

SEISMIC RETROFIT AND INSTRUMENTATION OF LOS ANGELES CITY HALL

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Introduction

The construction for the seismic rehabilitation of the Los Angeles City Hall was completed in 2001. An integral part of the project is the installation of seismic instrumentation throughout the building. The instrumentation program was a collaborative effort involving the Los Angeles City Department of Public Works Bureau of Engineering, California Geologic Services Strong Motion Instrumentation Program (CGS-SMIP) and the Engineering Design team. The future data recorded by these sensors will provide valuable insight on the actual response of the building during an earthquake. This information will aid the structural engineering community to better understand the behavior of base isolated structures with supplemental damping.

The building was originally constructed in 1926 and was the first building to exceed the 150 feet height limitation for all privately constructed buildings in Los Angeles. It is 32 stories (460 feet) tall. The original building was designed prior to the enactment of explicit seismic design requirements and therefore, was not specifically designed to resist earthquake generated forces.

Over the past 75 years, regional earthquakes have caused damage to the building. Terra cotta cladding has been cracked, broken or destroyed in portions of the building's exterior. With every significant earthquake, unanchored masonry debris has been scattered about the building's interior. Large cracks in the masonry walls appeared at the 24th floor after the 1971 Sylmar Earthquake, the 1987 Whittier Earthquake and the 1994 Northridge Earthquake.

The building has been seismically rehabilitated in order to preserve life safety, mitigate damage, maintain the integrity of the building's exterior facade, and protect the historic interior fabric from damage. Base isolation with supplemental damping was used to enhance its seismic performance. This approach was determined to be the most effective strengthening scheme based on performance and cost.

This paper presents an overview of the rehabilitation project including the development of seismic performance goals, identification of inherent seismic deficiencies of the original building, description of the final seismic strengthening and instrumentation program.

Building Description

The Los Angeles City Hall has three major structural portions: "podium" (sub-basement to second floor), "mid-rise" (third to ninth floor) and "tower" (tenth floor to the top of the dome).

The structural frame of the tower extends through the mid-rise and podium of the building to the mat-slab foundation. Similarly, the mid-rise frame extends through the podium to the foundation level (*See Figure 1*).

The gravity system of the building consists of a concrete encased steel frame and reinforced concrete slab/pan-joint floor system. The typical beam-to-column connection is a riveted 'wind connection' that utilizes top and bottom seat angles (*See Figure 2*).

The building was originally designed prior to the enactment of explicit seismic design requirements and therefore, was not specifically designed to resist seismic forces. Thus, the original building did not have a distinct seismic force resisting system that provided a competent load path for seismic loads. However, there were a number of structural components that, although not specifically designed to resist earthquake forces, participated in resisting these forces.

Lateral load resistance was provided by horizontal diaphragms, perforated unreinforced masonry infill walls, lightly reinforced concrete walls and light steel bracing. The unreinforced masonry infill walls provided most of the lateral force resisting capability of the original building.

Performance Criteria

Seismic performance objectives were established for the project. These objectives, as outlined below, were intended to satisfy both the life safety and damage mitigation objectives of the City of Los Angeles for the building.

1. Insure stability of the structural system during the maximum possible earthquake.
2. Prevent falling hazards which pose a significant life safety hazard.
3. Insure safe means of egress from the building.
4. Insure that life safety systems remain operable.
5. Maintain integrity of the building's exterior façade (*See Figure 3*).
6. Protect historic interior fabric of the building from damage (*See Figure 4*).
7. Protect emergency telecommunication systems including tower, satellite dishes, etc.
8. Preserve the basic functions of the building.

These objectives were quantified in engineering criteria to facilitate the evaluation of the seismic performance of the original building. The engineering criteria define the performance objectives in terms of specific analytical limit states. These limit states were determined using

the latest research data available regarding the seismic performance of existing buildings combined with guidelines developed for life safety protection and damage mitigation.

Limit states were established for inter-story drift, inelastic demand ratios for the various structural elements, and story accelerations. Inter-story drift limits are essential to maintaining global stability in the structural system by limiting the P- Δ effects. In addition, earthquake damage in many structural and non-structural building systems can be directly associated to the inter-story drift the building experiences. Inelastic demand ratios (IDR) represent a measure of the post-yield deformations of the structural members during a given earthquake. In order to insure the safety and stability of the structural system, limitations on the allowable inelastic demand ratios are required. Story accelerations affect the seismic performance of building contents and non-structural systems.

