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THREE DIMENSIONAL EXTENDED DISTINCT ELEMENT METHOD APPLIED TO BRIDGE COLLAPSE ANALYSIS

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ABSTRACT

We studied the failure process of a reinforced concrete bridge located at the intersection of West State Route 14 and the South Interstate 5 connector, Los Angeles, USA. This bridge collapsed with the January 17, 1994, Northridge Earthquake, Los Angeles, USA. We studied the properties of the bridge and the response to the earthquake load using a Finite Element Analysis. Then, the Three Dimensional Extended Distinct Element Method (3D-EDEM) was used to simulate the complete bridge collapse. We present here the result of the simulation as well as our comments on the advantage and limitations of the present 3D-EDEM simulation technique.

KEYWORDS

DEM; EDEM; Distinct Element Method; Three Dimensional; Simulation; Bridge Damage; Northridge Earthquake.

INTRODUCTION

An earthquake with 6.8 magnitude struck Los Angeles area in the Northridge region on January 17, 1994. The damage after this event was widespread and mainly affected highway bridges. The reports indicated that nine bridge structures collapsed. In addition to them, the earthquake affected houses, buildings, parking buildings, etc.

Our interest was concentrated in the collapse of the Reinforced Concrete Bridge located in the intersection of the West State Route14 and the South Interstate Connector -5. This bridge is a ten-span structure. The failure of this structure was spectacular, with complete collapse of one of the pier and the punching through the slab of the other pier.

We performed a FEM analysis to obtain the general vibration properties and the time history response of the bridge structural elements under the earthquake loads.

The 3D-EDEM analysis was used to visualize the complete failure process of the bridge. The 3D-EDEM is a 3 dimensional version of the so called Extended Discrete Element Method which uses the equation of motion of independent elements to follow the displacement history during the dynamic load (Mori, 1992).

BRIDGE CONSTRUCTION DETAILS AND DAMAGE.

The bridge is located at the intersection of the West SR-14 and the South I-5 (Fig. 1). It is a 10 span Reinforced Concrete structure. It is divided into 5 frames by movable joints. The collapsed section is the frame at one end. This frame consist of one abutment and 2 piers. There is a hinge located between pier 3 and pier 4 (Fig. 2).

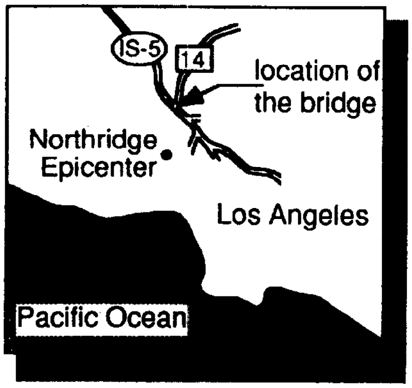

Fig. 1. Location of the Bridge.

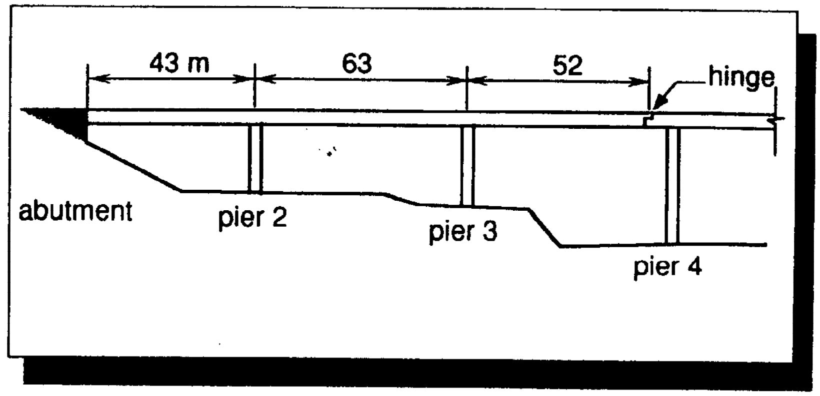

Fig. 2. Bridge South-end elevation.

