Delhi Police Headquarters (Multi-Story Office Building)

A Summary of the Seismic Evaluation and Retrofit Process

Delhi Earthquake Safety Initiative for Lifeline Buildings

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Executive Summary

The Delhi Police Headquarters building, also known as the Multi-storey Office (MSO) building, houses the main offices for the Police Department and the Delhi Public Works Department (PWD). Both agencies will play a key role following a damaging earthquake in Delhi. The building is fourteen stories tall and was built in the 1970’s and early 1980’s in three phases, which are essentially independent buildings separated by a six inch seismic joint. Phase 1 has very large shear walls that are stiff but weak and a reinforced concrete frame that can resist some earthquake forces. Phases 2 and 3 are flexible concrete moment frame buildings. Inadequate separation between these buildings with very different vibration characteristics will cause them to pound together during an earthquake. If not retrofitted, the buildings are likely to suffer major structural damage in the earthquake that the Indian code uses for engineering design, which could endanger the lives of building occupants.

Delhi PWD gathered information, conducted geotechnical investigations, and assessed the building’s condition. The building was built by the Central Public Works Department (CPWD), and the original structural drawings remain available. Based on the geotechnical data collected, Delhi PWD determined that liquefaction is unlikely. Engineering and Development Consultants conducted linear analyses of the building, and Indian Institute of Technology (IIT) Kanpur conducted nonlinear static pushover analyses of the building with and without retrofit solutions. The major seismic deficiencies were the Phase 1 shear walls that failed in shear (a brittle, undesirable mode of failure) at low levels of deformation, pounding between the phases, and brick infill walls that caused torsion and kept the Phase 2 and 3 frames from moving as designed.

Project participants had both to overcome a number of technical challenges and to balance architectural and disruption considerations, to arrive at a final recommended retrofit scheme. They investigated twelve schemes before recommending the following scheme consisting of: (a) stitching Phases 2 and 3 together but leaving them separate from Phase 1; (b) adding new shear walls to Phase 1 to prevent failure of the existing walls; (c) mitigating the effects of infill walls on frame movement; and (d) opening up the joint between Phase 1 and Phases 2 / 3 if needed, to avoid pounding. At the time when this report was prepared, that scheme was being designed.

The building is being designed for life safety plus damage control performance in the Design Basis Earthquake (DBE) and for collapse prevention in the Maximum Considered Earthquake (MCE). However, Phase 1 is likely to achieve performance near immediate occupancy in the DBE, because the new shear walls will have to be stiff enough to keep the building nearly elastic. This means that in the design earthquake (with shaking half as strong as that in the maximum earthquake), Phase 1 could possibly be used with minor cleanup soon after an earthquake. Phases 2 and 3 may be damaged enough to need repairs that could take a few months. In the MCE, all phases could be damaged enough to need major repairs before use, and Phases 2 and 3 might not be repairable. Once design and construction are complete, Delhi PWD plans to anchor building utilities, architectural elements, and furnishings to help reduce office downtime following the earthquake.

Project participants had to resolve many technical issues to develop a workable retrofit scheme. Many challenges remain: designing and detailing the scheme; obtaining approvals and sanctions; managing disruption and construction on a security-sensitive site. Despite these challenges, the Delhi Government and the other project partners remain committed to retrofitting the building to protect its occupants and functions from earthquakes.
Project Team Members

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Introduction
The Delhi Police Headquarters building, also popularly known as the Multistorey Office (MSO) building, houses two major departments that are critical to post-earthquake response: the Police Department and Delhi PWD. Important offices include the Police Commissioner’s office and the police control room (dispatch center), as well as the offices of Delhi PWD’s Engineer-in-Chief and the four zonal Chief Engineers. Approximately 2000 employees work in the building, and there are more than 1000 visitors on a typical day. The building was selected because of the functions that it houses and because it is a good example of a building type that requires the use of performance-based design concepts.

The 14-story building was constructed in three phases and is essentially three different reinforced concrete buildings separated by expansion joints 150 mm (6 in) wide. The first phase has a core with two massive H-shaped shear walls from foundation to roof, making it very stiff. The second and third phases have flexible moment-resisting frames and no shear walls. The overall performance goal for the building is life safety plus damage control, though there was discussion of whether the performance goal should be immediate occupancy, given the functions that the building houses. The peer review panel agreed on the compromise that anchorage and bracing of building utilities and furnishings would take place in the critical areas, such as the police control room (and the utilities serving it), to make them more likely to be operational immediately following an earthquake.

