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Resistant force model of viscous damping wall considering influence of loading frequency

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ABSTRACT

Due to the heterogeneity and velocity-dependency of viscous fluid, it's quite difficult to simulate the dynamic behavior of viscous damping wall (VDW). The existing formulae for resistant forces need different parameter values for different loading frequencies. This may lead to large errors in resistant forces of VDWs subjected to an earthquake with large frequency change. A small-scale shaking table test and a large-scale dynamic actuator test were performed to investigate the influence of loading frequency, showing that direct data fitting with a single set of parameter values for different frequencies will lead to erroneous hysteretic cycles. Based on experimental results, five assumptions were proposed and thereafter a unified model was developed considering the influence of loading frequency by means of introducing the effect of loading history. The proposed model was validated with satisfactory accuracy in predicting the test results.

1. Introduction

One of the most challenging tasks facing civil engineers in recent decades has been solving overwhelming earthquake problems, which causes heavy casualties. Researchers from various countries have been focusing on the damping effect using viscous damping components. Zhou et al. [1] proposed a method to seismically retrofit an existing RC frame structure by viscous dampers and the damping forces could be estimated as 30% of the story forces. Faridani and Capsoni [2] developed relevant viscous damping models through multi-beam systems in coupled shear walls and investigated the effects of viscous damping mechanisms on structural characteristics. Viscous damping wall (VDW) is a new type of wall-shaped energy absorber, which can be hidden in building walls and provides large energy absorbing capacity. It has wide ranges of application because of easy fabrication and installation. Furthermore, VDW doesn't need regular maintenance because the viscous fluid in VDW can remain stable over years. Because of these advantages, VDW is in people's graces once available.

VDW, a simple device incorporating a high-viscosity fluid sandwiched by three wall plates, was firstly proposed by Japanese scholar Miyazaki in 1986 [3]. The inner plate is attached to the upper floor of a building story while the two outer plates are mounted on the lower floor of the same story. When a building is subjected to dynamic forces induced by wind or earthquake, the inner plate will move relative to the outer plates and generate viscous damping forces to reduce dynamic response due to the presence of viscous fluid [4].

Miyazaki et al. [3] carried out a series of cyclic tests to investigate the performance of VDW itself and obtained a design formula. The effects of VDW and the dynamic response of buildings with VDWs were confirmed by shaking table tests using a five-story model. Miyazaki and Mitsusaka [5] designed the SUT-Building, the first building using VDWs as energy dissipation devices in the world, exhibiting excellent performance in the subsequent Hanshin earthquake. Thus, the VDW gradually attracted wide attention. However, there have been just a small number of literatures focusing on the performance of VDW itself so far. Ou et al. [6] designed a VDW model utilizing their self-developed viscous damping material, and conducted a series of experiments to study the dynamic performance of VDW with the change of temperature, displacement amplitude, velocity and vibration frequency. Lu et al. [4] performed dynamic experiments and analyzed the resistant force vs. displacement hysteretic curves. Based on the available results, a mechanical formula of VDW was put forward and compared with experimental curves. Sasaki et al. [7] conducted a series of oscillation tests against large earthquakes to clarify the characteristics of VDW. A simplified design formula neglecting the influence of stiffness was proposed and compared with experimental curves. Experimental results showed that VDW can still absorb energy of oscillations even though the damping force decreased over a long time. What's more, it had no damage and recovered after tests. Sun and Mo [8] proposed a shaking table test method to study the performance of VDW, which is suitable to

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provide the characteristics of VDW by using a relatively simple test.

Researchers have also carried out a lot of experimental and theoretical research on the damping effect of VDWs in structures. Reinhorn and Li [9] conducted a series of shaking table tests on a three story 1:3 scale reinforced concrete frame structure with VDWs. It indicated that the structure with VDWs achieved significant stiffness increase and deformation reduction through both damping and stiffness, while the lateral drifts and deformations were reduced about 85% and the damping ratio was increased by 50%. Pan and Yeung [10] performed wind tunnel tests on a four-story building model to study the effectiveness of VDWs in controlling the wind-induced vibrations. The results showed VDWs were effective in most cases and the reduction in displacement could reach 60% to 80% in along-wind direction. Yan [11] carried out shaking table tests on two frames equipped with and without VDWs respectively. The test results showed that under minor and moderate earthquake, the story drifts, floor accelerations and shear forces of the frame with VDWs were remarkably reduced in comparison to the undamped one. Meanwhile, the VDWs dissipated 60%-70% of the input seismic energy in the damped frame. Hejazi et al. [12] developed a finite element model of VDW by using a two-node element, where each node had six DOFs in space. A constitutive law considering the performance of VDW in each DOF was formulated and incorporated in the model, which integrates two plastic hinges to predict deterioration of damper connection and experimental velocity-dependent relation to evaluate VDW damping force.