Material and Dynamic Testing

Material and dynamic testing were performed to determine the strength and deformation characteristics of the original building materials and to determine the dynamic characteristics of the building.

Ambient and forced vibration tests were performed to determine the dynamic properties of the original building. The ambient vibration test measured the response of the building to vibrations which occur at the building site, such as vehicle traffic, wind, occupants, etc. Forced vibration tests were performed using a forced vibration oscillator to vibrate the building. The forced vibration test was used to determine the response of the building to high level excitations (*See Figure 5*). The results of these tests were used to verify the modeling assumptions made in the development of the computer model of the original building.

A variety of in-situ tests were performed on the unreinforced masonry. In-plane shear tests were performed on the masonry walls to determine the ability of the existing brick and mortar to resist shear stresses. Several flatjack tests were performed to determine the compressive strength and deformability properties of masonry (*See Figure 6*). The results of these tests were used in the development of computer models and in the determination of the strength capacity of the original building.

Computer Models

Computer models were developed to assess the global performance of the original and rehabilitated buildings. Nonlinear finite element models were developed to determine the limit state behavior of the unreinforced masonry infill. Computer models were also developed to perform nonlinear dynamic analysis for the base isolated building.

The primary steel frame skeleton, steel bracing, reinforced concrete walls, unreinforced masonry infill walls, and concrete diaphragms were included in the linear elastic computer models to accurately simulate the behavior of the original building (*See Figure 7*). In order to assess the dynamic behavior of the building, it was crucial to understand the behavior of the existing unreinforced masonry walls. These walls represent a significant portion of the overall

strength and stiffness of the original structural system. Nonlinear finite element analysis was performed on typical URM wall configurations of the building to determine their limit state behavior. Results from these analyses were incorporated into the global model of the building. The global model of the original building was then calibrated to the results of the vibration tests. Table 1 below summarizes the measured and eigen-analysis periods.

| Mode Number | Direction | Period (sec) | | | |
|-------------|-------------|--------------|--------|-------|-------|
| | | Ambient | Forced | ETABS | SAP90 |
| 1 | East-West | 2.38 | 2.50 | 2.62 | 2.78 |
| 2 | North-South | 2.08 | 2.27 | 2.44 | 2.52 |
| 3 | Torsion | 1.08 | 1.19 | 1.24 | 1.39 |

Table 1. Periods of Vibration - Original Building

Evaluation of Original Building

The seismic performance of the original was evaluated and deficiencies in the lateral force resisting system were identified. The computer model of the original building was verified by performing an eigen-analysis and comparing the results with the test data obtained from dynamic testing of the building. The periods obtained from the eigen-analysis were found to be in good agreement with the results of forced vibration tests.

The seismic performance of the original building was evaluated using linear dynamic analysis procedures. The design basis earthquake, representing a 10% probability of being exceeded in a 50 year time period was used.

The results of the analyses indicated high stress levels in the unreinforced masonry walls, relatively large inter-story drifts and story accelerations in the tower. Significant damage to the unreinforced masonry walls, terra cotta, partition walls, historic fabrics and all rigid/brittle non-structural systems would be expected. The original building did not satisfy the seismic life safety criteria established for the project and required strengthening.

Enhancement of Seismic Response

The building has been strengthened using base isolation with reinforced concrete shear walls and supplemental damping. Base isolation effectively decouples the building from ground motions, greatly reducing the level of seismic force transferred to the super-structure. The new reinforced concrete shear walls add strength, re-distribute seismic over-turning forces, stiffen the super-structure increasing the effectiveness of the isolation system, and improve the lateral force load path. The viscous dampers have been installed at the plane of isolation and between the 26th and 27th floors. The dampers at the plane of isolation increase the energy dissipation capacity of the isolation system and thus, reduce the energy transmitted to the super-structure. The dampers in the tower add damping to the higher modes of the building response and have the localized

effect of reducing whiplash at the top of the tower.

This approach to strengthen the building significantly reduces the accelerations, inter-story drifts and element stress levels throughout the height of the building.