The Police Headquarters Building was seismically assessed as part of the Delhi Earthquake Safety Initiative for Lifeline Buildings. This project was jointly funded by the Government of the National Capital Territory of Delhi and the United States Agency for International Development. GeoHazards International (GHI) formed a peer review panel of experts from India and the United States to guide Delhi PWD engineers through the seismic assessment and retrofit of five groups of important existing buildings, and to build their capacity to retrofit additional buildings in the future.

The Delhi PWD began the seismic assessment and retrofit process by gathering information on the building’s design, construction, and current condition and by conducting initial walk-through inspections. Because CPWD’s Central Design Office designed the building, the original structural drawings remain available. The peer review panel visited the sites with Delhi PWD engineers in April, 2005. Due to a heavy workload and a lack of internal analysis capacity, Delhi PWD contracted out both the linear and nonlinear analyses of the building to Engineering and Development Consultants and IIT Kanpur, respectively. The peer review panel reviewed the modeling assumptions, analysis methods, and results.

The nonlinear analyses showed that the large shear walls in Phase 1, which were initially thought to be the building’s strength, were actually its biggest weakness. These walls are very stiff but do not have adequate shear capacity, and they fail in shear well before the building reaches the anticipated level of displacement demand (the target displacement). The three phases do not have adequate seismic separation and will pound, because of their very different vibration characteristics. If the building were only being retrofitted to life safety, then pounding would be acceptable because the floors align. Because of the higher performance level, though, any potential retrofit scheme had to address the potential pounding. The retrofit scheme recommended by the peer review panel addresses the major seismic deficiencies. At the time when this report was written, IIT Kanpur still
needed to verify by analysis the efficacy of the recommended scheme, and Delhi PWD or a consultant needed to design the retrofit measures. GHI anticipates that it will be a year after USAID involvement ends, before retrofit construction begins.

**Building Description**

The complex is located on Vikas Marg at the ITO crossing. The Yamuna River flows less than two kilometers east of the complex. The building’s location with respect to the river and other Delhi landmarks is shown in Figure 1.

![Location of office complex](image)

**Figure 1. Location of office complex**

The Police Headquarters building, shown in Figure 2, was one of the first multi-storey office buildings in Delhi, hence its common name of MSO. The building has a nearly identical twin located just to the east, but that building is not part of this project. The MSO building was constructed in three phases: Phase 1 was built from 1970 to 1974; and Phases 2 and 3 were built from 1978 to 1982. Figure 3 shows how the three phases are arranged. The building covers a ground area of 1850 sq m (2121 sq ft) and has a total floor area of 26,180 sq m (281,696 sq ft). All three phases have a 3.65 m (12 ft) ground storey height and a 3.35 m (11 ft) storey height for the other 13 stories. The total building height is 47.2 m (155 ft). The east and west sides of the building have 23 cm (9 in) double wythe solid
architectural brick infill walls on their outer faces, as Figure 4 shows. These walls are interrupted at
the first story with an offset of 60 cm (23 in) toward the building interior. Figure 5 shows the
discontinuous infill walls and the open ground storey, which provides parking for officials.

Figure 2. South (front) and North (back) elevation. Back view shows building with sunshades removed for repairs.

Figure 3. Plan view showing the three phases in relation to each other
The foundation consists of driven cast-in-place piles with a diameter of 450 mm (18 in) in Phase 1 and of 500 mm (20 in) in Phases 2 and 3. The pile casings were driven to the point of refusal, which
occurred between 12 m (40’) and 16 m (53’), and the piles were then cast in place. The pile design capacity was 65 tons for Phase 1, and 101 tons for Phases 2 and 3.

Plan views of the three phases are shown in Figures 6-8. The primary lateral force resisting system in Phase 1 consists of the two large H-shaped reinforced concrete shear walls symmetrically located around the elevator shafts (lifts). These shear walls are continuous from the foundation to the terrace slab. The building also has a secondary system of reinforced concrete moment frames that were designed to take 25% of the seismic forces. Reinforced concrete moment frames provide the lateral force resisting systems for Phases 2 and 3. In all three phases, the columns are aligned from foundation to terrace as shown; only the brick infill walls are discontinuous. The frames do not have ductile details as defined by current standards. In particular, ties do not continue through joints, and 90° hooks are used throughout. Ties are more closely spaced (4 in versus 12 in) at column tops and bottoms than in the middle portion, which provides a limited amount of ductility. Longitudinal and transverse reinforcement in all structural elements consists of high strength (415 MPa or 60 ksi) cold-twisted deformed bars.

