Experimental investigation on seismic performance of nonlinear soil-structure system using MR dampers

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SUMMARY:
This paper reports the results of an experimental study conducted to demonstrate the feasibility and capability of magneto-rheological (MR) dampers commanded by a decentralized control algorithm for seismic control of nonlinear civil structures considering soil-structure interaction (SSI). A two-story reinforced concrete (RC) frame resting in a laminar soil container is employed as the test specimen, and two MR dampers equipped in the first story are used to mitigate the response of this frame. The energy distribution and cumulative damage evaluation of the test structure are investigated. The results indicate that the MR damper can effectively reduce the response of the soil-structure system, even when the soil-structure system presents complex nonlinear hysteretic behaviour. The robustness of the proposed decentralized control algorithm is validated through the shaking table tests on the soil-structure system with large uncertainty.

Keywords: energy distribution, cumulative damage, nonlinear control, soil-structure interaction

1. INSTRUCTIONS

Structural control as an advanced disaster mitigation strategy can protect the buildings against seismic excitations and improve the safety and economy of the buildings. Structural control can redistribute and dissipate the energy of a structure and enable it to survive a severe earthquake without globally collapse, contrary to the conventional means use material rigidity to resist external excitations.

The process of an earthquake propagation and structural vibration is an energy transferring process. Earthquakes release tremendous energy during their propagation, and the resulting movement of the ground transfers part of the energy to a structure to induce the structural vibration. The earthquake input energy is then transferred to form such as strain and kinetic energies. During the severe exciting conditions, the inelastic action is usually inevitably occurred in the critical regions of structures although such regions may be well detailed. Inelastic behaviour in structures, while able to dissipate substantial energy, also often results in significant damage to the structural member. It is a challenge to make a balance between the damage and dissipating energy. The redistributed and dissipated energy of structural control is an alternative way to reduce the seismic response and damage. The base-isolation, supplemental damping, and semi-active control have been validated to be able to reduce the damage potential by reducing the input and hysteretic energy demands and have significant influences on the distribution of energy through the height of the building (Khashaee et al 2003).Therefore, it is reasonable and important to study the energy characteristics and energy distribution in nonlinear structures during strong earthquakes.

Naturally, energy dissipation not only occurs in a structure, but also occurs during interaction between the structure, its foundation, and the supporting soil medium (Hao, 2002). Unfortunately, the researchers and designers often disregard the latter energy dissipation while creating a model representation of the prototype to proceed with design of earthquake-resistant structures. At present, the model most commonly used for the design and control research of buildings assumes the structure to be fixed to a rigid ground. In fact, the soil-structure interaction can have both beneficial and detrimental effects, and is dependent primarily on the structural dynamic properties, ground motions and soil environments. The increase in fundamental natural period and damping effect due to soil-structure interaction may not necessarily lead to smaller response, and that the prevailing view of the point in structural engineering of the beneficial role of soil-structure interaction, may result in unsafe design (Mylonakis and Gazetas 2000).

The aim of the present study is to experimentally investigate the seismic control and energy flow in the soil-structure system with MR dampers. A two-story reinforced concrete (RC) frame resting in a laminar soil container is employed as the test specimen, and two MR dampers equipped in the first story are used to mitigate the response of this frame. A nonlinear decentralized control approach for semi-active control of MR dampers is implemented in the shaking table tests. Energy balance concepts are used to exploring the characteristics of the energy distribution in the test structure. The dissipated energy in the structure, its foundation, the supporting soil medium and the control devices are analyzed. Based on the dissipated energy and maximum deformation of the test structure, a damage index representing the structural damage state is proposed and adopted to evaluate the seismic damage of the test structure.

2. SHAKING TABLE TEST

2.1. Experimental Setup

The test structure used in this experiment is a 3D frame structure build in reinforced concrete and steel reinforcement (Fig. 1(a)). The frame has one bay in each horizontal direction and two stories. The general dimensions of the physical model are shown in Fig. 1(b). The slab of each story with 0.06m thickness is designed to shoulder the additional masses of around 2400 kg. The consequent mass of each story is 3000 kg. The layout of the reinforced bars in the columns and beams is shown in Fig. 1(c).

