ANTISEISMIC PNEUMATIC SUSPENSION FOR BUILDINGS

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SUMMARY

This invention uses the mechanic proprieties of the pressurized air –as vehicles do- to give horizontal and vertical seismic isolation to the buildings.

INTRODUCTION

Using one or more BASE PRESSURIZED AIR ROOMS, we can provide to tall or large buildings with a very safe, simple and economical system, to protect them from horizontal and vertical seismic displacements and accelerations.

RESULTS

The design of a 69-story building using a base pneumatic suspension, establishing the system elements and the forces, efforts, materials, security factors, construction processes, horizontal and vertical seismic isolation parameters, hurricane performance, operation, maintenance, and cost of this base pneumatic suspension system.

DISCUSSION

A. THE BUILDING (FIGURES 1-2-3)

It is a 69-Story hotel located in the Port of Acapulco, Mexico. The building has four parking basements with 524 parking spaces and 65 floors over street level with lobbies, restaurants, stairs, elevators, offices, other facilities and 1089 rooms.

The total building area is 109 762 m².

The dead loads (structure, walls, facades and equipment) are 70 138 000 kg.
The live loads (furniture, automobiles and people) are 27 400 000 kg.

The maximum capacity of guests and employees is 3450 people.

The building rests on four BASE PRESSURIZED ROOMS (BPR) located in its base. Each one is 34.800 m by 34.800 m, therefore, the maximum pneumatic pressure is:

\[ \text{BASE PRESSURE} = \frac{\text{DEAD LOAD} + \text{LIVE LOAD}}{\text{BASE AREA}} \]  \[1\]
BASE PRESSURE = \( \frac{70\,138\,000\,\text{kg} + 27\,400\,000\,\text{kg}}{4\,\text{rooms} \times 3480\,\text{cm} \times 3480\,\text{cm}} \) = 2.014 kg/cm²

The detachments, between the 4 sides of the four parking basements, and the peripheral concrete retaining wall is 240 mm wide. These separations between the soil and the structure allow the free ground movement up to 240 mm in every direction during a seism.

B. 4-BASE PRESSURIZED ROOMS (BPR) (FIGURES 4-5-6)
The four BASE PRESSURIZED ROOMS constructed over a horizontal, impermeable concrete flat slab, over the traditional foundation, are 34.800 m by 34.800 m each. Each of this four BASE PRESSURIZED ROOMS has a STEEL SUPPORTING FRAME embedded in its perimeter, to receive the 600 mm width NYLON-RUBBER BAND (NRB). Over the four impermeable concrete slabs, there will be plastic channels, in the shape of a “U”, located all along the place of the concrete beams of the foundation caisson.

Below each plastic channel there will be expanded polystyrene plates of 20 mm thick, leaving the plates separated some centimetres between them, to allow the passage of the compressed air at the pressurization time.

Between the beams, there will be square pieces of corrugated and galvanized steel foil, 170 mm over the impermeable concrete slab. To support the steel foils and the concrete slab, which is going to be cast, there will be pieces of expanded polystyrene of 170 mm thick with the necessary size and separation, leaving the expanded polystyrene pieces separated some centimetres to allow the pass of the compressed air in the time of pressurization.

Over the steel foils will be placed the reinforced steel bars, the concrete of the beams and the plates of the foundation caisson.

Around each one of the upper concrete plates of the four BASE PRESSURIZED ROOMS, another STEEL SUPPORTING FRAME has been embedded, separated 300 mm from the first one.
During the construction of the building, the peripheral NYLON-RUBBER BANDS (NRB) could be placed and the four BASE PRESSURIZED ROOMS pressurized with the appropriate pressure to separate the two concrete plates at a maximum of 300 mm.

The detachments, between the 4 sides of the four parking basements, and the peripheral concrete retaining wall is 240 mm wide. These separations between the soil and the structure allow the free ground movement up to 240 mm in every direction during a seism.

FIGURE 3. FIRST, SECOND, THIRD AND FOURTH PARKING BASEMENTS. PLANT SCALE 1: 600
FIGURE 4. FOUR BASE PRESSURIZED ROOMS. EIGHT CONCRETE AIR SPRINGS (AS) CENTRAL AND PERIPHERAL WORKING AREA (WA). SCHEMATIC PLANT

FIGURE 5. CENTRAL WORKING AREA (WA) AND BASE PRESSURIZED ROOMS. SECTION SCALE 1: 50

FIGURE 6. BASE PRESSURIZED ROOM, PERIPHERAL WORKING AREA (WA) AND 6.000m by 4.500m CONCRETE AIR SPRING (AS). DETAIL SECTION SCALE 1: 50
C. NYLON-RUBBER BAND (NRB) (FIGURES 7-8-10)

A 600 mm width NYLON-RUBBER BAND CALCULATION: This peripheral band works with a normal separation of 300 mm –in static conditions- but in a seismic period, could close or open 240 mm; therefore, the minimum separation between the STEEL SUPPORTING FRAMES will be 60 mm, and the maximum separation will be 540 mm. The maximum effort in the peripheral NYLON-RUBBER BAND will be at its maximum separation and at its maximum air pressure.