Figure 6. Ground floor plan
Delhi PWD conducted a condition assessment and found that building’s concrete members were in fair to good condition, with the exception of the members in the elevator shafts and toilet areas, and the exterior sunshades. These sunshades, located on the north and south sides, had deteriorated so much that Delhi PWD was in the midst of replacing them all when the project began. Delhi PWD successfully removed and replaced all of the sunshades with the building fully occupied. As part of the condition assessment, Delhi PWD took concrete cores and conducted rebound hammer, USPV, and carbonation tests. Table 1 shows the results of these tests.
Table 1. Results of condition assessment tests

<table>
<thead>
<tr>
<th>Sl. No.</th>
<th>Floor Level</th>
<th>Phase</th>
<th>Col. No.</th>
<th>USPV Result</th>
<th>Core Test Result N/mm²</th>
<th>Rebound Test No.</th>
<th>Comprehensive Strength N/mm²</th>
<th>Carbonation Test</th>
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<tbody>
<tr>
<td>1</td>
<td>Ground I</td>
<td>C - 26</td>
<td>Medium</td>
<td></td>
<td>47</td>
<td>26</td>
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<td>17</td>
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<td></td>
<td>17.83</td>
<td>44</td>
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<td>3</td>
<td>Fourth I</td>
<td>C - 33</td>
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<td>42</td>
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<td>57</td>
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<tr>
<td>4</td>
<td>Fifth I</td>
<td>C - 48</td>
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<td>35</td>
<td>17</td>
<td>58</td>
</tr>
<tr>
<td>5</td>
<td>Sixth I</td>
<td>C - 37</td>
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<td>26.19</td>
<td>35</td>
<td>17</td>
<td>63</td>
</tr>
<tr>
<td>13</td>
<td>Ninth I</td>
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<td>14</td>
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<td></td>
<td></td>
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<td>7</td>
<td>Eleventh I</td>
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<td>8</td>
<td>Twelfth I</td>
<td>C - 33</td>
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<td>10.16</td>
<td>34</td>
<td>16</td>
<td>43</td>
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<td>9</td>
<td>First II</td>
<td>C - 8</td>
<td>Medium</td>
<td></td>
<td>46</td>
<td>25</td>
<td></td>
<td></td>
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<td>10</td>
<td>Fourth II</td>
<td>C - 7</td>
<td>Doubtful</td>
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<td>38</td>
<td>19</td>
<td></td>
<td></td>
</tr>
<tr>
<td>12</td>
<td>Eighth II</td>
<td>C - 14</td>
<td>Medium</td>
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<td>29</td>
<td>13</td>
<td></td>
<td></td>
</tr>
<tr>
<td>16</td>
<td>Thirteenth II</td>
<td>C - 3</td>
<td>Doubtful</td>
<td></td>
<td>35</td>
<td>17</td>
<td></td>
<td></td>
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<tr>
<td>2</td>
<td>Second III</td>
<td>C - 9</td>
<td>Doubtful</td>
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<td>22.65</td>
<td></td>
<td></td>
<td>60</td>
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<tr>
<td>11</td>
<td>Seventh III</td>
<td>C - 29</td>
<td>Doubtful</td>
<td></td>
<td>37</td>
<td>18</td>
<td></td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>Tenth III</td>
<td>C - 12</td>
<td>Medium</td>
<td></td>
<td>29</td>
<td>13</td>
<td></td>
<td>50</td>
</tr>
<tr>
<td>15</td>
<td>Eleventh III</td>
<td>C - 30</td>
<td>Doubtful</td>
<td></td>
<td>30</td>
<td>13</td>
<td></td>
<td></td>
</tr>
<tr>
<td>18</td>
<td>Twelfth III</td>
<td>C - 12</td>
<td></td>
<td></td>
<td>8.65</td>
<td>33</td>
<td>16</td>
<td></td>
</tr>
</tbody>
</table>

Core test results are standard cube compressive strengths. USPV results are the concrete quality grades based on IS 13311 Part 1. These tests show that there is wide variation in the compressive strength of the concrete members, and that in most cases, the strength of concrete was lower than the design strength. Design strengths were as follows: in Phase 1, M25, M20 and M15 grade concrete mixes were used in ground to 4th, 5th to 10th, and 11th to 14th floors respectively; in Phases 2 and 3, M25, M20 and M15 grade concrete mixes were used in ground to 4th, 5th to 6th, and 7th to 13th floors respectively. The carbonation tests show that significant carbonation has taken place in the concrete of the exterior concrete members. The carbonation depth is clearly more than the 40 mm clear cover given in the drawings, which enhances the risk of corrosion in thin members. Peer panel members recommended that Delhi PWD take measures to protect vulnerable members from corrosion.

