Application SDOF model to seismic base sliding analysis of concrete gravity dams subjected to earthquake load

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1. Introduction

Concrete gravity dams are typically constructed in blocks separated by vertical contraction joints. The design of straight concrete gravity dams is traditionally performed by assuming each block to be independent. Understanding the 2-D behaviour of individual monoliths is thus considered relevant and 2-D models are usually employed in safety evaluations of existing dams. During a strong seismic event, low to medium height concrete gravity dams tend to crack at the base which attract high stresses. The state-of-the-practice in the seismic evaluation of concrete gravity dams requires that the failure mode of the dam monolith sliding at its base must be considered.

It is well recognized that the pseudo-static loads determined on the basis of a seismic coefficient are very small when compared to the actual forces expected in a gravity dam during a strong earthquake [1]. Therefore, it is highly unlikely that the traditional safety criteria [2] for sliding stability can be satisfied if the pseudo-static lateral forces were to represent the true dynamic forces acting on a dam during a moderate to intense earthquake. However, the evaluation of seismic sliding safety on the basis of static loads has little meaning in the context of the oscillatory nature of earthquake loading and the corresponding dam response. Therefore, the normal criteria for evaluating static stability may not be appropriate to evaluate the seismic stability of concrete gravity dams. During an earthquake, as the forces acting on the dam change with time, it is desirable to assess the stability criteria at various time instants during the entire duration of the earthquake. Of particular importance is the evaluation of the critical earthquake accelerations at which the sliding of a dam could be expected.

In this paper, a numerical model to simulate seismic base sliding of concrete gravity dams preloaded by a constant horizontal force and subjected to base excitations is developed. The method bases on the assumption that the dam is considered as a block resting on a rigid foundation. It is called single degree of freedom method (SDOF). As the verification, results of present study are compared with results of experimental model carried out by MIR and Taylor [3]. Follow from this, the method is applied to analyze base sliding ability of Suoisap dam.

2. SDOF numerical model

The model SDOF considered concrete gravity dam as a block with mass M resting on rigid foundation. The dam is preloaded by a horizontal hydrostatic force H_{st}, uplift load and subjected to a base motions caused by earthquake.

The solution to the problem is based on the following assumptions:

- The dam and foundation are rigid;
- The dam - foundation interaction is horizontal;
- There is no mutual bond between the dam and the foundation and the motion is resisted by pure friction at the interface;
- The dam and foundation are always in contact, which means that any jumping or rocking motions of model is not considered;
- No cohesion between the dam and foundation is considered.

At any instant of time the dam is in equilibrium under a set of six forces:

- The weight of the dam, Mg, acting vertically downwards;

- The hydrostatic force, H_{st} , acting horizontally in or against the direction of motion;
- The frictional force, $F_r = \mu Mg$, acting against the direction of motion;
- The inertia force, $Ma_{(t)}$, acting opposite to the direction of motion;
- The hydrodynamic force, $H_{d,}$ computed by using Westergaad's added mass water;
- The uplift force U acting vertically upwards.

The critical horizontal acceleration a_c for inducing downstream sliding can be computed with the following equation:

$$a_c = \frac{1}{(M + M_{ao})}\left((W - U)\mu - H_{st}\right) \qquad (1)$$

Where:

μ is frictional coefficient between dam and foundation.

M_{ao} is the added water mass computed using Westergaad's approach. According to Chopra and Zhang [4], the added water mass is computed as:

$$M_{ao} = 0.54\rho h^2 \qquad (2)$$

Where: ρ is the density of water and h is upstream water level.

When the ground acceleration is greater than a_c, the dam is in motion, and the following dynamic equation of equilibrium must be satisfied at each time step [5].

$$(M + M_{ao})\ddot{S}(t) = -Ma(t) + H_{st} - H_d - F_r \qquad (3)$$

Where $\ddot{S}$ is the sliding acceleration of the dam.