Using the tables of the “CIRCULAR ARCS CALCULATION”, MONTERREY MANUAL [1] FORMULAS:

\[ \text{ARCH}(a) = \left( \pi \times \text{RADIUS} \times \text{ANGLE} \right) \div 180^\circ \]  

\[ \text{ANGLE}(A^\circ) = \left( 180^\circ \times \text{ARCH} \right) + \left( \pi \times \text{RADIUS} \right) \]  

\[ \text{RADIUS}(r) = \left[ \left(4 \times \text{HEIGHT}^2 + \text{CHORD}^2 \right) \div 8 \times \text{HEIGHT} \right] \]  

\[ \text{HEIGHT}(h) = r - \left( 0.5 \times \sqrt{4r^2 - \text{CHORD}^2} \right) \]  

\[ \text{CHORD}(c) = 2\sqrt{2hr - h^2} \]  

BAND EFFORT PER METER = \[ \frac{\text{PRESSURE} \times c \times 100\text{cm}}{2 \times \sin(A^\circ/2)} \]  

BAND EFFORT PER METER = \[ \text{PRESSURE} \times r \times 100\text{cm} \]  

PNEUMATIC COMPRESSION = \[ \text{PRESSURE} \times \text{HEIGHT} \times 100\text{cm} \]  

LATERAL PRESSURE = BAND EFFORT – PNEUMATIC COMPRESSION  

MAXIMUM BAND EFFORT: ARCH (a) = 600 mm, CHORD(c) = 540 mm, r = 381.8 mm

\[ \text{ANGLE}(A^\circ) = \left( 180^\circ \times 600\text{mm} \right) + \left( \pi \times 381.8\text{mm} \right) = 90^\circ \]  

Maximum band effort = \[ \frac{2.014 \text{ kg.f.}/\text{cm}^2 \times 54 \text{ cm} \times 100 \text{ cm}}{2 \times \sin(90^\circ/2)} = 7690\text{ kg.f.}/\text{m} \]  

**TABLE 1. BAND CHORDS, ARCHES, ANGLES, RADIUS, HEIGHTS, EFFORTS AND TOTALS LATERAL PressURES**

<table>
<thead>
<tr>
<th>Distance Between supports CHORD (c) mm</th>
<th>Seismic movement</th>
<th>BAND ARCH (a) mm</th>
<th>BAND ANGLE (A) Degrees</th>
<th>BAND RADIUS (r) mm</th>
<th>BAND HEIGHT (h) mm</th>
<th>BAND EFFORT tension Kg. f Per meter (-)</th>
<th>AIR Pressure Kg. f Per meter (+)</th>
<th>TOTAL Lateral Pressure Kg. f Per meter</th>
</tr>
</thead>
<tbody>
<tr>
<td>60</td>
<td>(-) 240</td>
<td>479.4</td>
<td>319.4</td>
<td>86.0</td>
<td>226.9</td>
<td>1732</td>
<td>4570</td>
<td>(+) 2838</td>
</tr>
<tr>
<td>120</td>
<td>(-) 180</td>
<td>479.4</td>
<td>283.4</td>
<td>96.9</td>
<td>233.3</td>
<td>1952</td>
<td>4699</td>
<td>(+) 2747</td>
</tr>
<tr>
<td>180</td>
<td>(-) 120</td>
<td>479.4</td>
<td>250.2</td>
<td>109.8</td>
<td>233.0</td>
<td>2211</td>
<td>4693</td>
<td>(+) 2482</td>
</tr>
<tr>
<td>240</td>
<td>(-) 60</td>
<td>479.4</td>
<td>213.9</td>
<td>128.4</td>
<td>234.4</td>
<td>2586</td>
<td>4721</td>
<td>(+) 2135</td>
</tr>
<tr>
<td>300</td>
<td>ZERO</td>
<td>479.4</td>
<td>183.1</td>
<td>150.2</td>
<td>214.4</td>
<td>3021</td>
<td>4318</td>
<td>(+) 1297</td>
</tr>
<tr>
<td>360</td>
<td>(+) 60</td>
<td>565.6</td>
<td>180.0</td>
<td>180.0</td>
<td>197.2</td>
<td>3625</td>
<td>3972</td>
<td>(+) 347</td>
</tr>
<tr>
<td>420</td>
<td>(+) 120</td>
<td>600.0</td>
<td>161.5</td>
<td>213.0</td>
<td>178.8</td>
<td>4285</td>
<td>3601</td>
<td>(-) 684</td>
</tr>
<tr>
<td>480</td>
<td>(+) 180</td>
<td>600.0</td>
<td>129.6</td>
<td>265.0</td>
<td>152.2</td>
<td>5342</td>
<td>3065</td>
<td>(+) 2277</td>
</tr>
<tr>
<td>540</td>
<td>(+) 240</td>
<td>600.0</td>
<td>90.0</td>
<td>381.8</td>
<td>111.8</td>
<td>7690</td>
<td>2252</td>
<td>(-) 5438</td>
</tr>
</tbody>
</table>