Site Seismic Hazard

Ground Shaking

The ground shaking hazard for the purposes of engineering design was defined by the seismic zoning map and response spectrum given in Indian Standard 1893 (Part 1):2002 Criteria for Earthquake Resistant Design of Structures. For Delhi, the Maximum Considered Earthquake (MCE) peak ground acceleration (PGA) is 0.24 g. The project did not have the time, political backing, or funding to conduct site-specific hazard analyses. Some existing studies helped panel members to assess, in a very limited sense, whether the code values were appropriate for design. A study of seismic hazard
by Iyengar (2000) indicates that acceleration between 0.18 and 0.23 g can be expected at rock level for an earthquake with a 2% probability of exceedance in 50 years (this corresponds to an earthquake with a return period of 475 years). An older analysis by Khattri (1992) suggests that Delhi will see shaking on the order of 0.2g from an event with a 10% probability of exceedance in 50 years (this corresponds to an earthquake with a return period of 475 years). Shaking will be stronger at soil sites due to site amplification, and the Indian Meteorological Department is preparing a microzonation map that will quantify the amplification in various areas. The Global Seismic Hazard Assessment Project (GSHAP) map gives a PGA of about 0.14g for Delhi.

However, these probabilistic assessments were made without the benefit of extensive earth science studies to better define the hazards posed by local seismic sources and the likely size and recurrence interval for Himalayan events. GHI anticipates that current and future studies by earth scientists will lead to better quantification of Delhi’s seismic hazard and to revision of the design shaking values. Based on the currently available earth science information and studies discussed above, the peer review panel did not view the code values as unconservative.

**Geotechnical Conditions**

The building sits on approximately 2 m of fill underlain by sandy soils with some gravels. As Figure 1 shows, the site is located on alluvial sediments deposited by the Yamuna River, currently less than two kilometers away. The river flowed much closer to the site only several hundred years ago, however. The site is not located near slopes, embankments, or fault traces, so the primary ground failure threat comes from liquefaction.

Delhi PWD conducted geotechnical investigations to determine the likelihood of liquefaction. The investigation included four 150 mm diameter boreholes drilled to depths between 17.5 and 20 meters. Standard penetration tests were conducted at 1.5m intervals or at a change of strata, whichever was earlier. Undisturbed and disturbed samples were collected at every 3.00m or at every change of strata, whichever was earlier. To judge the consistency of the strata, three dynamic cone penetration tests were conducted according to the protocols in IS: 4968-1976, using a cone of 50mm diameter and a 60 degree apex angle. Based on the data collected, Delhi PWD determined that liquefaction was unlikely.

**Design Criteria**

The peer review panel recommended the use of a two-level performance criterion for all project buildings. Relations between the performance level, the design earthquakes in the IS 1893 code, and the peak ground acceleration are shown in the table below. The peer panel attempted to relate the retrofit performance criteria back to the Life Safety performance intended by the IS 1893 code provisions, and decided that recommended criteria for enhanced performance are philosophically equivalent to designing the building to life safety for a larger ground motion.

<table>
<thead>
<tr>
<th>Buildings</th>
<th>Design Basis Earthquake</th>
<th>Maximum Considered Earthquake</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hospitals</td>
<td>Immediate Occupancy*</td>
<td>Life Safety</td>
</tr>
<tr>
<td></td>
<td>PGA (g) 0.12</td>
<td>0.24</td>
</tr>
<tr>
<td>Non-hospitals</td>
<td>Life Safety + Damage Control*</td>
<td>Collapse Prevention</td>
</tr>
<tr>
<td></td>
<td>PGA (g) 0.12</td>
<td>0.24</td>
</tr>
</tbody>
</table>
*These performance criteria are considered to be philosophically equivalent to using $I=2.0$ for hospitals and $I=1.5$ for non-hospitals, which give Life Safety performance at 0.24g for hospitals and 0.18g for non-hospitals. Any actual designs using IS 1893 will use 0.24g for hospitals and 0.18g for non-hospitals.