The superstructure consist of a five cell box (16.8m x 2.15 m). It is a prestressed section. The cross section of the pier 2 and pier 3 are rectangular ones. The vertical reinforcement for both columns consist of 40 #18 bars and the horizontal reinforcement is #4 @30 cm. The height of the columns varies. Pier 2 and pier 3 height are 9.00 m and 12.25 m respectively.

The spans between the abutment and the hinge collapsed and pier 2 was completely crushed. The span between the abutment and hinge was simply supported at the seat abutment and the hinge at the other end. The hinge and the abutment seats were both 35 cm width and hinge restrains had been installed at the hinge. The reports from the field observation said that the motion was primarily in the longitudinal direction of the bridge at abutment. The pier 3 remains standing and the slab fails punching through pier 3.

COLLAPSE MECHANISM ANALYSIS WITH FEM

We performed a dynamic non-linear analysis using Finite Element Method. We used two models: model one with the hinge fixed and model 2 with free horizontal translation hinge (Fig. 3). We applied the recorded accelerogram at CSMIP Sta. 24379 which is located at Newhall Fire Station (Darrag, *et al.*, 1994). We consider that this record could be similar to the site of the bridge. The central frequency of the ground motion is about 3 Hz. and the peak accelerations are more than 0.5 g for the 3 components. We applied the horizontal and vertical components. We used beam elements to model the bridge.

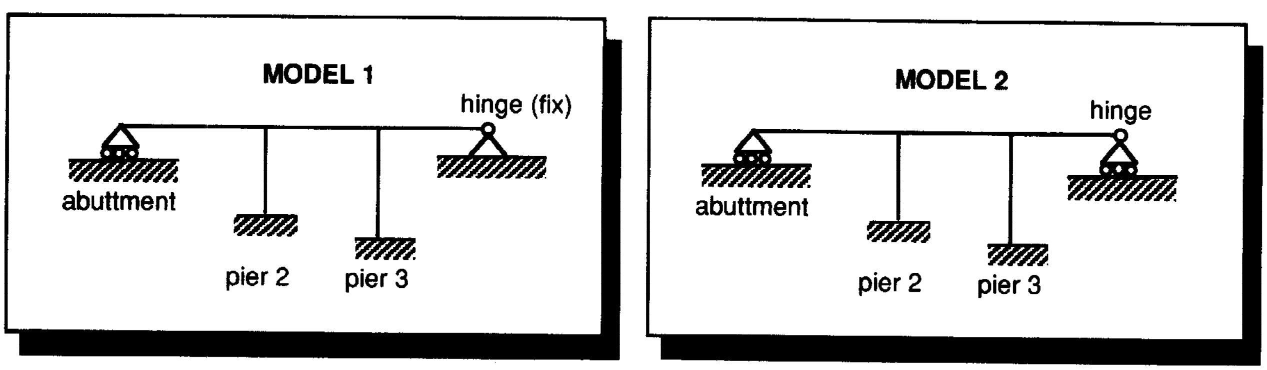

Fig. 3 FEM bridge model 1 and 2

We computed the axial resistance of the restrains at the hinge location. The axial resistance was 1,382 tons. According to the analysis the horizontal tensional force exceed this value (2750 ton). This suggest that the restrains at the hinge fails and the bridge behaves as in the model 2.

The shear force at pier 2 and pier 3 is presented in Fig. 4 for model 2 where the hinge has free horizontal displacement. We can see that pier 2 was subjected to a big shear force (3,110 ton) which exceeded the shear strength computed as 830 ton. This suggest that pier 2 fails first and the pier 3 remains standing.