(+ Means OPENING TENDENCY  (-) Means CLOSING TENDENCY)
Figure 7. 600mm width NYLON-RUBBER BAND (NRB) in normal distance between STEEL SUPPORTING FRAMES by 300mm. SECTION SCALE 1:4

Figure 8. STEEL SUPPORTING FRAME TO THE NYLON-RUBBER BAND. SECTION SCALE 1:2
Taking the tension of the peripheral band we used Nylon-6 wire, a common material used in the tire industry.

### TABLE 2. NYLON-6 WIRE

<table>
<thead>
<tr>
<th>WEAVED, PRIMED AND HOT STRETCHED NYLON-6 WIRE (caprolactam or 6-amino-caproic acid)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rupture stress per wire = 32.2 kg.</td>
</tr>
<tr>
<td>8.20 wires per centimetre</td>
</tr>
<tr>
<td>Rupture stress per meter = 26 404 kg</td>
</tr>
</tbody>
</table>

SECURITY FACTOR = \[ \text{rupture stress per meter} \div \text{maximum band effort} \]  
Dynamic Security Factor = \[ \frac{26 404 \text{kg.f./m}}{7690 \text{kg.f./m}} \] = 3.433 (satisfactory)  
Static Security Factor = \[ \frac{26 404 \text{kg.f./m}}{3021 \text{kg.f./m}} \] = 8.740 (satisfactory)

### D. WORKING AREA (WA) (FIGURES 4-5-6)
To install the 600 mm width NYLON-RUBBER BANDS (NRB) on the four peripheral STEEL SUPPORTING FRAMES, around the 4-BASE PRESSURIZED ROOMS, we need a 3.000m width WORKING AREA. This area will be used to give maintenance and eventually replace the NYLON-RUBBER BAND.

### E. EIGHT CONCRETE AIR SPRINGS (AS) (FIGURES 4-6)
The eight 6.000m-width by 4.500m-height air springs (8AS), placed in the periphery of the fourth basement and the foundation caisson (two on each side), transmit some of the soil movement to the building during a seism and transmit part of the wind effort to the soil. (figures 9-10-11)
Each one of the eight air springs is a parallel pair of 6.000m by 4.500m concrete plates. One of the plates is part of the periphery concrete retaining wall, and the other one is a precast concrete plate. The distance between the two concrete plates is 300 mm and has on its four sides 600 mm-width NYLON-RUBBER BANDS (NRB)-the same to the one used in the 4-BASE PRESSURIZED ROOMS (figures 5 and 6), shaping a hermetic space.
The interior air pressure is the ambient pressure, but if the wind forces move the building or the seism forces move the soil, the distance between the two concrete plates could increase, reducing the air pressure, or could reduce, increasing the air pressure. In both cases the air springs try to return to its 300 mm initial distance.
The atmospheric pressure at 200m over the sea level is 0.976 kg/cm². KONRAD DIEM [2]
The air pressure variation depends on the distance of the two concrete plates, and is:

\[
\text{FORCED PRESSURE} = \left( \frac{\text{original separation}}{\text{forced separation}} - 1 \right) \times \text{atmospheric pressure} \quad [12]
\]
The maximum pressure in an AIR SPRING is when the distance between the two concrete plates is 60 mm:

\[
\text{MAXIMUM PRESSURE} = \left( \frac{300 \text{mm}}{60 \text{mm}} - 1 \right) \times 0.976 \frac{\text{kg.f.}}{\text{cm}^2} = 3.904 \frac{\text{kg.f.}}{\text{cm}^2} \quad [12]
\]
The minimum pressure in the AIR SPRING is when the distance between the two concrete plates is 540 mm:

\[
\text{MINIMUM PRESSURE} = \left( \frac{300 \text{mm}}{540 \text{mm}} - 1 \right) \times 0.976 \frac{\text{kg}}{\text{cm}^2} = (-)0.434 \frac{\text{kg.f.}}{\text{cm}^2} \quad [12]
\]
TABLE 3. AIR SPRINGS PRESSURES AND FORCES