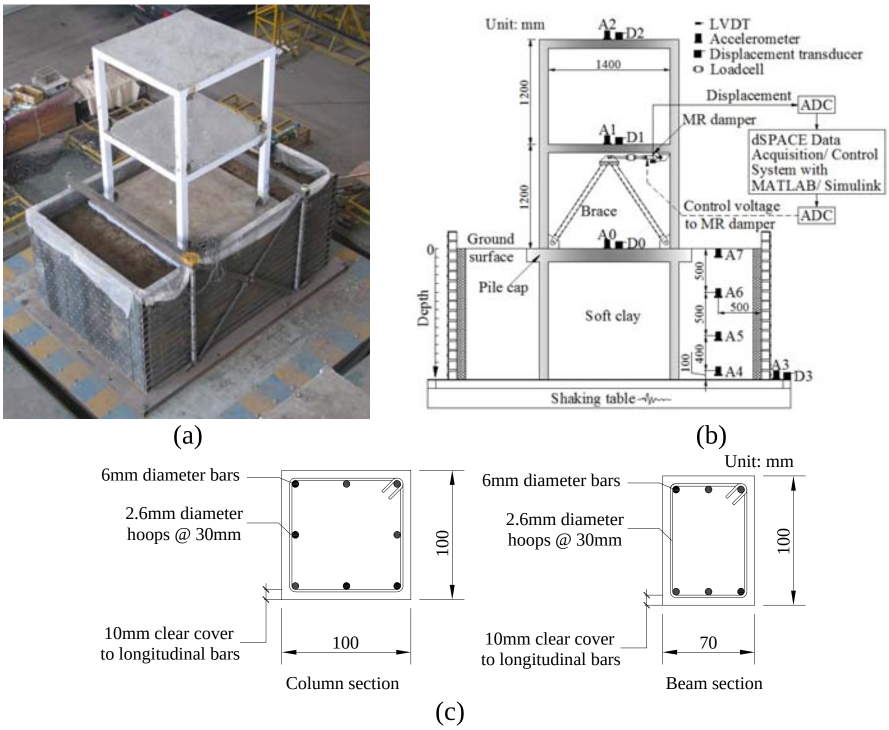


Figure 1. Photo of test setup on IEM shaking table and detailed design results of the frame: (a) top view, (b) schematic diagram of control test setup and (c) detailed design information.

In the soil-structure system, a laminar container aiming at simulating free field boundary conditions of the soil deposit is used to support the model soil and RC frame. A pile foundation designed for this study is composed a RC pile cap and four RC piles. The pile cap is designed to have a sufficient rigidity, with 2.0×2.0m in plan and 0.15m in thickness. The mass of the pile cap is 1500 kg. The piles have the same cross section with the columns of the superstructure. The test soil is deposited within the laminar container to a depth of 1.5m and its mass is 17.8 tons. The total mass of the flexible-based model after filled with soil is 28.5 tons. The density of the soil deposit is $1.64 g/cm^3$.

The MR damper used in the experiments is the RD-8040-1 manufactured by the Lord Corporation (www.lord.com). The MR damper has a stroke of 5.5 cm. The voltage supplied to the damper varies from 0V to 5V. Two MR dampers are placed at the first story of the test structure in the same direction and attached to the foundation via the rigid brace.

Sensors are installed in the test model for evaluating the energy distribution of the test structure and determining the control action. Displacement transducers and Accelerometers located on the base and each floor of the test structure provide measurements the absolute displacement and accelerations, respectively. In addition, some accelerometers are placed in various depths of soil to measure the acceleration response of the soil deposit. An LVDT measures the travel of the piston rod of the MR damper, and a loadcell is placed in series with the MR damper to measure the control force applied to the test structure. A dSPACE system with MATLAB Simulink is employed to perform data acquisition and control. A current drive converts the command voltage to the current for promoting the response speed of the electromagnetic circuit. The block diagram of experimental data acquisition and control system is shown in Fig. 1(b).

2.2. Test Program

The soil-structure system is tested at the Structure Laboratory of Institute of Engineering Mechanics (IEM), China Earthquake Administration. This shaking table is capable of providing maximum accelerations of $10 m/s^2$ in the horizontal directions and $7 m/s^2$ in the vertical direction. A ground motion record of the 1940 El Centro earthquake is used in the experiment. The ground motion is intended to be unidirectional in the direction parallel to the bracing system of the test structure, and scaled to generate different levels of intensity.