Isolation System

The plane of isolation is located below the basement level and above the foundation. The isolation system consists of 416 high damping rubber (HDR) bearings, varying in size from 29.5 in. to 51.2 in. diameter, and 90 flat sliding bearings. The HDR bearings vary in height from 9.6 inches to 16.6 inches. (*See Figure 8*) The sliding bearings are comprised of a teflon pad mounted on a natural rubber bearing, and a stainless steel sliding plate. The sliding bearings support less than 10% of the total building weight.

The bearings were installed using a loose-bolt connection to allow uplift to occur without loading the bearing in tension.

The bearings were rigorously tested to verify their properties used in the analysis and design. Bearing stability at a maximum lateral displacement of 21 inches was also verified (*See Figure 9*).

Supplemental Damping

The isolation system is supplemented with 52 viscous dampers, 26 in each direction, at the plane of isolation. These dampers bridge the plane of isolation, i.e. one end is connected to the foundation and the other to the underside of the basement slab. The dampers have a mid-stroke length of 143 inches, a force rated capacity of 300 kips at 50 in/sec, and a stroke of ± 21 inches (*See Figure 10*).

Twelve viscous dampers, six in each direction, have been installed between the 26th and 27th floor. These dampers have a force rated capacity of 225 kips at 10 in/sec, a stroke of ± 4 inches, and a mid-stroke length of 46 inches (*See Figure 11*).

Full-scale prototype 225 kip dampers were cyclic load and drop tested to verify the damper properties in the prototype test phase. The results from the cyclic load and drop tests were well correlated.

Structural Strengthening

The new walls are located along the perimeter walls of the tower extending to the basement and along the walls at the north and south ends of the mid-rise extending to the basement. The walls under the tower re-distribute the seismic over-turning forces and reduce the net uplift experienced by the isolators under the walls (*See Figures 12 and 13*).

The original basement diaphragm was demolished and a new 8 inch thick concrete diaphragm constructed. Demolition of the original diaphragm provided access to the foundation

and simplified the installation of the isolators. The new diaphragm system ties all of the isolators together and ensures proper force transfer between the super-structure and isolation system (*See Figure 14*).

A new horizontal steel truss diaphragm was added at the roof of the mid-rise to facilitate the transfer of seismic forces from the tower to the new RC walls at the north and south ends of the mid-rise. This diaphragm couples the new tower walls to end walls of the mid-rise providing an additional load path for seismic forces and reduces the over-turning demand at the base of the tower (*See Figure 15*).

Extensive work was done on the original foundation system to strengthen and tie individual footings together.

Constructability

The new 24 inch thick concrete walls at the basement level facilitated the installation of the HDR bearings located under these walls. Dowels were provided to transfer gravity loads from the column to the walls. After construction of these walls, the pedestals of the columns were removed. The gravity loads were transferred to the shear walls through the dowels. The bearings were then installed under the columns. A horizontal saw cut was then made in each wall at the basement level, to separate the wall from its foundation. The loads were then transferred back to the columns and bearings. This sequence of construction reduced installation time considerably.

Instrumentation (Installed and Maintained by CGS-SMIP)

The utility and need of strong motion data has grown over the years with advances in technology that allow real-time retrieval and processing of data, advances in geological information systems (GIS) and loss estimation methods. The introduction of shake-maps on-line that demarcate ground shaking intensity in affected areas immediately after an earthquake has proved a useful tool to emergency response personnel. These maps are produced using data recorded by sensors located in the affected area in the immediate aftermath of the earthquake. The growing interest in loss estimation and the release of the HAZUS software (funded by FEMA) for use by government agencies, has increased the need for data correlating building damage to ground shaking intensity. These developments have broadened the stakeholder base (engineers and earth scientists) for strong motion instrumentation programs to include government agencies, utilities and insurers, and demonstrate the value of these programs.

An instrumentation program for the building has been developed to comply with the base isolation system design provisions of the Uniform Building Code. The principal objective of this program is to further the understanding of the behavior of the building during a seismic event and to use this knowledge to improve future design and construction practice. The data recorded from these sensors will allow the engineering community to calibrate analytical models and assumptions that were used in the analysis and design of the rehabilitated building. This knowledge will enhance our understanding of how isolation systems, viscous dampers and URM infill behave under seismic loading.