<table>
<thead>
<tr>
<th>Displacement between concrete plates (mm)</th>
<th>Forced separations in opposite air springs (mm)</th>
<th>Unit pressures in two opposite air springs (kg.f/cm²)</th>
<th>Forces in four 6.000m by 4.500m air springs (kg.f)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>300 + 300 = 600</td>
<td>0 + 0 = 0</td>
<td>0</td>
</tr>
<tr>
<td>60</td>
<td>360 + 240 = 600</td>
<td>0.163 + 0.244 = 0.407</td>
<td>219 780</td>
</tr>
<tr>
<td>120</td>
<td>420 + 180 = 600</td>
<td>0.279 + 0.651 = 0.930</td>
<td>502 200</td>
</tr>
<tr>
<td>180</td>
<td>480 + 120 = 600</td>
<td>0.366 + 1.464 = 1.830</td>
<td>988 200</td>
</tr>
<tr>
<td>240</td>
<td>540 + 60 = 600</td>
<td>0.434 + 3.904 = 4.338</td>
<td>2 342 520</td>
</tr>
</tbody>
</table>

F. HURRICANE EFFECTS (FIGURE 9)

Normally the effects of the wind pressure over the building are imperceptible. But we can eliminate, partially or totally, the displacements and leaning of the building with a pressure control in the four BASE PRESSURIZED ROOMS, and in the eight concrete AIR SPRINGS (AS). (FIGURES 4-5-6).

The pressure control will be done with a computer program. In the hurricane case, predictable with some days in advance, it is possible to prepare the computer program control, but, if we don’t control the pressures, the hurricane effects are the next:

The structure efforts with a 160 km/hour (100 mile/hour) hurricane are the following:

The basic wind pressure with 160 km/hour is 192 kg.f/m². FRANK E. KIDDER [3]
The windward side factor is 0.8 and the leeward side factor is 0.5 CONSTRUCTION REGULATIONS OF MEXICO CITY [4] therefore, the wind force over the building is:

\[
WIND\ FORCE = BASIC\ PRESSURE \times (windward\ factor + leeward\ factor) \times area \quad [13]
\]

\[
192\ kg/f/m² \times [0.8 + 0.5] \times 36.9m \times [65 - STORY \times 3.6m] = 2155196\ kg \quad [13]
\]

And the torque to the centre of the concrete AIR SPRINGS (AS) in the fourth basement is:

\[
WIND\ TORQUE = WIND\ FORCE \times DISTANCE \quad [14]
\]

\[
WIND\ TORQUE = 2155196\ kg.f \times 131.400\ m = 283\ 192\ 754\ kg.f.m \quad [14]
\]

The equilibrium forces in the base pressurized rooms are:

\[
EQUILIBRIUM\ FORCES = \frac{WIND\ TORQUE}{distance\ between\ base\ pressurized\ rooms} \quad [15]
\]

\[
EQUILIBRIUM\ FORCES = \frac{283\ 192\ 754\ kg.f.m}{37.300\ m} = \pm\ 7\ 592\ 299\ kg.f \quad [15]
\]

The pressures in the rooms are:

\[
PRESSURE = \frac{[DEAD\ LOAD \div 2] \pm EQUILIBRIUM\ FORCES}{2 \times BASE\ PRESSURIZED\ ROOM\ AREA} \quad [16]
\]

The highest pressure = \[
\frac{[70\ 138\ 000\ kg.f. \div 2] + 7\ 592\ 299\ kg.f.}{2 \times 3480cm \times 3480cm} = 1.761\ \frac{kg.f}{cm²} \quad [16]
\]

The lower pressure = \[
\frac{[70\ 138\ 000\ kg.f. \div 2] - 7\ 592\ 299\ kg.f.}{2 \times 3480cm \times 3480cm} = 1.134\ \frac{kg.f}{cm²} \quad [16]
\]
HURRICANE EFFORTS: The wind force is 2 155 196 kg, and produces a 200 mm displacement between building and its foundation.

