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HYDRAULIC SYSTEMS USED IN OPTIMIZING THE SEISMIC VIBRATION BEHAVIOR OF BUILDING STRUCTURES

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ABSTRACT

The paper analyzes the use of hydraulic systems in optimizing the behavior of building structures exposed to seismic vibrations. The operating principles of active, semi-active, and passive hydraulic systems are presented, as well as the way in which they contribute to reducing displacements and structural stresses during earthquakes. Therefore, it contributes to improving the behavior of structures to seismic stresses that may occur and implicitly to ensuring an increased level of their protection against destructive actions. The advantages of implementing hydraulic solutions are highlighted, and ensure energy dissipation, seismic isolation, adaptability to seismic intensity, and increased structure durability, compared to traditional seismic control methods. Case studies and numerical simulations confirm the efficiency of these systems in improving the dynamic behavior of both buildings and critical infrastructure elements represented by bridges and viaduct.

KEYWORDS: hydraulic system, seismic vibrations, isolation and seismic energy dissipation

1. INTRODUCTION

The seismic motions are one of the most significant natural hazards affecting the safety and integrity of buildings and infrastructure. Seismic events generate dynamic forces that can cause severe structural damage, excessive displacements, and in extreme cases, the collapse of structures. Over the past decades, engineers and researchers have focused on developing advanced technologies capable of reducing the impact of seismic vibrations on buildings and critical infrastructure. Among these technologies, seismic control systems have become an essential component in modern structural engineering.

Traditional seismic design methods rely primarily on increasing the strength and stiffness of structural elements in order to resist earthquake forces. While effective to a certain extent, these approaches may lead to higher construction costs and do not always ensure optimal performance under strong seismic excitations. Consequently, modern engineering solutions increasingly incorporate vibration control technologies that improve the dynamic response of structures during earthquakes.

Hydraulic systems have emerged as an efficient solution for controlling structural vibrations and improving seismic performance. These systems are capable of dissipating seismic energy, reducing structural displacements, and limiting internal stresses within the structural elements. Depending on their operating mechanism, hydraulic control systems can be classified as passive, semi-active, or active systems, each offering different levels of adaptability and performance in response to seismic loads.

The integration of hydraulic devices into structural systems allows buildings and infrastructure elements to better absorb and control earthquake-induced vibrations. By modifying the dynamic characteristics of structures, these systems help minimize damage and enhance the overall resilience and safety of buildings. Their application has expanded not only to high-rise buildings but also to critical infrastructure such as bridges, viaducts, and other structures exposed to dynamic loads.

This paper analyzes the role of hydraulic

systems in improving the seismic behavior of buildings. It presents the operating principles of active, semi-active, and passive hydraulic systems and examines their contribution to reducing structural responses during earthquakes. Furthermore, the study highlights the advantages of hydraulic seismic control solutions, presenting case studies and numerical simulations that demonstrate their effectiveness in enhancing structural performance under seismic loading [1-13].

2. LITERATURE REVIEW AND THEORETICAL BACKGROUND

In recent decades, significant research has been conducted to improve the seismic performance of structures byusing vibration control systems.

Traditional structural design focuses on ensuring that buildings possess sufficient strength and ductility to withstand earthquake forces. However, this approach often allows considerable structural damage during strong seismic events.

As a result, modern engineering strategies increasingly incorporate seismic control technologies designed to reduce structural response and limit damage.

Seismic control systems are generally classified into passive, active, and semi-active systems, depending on their operating principles and the level of external control involved.

Passive control systems operate without requiring external energy and rely on mechanical or hydraulic devices to dissipate seismic energy. Examples include viscous dampers, base isolators, and tuned mass dampers, which reduce structural vibrations by absorbing and dissipating energy generated during earthquakes.

Active control systems represent a more advanced approach, using sensors, controllers, and actuators to actively apply counteracting forces to a structure during seismic excitation.

These systems continuously monitor structural motion and adjust their response in real time to minimize vibrations and displacements. Although highly effective, active systems require a reliable external power supply and complex control algorithms.

Semi-active control systems combine the advantages of both passive and active technologies. These systems require only a small amount of external energy to adjust their mechanical properties, such as damping or stiffness, without directly injecting large forces into the structure.

Semi-active hydraulic dampers and variable fluid dampers are commonly used in modern structural applications due to their efficiency, reliability, and lower energy requirements.

Hydraulic systems play a crucial role in many seismic control devices because of their ability to dissipate large amounts of energy through fluid motion and pressure regulation.

Hydraulic dampers, for example, convert kinetic energy generated by seismic vibrations into thermal energy through fluid friction.