Equation (3) can be written:

$$\ddot{S}(t) = -a(t) + \frac{(H_{st} - [Mg - U]\mu}{M + M_{ao}} \qquad (4)$$

Newmark [5] linear acceleration step-by-step scheme was used to compute sliding velocity and displacement. Within a time step h, delimited by the initial point with the subscript i, and the final point with the subscript i+1, the variation of the sliding acceleration $\ddot{S}$ after the time τ is obtained with the following equation:

$$\ddot{S}(\tau) = \ddot{S}_i + \left(\frac{\ddot{S}_{i+1} - \ddot{S}_i}{h}\right)\tau \qquad (5)$$

The sliding velocity $\dot{S}$ and sliding displacement S are given respectively by equations (6) and (7)

$$\dot{S}_{i+1} = \dot{S}_i + \frac{h}{2}(\ddot{S}_i + \ddot{S}_{i+1}) \qquad (6)$$

$$S_{i+1} = S_i + \dot{S}_i h + \ddot{S}_i \frac{h^2}{3} + \ddot{S}_{i+1}\frac{h^2}{6} \qquad (7)$$

Once sliding is instigated, it will only stop if two conditions are met:

+ The horizontal acceleration is inferior to the critical acceleration and.

+ The sliding velocity at the end of a time step is negative.

When both conditions are met, the rigid body falls in stick mode, and a correction is added to the previous time step displacement. The correction takes in account that during a time step where at the end the velocity is computed negative, a certain amount of sliding occurs before the velocity becomes negative. As can be noted in

Figure 1, the amount of sliding that must be added is that which occurs during the h_a portion of the time step h.

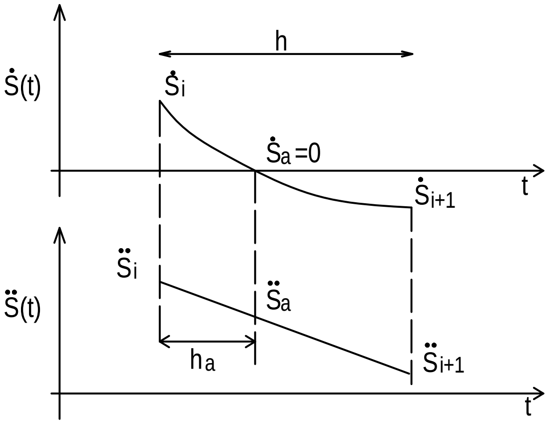


Figure 1. Correction of displacement

Referring to equations (5), (6) and (7), and putting the velocity $\dot{S}_a$ equal to O at the h_a, we can express h_a in the following manner:

$$h_a = -\frac{2\dot{S}_i}{\left(\ddot{S}_i + \ddot{S}_a\right)} \qquad (8)$$

From figure (1) and equation (8), the value $\ddot{S}_a$ is obtained with the following equation:

$$\ddot{S}_a = \sqrt{\ddot{S}_i^{\,2} - 2\dot{S}_i \frac{\ddot{S}_{i+1} - \ddot{S}_i}{h}} \qquad (9)$$

Having established $\ddot{S}_a$, from equation (7), the correction to be added to the sliding displacement, S_{cor}, is computed:

$$Scor = \dot{S}_i h_a + \ddot{S}_i \frac{h_a^2}{3} + \ddot{S}_{i+1} \frac{h_a^2}{6} \qquad (10)$$

Base on algorithm above, The DAS computer program was developed in this study to assess the downstream sliding of rigid concrete gravity dams subjected earthquake loads. The main menu of DAS program is showed in figure 2.