TABLE 4. HURRICANE RESISTANCE TO A 200 mm DISPLACEMENT

<table>
<thead>
<tr>
<th>ELEMENT AND NUMBER</th>
<th>FORCED SEPARATION mm</th>
<th>ELEMENT DIMENSION</th>
<th>TOTAL QUANTITY</th>
<th>UNIT RESISTANCE</th>
<th>TOTAL RESISTANCE Kg.f.</th>
</tr>
</thead>
<tbody>
<tr>
<td>600 mm WIDTH NYLON-RUBBER BAND IN 4 BASE PRESSURIZED ROOMS</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4 BANDS</td>
<td>500 mm</td>
<td>34.80 m</td>
<td>139.200 m</td>
<td>3048 kg/m</td>
<td>424 282</td>
</tr>
<tr>
<td>4 BANDS</td>
<td>100 mm</td>
<td>34.80 m</td>
<td>139.200 m</td>
<td>2807 kg/m</td>
<td>390 734</td>
</tr>
<tr>
<td>8 BANDS</td>
<td>300 mm</td>
<td>34.80 m</td>
<td>278.400 m</td>
<td>180 kg/m</td>
<td>50 112</td>
</tr>
<tr>
<td>EIGHT CONCRETE AIR SPRINGS (AS) (6.000 m. by 4.500 m. each one)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2 AS</td>
<td>500 mm</td>
<td>600 x 450 cm</td>
<td>540000 cm²</td>
<td>0.3904 kg/cm²</td>
<td>210 816</td>
</tr>
<tr>
<td>2 AS</td>
<td>100 mm</td>
<td>600 x 450 cm</td>
<td>540000 cm²</td>
<td>1.9520 kg/cm²</td>
<td>1 054 080</td>
</tr>
<tr>
<td>4 AS</td>
<td>300 mm</td>
<td>21.000 meter</td>
<td>84.000 m</td>
<td>180 kg/meter</td>
<td>15 120</td>
</tr>
<tr>
<td>TOTAL RESISTANCE</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>2 145 144</td>
</tr>
</tbody>
</table>
BUILDING SLOPE DURING A HURRICANE:
Height increase or decrease = \[
\frac{\text{Original Pressure} \times \text{Original Height}}{\text{FORCED PRESSURE}}
\] \[\text{[17]}\]
Height increase = \[
\frac{1.448 \text{ kg.f./cm}^2 \times 300 \text{ mm}}{1.134 \text{ kg.f./cm}^2} = 383.1 \text{ mm}
\] \[\text{[17]}\]
Height decrease = \[
\frac{1.448 \text{ kg.f./cm}^2 \times 300 \text{ mm}}{1.761 \text{ kg.f./cm}^2} = 246.7 \text{ mm}
\] \[\text{[17]}\]
Height difference = 383.1 mm – 246.7 mm = 136.4 mm

BUILDING SLOPE = \[
\frac{\text{HEIGHT DIFFERENCE}}{\text{Rooms Centres Distance}} = \frac{0.1364}{37.300} = 0.00365
\] \[\text{[18]}\]

G. AIR COMPRESSOR.
We will use the next equipment: 2 ROTARY SCREW AIR COMPRESSORS with a 40 H. P. electric motor. Style ES-40. Air delivery with a working pressure of 7.030 kg/cm² (6.9 bar): 5.23 m³/min, therefore:
COMPLETE PRESSURIZATION TIME = (C. P. TIME)
\[
\text{C. P. TIME} = \frac{\text{VOLUME} \times \text{PRESSURE}}{\text{Air Delivery} \times \text{Working Pressure}}
\] \[\text{[19]}\]
\[
\text{C. P. TIME} = \frac{4 \text{ rooms} \times 35.300 \text{ m} \times 35.300 \text{ m} \times 0.300 \text{ m} \times 2.014 \text{ kg/cm}^2}{2 \text{ compressors} \times 5.22 \text{ m}^3/\text{min} \times 7.030 \text{ kg/cm}^2} = 41.03 \text{ min}
\] \[\text{[19]}\]

