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OVERLAPPING LATTICE SIMULATION OF CONCRETE GRAVITY DAM COLLAPSE SCENARIOS

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Abstract. *Estimating the collapse limit state of concrete gravity dams within the framework of performance based design is challenging due to the uncertainty in modelling the response of these systems and the strong dependence of the behavior on the ground motion. The purpose of the study is to investigate the seismic expected damage levels by using the overlapping lattice modeling (OLM) approach with incremental dynamic analysis (IDA) for two representative dam monoliths. OLM employs pin connected bar elements extending over a predefined horizon to discretize the continuum similar to the concept used in peridynamics. The constitutive model of concrete was calibrated by using tension tests prior to the dam simulations. The most important advantage of the OLM approach was the ability of the simulations to capture the discrete crack propagation in a much better. Nonlinear finite element analyses by using a smeared rotating crack model for concrete were also conducted to compare the estimations of OLM. The results of IDA showed that initial cracking occurred at the dam base followed by the inclined cracking of the dam body resulting in significant damage. A strong dependence of the damage patterns on the ground motion was noted. OLM estimations of crack lengths tended to be longer and more discrete as opposed to the more diffused and shorter cracks obtained with the nonlinear finite element simulations. Results demonstrate the promising nature OLM to capture dynamic crack propagation in concrete media.*

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1 INTRODUCTION

Seismic damage and failure of dams possess important risks to the society due to the expected monetary and human loss. Concrete gravity dams are commonly built in seismically active zones. Accurate estimation of the expected damage during earthquakes is necessary both for the seismic response and for the design and assessment of these systems. There are only a few field observations on seismically damaged concrete gravity dams; Koyna, Sefid-Rud and HsingFengKiang Dams being the important examples [1, 2]. Given the scarcity of such cases, laboratory testing and computational simulations appear as the primary choices for estimating the damage and/or collapse mechanism of these systems. Some of the well-documented laboratory experiments were conducted on the scaled models of dam structures in the last two decades. However, most were focused on calibration of the material models with respect to the crack propagation [3-5]. Few shake table tests on scaled specimens were also conducted [6] in addition to a recent pseudo-dynamic testing approach [7]. However, all these tests are limited by the scaling laws, as well as the assumption of a simplified geometry and pre-defining the location of the crack. Moreover, the difficulties in the repetitions of the test significantly limit the use of these tests for understanding the collapse limit states.

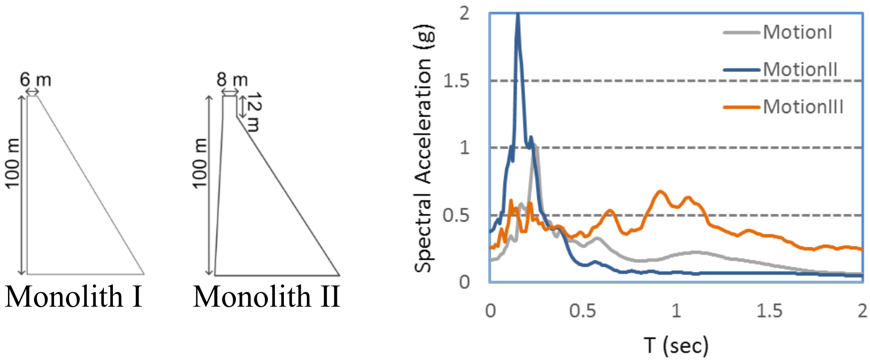
Carefully calibrated simulation techniques are commonly used for determining the performance of the concrete gravity dams both for research and design. Finite element method (FEM), with its well-established history, is one of the first choices for nonlinear dam simulations. One of the important limitations regarding the use of FEM in cracking analysis of plain concrete structures is the inability of tracing crack widths and directions. Moreover, the performance levels for these systems at the extreme scenarios require simulating the separation, rocking or sliding phenomena which is challenging to simulate in the continuum based finite element setting. The smeared crack with a rotating crack assumption [8] was widely utilized in the literature for the prediction and evaluation of the performance of monolithic concrete structures by Bhattacharjee and Leger [4], Ghaemian and Ghobarah [9], Mirzabozorg and Ghaemian [10], Çalayır and Karaton [11], Hariri-Ardebili et al. [12]. The simulation results were generally tested with the damage pattern observed in the Koyna Dam and they were found to be successful in replicating the “neck” cracking. However, crack pattern estimations for heavy damage situations, usually needed for loss estimation studies, are quite challenging.

