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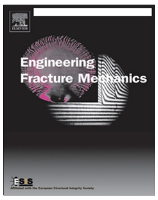

Discrete crack analysis of concrete gravity dams based on the known inertia force field of linear response analysis

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This paper presents a two-step approach for discrete crack analysis of concrete gravity dams under earthquake force. In this approach, the time-varying inertia forces in a dam are first obtained by linear response analysis. Then, for each time-step increment a discrete crack analysis of the dam is performed under the known force condition. This two-step approach transforms the seismic crack analysis of dams from dynamic analysis to static analysis, based on the intuitive conjecture that the effect of cracks on structural acceleration in gravity dams is small, thus allowing the actual inertia force (the product of mass and acceleration) to be approximately obtained by linear response analysis. This conjecture was proved, and numerical studies showed the strength of the method in tracing discrete cracking behaviours of a dam during large earthquakes. A mathematical generalisation of the solution strategy is also presented to enable the method to be applied to other nonlinear response problems that do not have exact solutions due to various mathematical difficulties in their solution processes.

1. Introduction

In Japan the building codes for dams have been upgraded in recent years in response to increasing seismic activity, and large earthquake response analyses are now routinely carried out for dams. In the case of concrete dams, the "Guideline for the Seismic Performance Evaluation of Dams against Large Earthquakes" requires a linear dynamic analysis to be carried out first. If the stress in a dam is found to exceed the material strength, a nonlinear response analysis including crack analysis is mandatory [1].

In a strict sense, crack analysis of concrete dams under earthquake force cannot be performed using the discrete crack approach by any of the known existing numerical methods. The problem can be well illustrated by solving the corresponding dynamic equation of motion using time history analysis, which has a rigorous mathematical basis and is possibly the most comprehensive analysis that can be undertaken. In time history analysis, step-by-step integration is usually performed by the finite difference method, and the solutions for the displacement, velocity and acceleration vectors at a time increment $t + \Delta t$ are also functions of the present and past solutions. To facilitate the discussion, the equation of motion for a dynamic system having n degrees of freedom at any instant of time t is:

$$[M]\{\ddot{X}_t\} + [C]\{\dot{X}_t\} + [K]\{X_t\} = \{R_t\} \tag{1}$$

where $[M]$ = mass; $[C]$ = damping; and $[K]$ = stiffness. The term $\{R_t\}$ is obtained by multiplying the ground acceleration data by the mass $[M]$. By applying the central difference formula to $\{\dot{X}\}$ and $\{\ddot{X}\}$ for time-step increment Δt, the following equations are obtained:

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Nomenclature

a acceleration
a_{max} maximum acceleration
A_F total fracture area including all the crack paths
AK crack opening displacement or crack sliding displacement due to a pair of unit cohesive forces
$AK_{nt}^{abik}, AK_{tt}^{abik}$ crack opening and sliding displacements at the ith node of crack A, due to a pair of unit shear forces at the kth node of crack B
$AK_{nn}^{bajk}, AK_{tn}^{bajk}$ crack opening and sliding displacements at the jth node of crack B, due to a pair of unit normal forces at the kth node of crack A
C damping matrix
D^{co} constitutive matrix of intact concrete between cracks
D^{cr} constitutive matrix of local cracks
D_1^{cr}, D_2^{cr} individual constitutive matrices of local cracks
$D_T(x, y, z, t)$ deformation function of $T(x, y, z)$
$D_T(x, y, z, t)|_L$ linear deformation function of $T(x, y, z)$
$D_T(x, y, z, t)|_{NL}$ nonlinear deformation function of $T(x, y, z)$
$D_T^*(x, y, z, t)|_{NL}$ approximate nonlinear deformation function of $T(x, y, z)$
E Young's modulus
$E(t)$ excitation or energy function
f_s shear strength of concrete
f_t tensile strength of concrete
f_σ tension-softening relation of concrete
f_τ shear-transfer relation of concrete
F_n^{ai}, F_t^{ai} normal and tangential components of the cohesive forces at the ith node of crack A
F_n^{bj}, F_t^{bj} normal and tangential components of the cohesive forces at the jth node of crack B
$F_T(x, y, z, t)$ force function of $T(x, y, z)$
$F_T(x, y, z, t)|_L$ linear force function of $T(x, y, z)$
$F_T(x, y, z, t)|_{NL}$ nonlinear force function of $T(x, y, z)$
G_F fracture energy of concrete
K stiffness matrix
m mass
M mass matrix; number of nodal points at a crack
n degrees of freedom
N crack transformation matrix; number of nodal points at a crack
N_1, N_2 individual crack transformation matrices
Q_n^a, Q_n^b tip forces at cracks A and B
r ratio of crack length to dam width
R_t external excitation matrix at time t
t time point
Δt time-step increment
$T(x, y, z)$, $T(x, y, z, t)$ target function
W_c^I critical crack opening displacement when normal traction vanishes
W_c^{II} critical crack opening displacement when tangential traction vanishes
W_F total fracture energy consumed for propagating all the cracks in the dam
W_F^* total fracture energy calculated from $D_T^*(x, y, z, t)|_{NL}$
W_{s1} critical crack opening displacement when shear occurs
W_{s2} crack opening displacement at the maximum shear
W_n^{ai}, W_t^{ai} crack opening and sliding displacements at the ith node of crack A
W_n^{bj}, W_t^{bj} crack opening and sliding displacements at the jth node of crack B
$W_n^{ai(0)}, W_t^{ai(0)}$ crack opening and sliding displacements at the ith node of crack A due to the inertia force and constant loads
$W_n^{bj(0)}, W_t^{bj(0)}$ crack opening and sliding displacements at the jth node of crack B due to the inertia force and constant loads
X_t displacement matrix at time t
$\dot{X}_t$ velocity matrix at time t
$\ddot{X}_t$ acceleration matrix at time t
α Rayleigh damping parameter
β Rayleigh damping parameter
γ concrete density
ε_{nn}^{cr} normal crack strain
$\Delta\varepsilon$ total crack strain increment