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FEM-based parametric analysis of a typical gravity dam considering input excitation mechanism

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ABSTRACT

This paper studies computer-aided parametric analysis on the finite element model of a typical concrete gravity dam. The coupled dam–foundation–reservoir system is modeled based on Lagrangian–Eulerian approach. The nonlinearity in the dam is originated from a developed rotating smeared crack model. Different types of input ground motions are used for excitation of the structural system, i.e. near-fault vs. far-field, real vs. artificial, and uniform *vs.* non-uniform. The spatial varying ground motions and endurance time acceleration functions are generated based on a non-stationary random process. Finally, results are presented in terms of displacement and crack propagation. Relative importance of different parameters is compared and an optimum numerical model is suggested for potential applications.

1. Introduction

In recent years, the nonlinear dynamic response of gravity dams under earthquake actions, mainly including cracking of concrete, has attracted more attention from engineers. There are several important factors that influence the finite element analysis of concrete gravity dams [1]. These factors are the semi-unbounded size of the reservoir and foundation rock domains; dam–reservoir interaction; wave absorption at the reservoir boundary; water compressibility; dam–foundation rock interaction; spatial variations in ground motion at the dam–rock interface, complex nature of material and loads and also their interaction in dam–reservoir–foundation coupled system. There is a wide literature where each problem is separately investigated by developing sophisticated models. However, it is worthy to mention that the integrative seismic analysis of a dam is combination of all these aspects which are required for realistic assessment of a coupled system [2].

Although the performance of the concrete dams can be threatened by natural phenomena such as floods, rockslides, earthquakes, and deterioration of the heterogeneous foundations and construction materials; in the present paper only the potential failure modes due to earthquake shaking on gravity dams are investigated. The major potential failure modes in gravity dams are due to overstressing, sliding along cracked surfaces in the dam or planes of weakness within the foundation, and sliding accompanied by rotation in the downstream direction. All these failure modes can be resulted due to cracking and consequently detaching whole or a part of the dam. Under severe ground shaking a typical gravity dam section may suffer tensile cracks at the base and/or near the downstream slope change discontinuity. The upper cracks usually initiate from the upstream or downstream face of the dam and propagate horizontally or at an angle toward the opposite face. The consequence of cracking, if extended through the dam section, may lead to sliding or rotational instability of the separated block [3]. Based on an extensive literature survey, the following limit state (LS) parameters which could lead to partial failure (in the sense that they are likely to result in uncontrollable release of water, or major economic losses) are identified, Fig. 1:

- LS-1: Concrete cracking at the neck
- LS-2: Concrete or rock cracking at the dam–foundation interface
- LS-3: Damage cracking at the key points (slope discontinuity)
- LS-4: Deflection of the crest point beyond the ultimate displacement
- LS-5: Overturning of the dam around the heel
- LS-6: Sliding along dam–rock interface due to joint breaking
- LS-7: Sliding along lift joints (weak planes)
- LS-8: Damage cracking due to fault movement in the foundation

The impact of the fluid–structure interaction on the seismic response of dams have been studied by Ghaemian and Ghobarah [4], Fahjan et al. [5], Bayraktar et al. [6], Akkose et al. [7],

