Nonlinear Effect of Fluid–Structure Interaction Modeling in the Rock-Fill Dam Jatiluhur

by Albert Sulaiman

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Nonlinear Effect of Fluid–Structure Interaction Modeling in the Rock-Fill Dam Jatiluhur

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Abstract. Earthquake effects, hydrodynamic forces and nonlinear effects (structure properties represented by elastic constants) on rock-fill dam vibrations are investigated with a special case in the Jatiluhur dam, Indonesia. Th evibration studied by using the SdoF model with hydrodynamic forces and earthquakes as external forces. The analytical solution is obtained by the Laplace transform. Variations in hydrodynamic forces are obtained from water level measurement data where three scenarios are carried out, namely the lowest water level, middle and highest. The results show that the resulting hydrodynamic force does not have a significant effect on the vibration of the dam. The change in the vibration amplitude corresponds to the earthquake amplitude when the earthquake ends. The effects of the earthquake are still felt for a few seconds. The second model is to study the inhomogeneous-isotropic behaviour of the Dam constituent material in a nonlinear elastic coefficient. We express the elastic properties of the material in terms of the Taylor expansion. By using the Taylor expansion for the nonlinear effect up to the fifth-order show that the nonlinear term did not give effect on the vibration amplitude but the vibration shift.

Keywords: Fluid-structure; Groundmotion; Jatiluhur; Rock-fill Dam.

1 Introduction

The Dam is a hydraulic structure that very important for humans life so that it has received serious attention, especially in the aspect of structural durability due to environmental influences. An important environmental effect is a force due to water itself which takes place continuously, the abundance of excess rainfall (overtopping), landslides and earthquakes, especially for earthquake-prone areas. The failure or breaking of a rockfill or gravity dam during an earthquake is extensive cracking and deformation in the zone between the base of the dam and the foundation rock. In the event of an earthquake, the interaction between rigid structures (dams) and water creates additional (hydrodynamics) pressure upstream of the dam. The hydrodynamic force which is manifested in continuous hydrodynamic pressure will give dam elastic deformation. This is called the water-structure interaction and the excitation effect due to earthquakes has become a hot topic that has been studied a lot [1,2]. Related to the research, many approaches have been developed where one of the most popular is the finite element method. This method is used to determine the acceleration demands of the floor in gravity dam vulnerability due to earthquakes. The studies and simulation are very useful for the evaluation of the safety of the dam structure [3].

Several studies related to the effects of earthquakes on dam structures have been carried out, such as soil-structure interactions where the material damage for both soil and structure occurs as a result of the dissipation of earthquake energy acting on it [4,5]. Studies related to earthquake wave response (seismic) on concrete gravity dam in near-fault and far-fault ground motion [6]. Several studies related to dam-reservoir interactions have been carried out, especially by looking at the effect of acceleration amplification on the dam crest which is calculated based on the harmonic acceleration load. Estimation of stress and strain on the dam will be underestimated if this effect is neglected [7,8]. On the other hand, earthquake is studied by taking into account the stochastic effect of vibrations on the dam structure. The results show that the random effect of vibrations after the peak of the earthquake affects the fragility and fatigue of the dam structure [9]. The stochastic effect also studied by using wavelet transform which is can be used to detect damage from noisy [10]. The physical model approach is also carried out by giving more realistic results but requires a large amount of money and time [11].

In this paper, the fluid-structure interaction of a rock-fill Jatiluhur Dam (see Fig.1) subjected to horizontal ground motion due to earthquake and hydrostatic pressure are investigated. This Dam started operations in 1967 with gravity construction with a rock embankment structure where the centre is filled with clay. This structure has a length of 1.2km and dams the Citarum river with water storage is about 4.500 km^2. The water capacity is 12.9 billion m^3/year and instaled six turbine units with the power of 187 MW with an average electricity production of 1,000 million kWh per year. In addition, Jatiluhur Dam has the function of providing irrigation water for 242,000 ha of rice fields (twice a year), drinking water, fisheries cultivation and flood control. In the case of the Jatiluhur dam, we use water level measurement to analyse the hydrodynamics force and seismograph waveform for earthquake effect.