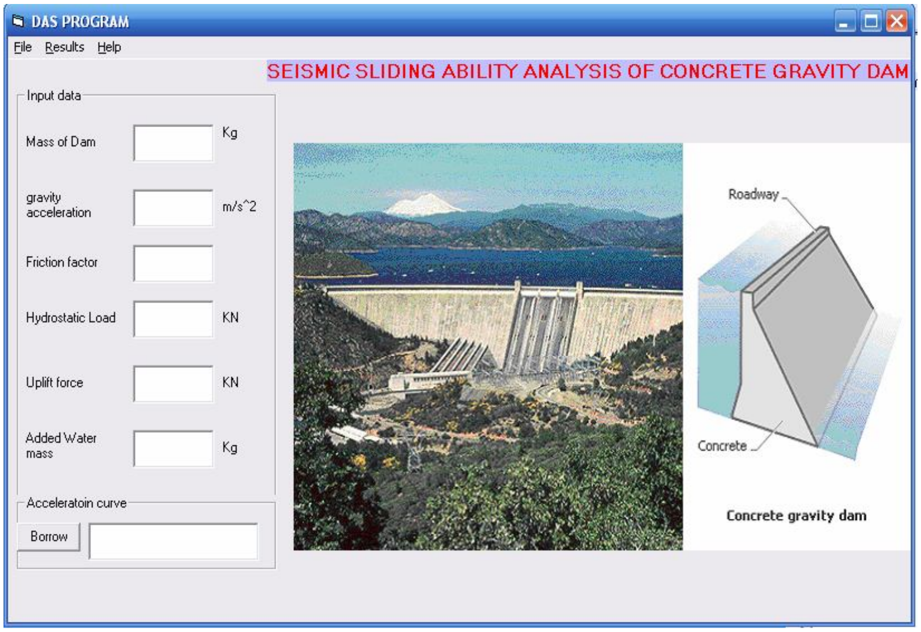


Figure 2. The main menu of DAS program

3. Verification of model

As the verification, the result of the DAS program is compared with result taken from experimental model carried out by (R.A.MIR and C.A. TAYLOR 1996) [3]. The details of the experimental model monolith are shown in Figure 3.

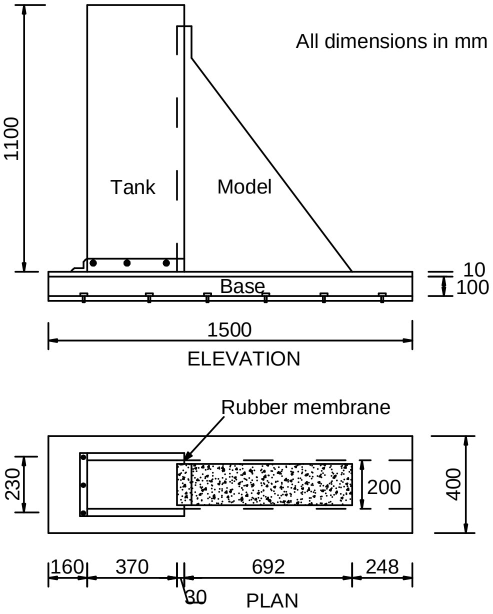


Figure 3. Experimental set-up taken from reference

In the case of dams, an important factor that influences the sliding response is the hydrostatic pressure acting on the upstream face of the dam. It was, therefore, important that this pressure was reasonably represented in the experiments. A considerable effort was needed to develop a reasonable arrangement for the simulation of hydrostatic pressure. A rigid rectangular steel tank (Figure 3) of 0.230m x 0400 m cross- section and 1.1m height was used for this purpose. The side of the tank adjacent to the upstream face of the dam was designed to consist of a watertight, flexible rubber membrane having sufficient slack to keep the hydrostatic pressure on the model engaged even if the model were to move up to 40mm downstream.

The measured coefficient of static friction at the dam-foundation interface was 0.72. The mass of the dam model was 186 kg and the height of the water in the tests was 0.95m. The input motion was a sine function of 5 HZ frequency having an initial rising ramp for 5 cycles followed by a 10cycle constant amplitude motion and finally a decaying ramp for another 5 cycles of motion as shown in Figure 4. The results of both SDOF model and experimental model are shown in Figure 5.