The overlapping lattice model (OLM) is a promising alternative for studying the performance of the concrete gravity dams under dynamic loading. The overlapping lattice approach employs pin connected bar elements extending over a predefined horizon to discretize the continuum similar to the concept used in peridynamics. OLM considers cracking by employing brittle or elastic-softening force displacement models [13, 14]. Hence OLM has the potential to model crack initiation, opening and propagation naturally. Aydin [15] conducted a detailed study to obtain the constitutive model properties of bar elements by employing direct tension test results. Further validation studies were conducted in that study by using sequentially linear analysis technique. In this study, we extend that work to explicit dynamic analysis of concrete gravity dams with an emphasis on crack prediction. Incremental dynamic analyses were conducted by using three ground motions on two different dam sections in order to investigate 1) the relationship of the level of damage on the system and the ground motion levels and 2) investigate the nature of the extreme behavior of these systems which can be called the state of collapse. Comparisons of OLM and finite element results are also presented to discuss the effect of simulation tools on the estimations of crack length and pattern estimations.

2 MONOLITHS AND GROUND MOTIONS

Two different 100m tall monoliths with similar cross-section areas and different geometries (Figure 1a) were analyzed in the course of this study. The upstream face of the first monolith was assumed vertical while the downstream side had a slope of 1H/0.6V. The upstream and downstream slopes of the second monolith were 0.05V/1H and 1H/0.65V respectively, with discontinuity points at the "neck" of the structure (Figure 1a). In the simulations, the monoliths were modeled as fixed base and the hydrodynamic forces were taken into account via Westergaard's added mass formulation [16]. Tensile strength and fracture energy were taken as 1.90 MPa and 200N/m in the simulations while compressive regime was assumed to remain elastic.

The monoliths were analyzed under three different ground motions (Table 1) each scaled to five different levels. It should be noted that the vertical components of the ground motions were also applied along with the horizontal components of the motions. The acceleration response spectra of the unscaled motions are presented in Figure 1b.



(a) Dam Models (b) Acceleration Spectra of Motions

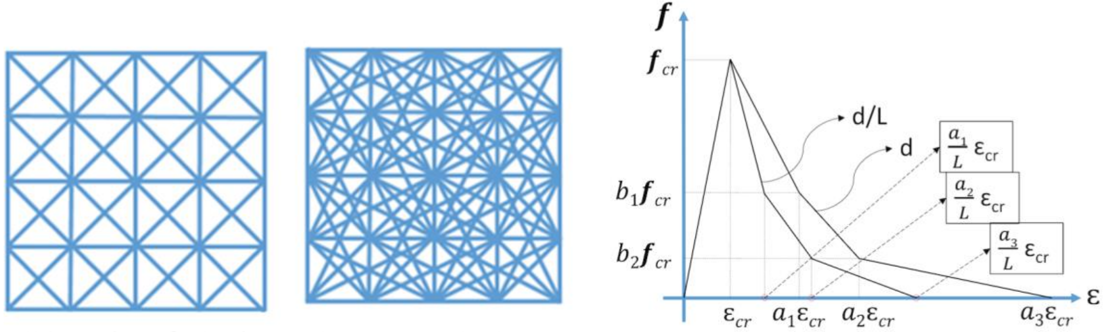
Figure 1: Dam Models and Spectra of Motions

Table 1: Selected Motions

No.	Earthquake Name	Component	Moment Mag. M_W	Distance (km)	Peak Ground Acc. (g)	Shear wave vel. V_{S30} (m/s)
1	Loma Prieta, 1989	90°	6.93	17.92	0.17	663.31
2	Chi-Chi, Taiwan-03	North	6.2	15.04	0.38	624.85
3	Chuetsu-oki, Japan	North-South	6.8	5.0	0.26	561.59

