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FINITE ELEMENT ANALYSIS OF AN EARTH DAM SUBJECTED TO BLAST-INDUCED LOADING USING A HIGH STRAIN-RATE BOUNDING SURFACE MODEL

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Abstract. *When soil or rock excavations near an earth dam are assisted with blasting, the dam may be damaged by the blast-induced loading. In order to investigate the response of an earth dam under blast-induced seismic loading, an artificial blast test on a 15 m-height earth dam is simulated. A recently proposed high strain-rate bounding surface model is adopted to model the stress-strain behavior of the dam materials. The detonation process of explosives is modeled by applying a pressure loading on the side wall of the borehole. Simulation results show that at a given elevation, the peak ground acceleration decreases with the distance to the blast hole. The peak horizontal acceleration on the upper parts of the dam is smaller than that at the dam bottom, which is different from responses to a tectonic earthquake. The maximum values of permanent and peak dynamic displacement occur near the upstream and downstream surfaces.*

1 INTRODUCTION

Although the design of earth dams against seismic loading still relies on empirical or semi-empirical methods, nonlinear finite element analysis has gained more attention, because it provides details about the performance of an earth dam under seismic loading conditions. Recently, Dakoulas [1] investigated the influence of canyon geometry on the seismic response of an earth dam; Elia and Rouainia [2] used a multi-surface kinematic hardening model to analyze the performance of a 42 m-height homogeneous earth dam under seismic loading; Zou et al. [3] and Liu et al. [4] reproduced the response of the 156 m-height Zipingpu Dam to the 2008 Wenchuan Earthquake. These are good examples that provide information on the seismic acceleration and deformation of various kinds of earth dams under earthquakes.

In addition to tectonic earthquakes, seismic loading can be induced by blasting operations for soil and rock excavation. Damage on earth dams caused by blast-induced seismic loading has been observed. For example, the upstream sand shell of the Swir II dam was reported liquefied by blasting operations 200 m upstream of the dam, and the upstream slope was reduced as a result [5]. When compared with a tectonic earthquake, the location of energy release in a blast-induced earthquake is much closer to the ground surface. The P- and S-wave cannot separate from each other within such a short distance, thus the responses to both waves are important. High frequency components of the seismic wave can also be reserved in a blast-induced earthquake. However, research on the response of an earth dam to blast-induced seismic loading is still rather limited.

In this research, finite element simulations are carried out to investigate the response of an earth dam to a blast-induced earthquake. The numerical model is developed following the set-up of an artificial blasting test on a 15 m-height earth dam. The earthquake is generated by applying a blast pressure loading in a borehole in the model such that the characteristics of blast-induced seismic waves can be captured. A recently proposed rate-dependent bounding surface model is used to model the dam materials, which is able to reproduce the soil behavior under high strain-rate cyclic loadings. The simulation results offer insight into the response of an earth dam under blast-induced seismic loadings.

2 FINITE ELEMENT MODEL

2.1 Test site

In order to investigate the feasibility of estimating the shear wave velocity of dam materials using artificial blast tests, Ha et al. [6] performed a series of borehole blasting tests near the Seongdeok dam, which is a 15 m-height core wall dam located near Choungsong, Korea. The geometry of the dam is shown in Figure 1. The width of the dam crest is 5 m. The upstream and downstream slopes are 1:2.0 and 1:1.8, respectively.

As reported by Ha et al. [6], four tests with weights of charge varying from 5 to 19 kg were performed. The explosives were detonated within boreholes at depths of 6 – 25 m. Before

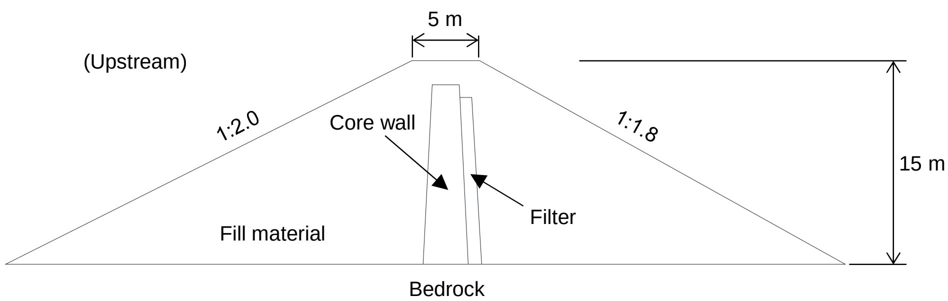


Figure 1: Profile of the Seongdeok dam.

detonation, the required amount of explosive was placed at the bottom of the borehole. Subsequently the borehole was backfilled with crushed rock. The boreholes were about 60 m from the dam axis downstream. Accelerometers were installed on the dam crest and the rock outcrop near the boreholes. The measured time histories of ground horizontal acceleration are used to verify the simulation results in this research.