<table>
<thead>
<tr>
<th>Buildings</th>
<th>PGA (g) for which above criteria correspond to Life Safety using IS 1893</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hospitals</td>
<td>0.24</td>
</tr>
<tr>
<td>Non-hospitals</td>
<td>0.18</td>
</tr>
</tbody>
</table>

Police Headquarters building users indicated that they wanted Immediate Occupancy performance for their building, but peer review panel members felt that this might not be necessary. The peer panel members disagreed over whether the pounding would adversely affect the performance. The prevailing opinion was that the expected amount of pounding would make achieving the desired performance unacceptably uncertain.

**Structural Assessment and Analysis**

The building underwent perhaps the most extensive assessment and analysis of any of the five buildings in this project. Delhi PWD performed an initial assessment using the ASCE 31 Tier 1 Checklist. Mr. H. S. Bakshi of Engineering and Development Consultants conducted linear analyses of the three blocks. Finally, IIT Kanpur performed eigenvalue and nonlinear static pushover analyses of the three blocks, both individually and in various combinations with retrofit measures in place.

**ASCE Tier 1 Checklist**

Noncompliant items from the ASCE 31 Tier 1 Checklist included:

- Interfering walls
- Column bar splices
- Column tie spacing

The Tier 1 checklist could not identify the building’s major problem: the weak Phase 1 shear walls and their incompatibility with Phases 2 and 3. In using the checklist, Delhi PWD considered all three phases as one building rather than as adjacent buildings, and failed to identify the pounding problem that would cause so much difficulty later. This building offers an example of why the checklist should be a first step in a more thorough evaluation and should be used with care and engineering judgment.

**Linear Analysis**

Linear analyses by Engineering and Development Consultants showed that the frame columns were overstressed in all buildings, particularly those in the Phase 1 shear walls. The analysis of Phase 2 showed that all columns at the ground floor were overstressed, while many at the 5th floor and a few at the 12th floor were overstressed. Results were similar for Phase 3 but showed that more columns were failing at the 12th floor level than in Phase 2. The analysis of Phase 1 showed that columns were not typically overstressed to the degree those in Phases 2 and 3. However, large forces were observed in those columns bordering shear walls, as a result of the overturning moment in the walls. This analysis did not identify shear yielding in the Phase 1 shear wall as the primary
failure mode and thus, could not provide an accurate picture of building behavior. This building demonstrates the value of performing more advanced analyses to determine the building’s likely seismic behavior.

**Nonlinear Analysis**

IIT Kanpur performed numerous nonlinear analyses, which are documented in detail in their report to Delhi PWD entitled “Pushover Analysis of Police Headquarter Building, New Delhi” and submitted in December, 2006. IIT Kanpur began by carrying out nonlinear static pushover analyses of a two-dimensional bare frame model of Phase 2 in SAP and another program called SNAP 2DX. Nonlinear static pushover analyses in both directions were then performed on three-dimensional models of each of the three phases of the building independently. At the time when this report was written, IIT Kanpur had conducted several analyses of the buildings with various retrofit measures and still needed to verify the behavior of the recommended retrofit scheme. As an academic exercise, IIT Kanpur performed analyses to determine the behavior of the buildings stitched together but without other retrofit measures. In one set, Phase -1 and Phase-2 buildings were stitched, and in the second set, all the three building phases were stitched together, across the expansion joint. Unsurprisingly, torsion was a problem. Detailed descriptions of the modeling assumptions and analyses can be found in the report by IIT Kanpur mentioned above. Modeling and analytical assumptions common to all the buildings, which were determined by consensus at the third meeting of the peer panel, are listed below:

- Shear walls will be modeled as wide columns
- Masonry infill walls will be modeled as braces with properties of equivalent struts
- Expected material strengths will be used: characteristic strength for concrete, 1.15 times mean Fy for steel
- Masonry material properties will be modeled using test results from IITs
- The IS 1893 parabolic distribution will be used for all buildings, with additional measures to take into account higher modes in the Police Headquarters building
- Foundations will be initially modeled as rigid, with springs added as necessary, with the addition of retrofit measures like shear walls
- The coefficient method from U.S. Federal Emergency Management Agency Report FEMA 440 will be used to determine target displacements
- Both moment and shear hinges will be placed at column ends

IIT Kanpur’s findings included the following major points:

- The unreinforced brick infill walls present in each phase are not effective in resisting lateral loads. In addition, these walls result in an unsymmetrical stiffness distribution that causes torsion and represents a significant falling hazard. Mitigation measures are needed.
- The existing shear walls around the Phase 1 lift core are very stiff and attract large shear forces. These walls do not have sufficient shear strength capacity and quickly yield in shear. Including foundation flexibility does not significantly change the observed performance. These shear walls must be strengthened, or additional elements must be provided, to keep the walls from experiencing unacceptable shear behavior.
• Due to inadequate seismic separation, pounding between the phases of the building is inevitable for both the DBE and MCE, and needs to be controlled if the blocks are not stitched together.
• Torsion is a problem and should be addressed by mitigating the effects of infill walls and by adding new shear walls.