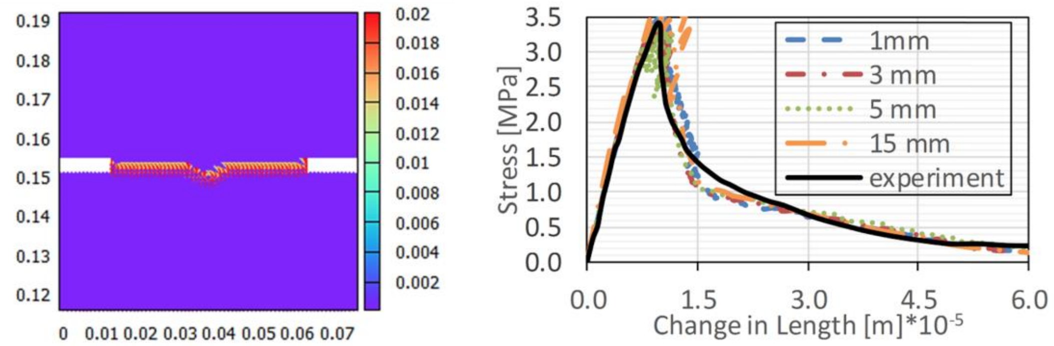
3 OVERLAPPING LATTICE MODELING

In the overlapping lattice model, each node interacts with points within a predetermined distance called horizon (δ) accounting for nonlocal effects (Figure 2a). For an initially uniformly distributed particles separated by d in x,y, and z directions, δ is commonly taken slightly more than three times d. Therefore, for two-dimensional problems, a particle located away from boundaries initially interacts with 28 neighboring points (Figure 2b). In this study, a classical structural analysis approach with explicit time integration was used [17]. The slope of the linearly elastic segment E_tA_t (elasticity modulus times cross sectional area of truss elements) was obtained using the energy balance. Introducing a deformation field, i.e. ε_x=constant, ε_y=0, the total elastic energy stored in the original problem using the actual elasticity modulus was calculated. Then, an identical deformation field was applied to the OLM and the total elastic energy was calculated by taking $E_tA_t=1$. As the stored energy is proportional to E_tA_t in the OLM, E_tA_t was obtained as the ratio of the original energy to the energy from the OLM with $E_tA_t=1$. As concrete exhibits tension softening, beyond this critical strain, the element can transfer further tension by softening as shown in Figure 1c. Nonlinear tension softening was assumed to be in the form of a stepwise linear softening function as shown in Figure 2c. Force-deformation curves for direct tension tests for a specific gauge length were employed to calibrate the input force-deformation response of the truss elements [15]. For elements with different sizes, the length scale was then used to adjust the input force-deformation function similar to the approach used in the mesh regularization in finite element simulations [18] as shown in Figure 2c. The results from the calibrated tension softening models are compared to the stress-deformation response from the tests by Gopalaratnam and Shah [19] in Figure 3, along with the obtained crack pattern from the simulations. A close agreement can be observed between the OLM and test results independent from the mesh size.



(a) Horizon δ=1.5d (b) Horizon δ=3.01d (c) Assumed material behavior stress-strain diagram (b_1=0.6, b_2=0.2)

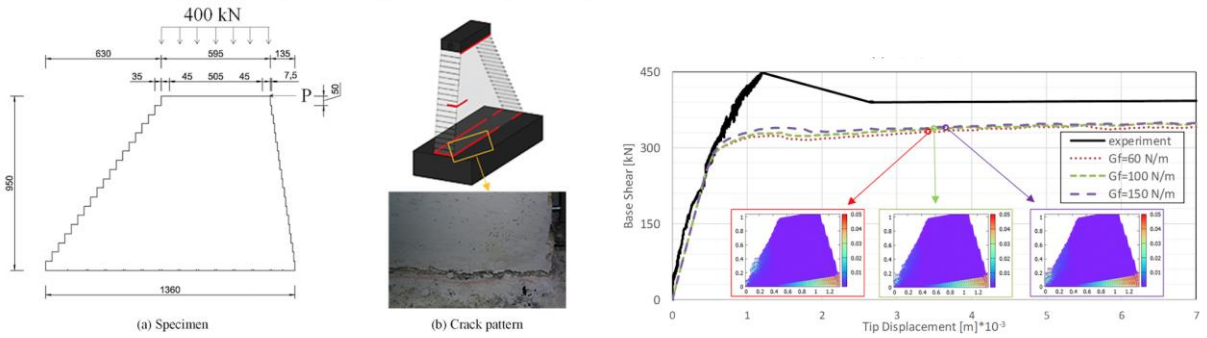
Figure 2: OLM and Constitutive Model in tension