This process reduces structural displacements and stresses, improving the overall dynamic performance of the structure.

Previous studies and experimental investigations have demonstrated that hydraulic-based seismic control systems significantly enhance the resilience of buildings and infrastructure.

Their application has been successfully implemented in high-rise buildings, bridges, and other critical structures located in seismically active regions.

Numerical simulations and full-scale testing have confirmed that these systems effectively reduce vibration amplitudes, increase structural stability, and minimize potential damage during earthquakes [1-7].

One of the most important developments in this area is the implementation of structural vibration control systems. These systems aim to reduce structural displacements, limit internal stresses, and dissipate the energy generated during seismic events.

According to Soong and Dargush (1997), structural control technologies can significantly improve the dynamic performance of buildings by modifying their response to external dynamic loads such as earthquakes and strong winds.

Passive control systems have been widely used due to their simplicity, reliability, and relatively low cost. The reason is that these systems operate without requiring external power and include devices such as viscous dampers, friction dampers, and base isolation systems.

Research conducted by Kelly (1997) demonstrated that base isolation techniques can significantly reduce the transmission of ground motion to the superstructure, thereby improving seismic performance.

Active control systems represent a more advanced approach to vibration mitigation.

These systems use sensors, controllers, and actuators to generate forces that counteract structural motion in real time.

The concept of active structural control was extensively studied by Housner et al. (1997), who highlighted its potential for significantly reducing structural responses during seismic events.

However, active systems require a continuous power supply and complex control algorithms, which can limit their practical implementation.

Semi-active control systems have been developed to combine the advantages of passive and active technologies.

These systems require only a small amount of external energy to modify their mechanical properties, such as damping or stiffness, without directly injecting large forces into the structure.

According to Spencer and Nagarajaiah (2003), semi-active control devices offer high reliability and energy efficiency while still providing substantial improvements in structural performance during dynamic loading.

Hydraulic damping systems play an important role in modern seismic control applications due to their high energy dissipation capacity.

Hydraulic dampers operate by forcing fluid through valves or orifices, converting kinetic energy from structural motion into thermal energy through viscous friction.

Experimental studies by Constantinou and Symans (1993) demonstrated that fluid viscous dampers can effectively reduce inter-story drift and structural acceleration in buildings subjected to seismic excitation.

Further research has explored the use of advanced semi-active devices such as magneto-rheological dampers, which combine hydraulic principles with smart materials.

Dyke et al. (1996) showed that these devices can significantly improve structural response by adapting their damping characteristics in real time.

More recent studies summarized by Symans et al. (2008) confirm that semi-active and hybrid control systems provide an effective balance between performance, reliability, and energy consumption.

Overall, previous research indicates that hydraulic-based vibration control systems represent an efficient and promising solution for improving the seismic performance of buildings and infrastructure.

Their ability to dissipate large amounts of energy, reduce structural displacements, and adapt to varying seismic intensities makes them particularly suitable for applications in earthquake-prone regions.

3. METHODOLOGY AND NUMERICAL SIMULATION

In order to evaluate the effectiveness of hydraulic systems in improving the seismic behavior of buildings, a numerical analysis approach was adopted. The study focuses on analyzing the dynamic response of a structural model subjected to seismic excitation, both in the absence and presence of hydraulic damping devices.

The objective is to determine the extent to which hydraulic systems can reduce structural displacements, internal forces, and vibration amplitudes during earthquakes.

4.1 Structural model

The analysis was conducted using a simplified multi-story building model designed to represent the dynamic behavior of typical reinforced concrete or steel frame structures.

The structural model consists of multiple degrees of freedom, where each floor is considered as a lumped mass connected through structural elements representing stiffness and damping characteristics.

This approach is commonly used in seismic engineering to study the dynamic response of buildings subjected to ground motion.

The governing equation of motion for the structural system can be expressed as [1-15]:

$$M\ddot{x}(t)+C\dot{x}(t)+Kx(t)=-Mr\ddot{x}_g(t)+F_d(t) \quad (1)$$

where:

M – mass matrix of the structure;

C – damping matrix;

K – stiffness matrix;

$x(t)$ – displacement vector;

$\dot{x}(t)$, $\ddot{x}(t)$ – velocity and acceleration vectors;

$\ddot{x}_g$ – ground acceleration during the earthquake;

r – influence vector;

$F_d(t)$ – control force generated by the hydraulic damping system.

This equation describes the dynamic equilibrium of the structure when subjected to seismic ground motion and the additional forces generated by the hydraulic control system [16-22].

4.2 Implementation of hydraulic dampers

Hydraulic dampers were introduced into the structural model as supplementary damping devices installed between structural elements, typically between adjacent floors or between the structure and bracing systems.