VDW has not been researched thoroughly so far because the viscous fluid is heterogeneous and velocity-dependent, causing it quite difficult to simulate dynamic behavior of VDWs. The existing formulae for resistant forces need different parameter values for different loading frequencies. This may lead to large errors in the resistant force of VDWs subjected to an earthquake with large frequency change. Thus, investigation of the influence of loading frequency on the hysteretic behavior of VDW was conducted in this paper by performing both a small-scale shaking table test and a large-scale dynamic actuator test. Simple direct data fitting for the test results was performed to confirm the influence of loading frequency. Assumptions were proposed based on experimental phenomena and physical reasoning, thereafter a unified model was developed considering the influence of loading frequency. The proposed model was then validated with the test results.

2. Review on existing resistant force formulae

Due to the complexity of dynamic behavior of VDW viscous fluid, all the existing resistant force formulae are regressed with experimental data.

2.1. Design formula by Arima and Miyazaki [13]

The resistant force Q_w is idealized by the sum of viscous damping force Q_d and restoring force Q_k. They are given by Eqs. (1)–(3):

$$Q_d = CA\left(\frac{V}{H}\right)^{\alpha} e^{-\beta t} \tag{1}$$

$$Q_k = CA\left(\frac{\delta^{\lambda}}{H^2}\right) e^{-\beta t} \tag{2}$$

$$Q_w = CA\left(\frac{V}{H}\right)^{\alpha} e^{-\beta t} + CA\left(\frac{\delta^{\lambda}}{H^2}\right) e^{-\beta t} \tag{3}$$

where Q_w is resistant force; Q_d is viscous damping force; Q_k is restoring force; C is coefficient of viscosity; V is relative velocity; δ is relative displacement; H is gap distance between two plates; A is effective area; β is temperature effect coefficient; t is temperature; α,λ are exponents obtained from experiment.

This formula is the most representative one and it can reflect the characteristic of VDW. However, the exponents in the formula are obtained under a certain frequency, without considering the influence of frequency change. Thus, the formula has no universality among different frequency conditions.

2.2. Design formula by OILES Company [7]

Since the restoring force of VDW is quite small at low frequency, OILES Company just neglects the influence of stiffness and proposes a simplified formula:

$$\begin{aligned} &V/H < 1 \quad Q_d = 0.42e^{-0.043t}A(V/H) \\ &1 \leqslant V/H < 10 \quad Q_d = 0.42e^{-0.043t}A(V/H)^{0.59} \\ &10 \leqslant V/H \quad Q_d = 0.42e^{-0.043t}A(V/H)^{0.4} \end{aligned} \tag{4}$$

where V is relative velocity; H is gap distance between two plates; Q_d is viscous damping force; t is temperature; A is effective area.

This formula is greatly simplified and can estimate the resistant force more easily to some extent. However, the formula curve has no slope because it only considers viscous damping force, and the stiffness characteristic can't be reflected, causing the shape of formula curves contradicting that of experimental curves. Furthermore, the experimental curves under different frequencies obviously show different shapes, but the formula doesn't take the frequency correlation into consideration.

2.3. Design formula by ADC Company (JSSI 2008) [14]

ADC Company found that frequency had a major influence on the viscosity of polymer materials and they put forward the following formula:

$$Q_w = CV^{\alpha} \tag{5}$$

$$\mathrm{C} = b\mu_{30} e^{\beta(f,t)} A/H \tag{6}$$

where Q_w is resistant force; C is coefficient of viscosity; V is relative velocity; α is velocity exponent; b is correction factor; μ_{30} is material viscosity at 30 °C; $\beta(f,t)$ is the exponential coefficient dependent of temperature and frequency; A is effective area; H is gap distance between two plates.

This formula is the first one directly taking the influence of frequency into consideration, which has a great guiding significance. But the problem is that in time domain, frequency is a vibration characteristic obtained by analyzing a time period; however, for time history analysis, there is no physical meaning of a frequency at any time point, so the frequency in an actual seismic action is always unpredictable, causing that the influence of frequency change cannot be reflected in numerical simulation using such a parameter $\beta(f,t)$.

2.4. Design formula by Nanjing University of Technology [6]

Ou et al. [6] carried out a series of performance experiments on VDW specimens and obtained a fitting formula in the form of Eq. (7).

$$Q_w = C\cdot V^{\alpha} + K\cdot\delta^{\lambda} \tag{7}$$

where Q_w is resistant force; C is coefficient of viscosity; K is dynamic stiffness; V is relative velocity; δ is relative displacement; α,λ are exponents obtained from experiment.

It was found that the shape of hysteretic curves was greatly affected by frequency. So different combinations of parameters were used to fit curves obtained at different frequencies and the fitting results are shown in Table 1, where *V/H* is the ratio of relative velocity to gap distance, distinguishing whether it's low-speed or high-speed.

The formula at each frequency was in good agreement with its corresponding experimental curve. But for an actual earthquake, the frequency is unpredictable. For example, the 2011 Tohoku earthquake is estimated in the frequency range 0.1–10 Hz using the empirical Green's function method [15].