H. CONTROL EQUIPMENT, OPERATION AND MAINTENANCE:
The air pressure and/or the interior height on the 4 BASE PRESSURIZED ROOMS change with the environmental temperature, the wind pressure, and the LIVE LOADS variations.
As an example, we take the effects of all the people and all the cars entering the building:
Weight = \[
[\text{persons} \times \text{average}] + [\text{cars} \times \text{average}]
\] \[\text{[20]}\]
Weight = \[
[3450 \text{ persons} \times 70 \text{ kg/person}] + [524 \text{ cars} \times 1140 \text{ kg/car}] = 838,860 \text{ kg}.
\] \[\text{[20]}\]
NEW LIVE LOADS = 27,400,000 kg – 838,860 kg = 26,561,140 kg
NEW INTERIOR HEIGHT IN THE PRESSURIZED ROOMS = NEW HEIGHT
NEW HEIGHT = \[
\frac{\text{New Loads} \times \text{Original Height}}{\text{ORIGINAL LOADS}}
\] \[\text{[21]}\]
NEW HEIGHT = \[
\frac{(70,138,000 \text{ kg} + 26,561,140 \text{ kg}) \times 300 \text{ mm}}{70,138,000 \text{ kg} + 27,400,000 \text{ kg}} = 297.420 \text{ mm}
\] \[\text{[21]}\]
Variation = 300 mm – 297.420 mm = 2.580 mm
To return to their original height the 4 BASE PRESSURIZED ROOMS, we need pressurize during this time: PRESSURIZED TIME (P. TIME)
\[
\text{P. TIME} = \frac{4 \text{ rooms} \times 35.300 \text{ m} \times 35.300 \text{ m} \times 0.00258 \text{ m} \times 2.014 \text{ kg/cm}^2}{5.22 \text{ m}^3/\text{min} \times 7.030 \text{ kg/cm}^2} = 0.706 \text{ min}
\] \[\text{[19]}\]
0.706 minutes = 42 seconds
Therefore, it is very easy to control the 300 mm height of the 4 BASE PRESSURIZED ROOMS by having the rotary screw compressors work for a few seconds or releasing some of the compressed air.
This pressure control can be done with the appropriate sensors, valves and electric equipment controlled by a computer program.

I. HORIZONTAL SEISMIC ISOLATION
The horizontal isolation margins depend on the displacements between soil and structure and are the following:

### TABLE 5. BASE HORIZONTAL ISOLATION

<table>
<thead>
<tr>
<th>Displacement Between soil and structure (mm)</th>
<th>Forced separations in opposite sides (mm)</th>
<th>Unit forces in opposite sides TABLE 2</th>
<th>Total forces in Opposite sides 4 rooms of 34.800m each</th>
<th>Total forces in Parallel sides 4 rooms of 2 x 4.800m each</th>
<th>TOTAL FORCES IN 4 SIDES OF 4 ROOMS</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>300+300=600</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>60</td>
<td>360+240=600</td>
<td>-347+2135</td>
<td>248 890</td>
<td>15 034</td>
<td>263 924</td>
</tr>
<tr>
<td>120</td>
<td>420+180=600</td>
<td>684+2482</td>
<td>440 707</td>
<td>30 067</td>
<td>470 774</td>
</tr>
<tr>
<td>180</td>
<td>480+120=600</td>
<td>2277+2747</td>
<td>699 341</td>
<td>45 101</td>
<td>744 442</td>
</tr>
<tr>
<td>240</td>
<td>540+ 60=600</td>
<td>5438+2838</td>
<td>1 152 019</td>
<td>60 134</td>
<td>1 212 153</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Displacement Between soil and structure (mm)</th>
<th>Forced Separation in Opposite sides (mm)</th>
<th>FORCES IN 4 BASE PRESSURIZED ROOMS (kg)</th>
<th>FORCES IN 8 AIR SPRINGS TABLE 4 (kg)</th>
<th>TOTAL FORCES IN BASE + AIR SPRINGS (kg)</th>
<th>TOTAL FORCES BY BUILDING WEIGHT * (ratio)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>300+300=600</td>
<td>263 924</td>
<td>219 780</td>
<td>483 704</td>
<td>0.005</td>
</tr>
<tr>
<td>60</td>
<td>360+240=600</td>
<td>263 924</td>
<td>219 780</td>
<td>483 704</td>
<td>0.005</td>
</tr>
<tr>
<td>120</td>
<td>420+180=600</td>
<td>470 774</td>
<td>502 200</td>
<td>972 974</td>
<td>0.010</td>
</tr>
<tr>
<td>180</td>
<td>480+120=600</td>
<td>744 442</td>
<td>988 200</td>
<td>1 732 642</td>
<td>0.018</td>
</tr>
<tr>
<td>240</td>
<td>540+ 60=600</td>
<td>1 212 153</td>
<td>2 342 520</td>
<td>3 554 673</td>
<td>0.036</td>
</tr>
</tbody>
</table>

* BUILDING WEIGHT = 70 138 000 kg + 27 400 000 kg = 97 538 000 kg

J. VERTICAL SEISMIC ISOLATION (FIGURE 10)
The analysis of the vertical isolation will be done considering in all cases with a horizontal 180mm displacement too. This is 300 mm + 180 mm = 480 mm.