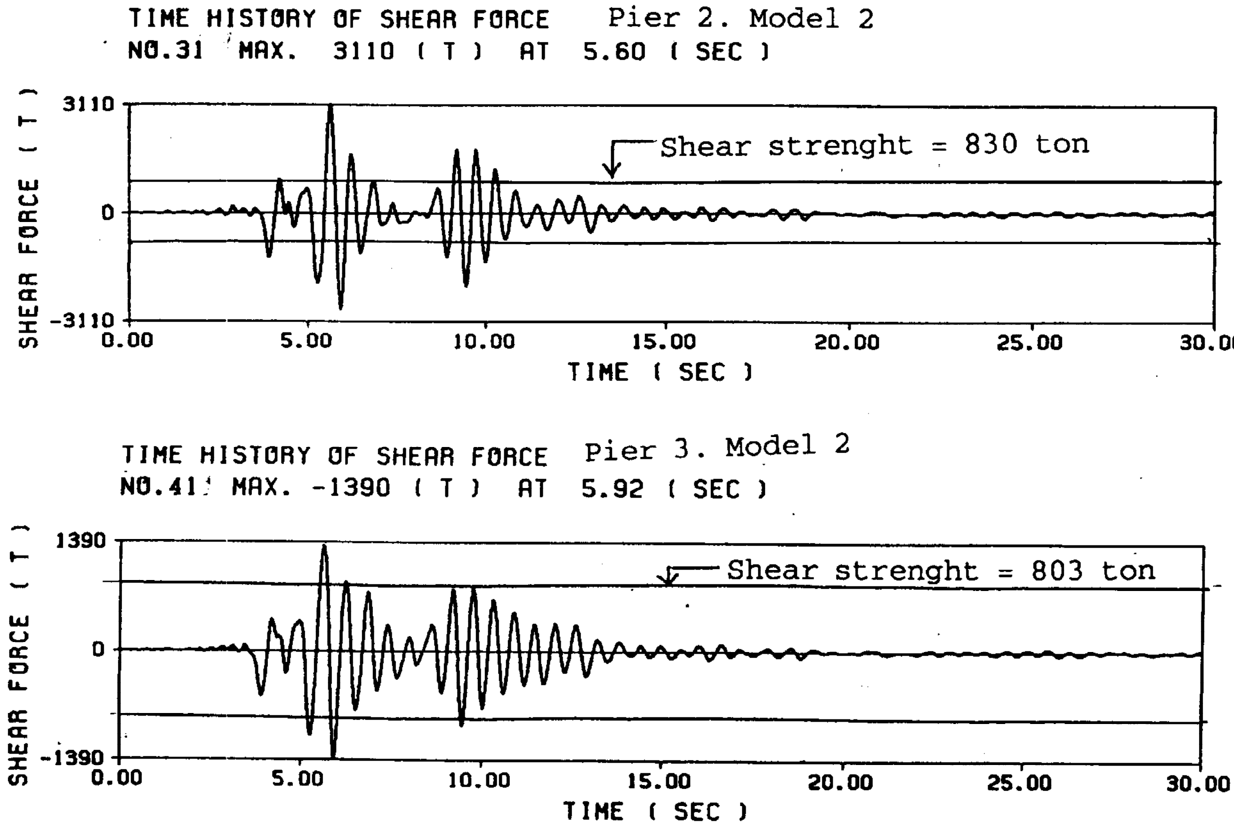

Fig. 4. Time history of Shear Force at pier 2 and pier 3. FEM Model 2.

3D-EDEM THEORY AND MODELING

The Extended Distinct Element Method (EDEM) is a numerical method applicable both to homogeneous and perfect discrete media and to complex, heterogeneous and continuous media. One particular point of the EDEM is that as the pore-springs are destroyed, the structural skeleton of the modeled media changes gradually from elastic to plastic and finally to discontinuous media so that nonlinear phenomena can be simulated.

The equations of three-dimensional motion of an element i, having the mass m_i and moment of inertia I_{xi}, I_{yi}, and I_{zi} are given by:

$$m_i\ddot{x}_i + F_{xi} = 0 \quad (1a)$$
$$m_i\ddot{y}_i + F_{yi} = 0 \quad (1b)$$
$$m_i\ddot{z}_i + F_{zi} = 0 \quad (1c)$$

$$I_{xi}\ddot{\phi}_{xi} + M_{xi} = 0 \quad (1d)$$
$$I_{yi}\ddot{\phi}_{yi} + M_{yi} = 0 \quad (1e)$$
$$I_{zi}\ddot{\phi}_{zi} + M_{zi} = 0 \quad (1f)$$

where x_i, y_i, z_i, and φ_{xi} , ϕ_{yi} ϕ_{zi} are the displacement in x, y and z-direction, and the rotational displacement around x, y and z-axis, respectively.. F_{xi}, F_{yi}, F_{zi} and M_{xi} M_{yi} M_{zi} denote the sum of all the forces in x-y and z-direction, and the sum of all the moment around x, y and z-axis, respectively.