The peak ground acceleration (PGA) at 60gal, 100gal, and 200gal of the ground motion are selected in this experiment. The passive control approaches and semi-active control method are both chosen to evaluate the seismic performance of the test structure with different control strategies. For the passive control approaches, the input voltage of MR dampers is set as two levels, 0V (passive-off) and 5V (passive-on). In each level of shaking intensity, the test sequence is semi-active, passive-on, passive-off and uncontrolled case in order to make the test structure at the same condition to the maximum extent.

3. STRUCTURAL MODEL FORMULATION

To describe the energy flow through a soil-structure system, we use the idealized mathematical model shown in Fig. 2. In this model, x_1 and x_2 are the displacement of the first story and second story with respect to the pile cap, respectively. h_1 and h_2 are the height of the first story and second story, respectively. m_1 and m_2 are the mass of the first story and second story, respectively. x_g is the displacement of the shaking table, representing the free ground motion. The building is founded on a rigid embedded rectangular foundation. The rectangular foundation has mass m_f and mass moment of inertia I_f. The foundation has two degrees-of-freedom with respect to its centre of gravity: horizontal translation x_f, and rotation θ. The foundation is surrounded by springs and dashpots, which model the reactive forces caused by deformation developed in the soil. k_u and c_u are the stiffness and damping constants of horizontal springs and dashpots around the foundation representing the horizontal reactive forces on the vertical faces of the foundation; k_θ and c_θ are the rotational stiffness and damping constant representing the resisting moments in the half-space. The parameters k_u, c_u, k_θ and c_θ depend on the circular frequency of the foundation, foundation geometric size, soil shear wave velocity, soil damping ratio and Poisson's ratio. The dynamic behaviour of entire soil-structure system can be completely described by the following four degrees of freedom: x_1 and x_2, x_f and θ. The equation of the motion of the entire system can be represented by

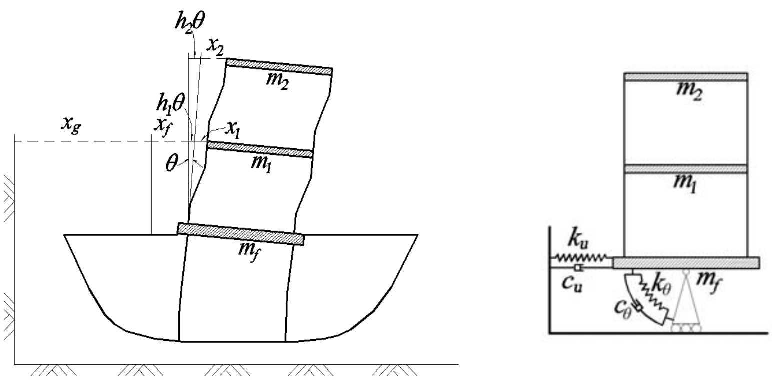
$$\mathbf{M}\ddot{\mathbf{X}}+\mathbf{F}\left(x_1,\dot{x}_1,x_2,\dot{x}_2,x_f,\dot{x}_f,\theta,\dot{\theta}\right)=-\mathbf{M}_g\mathbf{I}\ddot{x}_g+\mathbf{B_s}f_{\mathrm{MR}}\left(t\right) \tag{3.1}$$

where

$$\mathbf{M}=\begin{bmatrix} m_1 & 0 & m_1 & m_1h_1 \\ 0 & m_2 & m_2 & m_2h_2 \\ m_1 & m_2 & m_f+m_1+m_2 & m_1h_1+m_2h_2 \\ m_1h_1 & m_2h_2 & m_1h_1+m_2h_2 & I_f+m_1h_1^2+m_2h_2^2 \end{bmatrix}\quad \ddot{\mathbf{X}}=\begin{Bmatrix} \ddot{x}_1 \\ \ddot{x}_2 \\ \ddot{x}_f \\ \ddot{\theta} \end{Bmatrix}\quad \mathbf{F}=\begin{Bmatrix} f_1\left(x_1,\dot{x}_1,x_2,\dot{x}_2\right) \\ f_2\left(x_1,\dot{x}_1,x_2,\dot{x}_2\right) \\ c_u\dot{x}_f+k_ux_f \\ c_\theta\dot{\theta}+k_\theta\theta \end{Bmatrix},$$

$$\mathbf{M}_g=\begin{bmatrix} m_1 & 0 & 0 & 0 \\ 0 & m_2 & 0 & 0 \\ 0 & 0 & m_f+m_1+m_2 & 0 \\ 0 & 0 & 0 & m_1h_1+m_2h_2 \end{bmatrix}\quad \mathbf{I}=\begin{Bmatrix} 1 \\ 1 \\ 1 \\ 1 \end{Bmatrix}\quad \mathbf{B_s}=\begin{Bmatrix} 1 \\ 0 \\ 0 \\ 0 \end{Bmatrix}$$