(a) Crack Pattern (b) Comparsion with tests

(b) Figure 3: Direct tension test calibration of OLM

By using the calibrated force-deformation response for truss elements, a dam test was simulated to validate the OLM. A 1/75 scaled model of the 120-m-high Melen Dam (Fig. 4a) was tested using three different scaled ground motions by using the pseudo-dynamic testing technique [7]. The original setup enabled the use of only the bottom half of the dam section and the inertial and hydrodynamic load effects were simulated using a lateral hydraulic piston. The overlapping lattice model was constructed by using 25 mm grid size to observe performance estimation for a continuum unreinforced concrete structure. As information regarding the fracture energy value of the specimen was not reported, G_f values of 0.06 kN/m, 0.1 kN/m and 0.15 kN/m were employed to investigate response predictions over a wide range of G_f. The E_t, f_{cr}, and thickness values were taken as 10.5 GPa, 2.9 MPa and 200 mm, respectively, as reported in the test. After the application of a vertical load of 400 kN and corresponding to the initial stress conditions, the specimen was loaded from the upstream gradually (Fig. 10(a)). For all G_f values OLM results for *3.01d* horizon size were compared with the consecutive PsD and pushover test results in Fig. 4. It can be observed that the initial stiffness estimation of the specimen was perfect whereas the estimation of lateral load capacity was off by about 20%. The deformability of the specimen was predicted in a reasonable manner with some reduction in load carrying capacity around 1.5 mm. The crack patterns are shown in the same figure around 3.5 mm tip displacement. The crack pattern observed from the test seemed to agree well with the base cracking shown in Fig. 4. It is interesting to note that the variation of fracture energy or increasing the horizon seemed to affect the response in a limited manner.



(a) Specimen (b) Crack pattern

(a) **Figure 4: Validation of OLM with a dam test**

4 DYNAMIC ANALYSIS RESULTS

An explicit dynamic analysis program was prepared for dynamic dam simulation using OLM. Newmark explicit integration scheme was used with Rayleigh damping (α=1 and β= 0.0001, mass and stiffness proportional damping parameters). A time step of 4e-5 was used in the analyses. The tensile stress-strain behavior used in the static validation studies (Figure 2c) was modified with an origin oriented hysteresis model.

Estimated crack patterns are presented in Figure 5 at five different scales for Motion II for brevity. Base cracking was observed in all the simulations followed by body cracking. Locations and lengths of body cracks were observed to depend both on the motion type and motion scale factors. It can be observed that for Monolith 1 cracks occurring in the upstream and downstream sides tended to join within the top 1/3 portion of the dam height upon increasing the ground motion intensity beyond a spectral acceleration of 0.4g. Conversely, a section through crack could be observed for all ground motion intensities for Monolith 1. Despite severe cracking on the dam body, OLM simulations did not estimate any block separation or partial collapse. Results demonstrate that concrete gravity dams are extremely prone to body cracking under strong ground motions, but they are unlikely to exhibit partial collapse despite significant leakage potential that may require significant repairs.

Maximum crest displacements, accelerations and base shear forces obtained from OLM simulations are presented in Figure 6. Crest displacements tended to increase in a nearly linear manner with increasing motion scales, while the crest accelerations increased in an exponential manner when motions were linearly scaled. Crest accelerations and base shear forces tended to exhibit significant motion dependency, with Motion III producing the highest demands. It can be observed that crest accelerations and base shear force demands tended to be similar for Monoliths 1 and 2 for spectral acceleration values smaller than about 0.3g. For spectral acceleration values larger than 0.3g, the seismic demands on the two monoliths were significantly different. This results demonstrate the importance of dam section geometry on the seismic demands.

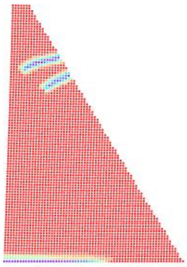
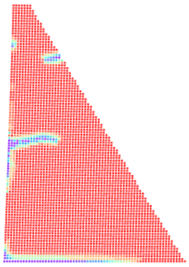
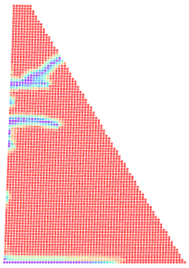
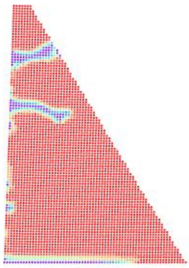
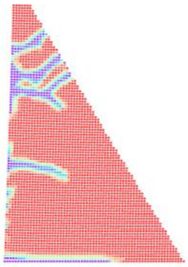
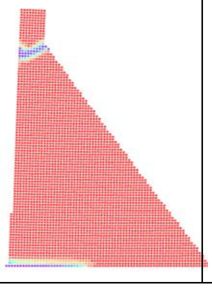
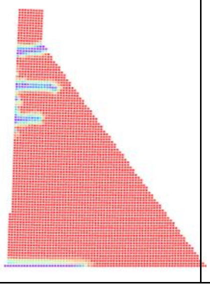
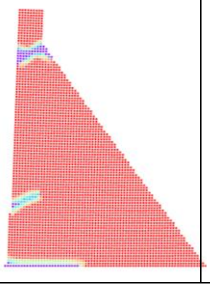
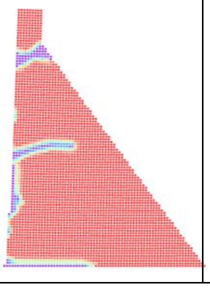
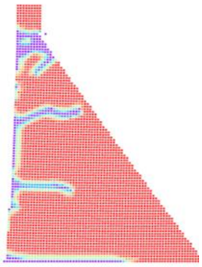
S_a/PGA	**0.16g/0.15g**	**0.24g/0.23g**	**0.32g/0.30g**	**0.40g/0.38g**	**0.48g/0.46g**
Monolith I					
Monolith II					

