DESIGN OF A SEISMIC ISOLATION SYSTEM WITH SUPPLEMENTAL VISCOUS DAMPING FOR A NEAR-FAULT ESSENTIAL SERVICES FACILITY

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ABSTRACT:

The subject building is the L.A. Regional Transportation Management Center. This steel building encloses five floors comprising about 88,000 square-feet. As an essential service facility it meets the Seismic Performance criteria of "Immediate Occupancy" after a Maximum Considered Earthquake (MCE).

Located within proximity of large active faults (closest at 400 feet), the facility can be subjected to high-velocity pulse-type ground motion. Conventional Base-Isolation utilizing different types of isolators would need to accommodate an impractical 40” of lateral displacement. A supplemental viscous fluid damping (VFD) system was selected combined with Natural Rubber Bearings isolators selected for their reliability, consistency of properties over time, cost effectiveness, wide availability and ease of modeling. Sixteen 320 kip nonlinear VFDs reduce the maximum lateral displacement to 24” without adding elastic stiffness to the system.

Due to the low initial stiffness of the isolators and low initial sticking force in the VFDs, an innovative wind-brake ring with adjustable tension bolts was added to the dampers to achieve the required wind load resistance.

The considerably lower tension capacity of the isolators compared to compression capacities created challenges when resisting seismic over turning forces. Double end bay spans were created and braced frames utilized as transfer trusses to concentrate dead loads at corners to minimize the upward displacement and isolator tension. A creative modeling technique was devised utilizing a combination of three finite elements, namely; a bilinear biaxial (horizontal) shear hysteretic element with linear axial (vertical) stiffness combined with a uniaxial gap element connected by a rigid link.

KEYWORDS:

Essential Facility, Isolation, Damping, Seismic, Steel

1.INTRODUCTION

Seismic isolation has become more popular than ever in the recent years. More government agencies have recognized its benefits and are utilizing this system to protect their critical facilities and their operations. The LARTMC building was designed to be the home of the Regional Transportation Management Center for California Department of Transportation (CALTRANS) District 7 and the Los Angeles Communications Center (LACC) for the California Highway Patrol (CHP). These agencies have made the decision to base isolate their Transportation Management Centers (TMCs) to ensure operational centers after major earthquakes.

In this paper, the authors attempt to shed some light on some of the challenges that a structural engineer faces when designing such buildings.

2.BUILDING DESCRIPTION

This four-story plus Mezzanine structural steel building encloses approximately 88,000 gross-square-feet. The building design meets the standards of the State's Essential Services Act and meets or exceeds the Seismic Performance criteria of "Immediate Occupancy" (IO). The applicable building code is the 2001 California Building Code (CBC'01).

> The operations center employs state-of-the-art computer and communications technology to gather real time data from permanently placed sensors, which include contact loops in the pavement, and CCTV cameras along the Los Angeles and Ventura Counties State highway system. Due to its function, the structure was designed to be seismically isolated and, in all likelihood, remain operational during and immediately after a major seismic event.

The lateral force resisting system for this steel framed superstructure consists of Special Concentrically Braced Frames (SCBFs). This system was selected to stiffen the superstructure and shift its fundamental period of vibration away from the period of the isolation system. The story and roof floors consisted of 4½in. of normal weight structural concrete topping on 3in formed steel deck utilizing composite action. The concrete slab thickness was chosen to add mass to the building in order to elongate its period and thus maximize the effectiveness of the isolation system. Typical bays of 28ft spanned in both directions of the building with the typical story heights being 20ft. The unusual story height was to enable clutter free routing of the myriad of complex mechanical and electrical systems which are an integral and essential part of this high-tech critical facility.

3.DESIGN OBJECTIVE

The seismically isolated structure's earthquake design basis is dual-level; Design Basis Earthquake (DBE): 10 percent probability of exceedance in 50 years (475-year ARP event), and Maximum Considered Earthquake (MCE): 10 percent probability of exceedance in 100 years (950-year Upper Bound Earthquake "UBD" per the CBC'01). The superstructure strength is determined by the DBE level while stability design is based on the MCE level. Anything at or below the isolation plane needs to be designed at the MCE level for strength and stability. The LARTMC in its entirety was designed for the MCE level based on a decision by the design team, peer reviewers, and the owner to increase the likelihood that the TMC would be fully operational immediately after an MCE event.