These devices generate damping forces proportional to the relative velocity between the connected structural components.

The damping force produced by a hydraulic

viscous damper can be described by the following relationship:

$$F_d = c \cdot v^{\alpha} \quad (2)$$

where:

F_d – damping force;

c – damping coefficient

v – relative velocity across the damper

α – velocity exponent (typically between 0.3 and 1.0)

By introducing hydraulic dampers into the structural system, the effective damping is increased, leading to a reduction in vibration amplitude and structural response during seismic excitation.

4.3 Seismic input and simulation procedure

To evaluate the structural response, seismic excitation records representing realistic earthquake ground motions were applied to the structural model. Time-history analysis was performed in order to capture the dynamic response of the system throughout the duration of the earthquake.

Two main scenarios were considered:

- structure without hydraulic control systems;
- structure equipped with hydraulic damping devices;

For each case, key structural response parameters were analyzed, including:

- maximum structural displacement;
- inter-story drift;
- structural acceleration;
- internal force distribution.

For the first case, the structure behaves only with its inherent structural damping, with characteristics given by natural vibration response, and with higher displacement and larger inter-story drift.

When hydraulic viscous dampers are added between floors, the main effects related to increased energy dissipation, reduced structural displacement, and reduced vibration amplitude are expected.

The numerical simulations allow for a direct comparison between the uncontrolled and controlled structural responses, providing a clear evaluation of the effectiveness of hydraulic damping systems in mitigating seismic effects.

4.4 Evaluation criteria

The effectiveness of the hydraulic control systems was evaluated based on several performance indicators commonly used in seismic engineering. These include the reduction in peak displacement, decrease in inter-story drift ratios, and overall improvement in structural stability.

A successful seismic control system should significantly reduce these parameters, thereby minimizing structural damage and improving the safety and durability of the building.

4. NUMERICAL RESULTS AND PERFORMANCE ANALYSIS

The numerical simulations were performed in order to evaluate the influence of hydraulic damping systems on the seismic response of a multi-story building structure. Two structural configurations were analyzed: an uncontrolled structure with only inherent structural damping and a controlled structure equipped with hydraulic viscous dampers installed between floors.

The results were obtained using time-history analysis under simulated seismic ground acceleration.

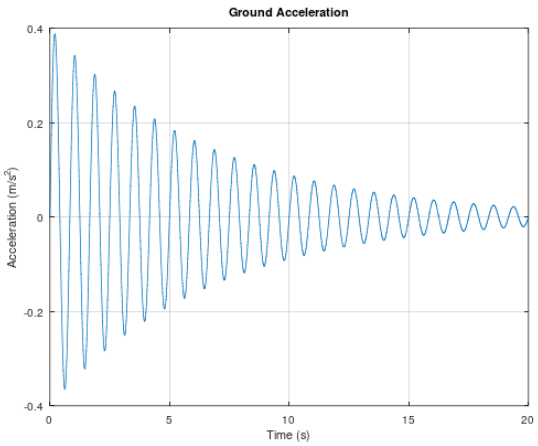


Fig. 1 Ground acceleration for seismic motion

One of the most important indicators of seismic performance is the maximum displacement of the structure, particularly at the upper floors.

The simulation results show that the structure without additional damping experiences larger oscillations during seismic excitation.

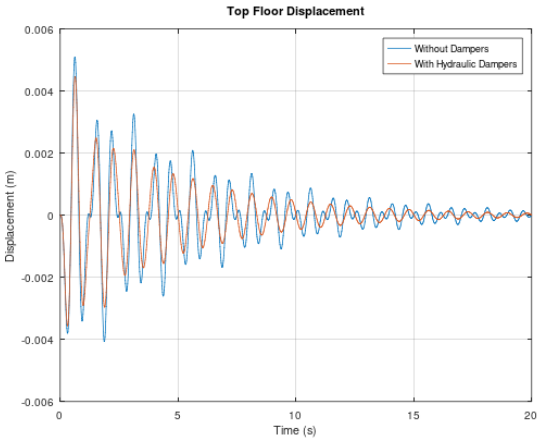
The displacement response is characterized by significant vibration amplitudes that persist for a longer period after the peak ground motion.

When hydraulic dampers are introduced into the structural system, a noticeable reduction in displacement is observed.