As shown in Fig. 5, EDEM use two springs and two viscous dashpots to simulate the behavior of the reinforced concrete material. One of the springs take into account the impact forces between elements. This spring is used in traditional DEM (Cundall, 1971). However, in EDEM we introduced an additional spring (named pore spring) and damping to take into account the continuos behavior of the material at the beginning of the simulation (Hakuno and Tarumi, 1988). Therefore, the EDEM model behaves as a continuous body while the pore springs are not broken, but once the springs exceed the breakdown criterion set up beforehand, the model gradually loses continuity and behaves as a discontinuous body.

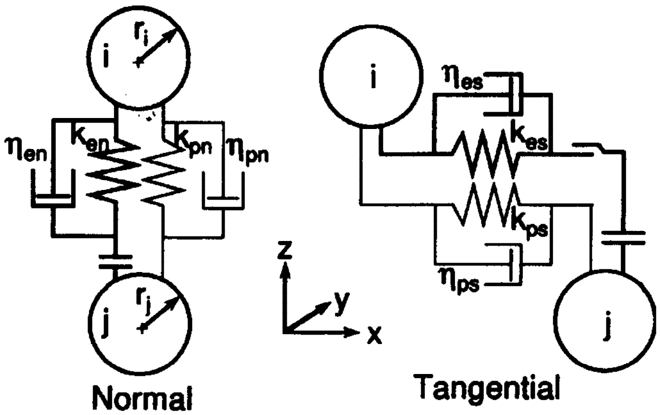

Fig. 5 3D-EDEM model for spring and dashpot

By analyzing the forces and moments acting on both element and pore springs, the resultant forces and moments acting on each element at time t can be given by

$$[F_x]_t = [F_{ex}]_t + [F_{px}]_t \quad (2a)$$
$$[F_y]_t = [F_{ey}]_t + [F_{py}]_t \quad (2b)$$
$$[F_z]_t = [F_{ez}]_t + [F_{pz}]_t \quad (2c)$$
$$[M_x]_t = [M_{ex}]_t + [M_{px}]_t \quad (2d)$$
$$[M_y]_t = [M_{ey}]_t + [M_{py}]_t \quad (2e)$$
$$[M_z]_t = [M_{ez}]_t + [M_{pz}]_t \quad (2f)$$

where $[F_{ex}]_t$, $[F_{ey}]_t$, $[F_{ez}]_t$ and $[M_{ex}]_t$, $[M_{ey}]_t$,$[M_{ex}]_t$ denote the resultant forces and moment acting on the element spring in x-, z-direction and around y-axis, respectively. $[F_{px}]_t$, $[F_{py}]_t$, $F_{pz}]_t$ and $[M_{px}]_t$, $[M_{py}]_t$, and $[M_{pz}]_t$ are the resultant forces and moment on the pore spring.

When the coordinates of element i and j with radius of r_i and r_j are assumed to be (x_{i0},y_{i0},z_{i0}) and (x_{j0},y_{j0},z_{j0}) at time zero, the critical equation for pore spring establishment is given by

$$(r_i + r_j) \cdot \alpha > [R_{ij}]_0 \quad (3)$$

where

$$[R_{ij}]_0 = \sqrt{(x_{i0} - x_{j0})^2 + (y_{i0} - y_{j0})^2 + (z_{i0} - z_{j0})^2} \quad (4)$$

and α is the critical value for the setting-up of pore spring.

When the pore spring is fractured not only by tensile force in the normal direction but also by shear force in the tangential direction, the fracture process of the pore spring will be promoted from the normal state to the failure state. When elongation of the pore spring at time t exceeds a specific ratio to its natural length, the pore spring is broken down.

$$[R_{ij}]_t > \beta \cdot [R_{ij}]_0 \quad (5)$$

where β is the critical strain by tensile force, $[R_{ij}]_t$ is the distance between two centers of elements i and j at time t, and $[R_{ij}]_0$ is the initial distance between two elements. Although this criterion shows that the pore material is broken down by tensile strain in the normal direction, the pore spring in both the normal direction and the tangential direction is assumed to be fractured.