4.PROJECT COMPLEXITY AND SEISMIC HAZARD

4.1.Methodology

A Probabilistic Seismic Hazard Analysis (PSHA) was performed to evaluate the likelihood of various earthquake shaking levels at the given site reflected in peak horizontal acceleration and horizontal spectral ordinate values. This was done by *Globus Engineering/Woodward-Clyde* and Peer Reviewed by *Paul Somerville* of URS. It involved the characterization of the seismic sources, transmission paths for seismic energy, the local site conditions, and uncertainties for each of these parameters. The effects of transmission paths and local site conditions were reflected through the use of attenuation relationships that provided the variation in peak horizontal acceleration (or spectral acceleration) with distance for a given local site condition. Key information on seismic sources and attenuation relationships used for this project is summarized below.

4.2.Attenuation Relationships

The TMC building site is located on artificial fill and dense old alluvial deposits at the southwestern front of the Santa Monica Mountains. The old alluvial deposits are underlain at depth by sedimentary and/or granitic bedrock. Based on limited available information, the depth to sedimentary bedrock was estimated to be on the order of 100 to 200 feet. Therefore, attenuation relationships by Idriss (1985, 1994) for stiff soil site conditions, Abrahamson and

Silva (1997) for both rock and soil site conditions, and Sadigh (1997) for soil site condition were used in the PSHA analysis. The recommended attenuation relationships were derived from equal weighting of each of the mentioned methods.

4.3.Horizontal Ground Motion Parameters

The contributions of various seismic sources to the total seismic hazard at the site are shown on Figures 1-2. As can be seen from the figures, a number of sources contribute to the overall hazard although the Santa Monica Mountains and the Verdugo - Eagle Rock fault systems are the dominant contributors at larger return periods. The Sierra Madre and the Whittier-Elsinore fault systems also provide significant contribution to the hazard at the site.

Because of the proximity of the site to significant seismic sources, the response spectra were adjusted for near-fault directivity effects (Somerville et al., 1997). An adjustment for the fault normal component based on a magnitude of 6.75 and a closest distance of 0 km were selected.

At most near-fault sites, the seismic hazard is dominated by a single fault whose strike direction is known, and so the orientation of the fault-normal component of ground motion can be readily identified. However, the seismic hazard at the TMC site was influenced by three nearby faults that have different strike directions. Consequently, for design, it was assumed that the fault-normal component could be oriented in any direction, and that the ground motion in the orthogonal direction is given by the fault parallel component.