In order to achieve the stated objective, an adequate amount of data needs to be recorded in order to reconstruct the actual response in sufficient detail to compare with the response from analytical models. More robust data also allows the use of system identification techniques to determine dynamic characteristics of the building (periods, mode shapes, damping, etc.). Thirty sensors have been installed throughout the building by CGS-SMIP in conjunction with the City of Los Angeles Bureau of Engineering in December of 2003. This array of sensors significantly exceeds the code requirement of “*horizontal displacement recording devices ... installed at the isolation interface*” and represents the “ideal extensive instrumentation scheme”.

There are a total of 27 accelerometers and 3 displacement sensors. The accelerometers are distributed throughout the building with 5 sensors at the foundation (below the plane of isolation), 7 at the basement diaphragm (immediately above the plane of isolation), 4 at the 5th and 10th floors, 3 at the 26th floor, and 2 at the 27th and 29th floors (*See Figure 16*). These locations were selected to optimize the value of the recorded data using the least sensors. The sensors at the foundation and basement levels provide response information above and below the plane of isolation. The sensors at the 5th and 10th floors are located at levels where major transitions (setbacks) in the building configuration occur. The sensors at the upper levels of the tower will provide data on the whiplash effect of the tower and the effectiveness of the viscous dampers at the 26th floor. All of the displacement sensors are located at the plane of isolation. The accelerometers and displacement sensors are also distributed in plan to capture any torsional response at each instrumented floor.

The sensors at the foundation and basement levels were judiciously located near isolators and dampers. Recorded data from these sensors will allow the study of the building response and the behavior of the isolators and dampers (*See Figure 17*). Sensors that measure vertical motion are located above and below an isolator near the center of the building (*See Figure 18*). Data from these sensors will provide information on the vertical response of the building and overturning/uplift.

Free field sensors will be installed in the park outside the building in the near future. Soil-structure interaction effects for the building may be investigated using the data recorded at the free-field and foundation.

In the future these sensors may be incorporated into a real time monitoring network that has the ability to detect damage to the building during an earthquake.

Conclusion

The original Los Angeles City Hall has sustained damage from earthquakes over the past 75 years. In an effort to preserve life safety and mitigate damage, the building was seismically upgraded using base isolation with supplemental damping. This approach was determined to be the most effective strengthening scheme based on performance and cost. Construction was completed in 2001.

As part of the upgrade, seismic instrumentation has been installed throughout the building. The data recorded by these sensors in the future will provide valuable insight on the actual response of the building during an earthquake. This information will aid the structural engineering community to better understand the behavior of base isolated structures with supplemental damping.