2.2 Finite element model

Figure 2 shows the finite element model used in the simulations. The model was developed in LS-DYNA [7]. The *x* and *y* directions of the model are indicated in the figure, and the *z* direction is perpendicular to the *x*-*y* plane pointing to the reader. The model is developed by extruding a 2D model from the plane $z = 0$ to the plane $z = 1$ m. The dam is modeled according to the actual dimensions. Two zones, the fill material and the core wall, are considered. The bedrock in the finite element model extends to a depth of 80 m below the bottom of the dam. The blast hole is located 60 m away from the dam axis. The bottom of the blast hole is 25 m below the ground surface. The diameter and length of the hole are 5 cm and 9.1 m, respectively.

The domain is discretized using 8-noded hexahedral Lagrangian elements. Each element uses one single Gaussian integration point. As the model is a pseudo-3D model, the *z* displacements of all nodes are constrained. The bottom of the finite element model, *BC* in Figure 2, is taken as a fixed boundary. Both the *x* and *y* displacements are set to 0 at this boundary. A silent boundary is adopted for the two sides of the model, *AB* and *CD*. These silent boundaries absorb the stress wave by applying a counter stress calculated according to the elastic wave velocity [6]. Before the dynamic simulation, gravitational force was applied to the whole model to reproduce the initial stress state. The gravitational force is retained during the entire dynamic simulation process.

In this research, the blast loading is simulated by applying a pressure loading with a time history suggested for borehole blasting [8, 9, 10], which can be represented by

$$p(t) = p_0\left(\exp(-\alpha t) - \exp(-\beta t)\right) \tag{1}$$

where $p(t)$ is the blast pressure acting on the side wall of the blast hole at time t; p_0, α and β are model parameters. Equation (1) can be written as

$$p(t) = \frac{p_{peak}}{k^{1/(1-k)}\left(1-k^{-1}\right)} k^{\frac{1}{1-k}\frac{t}{t_0}} \left(1 - k^{-\frac{t}{t_0}}\right) \tag{2}$$

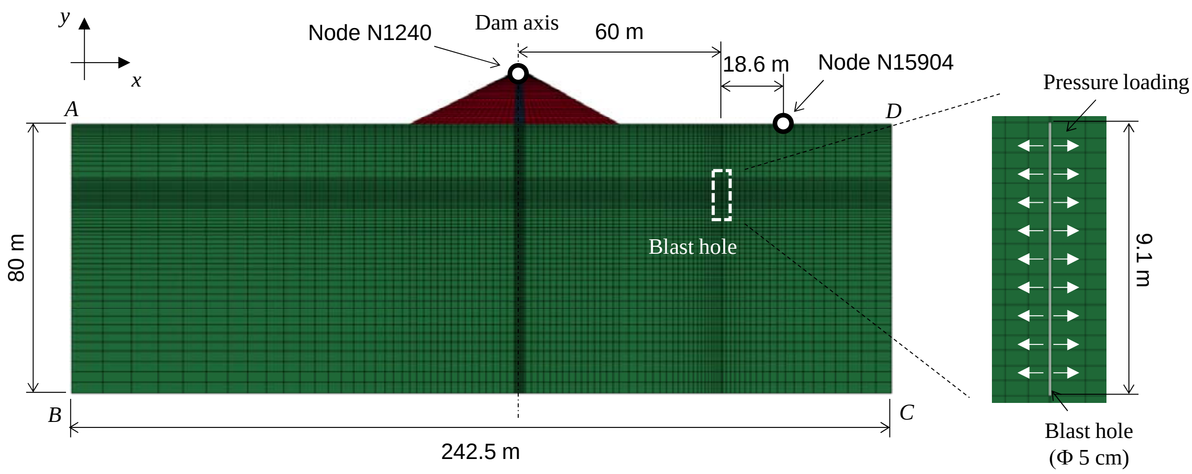


Figure 2: Finite element model used in the simulation.

where p_{peak} is the peak pressure, which is equal to $p_0[(k^{(1/(1\text{-}k))}\text{-}k^{(k/(1\text{-}k))})]$; $k = \beta/\alpha$; t_0 is the occurrence time of the peak pressure, which can be calculated by $t_0 = \ln(k)/(\beta - \alpha)$. According to Equation (2), the time history of the blast pressure can be determined by specifying three parameters: p_{peak}, k and t_0. Figure 3 shows the time histories of the normalized pressure, $p(t)/p_{peak}$, with different parameters. In the simulation, the adopted parameters are p_{peak} = 1 MPa, k = 1.5 and t_0 = 20 ms. These parameters are selected to reproduce the time history of ground acceleration measured at the rock outcrop and the dam crest to the greatest extend. The adopted time history of blast pressure is shown by the black curve in Figure 3.