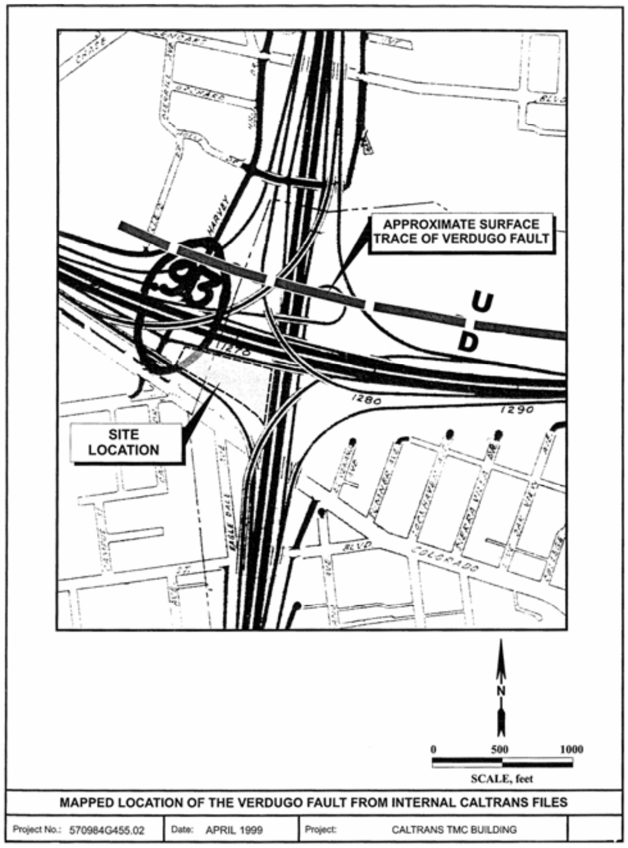

Figure 1 Mapped location of the Verdugo fault

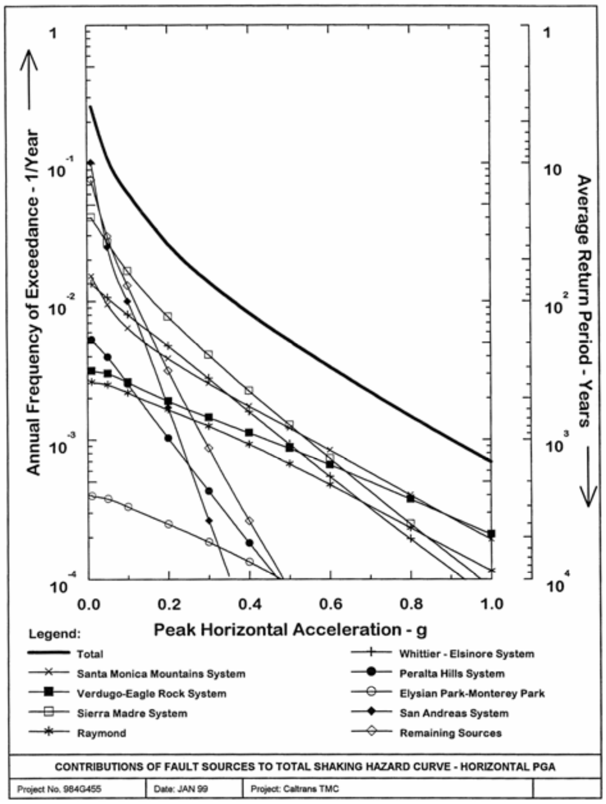

Figure 2 Combination of fault sources to total horizontal shaking hazard curves

4.4.Response Spectra and Time Histories

Time histories for use in the dynamic response analyses were developed to represent the design response spectra. For the 950 and 475 year return period ground motions, recordings that contain forward rupture directivity conditions were selected (which produce the near-fault pulse in ground velocity). These consist of recordings located around the top edges of the rupture planes of the 1971 San Fernando and 1994 Northridge earthquakes. With the exception of the Pacoima Dam recording of the 1971 San Fernando earthquake, ground motions recorded on stiff soil conditions were selected. Such recordings were considered representative of the subsurface conditions at the TMC site. As described below, the time histories were scaled to match the design response spectra which are also for stiff soil conditions. The selected time histories were as follows:

1. 475-year (DBE) shaking conditions: Newhall (Northridge), Sylmar (Northridge), and Rinaldi (Northridge) recordings.
2. 950-year (MCE) shaking conditions: Newhall (Northridge), Rinaldi (Northridge), and Pacoima (San Fernando) recordings.

Once the reference time histories were selected, they were adjusted to provide the response spectrum compatible time histories according to the following criteria:

1. Adjustment of the reference time histories could not be performed by a simple scaling of the peak ground acceleration alone. Adjustment of the response spectrum of the reference time histories was performed using a time-domain procedure described by Abrahamson (1991).
2. The response spectrum of the spectrum compatible time histories should follow reasonably the recommended design response spectra.
3. The adjusted time histories should conform to the CBC'01, Section 1659A.4.2.

Table 1 below summarizes the response spectra and time histories of the response spectrum compatible time histories. A sample of an adjusted time history record is presented in Figure 3.

Table 1 Response spectrum compatible time histories

Shaking Level	Component
475-year ARP (DBE)	Fault Normal - Newhall
	Fault Parallel - Newhall
	Fault Normal - Sylmar
	Fault Parallel - Sylmar
	Fault Normal - Rinaldi
	Fault Parallel - Rinaldi
950-year ARP (MCE)	Fault Normal - Newhall
	Fault Parallel - Newhall
	Fault Normal - Rinaldi
	Fault Parallel - Rinaldi
	Fault Normal - Pacoima
	Fault Parallel - Pacoima

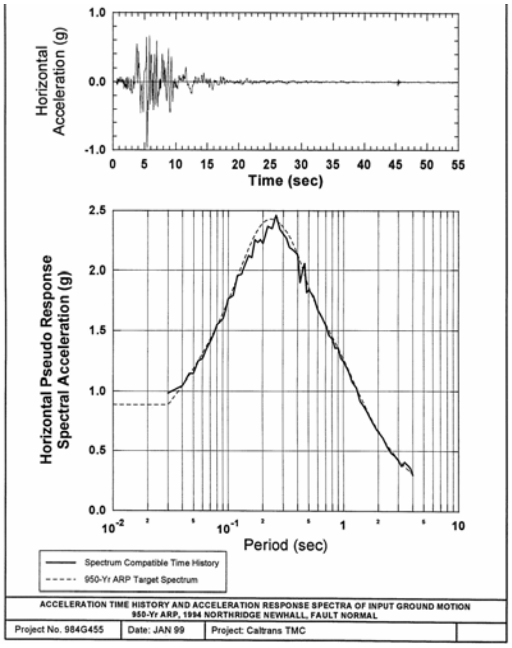

Figure 3 Sample of a response spectrum-matched time history record

5.DESIGN SOLUTION HIGHLIGHTS

5.1.Innovative Elastomeric Isolators with Viscous Fluid Dampers

With the facility in close proximity to active faults, its is prone to high-velocity pulse effects (near-field effects). Conventional Base-Isolation (without supplemental damping) with different types of isolators would have needed to accommodate an impractical 40” of lateral displacement.