(a) (b)

Fig.1. (a) Location of Jatiluhur Dam in Java Island, Indonesia. (b) The Rock-fill Jatilihur Dam (photo: perusahaan jasa tirta II.)

2. The Model

In this paper, we investigate the vibrational behaviour of the Dam structure due to the effects of earth echoes and hydrodynamic forces working on it. The geometry of the model is depicted in Fig.2. First, we use a one-dimensional vibration model with external forces in the form of the hydrodynamic forces and the earthquakes known as the single degree of freedom model. Second, we study the stiffness properties of the Dam structure on vibration due to hydrodynamic and earthquake forces where the effect of the structure is modeled by taking into account the nonlinear terms of the coefficient of elasticity. The description as follows,

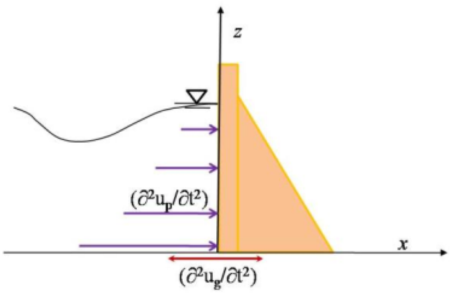


Fig.2. Idealized of the Jatiluhur dam, the purple arrow is hydrodynamics forces, the red arrow is the ground motion due to earthquake.

2.1. Single Degree of Freedom (SdoF)

In general, the interaction of rock-fill Dam with water in a reservoir is formulated in terms of finite elements that describe the interactions solid field elasticity and fluid-based potential expressed in the following matrix form [3],

$$\begin{bmatrix} m & 0 \\ 0 & -\varepsilon_k \end{bmatrix}\begin{bmatrix} \ddot{u} \\ \ddot{\phi} \end{bmatrix}+\begin{bmatrix} c_s & c_{fs} \\ c_{sf} & c_f \end{bmatrix}\begin{bmatrix} \dot{u} \\ \dot{\phi} \end{bmatrix}+\begin{bmatrix} k_s & 0 \\ 0 & k_f \end{bmatrix}\begin{bmatrix} u \\ \phi \end{bmatrix}=[I]\begin{bmatrix} -\ddot{u}_g \\ -\dot{u}_g \end{bmatrix} \tag{1}$$

where u is an element of dam displacement (x-coordinate, m is the mass of an element of structure, k_s is the stiffness, c_s is a damping factor, c_f is a viscous damping, c_{sf} is a damping of water-structure interaction, ϕ is the potetial velocity of water, ε_k and k_f are the potential and kinetic energy of water particle and u_g is displacement due to earthquake. The *'dot'* means a derivative respect to time coordinate.

In this paper, the hydrodynamic force is studied with the water level data at the Jatiluhur Dam so that to simplify the problem we look at the hydrodynamic force as an input to the vibrational dynamics of the dam structure. Many external forces affect vibration in a Dam, but the most important are hydrodynamic forces and earthquakes [1]. With the heigh (H_d) of a rock-fill Dam subjected to a horizontal ground acceleration due to earthquake $(\partial^2 u_g/\partial t^2)$ and hydrodynamics acceleraton $(\partial u_p/\partial t)$ with

u_p is a particle fluid veloccity then the single degree of freedom of the Dam system is given by [3],

$$\frac{d^2u}{dt^2}+\gamma\frac{du}{dt}+\omega^2u=-\left(\frac{\partial u_p}{\partial t}+\frac{\partial^2 u_g}{\partial t^2}\right) \tag{2}$$