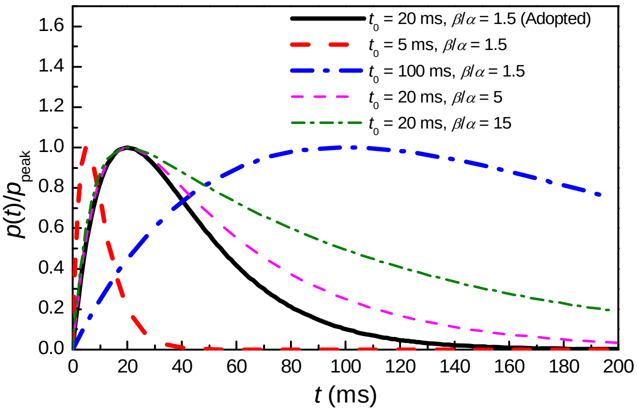
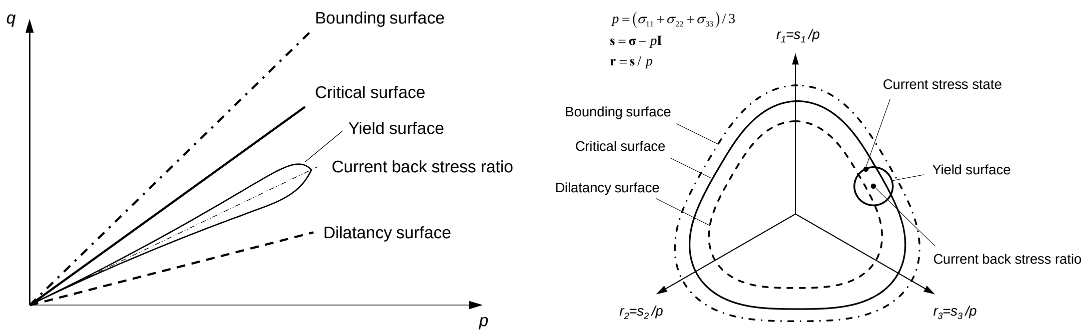


Figure 3: Time histories of normalized pressure loading with different parameters.

3 MATERIAL MODELS

3.1 Dam materials

A recently proposed high strain-rate bounding surface model is utilized in this research to model the behavior of dam materials [11]. The model was proposed on the basis of the bounding surface framework. As shown in Figure 4, a spindle-like yield surface is used in the model. Both isotropic and kinematic hardening conditions are defined, so both the shape and location of the yield surface evolve during a loading process. In the general stress space, the critical stress states are represented using a critical surface. A dilatancy surface is introduced as the boundary of shear-induced contractive and dilative behavior. Moreover, a bounding surface is used to enclose all the possible stress states. These model surfaces reproduce the plastic behavior of soil. The sizes of these model surfaces depend on the strain rate, thus the influence of strain rate on the mechanical behavior can be considered. The model formulations have been presented by Xu and Zhang [11].



(a) (b)

Figure 4: Model surfaces in the high strain-rate bounding surface model: (a) on the *p*-*q* plane; (b) in the general stress ratio space.

Soil behavior	Parameters	Fill	Core wall
Soil property	ρ (g/cm^3)	2.00	1.80
Rate-dependent elasticity	$G_{0,ref}$	45.00	35.00
	$K_{0,ref}$	71.30	57.55
	k_G	0.10	0.10
	k_K	0.10	0.10
Critical state	$\alpha^c_{c,ref}$	1.70	1.25
	k_c	0.01	0.005
	c	0.75	0.75
	e_0	0.3634	0.3387
	λ	0.0069	0.0044
	ξ	0.70	0.70
Dilatancy	n^d	2.29	1.50
	A_d	1.68	1.91
	k_d	-0.15	-0.50
Kinematic hardening	n^b	2.26	2.87
	k_b	0.20	0.10
	h_0	30.00	50.00
	c_h	0.50	0.50
Limit compression line	p_r	5500	5500
	ρ_c	0.374	0.374
	θ	0.20	0.20
	X	0.80	0.80

Table 1: Model parameters for dam materials.