**STRAIGHT SEPARATION BETWEEN BAND SUPPORTS = STRAIGHT SEP.**

\[
\text{STRAIGHT SEP.} = \sqrt{(\text{HORIZONTAL SEP.})^2 + (\text{VERTICAL SEP.})^2} \tag{22}
\]

To the maximum effort:

\[
\text{STRAIGHT SEP.} = \sqrt{(480mm)^2 + (150mm)^2} = 502.9 \text{ mm} \tag{22}
\]

**BAND ANGLE:** Using the “MONTERREY MANUAL [1]”, to \( \text{ARCH} = 600 \text{ mm} \)

\[
\text{CHORD} = 502.9 \text{ mm}, \quad \text{BAND ANGLE} = 115.78^\circ
\]

\[
\text{BAND RADIUS} = \frac{\text{ARCH} \times 360^\circ}{2\pi \times \text{ANGLE}} = \frac{600 \text{mm} \times 360^\circ}{2\pi \times 115.78^\circ} = 296.9 \text{ mm} \tag{23}
\]

**FORCED PRESSURE = \frac{\text{Original Height} \times \text{Original Pressure}}{\text{FORCED HEIGHT}} \tag{24}**
FORCED PRESSURE = \( \frac{300\text{mm} \times 2.014 \text{kg/cm}^2}{150\text{mm}} = 4.028 \frac{\text{kg}}{\text{cm}^2} \) \[24\]

BAND EFFORT = \( 4.028 \frac{\text{kg.f.}}{\text{cm}^2} \times 29.69 \times 100\text{cm} = 11959\text{kg.f./meter} \) \[8\]

**TABLE 7. VERTICAL SEISMIC ISOLATION**

<table>
<thead>
<tr>
<th>Separation Between 2 Concrete plates (mm)</th>
<th>Straight separation between supports (mm)</th>
<th>BAND ANGLE DEGREE</th>
<th>BAND RADIUS (mm)</th>
<th>Vertical acceleration GRAVITY</th>
<th>AIR PRESSURE ( \frac{\text{kg}}{\text{cm}^2} )</th>
<th>NYLON-RUBBER BAND EFFORT Kg. f.</th>
</tr>
</thead>
<tbody>
<tr>
<td>150</td>
<td>502.9</td>
<td>115.78</td>
<td>296.9</td>
<td>2.000</td>
<td>4.028</td>
<td>11,959</td>
</tr>
<tr>
<td>180</td>
<td>494.8</td>
<td>120.85</td>
<td>284.5</td>
<td>1.666</td>
<td>3.357</td>
<td>9550</td>
</tr>
<tr>
<td>210</td>
<td>488.4</td>
<td>124.69</td>
<td>275.7</td>
<td>1.428</td>
<td>2.877</td>
<td>7932</td>
</tr>
<tr>
<td>240</td>
<td>483.7</td>
<td>127.45</td>
<td>269.7</td>
<td>1.250</td>
<td>2.517</td>
<td>6790</td>
</tr>
<tr>
<td>270</td>
<td>480.9</td>
<td>129.10</td>
<td>266.3</td>
<td>1.111</td>
<td>2.238</td>
<td>5960</td>
</tr>
<tr>
<td>300</td>
<td>480.0</td>
<td>129.60</td>
<td>265.2</td>
<td>1.000</td>
<td>2.014</td>
<td>5341</td>
</tr>
<tr>
<td>330</td>
<td>480.9</td>
<td>129.10</td>
<td>266.3</td>
<td>0.909</td>
<td>1.831</td>
<td>4876</td>
</tr>
<tr>
<td>360</td>
<td>483.7</td>
<td>127.45</td>
<td>269.7</td>
<td>0.833</td>
<td>1.678</td>
<td>4526</td>
</tr>
<tr>
<td>390</td>
<td>488.4</td>
<td>124.69</td>
<td>275.7</td>
<td>0.769</td>
<td>1.549</td>
<td>4271</td>
</tr>
<tr>
<td>420</td>
<td>494.8</td>
<td>120.85</td>
<td>284.5</td>
<td>0.714</td>
<td>1.438</td>
<td>4091</td>
</tr>
<tr>
<td>450</td>
<td>502.9</td>
<td>115.78</td>
<td>296.9</td>
<td>0.666</td>
<td>1.343</td>
<td>3987</td>
</tr>
<tr>
<td>480</td>
<td>512.6</td>
<td>109.60</td>
<td>313.7</td>
<td>0.625</td>
<td>1.258</td>
<td>3949</td>
</tr>
</tbody>
</table>

DYNAMIC SECURITY FACTOR = \( \frac{26,404 \text{kg.f./m}}{11,959 \text{kg.f./m}} = 2.208 \) (satisfactory) \[11\]
K. SYSTEM COST IN U.S. DOLLARS