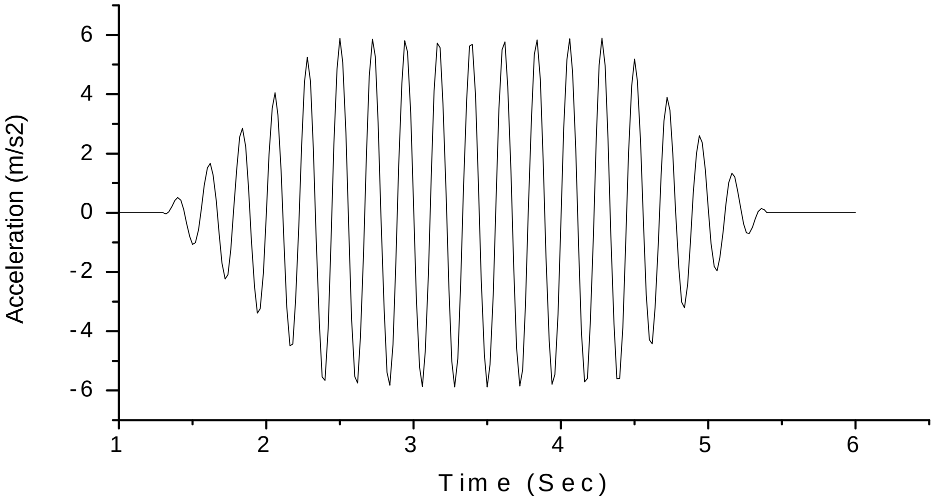
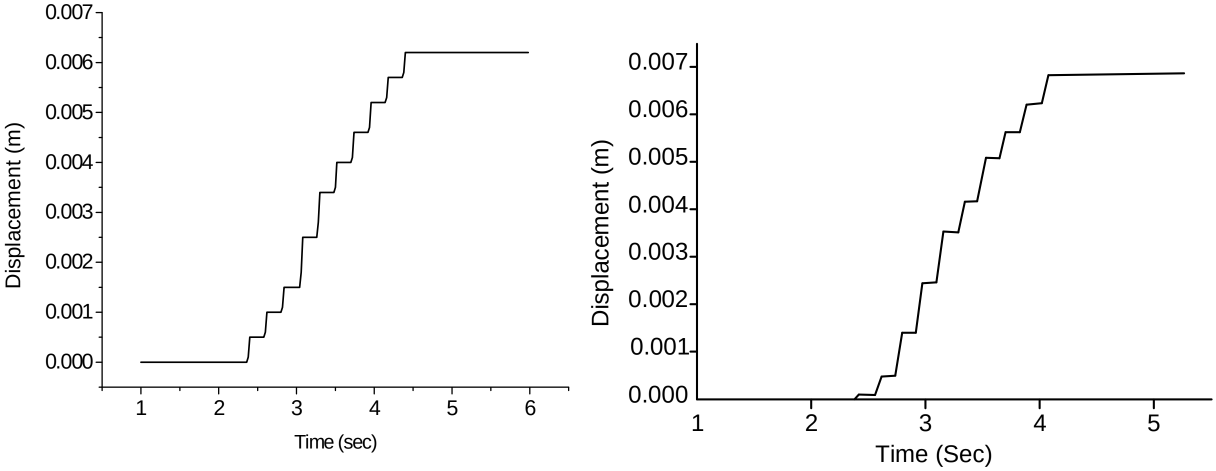