Coulomb's equation is used as the criterion for the breakdown of the pore spring in the shear direction.

$$\tau_c = C + \mu F_n \quad (6)$$

where τ_c is the maximum resistance shear force between particles in the tangential direction, C is the cohesive constant force, μ is the friction coefficient and F_n is the normal force between particles i and j. When the force acting tangential on the pore spring is larger than τ_c, the state of the pore spring in both the normal and tangential directions is assumed to be changed to the failure state.

ESTIMATION OF MATERIAL PARAMETERS

Although the material parameters of the EDEM analysis should be determined experimentally, it is difficult to do so. Therefore we follow the simple method by Meguro and Hakuno (1989) taking the physical significance of each parameter into account. The elastic propagation velocities of the P and S waves are obtained by use of elastic modulus E, Poisson's ratio ν and the material mass density γ.

$$V_p = \sqrt{\frac{E(1-\nu)}{\gamma(1+\nu)(1-2\nu)}} \tag{7a}$$

$$V_s = \sqrt{\frac{E}{2\gamma(1+\nu)}} \tag{7b}$$

The mass m_i is given by the element density ρ. We assume that the elastic constant of the normal spring K_N is estimated by P wave velocity V_p and that of the shear spring K_S is estimated by S wave velocity V_s as follows:

$$K_N = \frac{\pi}{4}\rho V_p^2 \tag{8a}$$

$$K_S = \frac{\pi}{4}\rho V_s^2 \tag{8b}$$

where K_N and K_S are the composite elastic spring constant of the element spring and the pore spring in the normal direction and shear direction, respectively. Hence, these composite constants are given by

$$K_N = k_{en} + k_{pn} \tag{9a}$$

$$K_S = k_{es} + k_{ps} \tag{9b}$$

Considering the reduction factors from the element spring to the pore spring s_n and s_s in the normal and shear direction, respectively, every elastic spring constants in both directions can be calculated.

$$k_{pn} = s_n \cdot k_{en} \tag{10a}$$

$$k_{ps} = s_s \cdot k_{es} \tag{10b}$$

The EDEM is based on numerical integration. The stability of the analysis depends on the value of the time increment Δt. The forces that act on each element are calculated taking into account all the contacting elements and the pore material surrounding an element. The reaction forces can not be estimated well if the stress wave goes over the contacting element during the time increment Δt. Therefore, a determination of Δt is given by

$$\Delta t < \frac{D_{min}}{V} \tag{11}$$

where V is the elastic wave propagation velocity and D_{min} is the minimum distance between two elements.

BRIDGE 3D-EDEM MODEL AND FORCES

The model of the bridge consists of 5578 spherical elements with radius of 0.5 m. We modeled the abutment and the hinge-pier 4 part as fixed elements. Pier 2 and 3 rest on the base fixed elements. We obtained the model parameters as explained above. The time step used was 1×10^{-5} sec. We can see the model in Fig. 6

As dynamic forces, we applied a sinusoidal acceleration in x, y and z directions with a frequency of 3 Hz plus the effect of the vertical gravity g. This frequency was selected to be similar to the observed record near to the location of the bridge (Delgado *et al.*, 1994).

COLLAPSE SIMULATION WITH 3D-EDEM

We performed a 3D-EDEM simulation after the previous FEM analysis of the bridge. Our opinion for the collapse process is as follows:

1) The FEM analysis indicate that the tensional force in the hinge connectors exceed the tensional capacity of them so that the connectors failure occurred.

2) The longitudinal displacement and the longitudinal horizontal forces generated the loss of axial capacity of the pier 2 and it's complete collapse.

3) The bridge was transformed in a large span from the abutment to the pier #3. This generated a big positive flexural moment at the connection with bent 3 and generate the failure of this connection.

4) Finally the pier punched through the slab which came down and rested on the ground.

