>
<td>(CO₂ Reduction -16%)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(CO₂ Reduction -23%)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Material Quantity</strong>*</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Reinforcement (kgf)</td>
<td></td>
<td>11,727</td>
<td>2,911</td>
<td>7,975</td>
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<tr>
<td>PT Strand (kgf)</td>
<td></td>
<td>-</td>
<td>1,770</td>
<td>1,130</td>
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<tr>
<td><strong>Economics</strong></td>
<td>(Unit Price)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Concrete (21MPa)</td>
<td>$</td>
<td>47.6</td>
<td>$7,722</td>
<td>-</td>
</tr>
<tr>
<td>Concrete (30MPa)</td>
<td>$</td>
<td>54.8</td>
<td>-</td>
<td>$7,464</td>
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<td>Plastic Ball</td>
<td>$</td>
<td>12.7</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Form</td>
<td>$</td>
<td>10.8</td>
<td>$7,015</td>
<td>$7,015</td>
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<tr>
<td>Rebar</td>
<td>$</td>
<td>890</td>
<td>$10,437</td>
<td>$2,590</td>
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<tr>
<td>Tendon</td>
<td>$</td>
<td>4,550</td>
<td>-</td>
<td>$8,054</td>
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<tr>
<td><strong>Total Price (Korean Won)</strong></td>
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<td>$25,174</td>
<td>$25,123</td>
<td>$29,171</td>
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<tr>
<td>Ratio</td>
<td></td>
<td>100%</td>
<td>99.8%</td>
<td>116%</td>
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</tbody>
</table>

*Material Quantity Calculated for One Typical Floor*
4) Evaluation of Structural Performance
Evaluation of Structural Performance

**Determine Natural Frequency (Hz)**

<table>
<thead>
<tr>
<th>ADAPT Vibration Analysis Result</th>
<th>Slab System</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>[ALT 1] RC Slab</td>
</tr>
<tr>
<td><strong>Uncracked Vibration</strong></td>
<td></td>
</tr>
<tr>
<td>Vibration Mode 1 (Hz)</td>
<td>9.76</td>
</tr>
<tr>
<td>Vibration Mode 2 (Hz)</td>
<td>10.56</td>
</tr>
<tr>
<td>Vibration Mode 3 (Hz)</td>
<td>10.79</td>
</tr>
<tr>
<td><strong>Cracked Vibration</strong></td>
<td></td>
</tr>
<tr>
<td>Vibration Mode 1 (Hz)</td>
<td>9.26</td>
</tr>
<tr>
<td>Vibration Mode 2 (Hz)</td>
<td>9.80</td>
</tr>
<tr>
<td>Vibration Mode 3 (Hz)</td>
<td>9.82</td>
</tr>
</tbody>
</table>

- **Uncracked Vibration**
  - Vibration Mode 1 (Hz): 9.76
  - Vibration Mode 2 (Hz): 10.56
  - Vibration Mode 3 (Hz): 10.79

- **Cracked Vibration**
  - Vibration Mode 1 (Hz): 9.26
  - Vibration Mode 2 (Hz): 9.80
  - Vibration Mode 3 (Hz): 9.82

---

< ALT 1 - RC Slab >    < ALT 2 - PT Slab >    < ALT 3 - PT Void Slab >
**Calculate Peak Acceleration (a_p/g)**

![Graph showing Dynamic Load Factor (DLF) vs Frequency Hz]

1) **Exciting Force of Vibration (P_o)**

\[
P_o = DLF \times (Weight \ of \ Person)
\]

\[
P_o = 0.53 \times 700N = 371N
\]

2) **Damping Factor (\beta)**

\[
\beta = 0.03
\]

<table>
<thead>
<tr>
<th>Occupancy</th>
<th>Damping Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bare concrete floor</td>
<td>0.02</td>
</tr>
<tr>
<td>Furnished, low partition</td>
<td>0.03</td>
</tr>
<tr>
<td>Furnished, full height partition</td>
<td>0.05</td>
</tr>
<tr>
<td>Shopping malls</td>
<td>0.02</td>
</tr>
</tbody>
</table>

< DLF for First Harmonic of Walking Force >
**Evaluation of Structural Performance**

- **Calculate Peak Acceleration** \( (a_p/g) \)

3) **Weight of Vibrating Floor Panel** \( (W) \)

\[
W = (\text{Dimension of Panel}) \times (\text{Selfweight} + \text{Partition})
\]

\[
= (8\text{m} \times 6\text{m}) \times (\text{Slab Depth} \times 24\text{kN/m}^3 + 1.5\text{kN/m}^2)
\]

4) **Acceleration caused by Walking Person** \( (a_p/g) \)

\[
\frac{a_p}{g} = \frac{P_o \times e^{-0.35f_n}}{\beta W}
\]

<table>
<thead>
<tr>
<th>Alternatives</th>
<th>( f_n ) (Hz)</th>
<th>( P_o ) (N)</th>
<th>( \beta )</th>
<th>( W ) (kN)</th>
<th>( \frac{a_p}{g} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>[ALT 1] RC Slab</td>
<td>9.26</td>
<td>371</td>
<td>0.03</td>
<td>315</td>
<td>0.15</td>
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<td>[ALT 2] PT Slab</td>
<td>8.61</td>
<td>371</td>
<td>0.03</td>
<td>275</td>
<td>0.22</td>
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<td>9.16</td>
<td>371</td>
<td>0.03</td>
<td>254</td>
<td>0.20</td>
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< Floor Plan for Vibration Evaluation >
Evaluation of Structural Performance

Evaluate Floor Vibration

- Evaluate Floor Vibration
- Threshold of Human Sensitivity to Vertical Vibration - ATC
- First Mode of Floor Vibration
Thank You!