Figure 1: Aerial view of building



Figure 2: Historic view of building



Figure 3: Courtyard colonnade

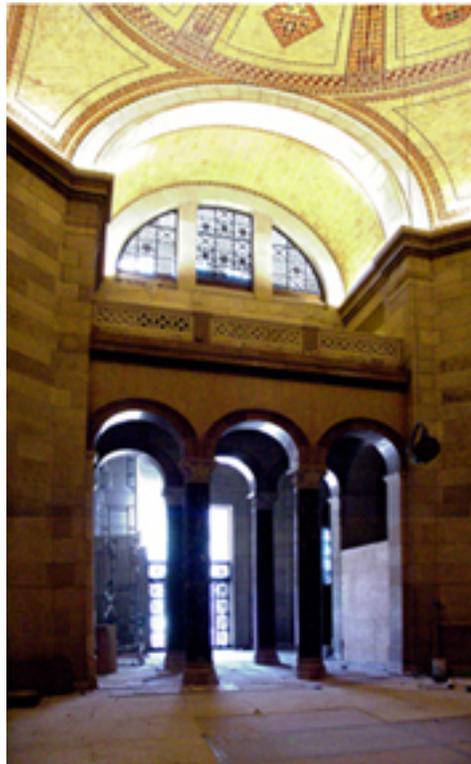


Figure 4: Rotunda



Figure 5: Forced vibration oscillator setup



Figure 6: URM in-stu test setup

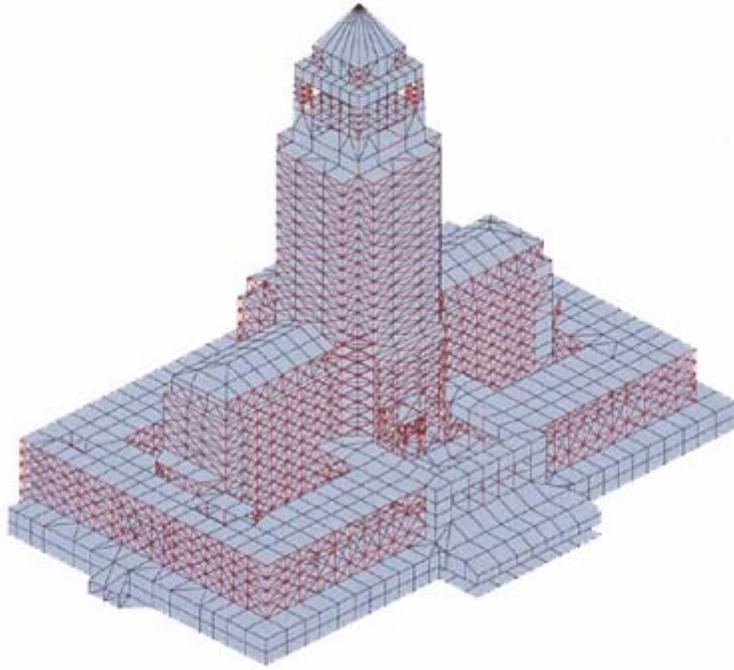


Figure 7: Plot of 3D computer model



Figure 8: High damping rubber bearings installed under tower wall

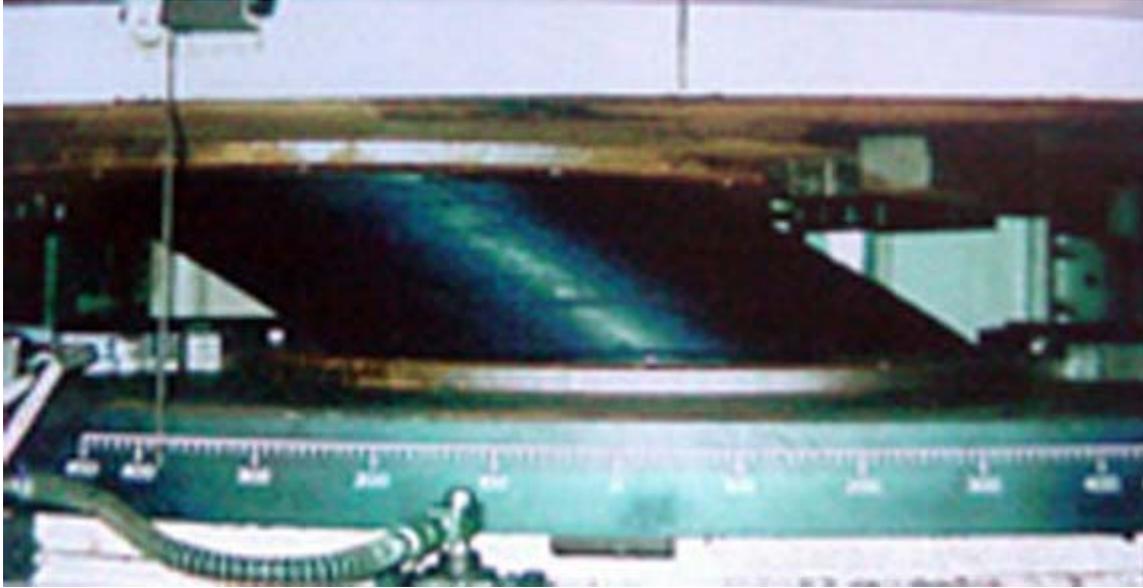


Figure 9: Shear displacement test of bearing



Figure 10: 300 kip damper installed at plane of isolation



Figure 11: 225 kip damper installed at 26th floor