The general process of the failure was simulated using the 3D-EDEM. We presented the results in Fig. 7. Some of the parameters have big influence in the overall simulation. The value of β control the performance of the model. If we use a small value the model behaves as a rigid body but if we use a big value the model is considered as a flexible one.

There are several limitations with the present version of 3D-EDEM which is a numerical method under development. Each trial requested a big ammount of CPU time. A Super-Computer machine or parallel computer is required to optimize the usefulness of the present method. To select the model parameters (especially β and the cohesion) is difficult. We performed the presented simulation after a series of trial and error which were time consuming. We used a HP engineering workstation and the total running time for each simulation was several days. We used a comercial Scientific Software (called AVS) to visualize the results. This software has the capability to show the total simulation in real time.

The result presented in this paper shows one of the possibilities of the collapse of the bridge. (See Fig. 7). We can see also the representation of the failure of the pore spring at the joint between pier 3 and the slab.

CONCLUSIONS

We presented here the 3D-EDEM simulation of the reinforced concrete bridge which collapsed after the Northridge earthquake. The results showed that the present version of the 3D-EDEM should be improved. It is necessary to use this method in parallel computers or faster machines. The simulation of 3D reinforced concrete structures could be realized only after several trial and error runs. The present level of Scientific Visualization software provided all the necessary power to visualize the dynamic simulation in real time.

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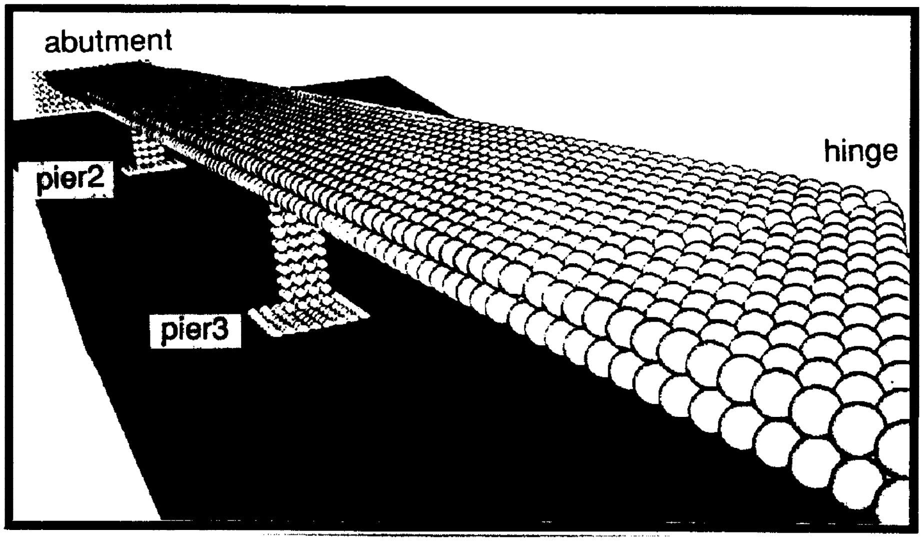

Fig. 6(a) 3D-EDEM model at initial state.

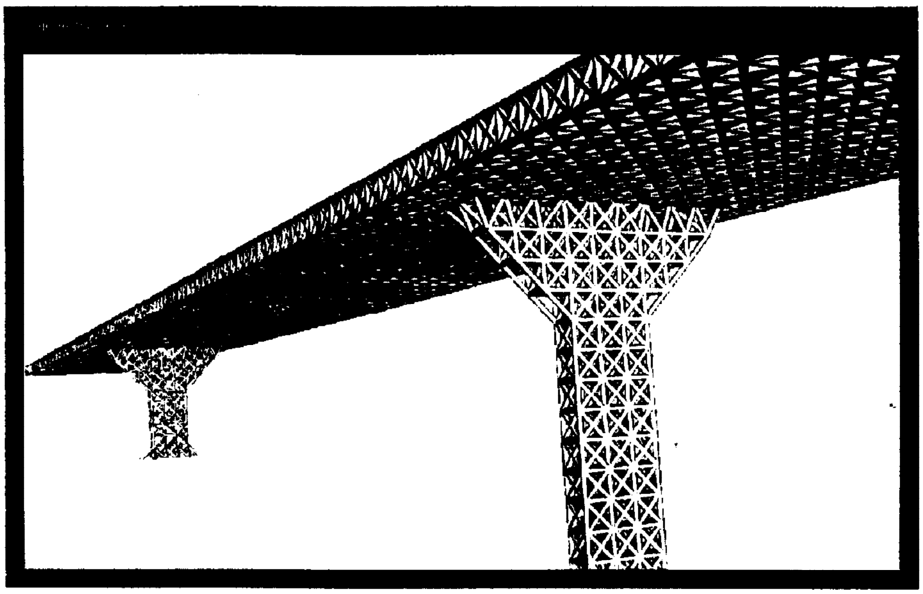
Fig. 6(b) 3d-EDEM pore spring distribution at initail state.