$\mathbf{F}\left(x_1,\dot{x}_1,x_2,\dot{x}_2,x_f,\dot{x}_f,\theta,\dot{\theta}\right)$ is the nonlinear restoring force vector including viscous damping effects and hysteretic behaviour, **I** is the location vector of earthquake excitation, $\mathbf{B}_s$ is the location vector of control force, $f_{\mathrm{MR}}\left(t\right)$ is the damping force generated by MR dampers.



(a) (b)

Figure 2. Model of soil-structure system: (a) schematic of model deformation and (b) simplified model.

For complicated civil structures, it is impossible to implement control devices at every degree-of-freedom in the view of economy. Considering that only some parts are weak to enter nonlinear response stage, it is more reasonable to install control devices at these weak locations and utilize the decentralized control approaches making command to control devices. Furthermore, because the nonlinear behaviour of the structure and soil, as well as interaction between soil and structure are difficult to precisely obtain, the robust control algorithm is needed. Considering that the shear force in the first story is the largest, the MR dampers are only incorporated into the first story herein. A decentralized control method described by Li et al (2011) is used to implement the semi-active control in this experiment. The first story segment is separated from the entire system to conduct the decentralized adaptive control, then yielding the following equation of motion of the first story

$$m_1\ddot{x}_1 + f_1\left(x_1,\dot{x}_1,x_2,\dot{x}_2\right) = -m_1\left(\ddot{x}_g + \ddot{x}_f + h_1\ddot{\theta}\right) + f_{\mathrm{MR}}\left(t\right) \tag{3.2}$$

The damping force of MR dampers is determined by

$$u = f\left(\underline{\mathbf{x}}_1 \mid \Theta\right) + m_1 f_a \tag{3.3}$$

where u is an active control force; $f\left(\underline{\mathbf{x}}_1 \mid \Theta\right)$ is a fuzzy logic system to approximately estimate the unknown nonlinear function in Eqn. 3.2; $\underline{\mathbf{x}}_1 = \left[x_1 \quad \dot{x}_1\right]^T$ is the input vector of the fuzzy logic system; f_a is the auxiliary control compensation to attenuate external excitations and fuzzy approximation error. An H infinity performance can be achieved for a prescribed attenuation level $\eta = 0.1$ for the separated system (3.2) with the control law (3.3). More detailed information about this control algorithm can be found in Li and Wang (2011). In the shaking table test, only the inter-story drift of the first story, which is obtained from the piston rod travel, is used to calculate the control decision.

Generally, the energy balance equation can be yield by integrating the equation of the motion of the entire system in Eqn. 3.1. For the test structure, the viscous damping is difficult to obtain in the test, especially for the nonlinear soil-structure system. Therefore, the irrecoverable plastic hysteretic energy and viscous damping energy cannot be separated exactly in the energy flow of the nonlinear soil-structure system. During the severe seismic excitation, the irrecoverable plastic hysteretic energy dominates the dissipated energy in the structure. In this study, the dissipated energy is separated by the location in the soil-structure system. Consequently, the total input energy is repartitioned on the hysteretic energy in MR dampers, hysteretic energy in soil deposit (including the piles), dissipated energy of the first story and dissipated energy of the first story. For this test, the rotation of the pile cap is very small and is ignored in calculating the dissipated energy. Each energy part is calculated by

$$\begin{aligned}
E_{\mathrm{MR}} &= \int_0^{t_f} f_{\mathrm{MR}}\,dx_1 \\
E_{\mathrm{Soil}} &= \int_0^{t_f} \left(-m_f\ddot{x}_f^{Ab} - m_1\ddot{x}_1^{Ab} - m_2\ddot{x}_2^{Ab}\right)dx_f \\
E_{\mathrm{Str1}} &= \int_0^{t_f} \left(-m_1\ddot{x}_1^{Ab} - m_2\ddot{x}_2^{Ab}\right)dx_1 \\
E_{\mathrm{Str2}} &= \int_0^{t_f} \left(-m_2\ddot{x}_2^{Ab}\right)d\left(x_2 - x_1\right)
\end{aligned} \tag{3.4}$$

where E_{MR}, E_{Soil}, E_{Str1} and E_{Str2} are the hysteretic energy in MR dampers, soil deposit, first story and second story, respectively. $\ddot{x}_f^{Ab}$, $\ddot{x}_1^{Ab}$ and $\ddot{x}_2^{Ab}$ represent the absolute acceleration of the pile cap, first story and second story, respectively. t_f is the terminal time of input the seismic excitation.