For the isolation system, NRBs were selected for their reliability, consistency of properties over time, cost effectiveness, wide availability, and ease of modeling. Figure 4 below shows an installed NRB. Alternative systems such as Lead Rubber (LR) isolators and High Damping Rubber (HDR) isolators were also evaluated. However, the hysteretic damping provided by the devices was inadequate to reduce the peak horizontal displacement to 24” or even close to that desired number.

A supplemental damping system was, therefore, needed in combination with the no/low damping isolators. VFDs were incorporated which offer pure viscous damping without adding displacement dependent elastic stiffness to the system; i.e: all the system stiffness is in the isolators, with all the damping in the VFDs. These devices which offer velocity proportional damping are especially effective, particularly with a velocity exponent equal to or less than 0.5, in reducing the calculated displacement down from about 40” to below 24” at the MCE. Figure 5 shows the effectiveness of the supplemental damping in reducing the displacement.

Figure 4 An installed NRB

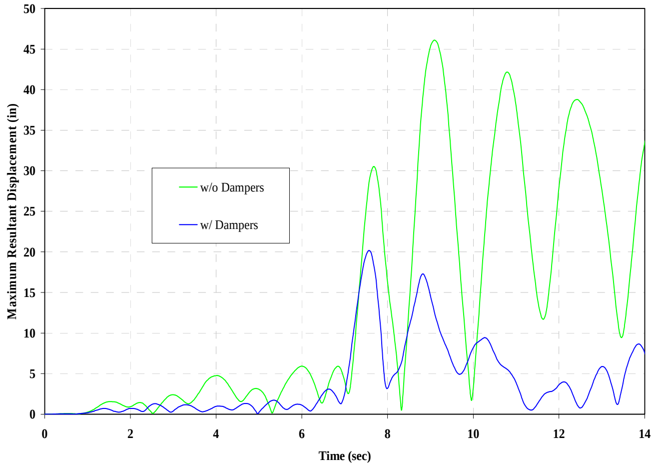

Figure 5 Effectiveness of dampers

5.2.Effectively Minimized Uplift Tension

Seismic-isolators have considerably lower tension capacities compared to compression strength. This creates challenges when resisting seismic overturning forces. The design team devised a bracing scheme that dramatically reduces tension forces on the isolator bearings at the corners of the building where lower gravity loads are present and the overturning forces are likely to cause uplift. By skipping isolators adjacent to each corner and utilizing the braced frames as transfer trusses, gravity loads were concentrated at the building corners to minimize the upward (tension) forces. Figures 6 illustrates this bracing scheme.

Figure 6 LARTMC bracing scheme (SCBF)

5.3.Modeling Technique

The structure was modeled using the ETABS software. Typical linear elastic frame elements were used to model the steel beams, columns, and braces. Rigid diaphragms were assumed for all slabs, and “ISOLATOR1” elements were used to model the rubber isolator bearing. The VFDs were explicitly modeled using the “NLLINK” with velocity dependent damping and nonlinear exponents.

Since the behavior of the rubber isolator bearings is different in compression than in tension, an exceptional modeling technique had to be devised to account for the different properties. Each isolator was modeled using combinations of different ETABS elements. Three elements were utilized to accurately model the isolators; a bilinear biaxial (shear) hysteretic element with linear axial stiffness combined with a uniaxial gap element connected by an extremely stiff link element. This combination could closely model the isolators even when they undergo uplift. Four elements were used at damper locations. Figures 8-9 illustrate this modeling technique.