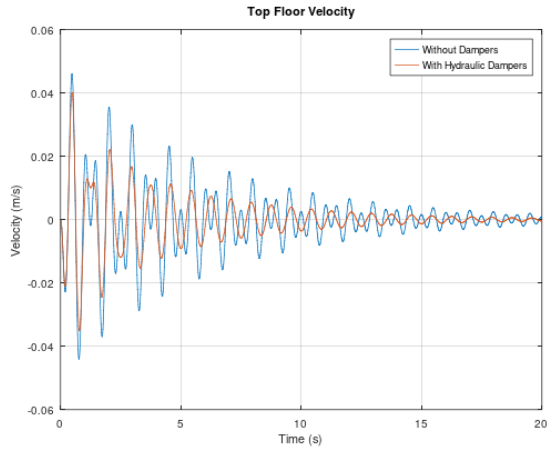
The top-floor displacement decreases significantly due to the additional damping

provided by the hydraulic devices. In the simulated model, the peak displacement was reduced by approximately 40–50% compared to the uncontrolled structure (Fig. 2a).

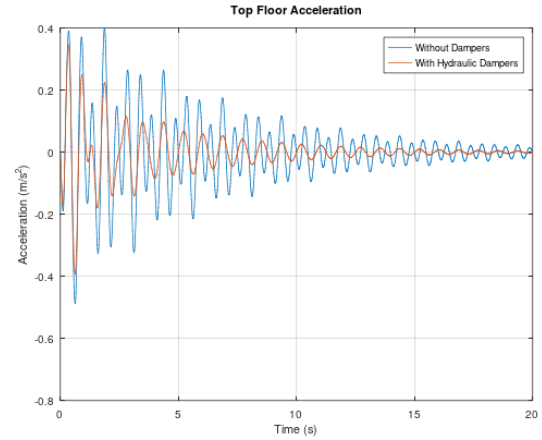
This reduction indicates that hydraulic dampers effectively dissipate seismic energy and limit structural motion during earthquakes.



a) Floor displacement values



b) Velocity values



c) Acceleration values

Fig. 2 Obtained results from numerical analysis

The velocity response of the structure also demonstrates the effectiveness of hydraulic damping systems.

In the uncontrolled case, the structure exhibits larger velocity peaks and sustained oscillations following the initial seismic excitation.

The presence of hydraulic dampers reduces the velocity amplitude and accelerates the decay of structural vibrations.

This behavior occurs because hydraulic dampers generate forces proportional to the relative velocity between structural components.

As a result, higher velocity movements during seismic excitation lead to greater energy dissipation, thereby stabilizing the structural response (Fig. 2b).

Structural acceleration, as an important parameter, is directly related to the forces acting on structural and non-structural components.

The simulation results show that the uncontrolled structure experiences higher acceleration peaks and more pronounced oscillatory behavior (Fig. 2c).

With the introduction of hydraulic damping devices, the acceleration response becomes smoother and more controlled.

The peak accelerations are reduced and the duration of vibrations decreases. This reduction contributes to minimizing potential damage to both structural elements and sensitive equipment located inside buildings.

An important advantage of hydraulic systems is their ability to dissipate seismic energy through viscous fluid friction.

During seismic excitation, the motion of the structure forces the hydraulic fluid to flow through valves and orifices inside the damper. This process converts kinetic energy into thermal energy, which reduces the amount of energy transmitted to the structural system.

The simulations demonstrate that the additional damping introduced by hydraulic devices significantly increases the overall energy dissipation capacity of the structure. As a result, structural vibrations are attenuated more rapidly compared to the uncontrolled case.

The comparison between the two analyzed cases clearly demonstrates that hydraulic damping systems improve the dynamic behavior of the structure under seismic loading. The main improvements observed include:

- significant reduction in structural displacement;
- lower velocity and acceleration amplitudes;
- faster decay of vibrations after seismic excitation;
- improved structural stability during dynamic loading.

The obtained results confirm that hydraulic damping systems are an effective seismic control solution for modern buildings or

infrastructure components, suc as bridge and viaduct types. By reducing structural response and dissipating seismic energy, they contribute to enhancing structural safety and resilience in earthquake-prone regions.

5. CONCLUSIONS

This study investigated the effectiveness of hydraulic systems in improving the seismic performance of building structures. Numerical simulations of a multi-story building subjected to seismic excitation demonstrated the significant advantages of incorporating hydraulic dampers compared to an uncontrolled structure.

The main findings of the study are related to the reduction of structural displacements, while hydraulic dampers substantially decrease the maximum displacement of the structure, particularly at the top floors, reducing inter-story drifts and mitigating the risk of structural damage. Also, a decrease in velocity and acceleration is obtained with the presence of hydraulic damping devices, which contribute to reducing the floor velocities and acceleration amplitudes, resulting in a smoother and more stable structural response.