4. EXPERIMENTAL RESULTS

4.1. Robust Performance of the Decentralized Control Algorithm

In order to investigate the robust performance of the decentralized control algorithm, the H infinity performance index η_0 is calculated for various input levels as follows

$$\eta_0 = \frac{\left(\int_0^{t_f} \underline{\mathbf{x}}_1^T \mathbf{Q} \underline{\mathbf{x}}_1 dt\right)^{\frac{1}{2}}}{\left(\int_0^{t_f} \tau_1^2 dt\right)^{\frac{1}{2}}} \tag{4.1}$$

where **Q**=diag[0.01, 0.01] is a positive definite matrix; $\tau_1 = m_1^{-1}\varepsilon_1^* - \left(\ddot{x}_g + \ddot{x}_f + h_1\ddot{\theta}\right)$ is the external disturbance of the separated system; ε_1^* is the optimal fuzzy approximation error. Notice that the optimal fuzzy approximation error is artificial constant quantity introduced only for analytical purpose, and its value is not needed for the implementation. $\ddot{x}_g + \ddot{x}_f + h_1\ddot{\theta}$ is the absolute acceleration of the pile cap, which shown in Fig. 2. The calculated H infinity performance index is shown in Fig. 3. It is clear that all the calculated performance indices are less than the prescribed attenuation level $\eta = 0.1$. It indicates that the decentralized control algorithm has good robust performance for all input levels.

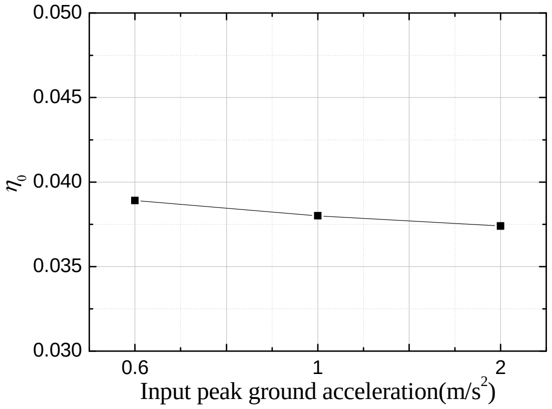


Figure 3. H-infinity performance of the decentralized control algorithm

4.2. Cumulative Damage of Test Structure

The force-deformation loop is usually used to represent the dynamic behaviour of the structure. In this experiment, the shear force of first story is obtained by summing up the floor inertia forces, given by the product of the recorded accelerations times the corresponding floor mass. While the shear force of second story is obtained by the product of the recorded accelerations of the second story times the corresponding floor mass. Fig. 4 shows the shear force of each story versus inter-story drift curves recorded during the tests with 200gal PGA excitation for the uncontrolled structure. It can be seen that the test structure exhibits a strong hysteretic behaviour and evident pinching effect in the first story. In order to quantitatively describe the damage state of the test structure, a damage index based on the hysteretic characteristic of the test structure is proposed. The proposed damage index combining the pinching deformation and hysteretic energy dissipation can be represented by

$$D_j = \frac{\delta_{pj}}{\delta_n} + \beta_e \left(\frac{\sum_{i=1}^{j} E_i}{\sum_{i=1}^{n} E_i} \right) \tag{4.2}$$

where D_j is the damage index after the jth excitation event; δ_{pj} is the pinching deformation after the jth excitation event; δ_n is the maximum travel during the all test events; E_i is the dissipated energy during the ith excitation event; n is the total number of test cases; the parameter β_e represents the weight of dissipated energy in the cumulative damage. The parameter β_e is an empirical factor determined usually on the basis of a large number of test results. In this study, the empirical formula (Park and Ang 1985, Zhang and Lu, 2005) in Eqn. 4.3 is employed to determine the parameter β_e.

