I－B 438

Session 1

Nonlinear Analysis on the Collapse of Daikai Station Subway Tunnel during the Hyogo-ken Nambu Earthquake of January 17th 1995

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1. Purpose of this research

The tunnel at Daikai Station of Kobe City Municipal Subway had collapsed as a result of the Hyogo-ken Nambu Earthquake of January 17th, 1995. A two-dimensional finite element computer program is developed in order to investigate the behavior of this tunnel during the earthquake. The program utilizes a new finite element reinforced concrete inelastic model which could take account of concrete cracking, concrete and/or reinforcing steel yielding, concrete crushing, reinforcing steel failure, and shear failure in concrete and in shear reinforcement. Other features such as soil plasticity, soil-structure interaction, dead load, dynamic earth pressure, and large displacement analysis are also considered in the program.

2. Analytical model of the tunnel

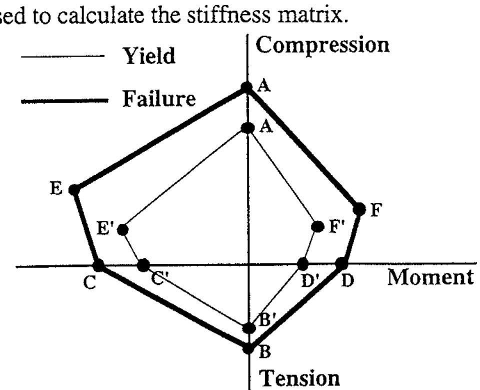
A new inelastic stiffness matrix for straight reinforced concrete elements is derived based on the "Plastic Hinge Idealization" and the "Basic Principles of Reinforced Concrete Structures". The material non-linearity is simplified to a bilinear model with strain-hardening. The criteria (based on the Japanese Standard Specification[1]) for various critical states of stress (strain) are as follows:

(1) Concrete cracking

Two types of cracks are assumed. An elastic crack, which will close if the bending moment is reversed (if yielding does not occur), and a plastic crack developed by yielding (unless compression yielding occurs). If a crack occurs, the area and inertia of the virtual section is used to calculate the stiffness matrix.

(2) Yield and failure interaction surfaces

Yielding may take place in concrete if a 0.002 strain is reached, or in steel bars if the yield stress is reached. A balanced yielding occur if both concrete and steel bars yield at the same instant. An interaction surface is constructed for each section as shown in Fig.1. If a plastic hinge is formed, the stiffness matrix coefficients shall be modified. The failure interaction surface shown in Fig.1 is constructed based on an ultimate concrete strain of 0.0035[1], an ultimate concrete stress of 0.85 the maximum[1] distributed over a distance of 0.80 the neutral axis depth[1]. Once concrete failed in one section, its area and inertia are modified to be the area of steel reinforcement.



A,A': Pure Compression Yielding and Failure
B,B': Pure Tension Yielding and Failure
C,C': Pure Bending Yielding and Failure
D,D': Pure Bending Yielding and Failure
E,E': Balanced Yielding and Failure
F,F': Balanced Yielding and Failure

Fig.1 Yield and failure of concrete material interaction surfaces

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(3) Concrete failure by shear

Shear failure in a member occur by yielding and then failure of shear reinforcement as a tension chord of the truss type mechanism, or by the compressive failure of web concrete as a compression chord of the truss.

(4) Reinforcement failure

Failure of reinforcement at one section will only take place after concrete failure of that section, either by tension if the strain reaches its ultimate value of 0.35, or by buckling if the critical buckling load is attained.

(5) Element stiffness matrix

During the seismic analysis, the two ends of an element may not have the same area and inertia, because of cracking. Assuming a linear change of area and inertia between the two ends, the integral expressions of the elastic stiffness matrix of such element are solved using the computer program *Mathematica*. The inelastic stiffness matrix including the geometric nonlinearity is then derived from the elastic one.

3. Numerical results

The tunnel is analyzed under the accelerograms recorded at Kobe Ocean Meteorological Observatory. The preliminary results show that the response increases rapidly after 3.86sec and the tunnel collapsed mainly due to flexural and shear failure of many sections of the middle column starting 4.06sec, as well as yielding in reinforcement and concrete crushing in some sections. Time history of the horizontal displacement on ground surface is shown in Fig.2. The failure shape of the tunnel at the end of the analysis as well as that of site investigation are shown in Fig.3, which are in good agreement. However, minor refinements and modifications in the computer program are still under consideration. Moreover, it was observed that the increments of the obtained acceleration and velocity vectors at a time step increment is not so small after 4.0sec, because the inelastic behavior of the tunnel was so severe. Therefore, it is more appropriate to decrease the time step increment for more accurate results.

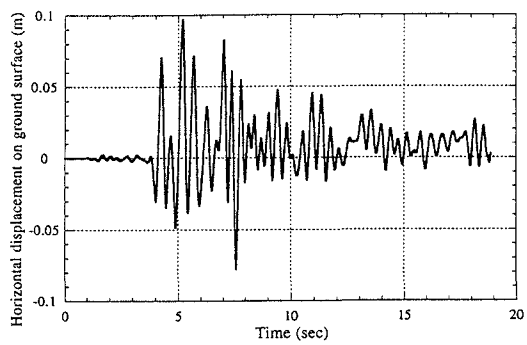

Fig.2 Horizontal displacement on ground surface

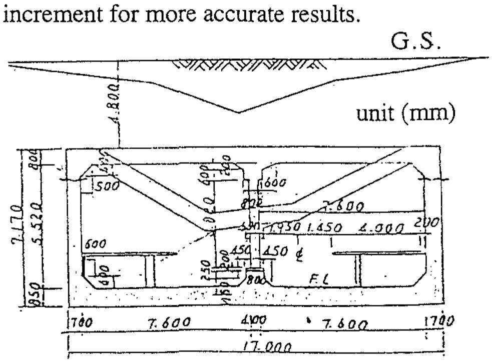

Fig.3a Tunnel failure shape

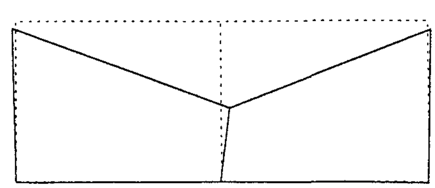

Fig.3b Tunnel deformation by analytical results

Reference

1. Standard Specification for Design and Construction of Concrete Structures, Part I (Design), 1986.