Figure 5: Earthquake Induced Damage Estimations

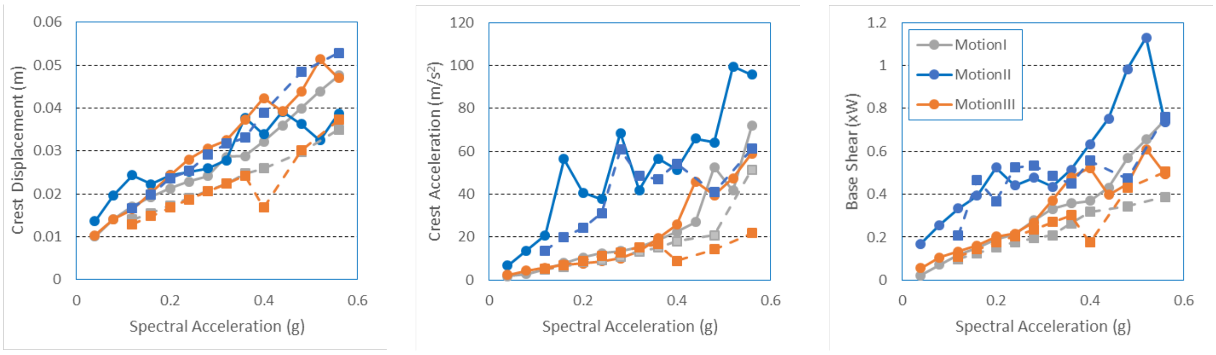


Figure 6: Seismic Demand Parameters in IDA

5 OLM VERSUS FINITE ELMENT SIMULATIONS

The results of OLM simulations were compared with the results obtained from the nonlinear finite element simulations conducted by using DIANA [20]. The material model employed in FEM simulations followed the rules described by Selby and Vecchio [21]. The behavior of concrete was described by elastic isotropic stress-strain relationship prior to cracking. Upon cracking, the material was treated as orthotropic [8]. The tensile and compressive strengths and the shape of the post-peak response were the key characteristics of the stress-strain models. Mesh dependence of the model was addressed by using the fracture energy (G_f), which was taken as the area under the stress-strain response multiplied by an equivalent size of the finite element (h) similar to the treatment in OLM. Secant unloading was applied in cyclic loading. The description and the validation of the finite element model was previously presented by Soysal et al. [22] in detail.

The crack patterns obtained from finite element simulations are presented in Figure 7. It can be observed that cracks obtained from finite element results are much more dispersed compared to OLM results with shorter and fewer cracks. OLM appears to do a better job in obtaining discrete crack patterns that are closer to reality. The time history comparison of lattice model and finite element model for the crest displacement, crest acceleration and base shear for model I, motion II is given in Figure 7. It can be observed that except for the crest acceleration, the difference between the time histories for the lattice and finite element models were minimal. Furthermore, there was approximately 6% difference between the maxima values of the acceleration and base shear quantities and the two methods differ from each other by about 15% for the maximum crest displacement. These results show that global demand parameters can be obtained with similar order of magnitudes for FEM and OLM. However, crack location, length and density estimations were quite different between finite element and OLM simulations.