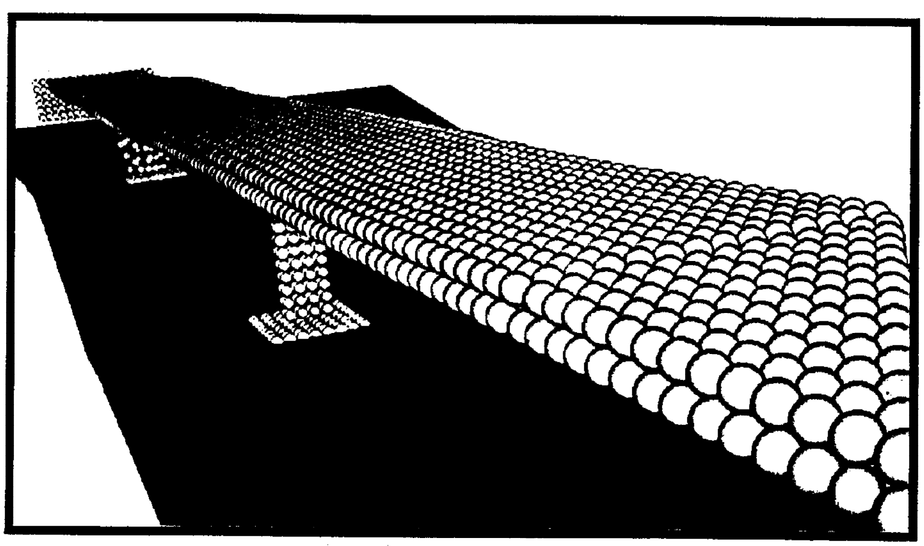
Fig. 7(a) Collapse of the pier 2.

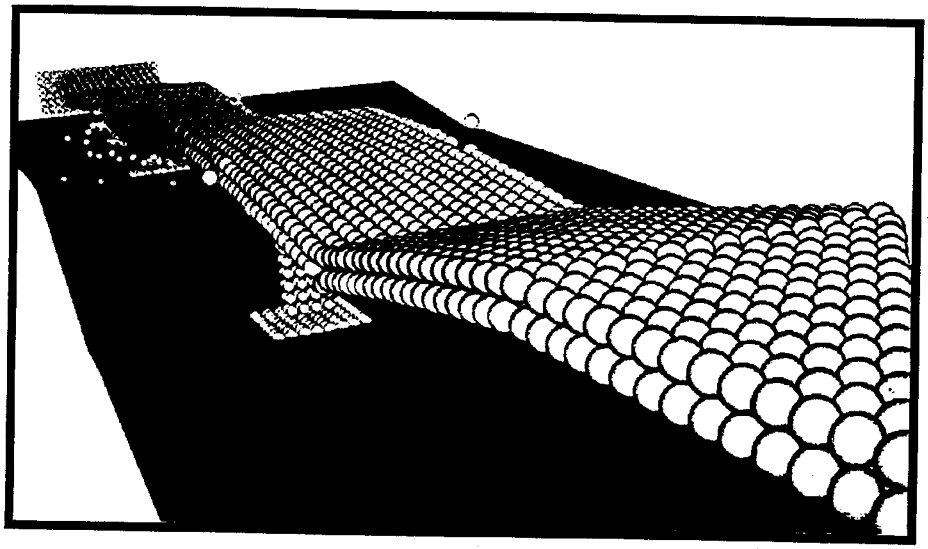

Fig 7(b) Collapse of the bridge and the slab is falling.