The nonlinear analyses described above revealed the building’s major problems, despite the fact that they were static rather than dynamic analyses. At fourteen stories, the building is almost tall enough that pushover analysis would not give meaningful results. If the project had unlimited time and funding, it would have been very interesting to subject the building model to nonlinear time history analysis.

Retrofit Scheme Selection

Recommended Retrofit Scheme
After investigating many potential schemes, the peer review panel recommended the following scheme:

• Tie Phases 2 and 3 together at every third floor, but do not join them to Phase 1;
• Add new shear walls to Phase 1 to keep the shear walls from failing;
• Mitigate the effects of infill walls that cause torsion in Phase 2 and 3; and
• Determine by analysis if pounding remains a problem, and if so, then open the joints between Phase 1 and Phase 2 / 3.

The Alternative Schemes Investigated section below contains a chronological narrative that explains how and why Delhi PWD, the peer panel, and IIT Kanpur arrived at the above scheme. Technical challenges and disruption considerations governed the selection process. This building was the most challenging of the five studied, and the lengthy duration of the scheme selection process illustrates that clearly. At the time when this report was written, the scheme still needed to be designed and verified by analysis, so no drawings were available.

Anticipated Performance After Retrofit
The main building is expected to perform at a level above life safety for the DBE. Phases 2 and 3 will perform at the life safety plus damage control level. Phase 1 is likely to perform at or near the immediate occupancy level, because the amount of new shear walls needed to keep the existing shear walls from failing will make the building nearly elastic. Because the building retrofit was still in the design phase when this report was written, the designers have the option of further improving performance.

Alternative Schemes Investigated
The IIT Kanpur and Delhi PWD proposed a total of thirteen potential retrofit schemes to address the building’s major seismic deficiencies: the stiff but weak Phase 1 shear walls, pounding between Phase 1 and the much more flexible Phases 2 and 3, and the problematic brick infill walls.

As its common name implies, the MSO building was one of the first tall office buildings constructed in Delhi and is something of a landmark. Accordingly, any changes to the exterior must be approved
by the Delhi Design Authority. This requirement limited the potential retrofit schemes to those that did not markedly change the building’s external appearance, because that would make the necessary approvals very hard to obtain. The building also houses important officials who do not like to be disturbed, so disruption was an important consideration when selecting potential retrofit schemes. Disruption concerns made an unobtrusive exterior scheme the most appealing choice.

The most instructive means of describing the alternate schemes, and more importantly, why they were suggested, is through a chronological narrative. This narrative was compiled from meeting summary reports, analysis reports by Indian Institute of Technology (IIT) Kanpur, reports and presentations by Delhi PWD, and correspondence. The summary is arranged in chronological order by major meetings where results were reported and discussed. The narrative traces the evolution of proposed retrofit alternatives and of the project team’s collective understanding of the building’s seismic behavior.

First peer review panel meeting and site visits (May 7, 2005)
Delhi PWD gathered basic information about the building, including the structural drawings for all three phases. Prior to the meeting, peer panel members visited the site with Delhi PWD to make first-hand observations. Peer panel member Bill Holmes recommended that Delhi PWD consider tying the phases together to eliminate the pounding that would be caused by the inadequate seismic separation. The panel recommended nonlinear analysis of the building to determine stiffness and drift limitations, frame interaction with new or existing shear walls, and shear wall capacity. The panel also recommended investigating potential rocking of the shear walls and soil-structure interaction. Administrators for the agencies located in the building communicated to the project team that they believed immediate occupancy performance is necessary. Mr. Anil Pandit was selected as the Engineering Team Leader for the building.

Second peer review panel meeting (Aug. 8-12, 2005)
Delhi PWD reported the results of the ASCE 31 Tier 1 analysis, which showed that the building had several seismic vulnerabilities, including discontinuous infill walls and inadequate ductile details. Delhi PWD also presented elastic analysis results, which showed that some columns were overstressed in all three phases and that the boundary elements in Phase 1’s shear walls could be overstressed (further checks were recommended). Peer review panel members recommended nonlinear static analysis to better understand building behavior. Peer panel members offered the consensus opinion that Phases 2 and 3 would need to be stiffened with shear walls, if they were to be joined to Phase 1 to avoid pounding.