Comprehensive element test data are not available for the materials in the Seongdeok dam. Considering that this research is to provide a general understanding of the response of an earth dam under blast-induced seismic loading, the model parameters for the dam fill and core wall material of the Nuozhadu dam in China are adopted in the simulation. The model parameters adopted in this research are listed in Table 1. Moreover, the Rayleigh damping is applied to dam materials to provide basic damping at low strain levels [12]. The Rayleigh damping coefficients are determined so that the damping ratio is 10% for the motions at the frequencies of 10 and 200 Hz.

3.2 Bedrock

The bedrock in the finite element model is modeled using the Mohr-Coulomb model. According to the site investigation [6], the bedrock at the test site is hard rock with an RQD (Rock Quality Designation) value of 90%. The shear modulus of the bedrock is 5.05 GPa, and the Poisson's ratio is assumed to be 0.20. The friction angle and cohesion are 40° and 3.5 MPa, respectively. The Rayleigh damping is also applied to the bedrock with the same damping coefficients as the dam materials to consider the attenuation of blast wave in the bedrock.

4 RESPONSE OF THE DAM SUBJECTED TO BLAST-INDUCED LOADING

4.1 Ground acceleration

Figure 5 shows the time histories of horizontal acceleration at two typical nodes shown in Figure: N15904 and N1240. N15904 is located on the surface of bedrock. The distance between N15904 and the blast hole in the model is the same as that between the accelerometer at the rock outcrop and the blast hole in the tests. N1240 is at the same location with the accelerometer at the dam crest. The measured data at these two locations are also shown in Figure 5. For comparison, the time shown in the *x*-axis has been translated so that the peaks of the curves match each other. The peak values of the simulated horizontal acceleration at the rock outcrop and the dam crest are 0.36 g and 0.04 g, respectively, which are of the same magnitude with the measured data. The measured and simulated duration of the blast-induced seismic vibration are both within 600 ms. The comparison between the measured and simulated data shows that the artificial blasting test at the Seongdeok dam is well simulated.

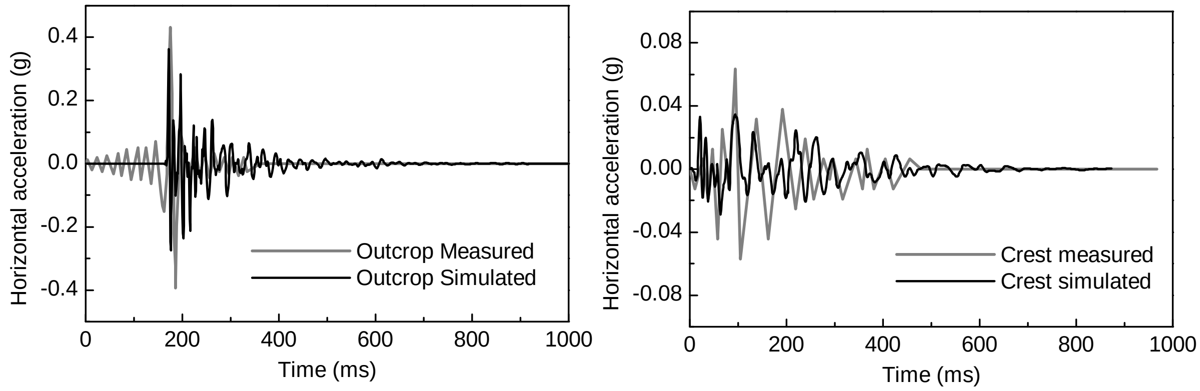


Figure 5: Time histories of ground acceleration of typical nodes.

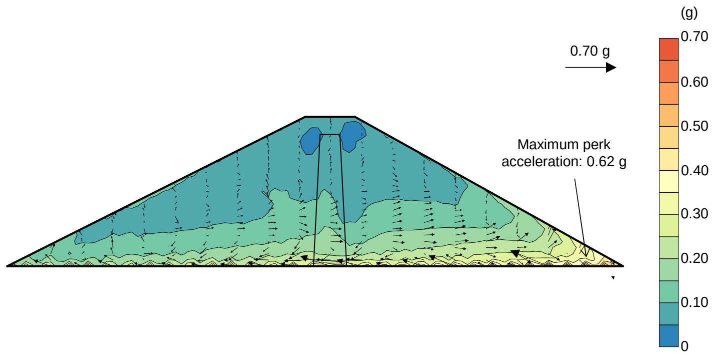


Figure 6: Distribution of peak resultant acceleration in the dam body.