where $\gamma= c_s/m$, $\omega=\sqrt{k_s}/m$, m is the mass of an element of structure and $u_p=\partial\phi/\partial z$ is horizontal particle velocity due to hydrodynamics pressure. It is not difficult to show, by using Laplace transform we have an analytic solution of Eq-2 as,

$$\begin{aligned} u(t)&=u(0)e^{-\gamma t}\cos\left(\sqrt{\omega^2-\gamma^2 t}\right)+\frac{\left(u(0)+u'(0)\right)}{\sqrt{\omega^2-\gamma^2}}e^{-\gamma t}\sin\left(\sqrt{\omega^2-\gamma^2 t}\right)\\ &+\frac{1}{m\sqrt{\omega^2-\gamma^2}}\int_0^t e^{-\gamma(t-\tau)}\sin\left(\sqrt{\omega^2-\gamma^2}(t-\tau)\right)\left(\frac{\partial u_p}{\partial\tau}+\frac{\partial^2 u_g}{\partial\tau^2}\right)d\tau \end{aligned} \tag{3}$$

2.2. Nonlinear Model

The elastic coefficient in Eq-2 is constant so that the material making up the dam is considered to be homogeneous-isotropic. For rock-fill Dam such as Jatiluhur, the material is not homogeneous isotropic so that the elastic coefficient is not constant and the material properties are no longer linear. The relationship between stress and strain is no longer linear. In this paper, we study the inhomogeneous-isotropic behaviour of the Dam constituent material in a nonlinear elastic coefficient. We express the elastic properties of the material in terms of the Taylor expansion. This is the simplest method in the theory of nonlinear elasticity. The expresion of Taylor series of the sine function is $sin(ku) \sim ku-1/3!k_3u^3+1/5!k_5u^5$-..... By maintaining until the second term then Eq-2 becomes,

$$\frac{d^2u}{dt^2}+\gamma\frac{du}{dt}+\omega^2u-\alpha u^3+\beta u^5=-\left(\frac{\partial u_p}{\partial t}+\frac{\partial^2 u_g}{\partial t^2}\right) \tag{4}$$

If we perform the following transformation $du/dt=v$, this yields,

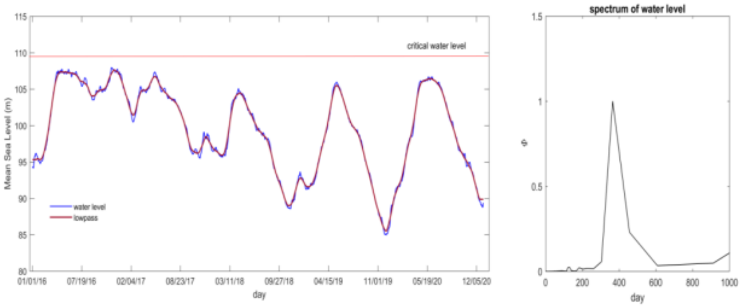
$$\frac{du}{dt}=v \tag{5}$$

$$\frac{dv}{dt}=-\gamma v-\omega^2u+\alpha u^3-\beta u^5-\left(\frac{\partial u_p}{\partial t}+\frac{\partial^2 u_g}{\partial t^2}\right) \tag{6}$$

This is a system of first-order nonlinear ordinary differential equations with unknown functions u and v. This equation will be solved using the Runge-Kutta method with Matlab software.

3. Result and Discussion

The multipurpose Jatiluhur Dam is located in West Java Province at a position of 7° South and 107° East, 130 km southeast of Jakarta. This dams the Citarum River in the Purwakarta Regency area and has functions for flood control, water supply irrigation, drinking water and industrial and hydroelectric power plants. With a design capacity of 3.00 billion m^3, this dam capable of ensuring water supply to irrigation areas to the west, north and east of the River Citarum. In addition to controlling the irrigation area, the Jatiluhur Dam is also a source of hydroelectric power plants with a production of 1.12 billion kWh per year and flood control as well as tourism and freshwater aquaculture. Jatiluhur Dam is designed to hold water with a maximum height of 109 meters above sea level. The varying water level is depicted in Fig.3. The result shows that the time series of water level has the peak of spectrum around 370 days. This indicates that the annual variability is influenced strongly by the monsoon system. The lowpass filter pattern (30 days cutoff period) is significant, indicating that the daily-weekly variability is not dominant. So the quantity of water sources in the Jatiluhur reservoir is stable.