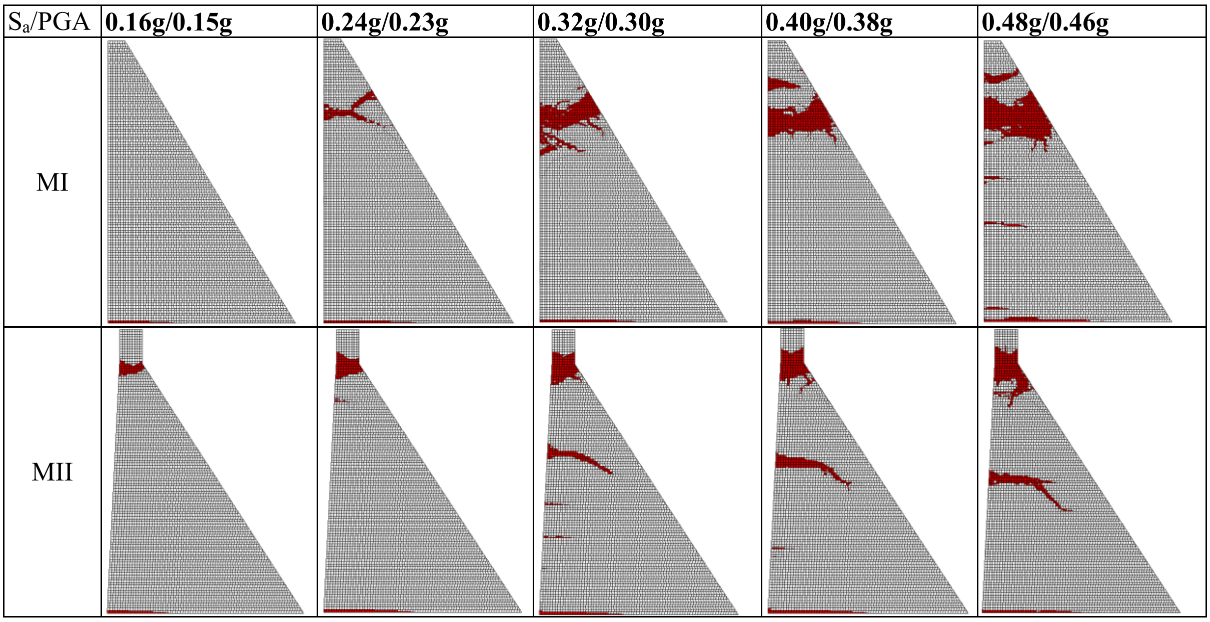


Figure 7: Earthquake Induced Damage on Model II, Varying Scales

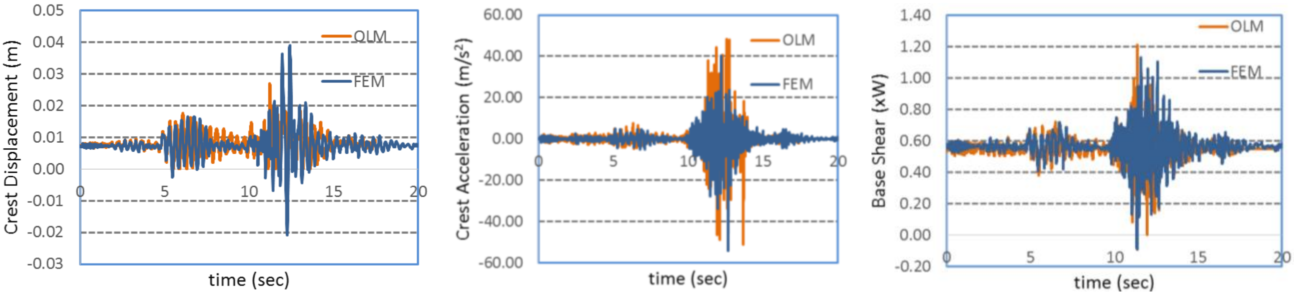


Figure 8: Earthquake Induced Damage on Model II, Varying Scales

6 SUMMARY AND CONCLUSIONS

Overlapping Lattice Model proposed by the authors was applied in the nonlinear dynamic simulation of concrete gravity dams for the first time in the literature. A strong dependency on the motion and section type was observed for the crack patterns, lengths and widths. Results demonstrated that concrete gravity dams are extremely prone to body cracking under strong ground motions, but they are unlikely to exhibit partial collapse, although significant leakage and repair costs are expected. The comparison of OLM and FEM showed that global demand parameters can be obtained with similar order of magnitudes by using either simulation technique. However, the crack location, length and density estimations were quite different between the finite element and OLM simulations. OLM appeared to perform better in obtaining discrete crack patterns closer to reality as opposed to the extremely diffused cracking found with the FEM approach.

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