Meetings of the India-based peer review panel members (Sept. 30, Oct. 6, Nov. 7, 2005)
Delhi PWD selected IIT Kanpur to carry out the pushover analysis of the building. At the Nov. 7 meeting, Mr. H. S. Bakshi presented the results of his temperature analysis of the building, which showed that temperature stresses were not very significant when the three phases were connected. At the same meeting, Prof. Arya requested a linear analysis of the building with R=4.

Third peer review panel meeting (Dec. 5-9, 2005)
Participants decided on a two-level performance criterion for the building: Life Safety plus Damage Control (LS+DC) for the Design Basis Earthquake (DBE) with peak ground acceleration (PGA) equal to 0.18g, and Collapse Prevention (CP) for the Maximum Considered Earthquake (MCE) with PGA equal to 0.24g. IIT Kanpur presented preliminary results of nonlinear static analyses, which showed a weak
story mechanism in Phase 2 and deficiencies in the other phases. IIT Kanpur noted that adding shear walls to remove torsion becomes very important if the phases are stitched together. Participants agreed on common modeling and analysis procedures for all of the buildings. Meeting participants proposed several alternate retrofit schemes for further investigation. These alternate schemes will be identified with capital letters, to simplify tracking when they are subsequently mentioned in this summary.

Scheme A: All three phases stitched together, with external shear walls added along existing wall lines at building cutouts, and diaphragms added to transfer shear to elevator core shear walls in Phase 1.

Scheme B: All three phases stitched together, with external shear walls added in box configurations filling in building cutouts, and diaphragms added to transfer shear to elevator core shear walls in Phase 1.

Scheme C: All three phases stitched together, with internal shear walls, and diaphragms added to transfer shear to elevator core shear walls in Phase 1.

Scheme D: Phases 1 and 2 stitched together, and Phase 3 left free. External shear walls to be added to both Phase 3 and Phase 1/2 combination, and diaphragms added in Phase 1.

Scheme E: Same as 3, conceptually, but with dampers installed between Phase 3 and Phase 1/2 combination.

Meetings of the India-based peer review panel members (Dec. 21 & 29, 2005, Jan. 13, 2006)
IIT Kanpur recommended that Schemes D and E would likely not produce a viable solution because of the weaknesses of Phase 1 and should only be examined as an academic exercise.

Mini-panel meeting (September 1, 2006)
IIT Kanpur reported the results of pushover analyses of the building with retrofit measures. Schemes that tie the buildings together and add shear walls (Schemes A-C) did not work because the shear walls in Phase 1 are very stiff but weak, and there is no room (because of architectural constraints) to add enough new shear walls to prevent the existing Phase 1 shear wall from failing in shear. Bill Holmes suggested adding foundation flexibility via a soil spring to see if rocking will help to keep the Phase 1 walls from failing in shear and, if that doesn’t work, cutting the wall flanges (walls are H-shaped) or webs to reduce their stiffness to an acceptable level. Incorporating foundation flexibility with the most promising arrangement of new shear walls, and tying the three phases together will be hereafter referred to as Scheme F.

Meeting of the US-based peer panel members with Hari Kumar (November 29, 2006)
Mr. Kumar presented the results of IIT Kanpur’s analysis, which shows that adding foundation flexibility does not to keep the Phase 1 shear walls from failing. The US-based members of the peer panel recommended analyzing Scheme F with cuts to the existing Phase 1 shear wall, which will be hereafter referred to as Scheme G.

Fourth peer review panel meeting (January 29-31, 2007)
IIT Kanpur reported that they tried several cutting patterns for Scheme G that did not soften the Phase 1 wall enough to prevent failure. Peer panel members recommended that IIT Kanpur continue to try Scheme G with additional cuts to the Phase 1 walls. Some peer panel members suggested
allowing the Phase 1 shear walls to fail (Scheme H), but this idea was rejected by others due to concerns over gravity load carrying capacity and the impact of large visible shear cracks on building users. Engineer-in-Chief Subramanian then suggested Scheme I, which would add towers containing the new shear walls. Peer panel members recommended that Delhi PWD check with the proper authorities to determine if they would permit Scheme I before beginning evaluations or design work, because it would increase the percentage of the lot that the building covers to the point at which an exemption from local building laws would become necessary.