$$\beta_e = \left(0.37 n_0 + 0.36\left(k_\rho - 0.2\right)^2\right) \times 0.9^{100\rho_w} \tag{4.3}$$

where n_0 is normalized axial stress; k_ρ is normalized longitudinal steel ratio; ρ_w is confinement ratio. The resulting parameter β_e is 0.23. Fig. 5 shows the damage index of the test structure for all test events. It can be found that the damage index is lower than 0.1 before the input peak ground acceleration of 200gal. At the test case with PGA of 200gal, the damage of the test structure can be significantly reduced through MR dampers, so that the structural safety can be guarantee. The growth rate of the damage index can illustrate the damage state of each test event. It can be observed that the growth rate of the cumulative damage is suppressed. This phenomenon indicates that MR dampers can effectively reduce the structural damage even if the structure suffers severe seismic excitation to enter the nonlinear stage.

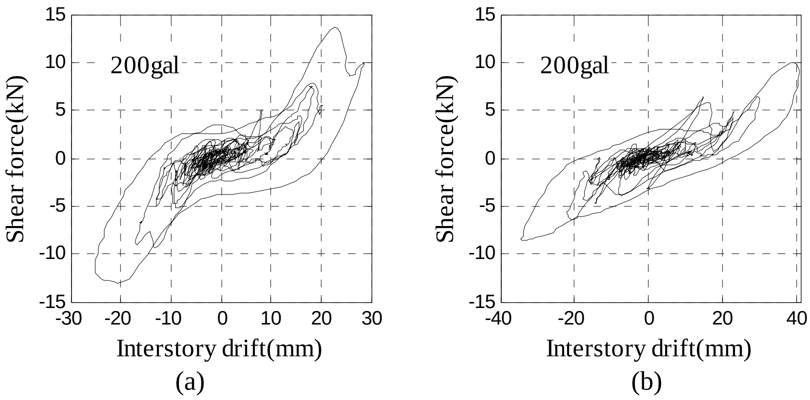


Figure 4. Shear force versus inter-story drift curves of: (a) first story and (b) second story of uncontrolled structure.

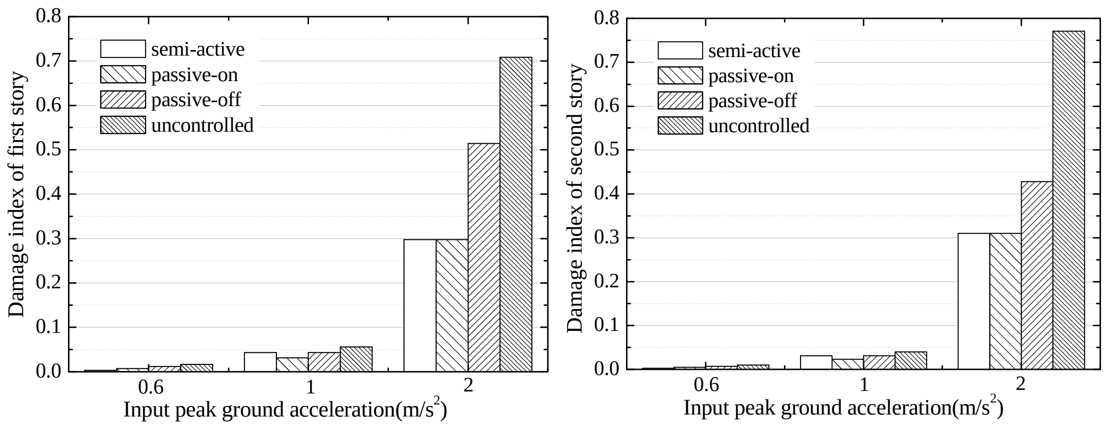


Figure 5. Damage index of each story under various excitation levels.

4.3. Energy Dissipation and Distribution among Soil-Structure System

For uncontrolled structure, the input energy of the entire structure system is dissipated through the irrecoverable plastic hysteretic energy and viscous damping energy. The irrecoverable plastic hysteretic energy induced by the inelastic behaviour often leads to significant damage to the structural member. The role of MR dampers is to increase the hysteretic damping in the controlled structure. In order to investigate the energy flow among the soil-structure system, the total dissipation energy is repartitioned on the hysteretic energy in MR dampers, hysteretic energy in soil deposit (including the piles) , dissipated energy of the first story and dissipated energy of the first story. Dissipated energy among the soil-structure system under various PGA levels is shown in Fig. 6.