TABLE 8. VALUE----PNEUMATIC BASE SUSPENSION VALUE
JULY 2003                                         US DOLLARS

<table>
<thead>
<tr>
<th>ELEMENT</th>
<th>QUANTITY</th>
<th>UNIT AMOUNT</th>
<th>TOTAL AMOUNT</th>
</tr>
</thead>
<tbody>
<tr>
<td>4-BASE PRESSURIZED ROOMS 4-(BPR)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bottom concrete plate.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Concrete f’c=250 kg/cm² (72.900m X 72.900m X 0.150m)</td>
<td>797.16 m3</td>
<td>133.20</td>
<td>106 182.00</td>
</tr>
<tr>
<td>Steel corrugated bars fy = 4200 kg/cm²</td>
<td>67 493 kg</td>
<td>0.47</td>
<td>31 722.00</td>
</tr>
<tr>
<td>Top concrete plates (4)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Concrete f’c=300 kg/cm² (4 X 34.450m X 34.450m X 0.300m)</td>
<td>1424.20 m3</td>
<td>140.90</td>
<td>200 670.00</td>
</tr>
<tr>
<td>Steel galvanized foil</td>
<td>4747.21 m2</td>
<td>7.40</td>
<td>35 129.00</td>
</tr>
<tr>
<td>Steel corrugated bars fy = 4200 kg/cm²</td>
<td>200 570 kg</td>
<td>0.47</td>
<td>94 268.00</td>
</tr>
<tr>
<td>Steel supporting frames to the NRB (34.450m + 35.450m) X 4 X 4</td>
<td>1118.40 m</td>
<td>69.70</td>
<td>77 953.00</td>
</tr>
<tr>
<td>Nylon-rubber band (NRB) 34.950m X 4 X 4</td>
<td>559.20 m</td>
<td>80.45</td>
<td>44 988.00</td>
</tr>
<tr>
<td>PERIPHERAL AND CENTRAL WORKING AREA (WA)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Service entrance</td>
<td>21 pieces</td>
<td>325.45</td>
<td>6 835.00</td>
</tr>
<tr>
<td>Steel galvanized stairs</td>
<td>21 pieces</td>
<td>166.50</td>
<td>3 497.00</td>
</tr>
<tr>
<td>8-AIR SPRINGS 8-(AS)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Precast concrete plates 4.50m X 6.00m</td>
<td>8 pieces</td>
<td>3292.00</td>
<td>26 336.00</td>
</tr>
<tr>
<td>Steel supporting frames to the NRB (4.500m + 6.000m) X 2 X 2 X 8 pieces</td>
<td>336.00 m</td>
<td>69.70</td>
<td>23 419.00</td>
</tr>
<tr>
<td>Nylon-rubber band (NRB) (4.500m + 6.000m) X 2 X 8</td>
<td>168.00 m</td>
<td>80.45</td>
<td>13 516.00</td>
</tr>
<tr>
<td>ROTARY SCREW AIR COMPRESSOR AND CONTROL EQUIPMENTS</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>40 H.P. rotary screw air compressor</td>
<td>2 pieces</td>
<td>16 417.00</td>
<td>32 834.00</td>
</tr>
<tr>
<td>Control equipments and fitting</td>
<td>1 pieces</td>
<td>45 640.00</td>
<td>45 640.00</td>
</tr>
</tbody>
</table>

PNEUMATIC BASE SUSPENSION VALUE
(JULY 2003- US DOLLARS) $ 742 989.00

69-STORY BUILDING VALUE (JULY 2003 – US DOLLARS)
109 762 m² Building area $ 93’896,650.00

RELATION BETWEEN THE BASE PNEUMATIC SUSPENSION VALUE AND THE 69-STORY BUILDING VALUE:

RELATIVE VALUE = SYSTEM VALUE / BUILDING VALUE
RELATIVE VALUE = $ 742 989.00 / $ 93’896 650.00 = 0.0079
(LESS THAN THE 1%)
CONCLUSIONS

This ANTISEISMIC PNEUMATIC SUSPENSION FOR BUILDINGS system, avoids more than the 99 per cent of the seismic movements.

The system cost is less than one per cent of the building value.

REFERENCES

1. MONTERREY MANUAL FOR STEEL BUILDERS, published by the MONTERREY IRON AND STEEL COMPANY, (Mexico, 1965) Tables of the “CIRCULAR ARCS CALCULATION”, pages 434, 444 and 445


3. FRANK E. KIDDER, “KIDDER-PARKER ARCHITECTS’ AND BUILDERS’ HANDBOOK”, (UTEHA, MEXICO, 1959), Wind pressure table, page 2195