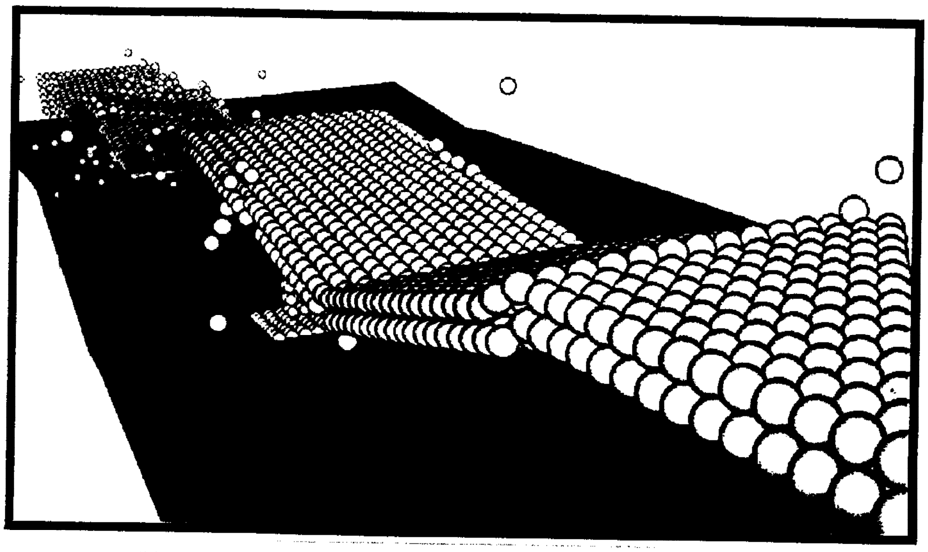

Fig. 7(c) Final stage of the failure of the bridge.

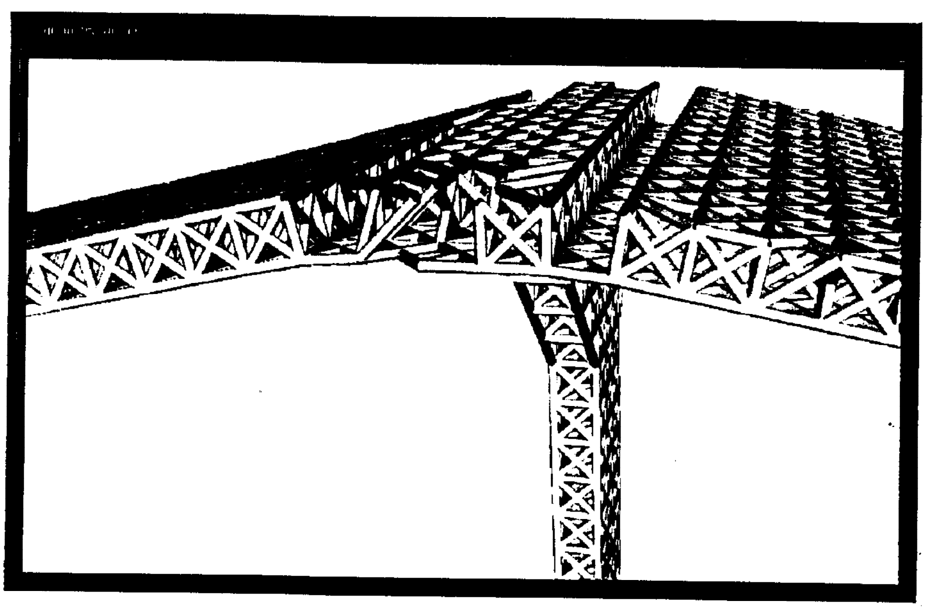

Fig. 7(d) The slab fails by negative moment at pier 3 and started the punching. (Por Spring representation)