(a) (b)

Fig.3. (a) The time series of water level on the Jatiluhur dam and the lowpass filter with cut-off period 30 day, (b) Normailized power spectrum with the maximum energy 370 day.

We study the effects of earthquakes and hydrostatic pressure on the upstream face of the dam. The hydrodynamic pressure can be estimated by using Westergaard's (1933) formula, which uses a parabolic approximation for additional stress due to an earthquake. Westergaard's hydrodynamics pressure $p=7/8\rho a_x\sqrt{(hz)}$ where ρ water density, $a_x=\partial u_p/\partial t$ horizontal acceleration, h the depth of dam and z is the water level. In calculations it is assumed that ρ = 1000 kgm^{-3} and g = 10 ms^{-2}. With the length of Jatiluhur dam is about 1220m, the maximum depth is 110m then hydrodynamics acceleration is given by $a_h=p/(\rho A)$ with A is area of interest. The Dam vibration due to groundmotion and the hydrodynamics forces for the lowest water table is depicted in Fig.4. In the simulation we assume the Dam has m ~ 2 ton/m^3, k=0.5 N/m [5] and damping coefficient is about 0.0005 Nms^{-1}.

By using the Westergaard formula and the synthetic ground motion data, we calculate the Dam vibration due to these two forces as shown in Fig.4. In general, changes in the vibration amplitude correspond to the earthquake amplitude when the earthquake ends, the effects of the earthquake is still felt for a few seconds. Meanwhile, the change in hydrodynamic force (as seen from the change in water level) is depicted in Fig.5. In general, a change in depth of about 10-20 m does not give a significant change in the vibration amplitude.

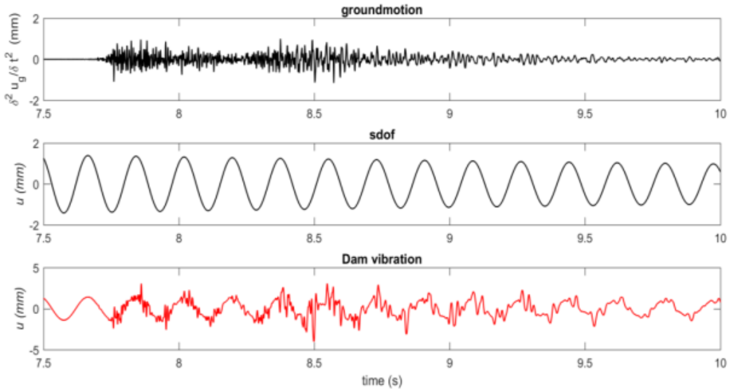


Fig.4. The groundmotion and the Dam vibration with normalized of groundmotion and SdoF.

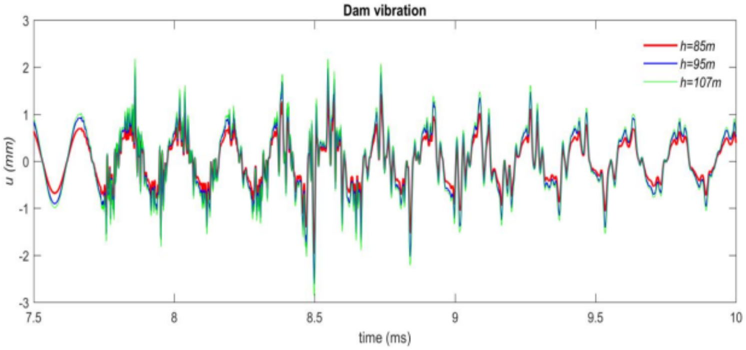


Fig.5. The Dam vibration with the middle and the highest water table.