Figure 4. Sine dwell input



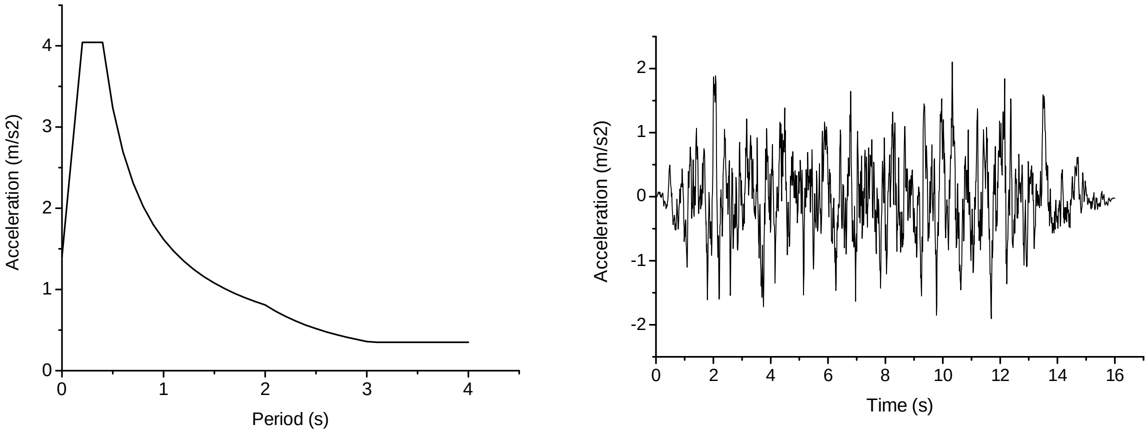
a) b)

Figure 5. Displacement of dam; a) From DAS program; b) From experiment model

From figure 5, it is observed that the displacements of dam block calculated by DAS program and taken from reference are almost similar. The total displacement calculated by DAS program is 6.4mm while the total displacement of dam taken from experimental model is 6.9mm.

4. Seismic sliding analysis of Suoisap dam

Suoisap dam is being built in Suoisap stream a branch of Da river, Sonla province. The dam is 35 m in height. The trapezoidal section of the dam is 5 m wide at the top and 30m at the base. The reservoir level is 29 m above the base of the dam. The loads considered in the analyses are the self - weight, the hydrostatic forces acting horizontally on the upstream face of the dam, the uplift force acting at the base of the dam and the earthquake load. The uplift force was computed using trapezoidal shape of uplift pressure with 29m of water pressure upstream and 12.5m downstream to account for the pressure induced by flow through the opening. The dynamic excitation considered in this paper is the acceleration spectrum given by the Vietnam code for seismic design of construction [6] (figure 6). The history corresponding artificial acceleration curve is computed from the acceleration spectrum correlatively by utilizing SIMQKE program. The result of displacement of the dam is shown in figure 7. The total displacement of the dam is 18mm.



a) *b)*

Figure 6. Dynamic excitation a) Design Spectrum; b) Time history acceleration

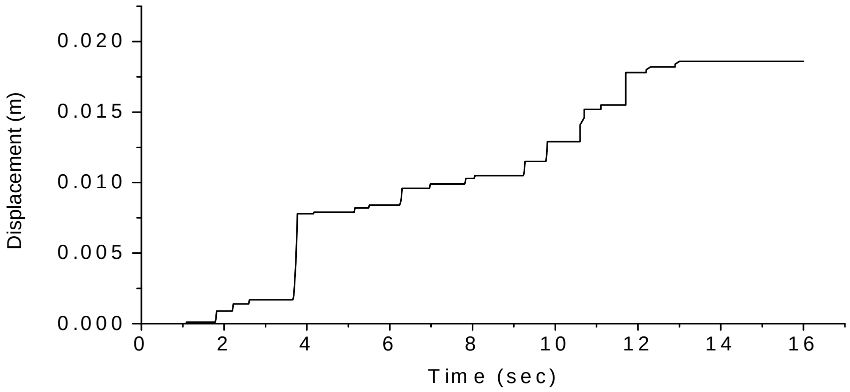


Figure 7. Displacement of Suoidap Dam

5. Conclusions

A method is proposed for the dynamic base sliding analysis of concrete gravity dams. The method based on the assumption that the dam is considered as a block resting on a rigid foundation. A computer program was developed to analyze seismic base sliding of concrete gravity dam. The result of this program is in close agreement with the result of the experimental model taken from reference.

The method in this study is suitable for base sliding analysis of low to medium height gravity dams, around 20-60m height. In general, dams of this height have relatively high fundamental frequencies, which tend to be outside the dominant frequency range of most earthquakes. Therefore, the use of a rigid dam model is reasonable simplification for dams of thi height.

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