Fifth peer review panel meeting (September 10, 2007)
Due to difficulties in making Scheme G work and concerns about whether weakening walls is an acceptable idea, the peer review panel recommended several revised options:

**Scheme J**: Join Phases 2 and 3 together, but do not join them to Phase 1. Add shear walls to the lower floors of Phase 1 and/or weaken the existing walls. Mitigate the effects of infill wall, and open the joints between Phase 1 and Phase 2 / 3.

**Scheme K**: Same as Scheme J but mitigate pounding between Phase 1 and Phase 2 / 3 by reducing the drifts of Phase 2 / 3 through adding shear walls or dampers.

**Scheme L**: Tie all three phases together, but deal with the existing Phase 1 walls by a combination of adding shear strength to the existing walls through fiber wrap to change the failure mode from shear to flexure, adding new shear walls, and reducing the stiffness of the existing Phase 1 walls.

Sixth peer review panel meeting (March 6, 2008)
No further progress was reported. Delhi PWD agreed to contact IIT Kanpur to determine the future course of action.

Meeting of Delhi PWD and IITs in Roorkee (April 24, 2008)
IIT Kanpur recommended that they themselves analyze only Scheme L.

Seventh peer review panel meeting (March 6, 2008)
Delhi PWD and the peer panel determined that Scheme L would be too costly and disruptive. The idea of weakening the Phase 1 walls was abandoned. The peer panel instead suggested a modification of several previously suggested schemes, hereafter called Scheme M:

- Tie Phases 2 and 3 together at every third floor, but do not join them to Phase 1;
- Add new shear walls to Phase 1 to keep the shear walls from failing;
- Mitigate the effects of infill walls that cause torsion in Phase 2 and 3; and
- Determine by analysis if pounding remains a problem and if so, then open the joints between Phase 1 and Phase 2 / 3.

Peer review panel recommended that IIT Kanpur demonstrate by analysis that Scheme M works and that Delhi PWD retain a structural engineering consultant to design the retrofit solution. Peer panel members agreed to make themselves available if needed to discuss the pounding issue.
Functionality, Architectural, and Disruption Considerations
The building has significant architectural, functional and disruption issues, which affected the choice of retrofit scheme, as discussed above. Any retrofit scheme will have to be approved by an architectural review board, so Phase 1’s new shear walls have to be carefully located. Retrofit schemes that added square footage on the ground floor would have to get a special exemption from the building bylaws, but the new shear walls in the recommended scheme will not add enough area to require an exemption. During construction, disruption will need to be carefully managed. Delhi PWD is convinced that the building must be retrofitted while occupied and has confidence this can be done, based on their experience of replacing the sunshades with the building occupied.

Engineering Design and Construction Documents
At the time when this report was written, engineering design was in progress but not yet complete. As discussed in the retrofit scheme selection section, there are several difficult technical issues that will continue to affect the design process. These include how to deal with pounding in a way that minimizes disruption, locating and detailing the new shear walls, and strengthening or weakening the existing Phase 1 shear walls. Engineering drawings, specifications, and cost estimates were not available when this report was written.

Construction and Quality Control
At the time when this report was written, the retrofit was still in the design process and had not been constructed.

Mitigation of Falling Hazards
Several areas of the building, including the police offices, will need to have their furnishings, architectural elements and utilities braced, so that they will be functional after an earthquake. Delhi PWD plans to anchor these items after the structural retrofit is complete.

Conclusions
The Delhi Police Headquarters was the most technically challenging building of the five assessed in this project. The stiff but weak shear walls in Phase 1 failed under the design earthquake loading, but the inadequate separation from very flexible Phases 2 and 3, and the architectural and disruption constraints made developing a solution very challenging. IIT Kanpur, Delhi PWD, and the peer review panel discussed a total of thirteen potential retrofit schemes before deciding on the recommended scheme. When constructed, this scheme will provide performance that is better than life safety. Phase 1 will probably achieve even higher performance; the amount of new shear walls needed to keep the existing shear walls from failing will make the building nearly elastic. At the time when this report was written, many challenges remained: the technical challenge of designing the retrofit scheme; the administrative challenges of getting the design approved and funds sanctioned, and; the challenges of constructing the retrofit measures on a constrained, security-sensitive site. Delhi PWD, the Delhi Government, and the other project participants remain committed to constructing this retrofit and to protecting the building’s occupants and functions from earthquakes.