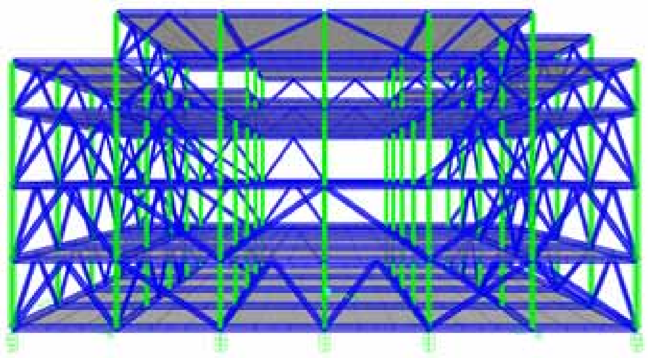

Figure 7 LARTMC model in ETABS

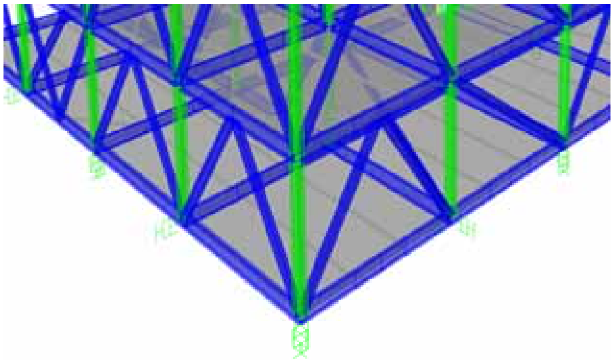

Figure 8 LARTMC modeling technique

5.4.Inventive Wind Brake Device

Sixteen 320kip nonlinear VFDs were incorporated into the analysis and design of the TMC. Due to the low initial stiffness of the NRB isolators and the low initial sticking force in the VFDs, the wind load resistance did not meet code requirements. An innovative wind-brake ring with adjustable tension bolts was added to the dampers to provide just enough resistance against design wind forces before the VFDs start displacing (Figure 9 below).

Figure 9 Installed 320kip VFD with wind brakes

Figure 10 Flex utility joint accommodating a displacement of 24in

5.5.Novel Flex Joint System

The LARTMC seismic isolation system design accommodated lateral displacements of 24in at the MCE level. All utility connections were designed and detailed to remain functional at this displacement by accommodating unhindered relative movement of 24in in any horizontal direction. Figure 10 shows a sample flexible utility connection.

6.EFFECT OF DAMPING ON PERFORMANCE

Supplemental damping is beneficial in reducing the building displacement. Counter intuitively, high ratios of critical damping are not necessarily beneficial to the overall performance of a base isolated building. Higher damping ratios lead to more restraint to the movement of the base which in turn translates to higher story accelerations and thus higher overturning moments are generated. The limited uplift tension capacity of the isolator bearings is usually the limiting factor in resisting the overturning moments. Thus the base isolation designer needs to constantly monitor the uplift of the bearings and the effect of changing any of the design parameters on them. Although uplift is allowed by the CBC'01 at individual isolator bearings, multiple simultaneous uplifts at multiple locations or excessive uplift at a single location may cause undesirable instabilities and excessive damage to structural or nonstructural components.

The effect of supplemental damping has been investigated by the authors on multiple seismically isolated projects. The most recent of which is in its final design stages as of the writing of this paper. The building is a 3-story TMC essential facility located about 4.2km south of the main trace of the Cucamonga fault, approximately 11km southwest of the main trace of the San Jacinto fault, and about 15km southwest from the San Andreas fault. The two buildings (LARTMC and the other TMC) have many similarities in the seismic hazard and performance targets.

Table 2 demonstrates the effect of increased damping on the story accelerations and overturning moments from the analyses of the other TMC. The increase in story accelerations (and forces) causes the overturning moments to increase. The increase could be critical to the isolator bearing design. If the bearing cannot resist the additional uplift and needs to be upgraded to a larger size, the increase is usually associated with an increase the lateral stiffness which in turn stiffens the system attracting more load.

Table 2 Effect of damping on building story forces

	Lower Bound Damper Properties		Upper Bound Damper Properties	
	Story Disp. 25.3 in	Base Shear 2935 kip	Story Disp. 22.9 in	Base Shear 2994 kip
	Story Accel. (g)	O/T Moment (ft-kip)	Story Accel. (g)	O/T Moment (ft-kip)
Roof	0.43	4,693	0.52	5,668
2nd	0.41	21,387	0.39	23,212
1st	0.36	52,412	0.37	55,614

CONCLUSIONS:

The project complexities and challenges were unusual even for an essential facility. Some of those arose from the location and others from the essential functionality of the building. The elaborate and comprehensive design solution was able to meet the project requirements as well as resolve the seismic hazard issues associated with the TMC location. The seismic isolation design was awarded the SEAOSC, SEAOC and NCSEA Structural Engineering Excellence awards in 2006 for the best use of new technology.

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