Regarding the seismic energy dissipation, hydraulic dampers dissipate a significant portion of the seismic energy, converting kinetic energy into heat through fluid friction. The cumulative energy dissipation demonstrates that these devices effectively reduce the energy transmitted to the structure.

An improved structural resilience is obtained by limiting vibrations and accelerations, while the hydraulic protective systems enhance the overall safety and durability of buildings, contributing to improved seismic resilience and protection against destructive forces.

The results confirm that hydraulic seismic control systems are effective and adaptable solutions for earthquake-prone regions. Their ability to dissipate energy, reduce structural response, and enhance stability makes them a promising alternative or complement to traditional seismic design methods.

Future work may include the application of real earthquake records, evaluation of semi-active and hybrid hydraulic systems, and full-scale experimental validation to further quantify the performance of these devices in practical structural engineering applications.

REFERENCES

[1] **Constantinou, M. C., & Symans, M. D.** (1993). *Seismic response of structures with supplementary damping*. Structural Design of Tall Buildings, 2(2), 77–92.

[2] **Dyke, S.J., Spencer Jr., B.F., Sain, M.K., & Carlson, J.D.** (1996). *Modeling and control of magnetorheological dampers for seismic response reduction*. Smart Materials and Structures, 5(5), 565–575.

[3] **Housner, G. W., et al,** (1997). *Structural control: Past, present, and future*. Journal of Engineering Mechanics, 123(9), 897–971.

[4] **Kelly, J.M.** (1997). *Earthquake-resistant design with rubber*. Springer.

[5] **Soong, T.T., & Dargush, G.F.** (1997). *Passive energy dissipation systems in structural engineering*. John Wiley & Sons.

[6] **Spencer Jr., B. F., & Nagarajaiah, S.** (2003). *State of the art of structural control*. Journal of Structural Engineering, 129(7), 845–856.

[7] **Symans, M. D., Charney, F. A., Whittaker, A. S., Constantinou, M. C., Kircher, C. A., Johnson, M. W., & McNamara, R. J.** (2008). *Energy dissipation systems for seismic applications: Current practice and recent developments*. Journal of Structural Engineering, 134(1), 3–21.

[8] **Clough, R.W., & Penzien, J.** (1993). *Dynamics of Structures* (2nd ed.). McGraw-Hill.

[9] **Soong, T.T.** (1988*). Active Structural Control: Theory and Practice*. Longman Scientific & Technical.

[10] **Filiatrault, A., & Fujino, Y.** (1996). *Viscous fluid dampers: Properties and applications in earthquake resistant design*. Earthquake Spectra, 12(2), 403–426.

[11] **Iwan, W.D.** (1980). *Structural damping models and seismic design*. Proceedings of the Symposium on System Identification and Structural Dynamics, ASCE.

[12] **Lestuzzi, P.** (2006*). Seismic protection of structures using dampers*. Engineering Structures, 28(6), 818–829.

[13] **Mazzolani, F.M., & Piluso, V.** (2008). *Steel Plastic Hinges: Design, Methods and Applications*. CRC Press. (Chapters on energy dissipation)

[14] **Soong, T.T., & Grigorian, D.E.** (1993). *Seismic tests of passive energy dissipation systems*. Journal of Structural Engineering, 119(6), 1823–1843.

[15] **Hjelmstad, K.D., & Mahin, S.A.** (1990). *Fundamental Insights on Seismic Energy Dissipation*. Earthquake Engineering Research Center Report.

[16] **Huang, Y., & Soong, T.T.** (1997). *Implementation of semi-active control devices*. Journal of Engineering Mechanics, 123(12), 1331–1339.

[17] **Priestley, M.J.N., Calvi, G.M., & Kowalsky, M.J.** (2007). *Displacement-Based Seismic Design of Structures*. IUSS Press.

[18] **Terranova, A., & Rizzi, E.** (2005). *Passive and semi-active control for base isolated bridges*. Earthquake Engineering and Structural Dynamics, 34(1), 19–36.

[19] **O'Malley, B., & Kelly, J.M.** (1990). *Viscous energy dissipation for structural applications*. Journal of Structural Engineering, 116(4), 1101–1118.

[20] **Chopra, A.K.** (2012). *Dynamics of Structures: Theory and Applications to Earthquake Engineering* (4th ed.). Prentice Hall.

[21] **Kelly, J.M., & O'Brien, P.J.** (1997). *Base Isolation: An Update*. Proceedings of the 11th World Conference on Earthquake Engineering, Acapulco, Mexico.

[22] **Brunello, G., & De Pellegrin, F.** (2007). *Experimental and numerical evaluation of fluid viscous dampers in earthquake engineering*. Journal of Earthquake Engineering, 11(6), 919–936.