Figure 12: Rebar for new concrete shear wall at basement level



Figure 13: Rebar for new concrete shear wall in tower



Figure 14: New basement diaphragm in construction



Figure 15: New horizontal steel truss diaphragm at 11th floor

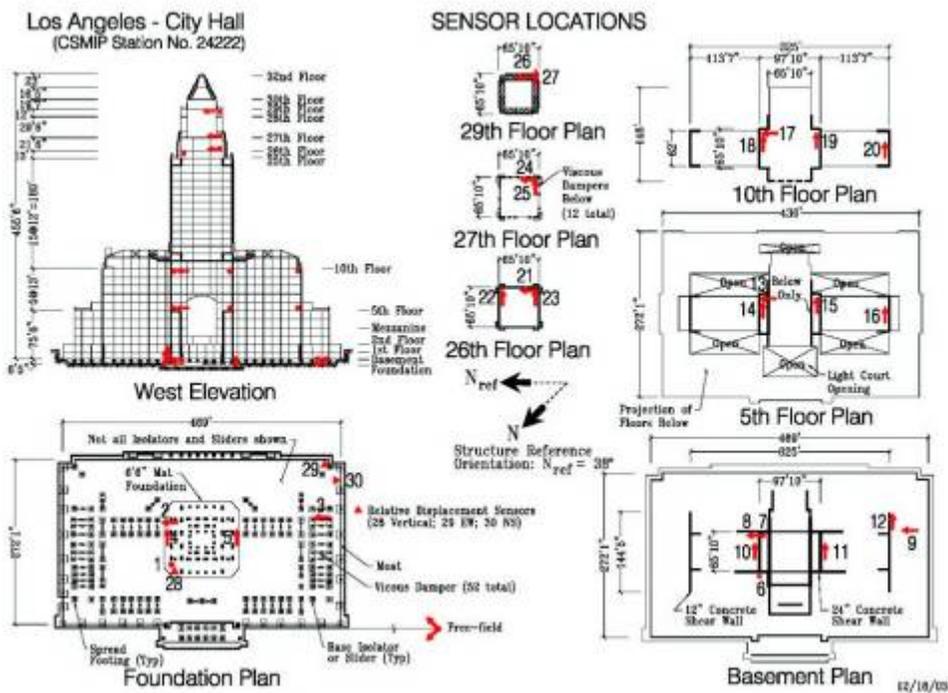


Figure 16: Sensor layout (from CGS/CSMIP)

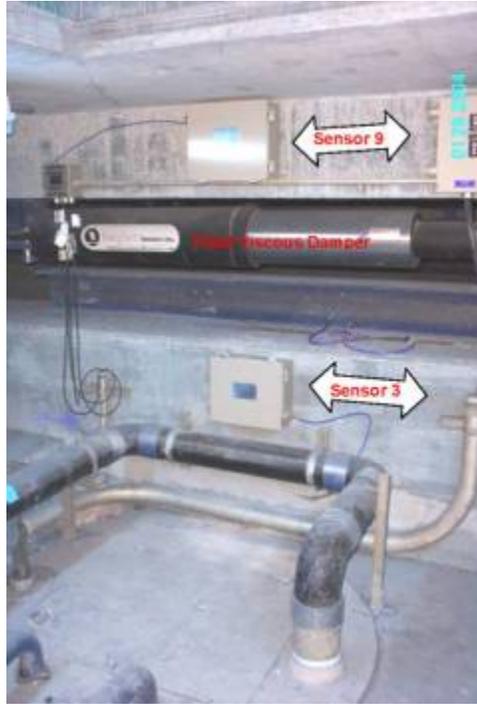


Figure 17: Sensors installed above and below damper at plane of isolation (from CGS/CSMIP)

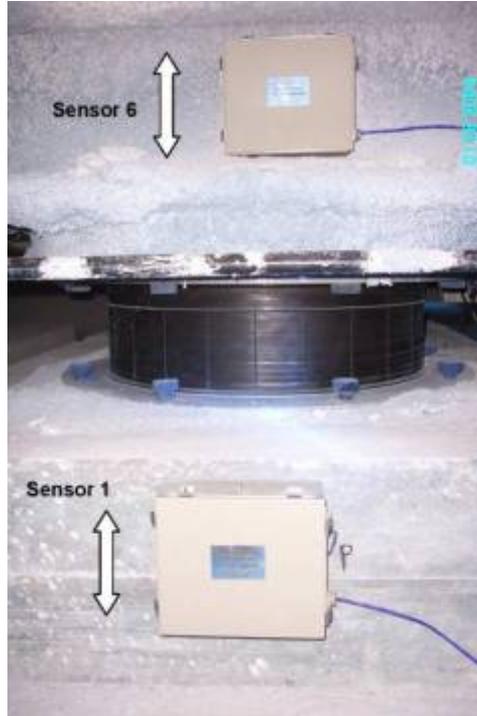


Figure 18: Sensors installed above and below isolator at plane of isolation (from CGS/CSMIP)