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Nomenclature

$a_n(x,y,z,t)$ Normal acceleration on the fluid–solid interface
a_g Endurance time acceleration parameter
$A(i\omega)$ Filtered acceleration function
A_{HV} Harichandran and Vanmarcke coherency model parameter equal to 0.626
b_{HV} Harichandran and Vanmarcke coherency model parameter equal to 3.47
c_0 Shape controlling parameter in the modulating function
C_0 Velocity of pressure wave in water
E_c Elasticity modulus of concrete
E_f Elasticity modulus of foundation
Err_C Cumulative error function
Err_L Local error function
f_c Compressive strength of concrete
f_t' Tensile strength of concrete
$f(t)$ Non-stationary stochastic vector
F_{mech} Fault mechanism
$g(t)$ Stationary stochastic vector
G_f Fracture energy of concrete
H_0 Total height of the dam
$H_1(i\omega)$ Clough and Penzien low-pass filter function
$H_2(i\omega)$ Clough and Penzien high-pass filter function
i Imaginary unit
j Dummy index
k Dummy index
k_{HV} Harichandran and Vanmarcke coherency model parameter equal to 19,700 m
$l(t)$ Linear profile function
M_i Growth shape function in infinite elements
M_w Earthquake magnitude
n_i Cartesian component of normal boundary vector on the reservoir–solid interface
N_i Standard shape function in infinite elements
$P(x,y,z,t)$ Hydrodynamic pressure at the specific location and time
r Number of total time steps in generating an ETAF
R A multiplier for $\widehat{\omega}$ representing upper bound of frequency range ($R>1$)
R_{rup} Closest distance to co-seismic rupture
$S_a\ (T,\xi)$ Spectral acceleration at the period T and damping ratio ξ
S_a^{target} Target acceleration response spectrum of ETAFs
$S_a^{generated}$ Generated acceleration response spectrum
$S_a{}^{EQGM}$ Acceleration response spectrum of a selected ground motion
$S_a{}^{TARGET}$ Site spectrum or design spectrum (as target one)
$S_{ac}(T)$ Target acceleration response for structure with period T
$S_{ac}(T,t)$ Target acceleration response at time t for structure with period T
$S_{uc}(T,t)$ Target displacement response value for period T at time t
$S_a(T,t)$ ETAF acceleration response value for period T at time t
$S_u(T,t)$ ETAF displacement response value for period T at time t
$S_{jk}(\omega)$ Frequency dependent power spectral density function between nodes j and k
S_0 Constant power spectral density function
t Time
t_1, t_2 Transition times in the modulating function
t_{tot} Total duration of the simulated ground motion
$t_{\max}$ Maximum duration of ETAFs
t_{target} Target time
T The natural period of structure
T_p Predominant period
$T_{\max}$ Maximum period in the optimization process
T_1 Structure's small-amplitude fundamental period of vibration
$T_{\min}$, $T_{\max}$ Lower and upper bounds of structural period range in ground motion scaling
$u_{\max}$ Unacceptable ultimate displacement at the index point
u_{ult} Maximum displacement at the index point
V_S Velocity of wave propagation in soil/rock
α_0 Wave reflection coefficient at the reservoir boundaries
α_{HV} Harichandran and Vanmarcke coherency model parameter equal to 0.022
α_M Mass proportional Rayleigh damping coefficient
β_0 Scaling factor of modulating function
$\beta(t)$ Modulating function
β_K Stiffness proportional Rayleigh damping coefficient
χ_0 Relative penalty in optimization function for ETAF (weight parameter)
η_1, η_2, η_3 Local coordinate system for infinite element assuming η_1 as infinite direction
χ_0 Relative penalty in optimization function (weight parameter)
δt Time step used for generation of an ETAF
$\delta(t)$ Time-dependent displacement response
ρ_c Mass density of concrete
ρ_f Mass density of foundation
ρ_w Mass density of water
υ_c Poisson's ratio of concrete
υ_f Poisson's ratio of foundation rock
$\gamma_{jk}(\omega)$ Empirical coherence model between nodes j and k
τ Any specific value inside the predefined time interval
ω Frequency
$\widehat{\omega}$ Lower bound of frequency range
ω_1, ω_2 Frequency coefficient for the low- and high-pass filter functions
ω_{HV} Harichandran and Vanmarcke coherency model parameter equal to 12.692 *rad/s*
ξ Damping ratio
ξ_1, ξ_2 Damping ratio for the low- and high-pass filter functions
$\xi_{\min}$, $\xi_{\max}$ Lower and upper bounds of the damping ratio
$\overline{\Psi}$ Linear scaling factor for the ground motion
$\Gamma_{jk}(\omega)$ Complex coherence function between nodes j and k
Δ Parameter for computing the extreme values of the effective damping ratio
Δr_{jk} Distance between the nodes j and k
$[B^{inf}]$ Strain–displacement relationship in the infinite element
$[C^F]$ Equivalent damping matrix for fluid part
$[C^S]$ Damping matrix for structural part
$[C(t)]$ Time-dependent damping matrix of the system
$[D^{inf}]$ Stress–strain relationship in the infinite element
$\{f^S\}$ Vector of body force and hydrostatic force
$\{f^F\}$ The component of the force due to acceleration at the reservoir boundaries
$[G^F]$ Equivalent mass matrix for fluid part
$[\bar{J}]$ Jacobian matrix for the infinite elements
$[K^F]$ Equivalent stiffness matrix for fluid part