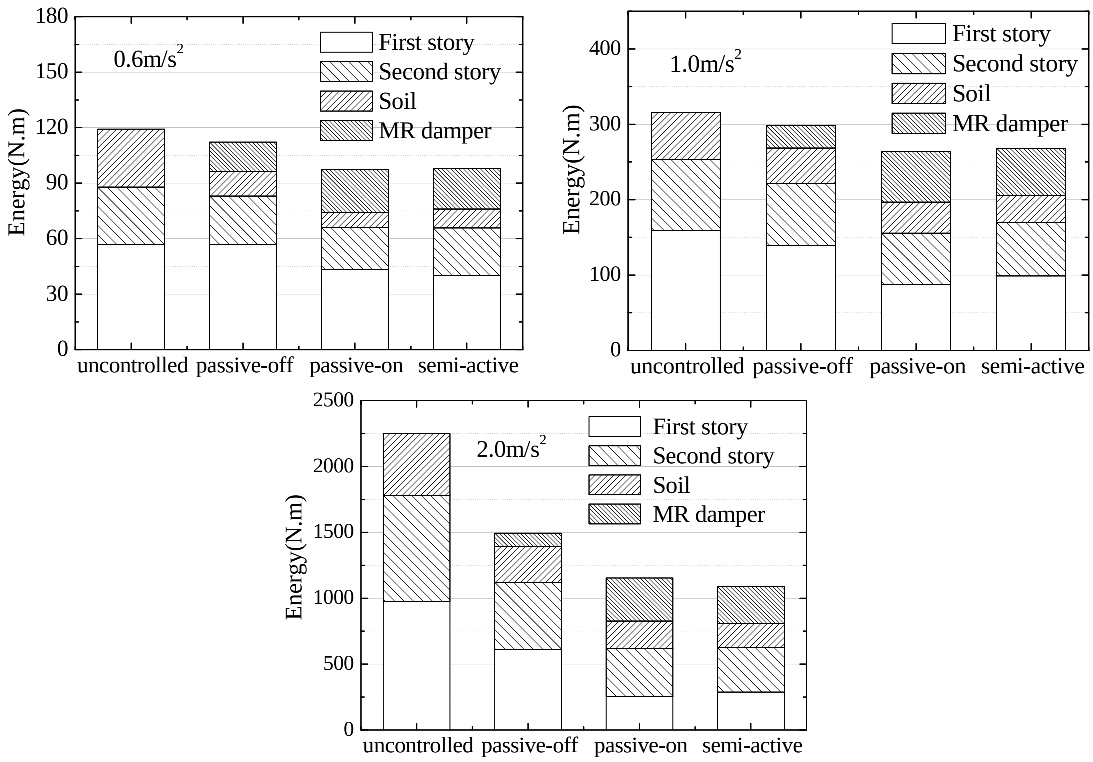


Figure 6. Dissipation energy of soil, superstructure and MR dampers in soil-structure system under various excitation levels.

For uncontrolled structure, the percentage of the soil energy dissipated in total energy dissipated decreases from 26.3% at input PGA of 60gal to 19.7% at input PGA of 100gal. At input PGA of 60gal, the soil dissipated energy has a high proportion in total dissipated energy due to the basically elastic behaviour in the superstructure. For the input PGA of 200gal, the percentage of the soil dissipated energy in total dissipated energy is 20.7%. The evident nonlinear behaviour of the superstructure and soil deposit can be both observed at input PGA of 200gal. In the dissipated energy aspect, MR dampers reduce the hysteretic energy both in soil deposit and superstructure, especially for input PGA of 200gal, which results in the reduction in superstructure response and the input of the superstructure.

5. CONCLUSIONS

This paper presents the performance evaluation of MR dampers to suppress the vibration of soil-structure system. The robustness of the decentralized control algorithm is validated through the shaking table tests on the soil-structure system with large uncertainty and nonlinearity. Based on the hysteretic characteristic of the test structure, a damage index combining the pinching deformation and hysteretic energy dissipation is proposed to assess the cumulative damage and damage evolution. The MR dampers can effectively reduce the cumulative damage and decrease the growth rate of the cumulative damage, especially for the strong seismic excitation. The energy flow in the soil-structure system with/without MR dampers indicates that MR dampers dissipate the energy directly by their hysteretic behaviour and reduce the input energy into the test structure. Besides reducing the dissipated energy and seismic response of the superstructure, the dissipated energy in soil deposit is also reduced so that the seismic response of the soil deposit is mitigated.

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