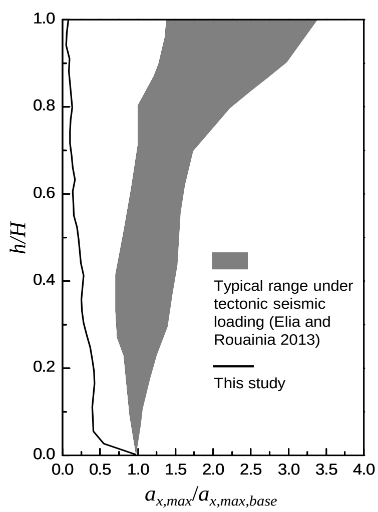


Figure 7: Amplification of horizontal acceleration along dam axis.

The distribution of peak resultant acceleration is shown in Figure 6. At the same elevation, the peak resultant acceleration is larger near the blast hole. The maximum value of the peak resultant acceleration, 0.62 g, occurs near the bottom right corner of the dam body. Figure 7 shows the distribution of the amplification factor of horizontal acceleration along the dam axis. In the figure, $a_{x,max}$ is the peak horizontal acceleration, $a_{x,max,base}$ is the peak horizontal acceleration at the bottom of the dam, h is the height over the dam bottom of a location, and H = 15 m is the height of the dam. Based on the simulation result, the peak horizontal acceleration occurs at the bottom of the dam. Generally, the peak horizontal acceleration decreases with increasing elevation. The typical range of the distribution of $a_{x,max}$ / $a_{x,max,base}$ along the dam axis for an earth dam under a tectonic earthquake is also shown in the figure. When subjected to tectonic seismic loading, the peak horizontal acceleration at the dam crest is larger than that at the dam bottom, which differs greatly from the observation in this study.

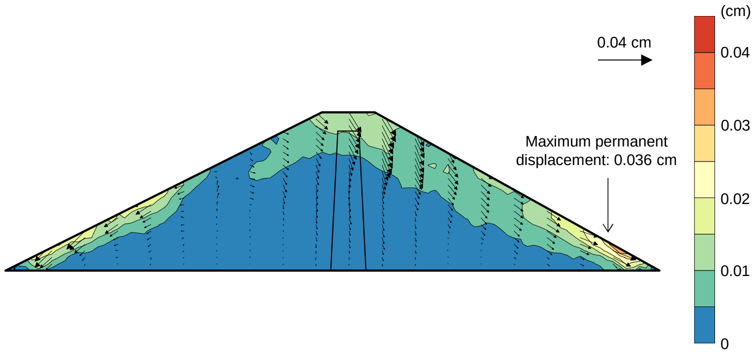


Figure 8: Contour of permanent resultant displacement.

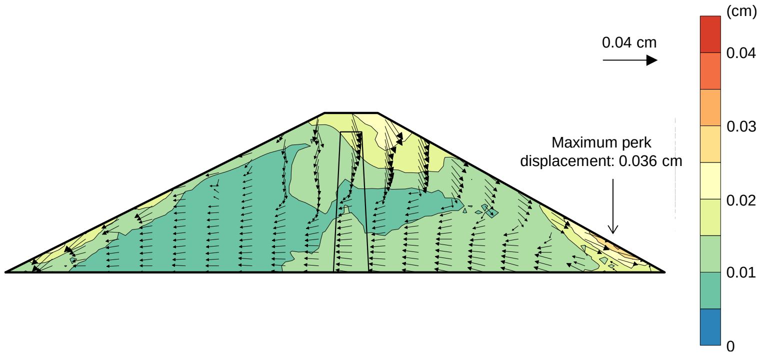


Figure 9: Contour of peak permanent displacement.

4.2 Ground displacement

As the artificial blasting test is performed solely for the measurement of the shear wave velocity of dam materials, the deformation of the dam body should be small. However, the characteristics of the dam deformation under blast-induced seismic loading can still be captured by the numerical simulation in this research. Figure 8 shows the permanent resultant displacement within the dam body. According to the figure, the deformation zone appears mainly on the dam surfaces near the bottom of the dam. The peak permanent displacement is 0.04 cm in this artificial blasting test and occurs at the bottom right of the dam body. The deformation zone is larger at the downstream part than that at the upstream part. The maximum dynamic displacement is shown in Figure 4.2.2. The maximum dynamic displacement in a large part of the dam body is along the direction of the blast wave propagation and larger than the permanent displacement.

5 SUMMARY

In this research, the response of an earth dam subjected to the seismic loading induced by nearby borehole blasting was investigated with the aid of finite element simulation. The blasting was simulated by applying a pressure loading on the side wall of the borehole. A rate-dependent bounding surface model was adopted to model the mechanical behavior of dam materials. According to the simulation result, the peak resultant acceleration will be larger near the blast hole at a given elevation. For locations along the dam axis, the peak horizontal acceleration decreases as the elevation increases. The permanent deformations of the dam body are the largest near the upstream and downstream surfaces.

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