In this study, hydrodynamic data has different time intervals from earthquakes where the water table has daily intervals. In an earthquake interval of milliseconds, the hydrodynamic force is constant. So that, we consider the hydrodynamic forces in the three scenarios above. Next, we calculate the effect of changes in hydrodynamic forces due to changes in water level on the vibration response during an earthquake.

These results are shown in figure-6. The results show that the change in hydrodynamic force due to changes in the water level of about 20 m (green line) has no significant effect on the vibration amplitude.

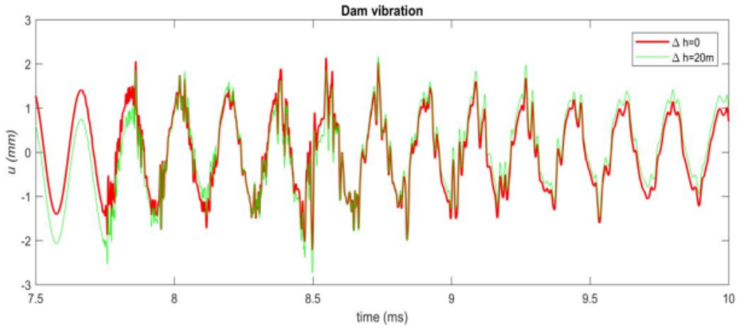


Fig.6. The Dam vibration or conditions without hydrodynamic forces and with hydrodynamic forces due to changes in water level 20m..

Furthermore, by expanding the elastic terms in the nonlinear term to the fifth-order (Eq-4), the simulation results are expressed in Fig.7. This solution is obtained by converting second-order differential equations into a first-order system of differential equations by transforming through Eq-5. The solution is solved by the Runge-Kutta method. The simulation shows that the nonlinear effect does not significantly contribute to the amplitude but has a shift effect on the vibrational motion. Previous paper studies have shown that an earthquake acceleration amplitude of 1m/s^2 can increase the vibration amplitude by about 10mm [5]. In this paper, we use normalized synthetic data which increases amplitude by about 5mm. The use of real waveforms will give more qualitative results. This will be done in future research.

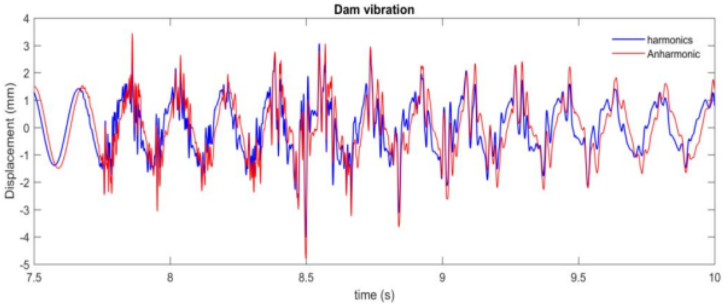


Fig.7. Nonlinear effect of SdoF related to hydrodynamics and earthquake in Dam vibration.

4. Conclussion

The behaviour of Jatiluhur Dam vibration with the hydrodynamic forces and earthquakes as external forces have been investigated in this paper. The basic model used in the investigation is called the SdoF where the analytical solution has been founded with the Laplace transform methods. The result show that changes in the vibration amplitude correspond to the earthquake amplitude when the earthquake ends, the effects of the earthquake is still felt for a few seconds. Variations in hydrodynamic forces are obtained from water level measurement data where three scenarios are carried out, namely when the water level is lowest, middle and highest. The results show that the resulting hydrodynamic force does not have a significant effect on the vibration of the dam. The second model is to study the stiffness behaviour of building materials by looking at the non-linear stiffness coefficients. By using the Taylor expansion for the nonlinear effect up to the fifth-order show that the nonlinear term did not give effect on the vibration amplitude but the vibration shift.

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