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SC-R2

State-of-the Art Report
SEISMIC UPLIFT AND SLIDING OF STRUCTURES FROM SUPPORTING GROUND

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SUMMARY

The state-of-the-art for the nonlinear analysis of soil-structure interaction is presented. Analytical research in this field falls into three types of procedures; the Finite Element Method, Lumped Mass System, and Distinct Element Method. Outlines of present research and the future prospects for each procedure type are given.

INTRODUCTION

The results of research done on soil-structure interaction over the past twenty years have been mainly linear and are now being assimilated into aseismic design codes. From results of studies of damage done by past earthquakes, researcher's interest has been drawn to the nonlinear interaction of soils and structures.

Examples of nonlinear phenomena are the uplifting and pulling out of buildings' foundation piles by earthquakes, the separation of the pile surface from its surrounding soil because of the horizontal earthquake force, and early liquefaction of the soil that supports underground structures such as foundations. Nonlinear interaction of soils and structures has been studied for the past decade. The methods used in these nonlinear studies can be divided broadly into three analytical techniques and an experimental technique. The former three; the FEM (Finite Element Method), Lumped Mass System and DEM (Distinct Element Method) group are shown in Figure 1. The last of these, (DEM), has been used in Earthquake Engineering for only five years and most of the researchers in this field are concentrated in Japan. For this reason, I will talk about the

A. Finite Element Method

- o Nonlinear Treatment
  - Joint Element (Dr. Toki). etc
- o Transmitting Boundary in the time domain
  - BEM (Dr. Wolf)
  - Superimposing. etc.

B. Lumped Mass System

C. Granular Assembly Simulation

- o Distinct Element Method

Fig.1 Analytical methods of Nonlinear Soil-Structure Interaction

DEM in greater detail than the other methods.

ANALYTICAL METHODS FOR THE STUDY OF NONLINEAR SOIL-STRUCTURE INTERACTION

Finite Element Method (FEM) (Ref.1-11)

The Finite Element Method can be broken down into several catagories based on the method used to solve the nonlinear problem. As shown in Fig.2, the area for analysis is divided into two regions: region (A) has the nonlinear phenomenon and finite meshes; whereas, region (B), which is outside of region (A), is considered linear to infinity.

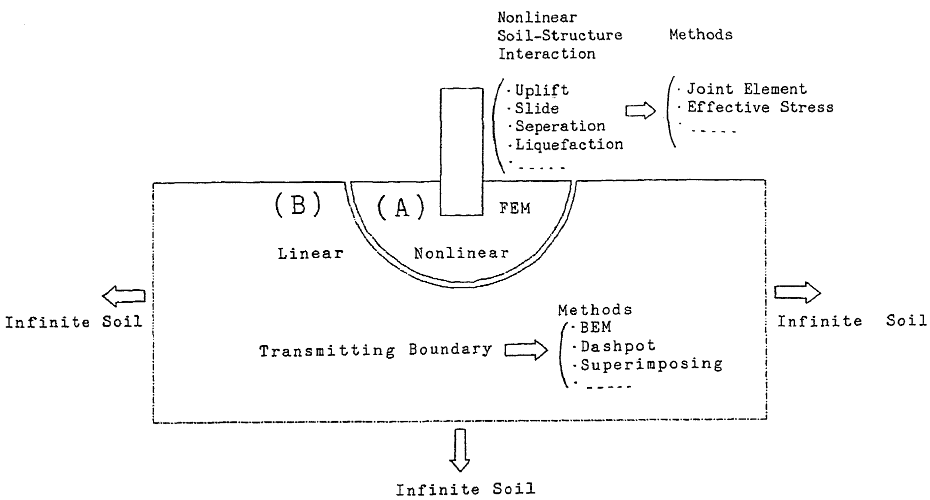

Fig.2 Illustration of FEM Group

Each FEM group is divisible into several smaller groups according to the treatment used to solve the nonlinear problem in region (A).

For linear problems, treatment in the frequency domain is preferable; but for nonlinear problems no superimposing of the solution procedure is available. Therefore, the method used to solve the problem, is step-by-step calculation together with an iterative procedure for taking into account nonlinearity in the time domain, rather than making direct change in the stiffness matrix, as by the Load Transfer Method, etc . In this group,the Joint Element Method that has been introduced by Dr.Toki provides a typical example and has been used in the research reported in paper SC-10.

At the boundary of regions (A) and (B), no reflecting wave should be produced. Several procedures for realizing the non-reflecting boundary have been proposed. This non-reflecting boundary (transmitting boundary) must be in the time domain because of the nonlinear calculations in region (A). Dr.Wolf has introduced an integral expression in the (B) region using the Boundary Element Method for realizing the transmitting boundary and has idealized the infinite soil. His treatment has been used in several of the papers reported in this session; SC-07, 08 and 09.

Paper SC-08 uses the FEM to solve the nonlinear problem by modifying the system matrix only when the system changes its characteristics in the nonlinear range and by using the Laplace Transform in the linear range. In the future, this procedure should find use in making detailed analyses when there is little nonlinearity.

Lumped Mass System (Ref.12-19)

This method models the objective as a discrete mass spring system (Fig.3); thus, differing from the FEM in which the objective is discretized automatically when formulating the equation of motion.

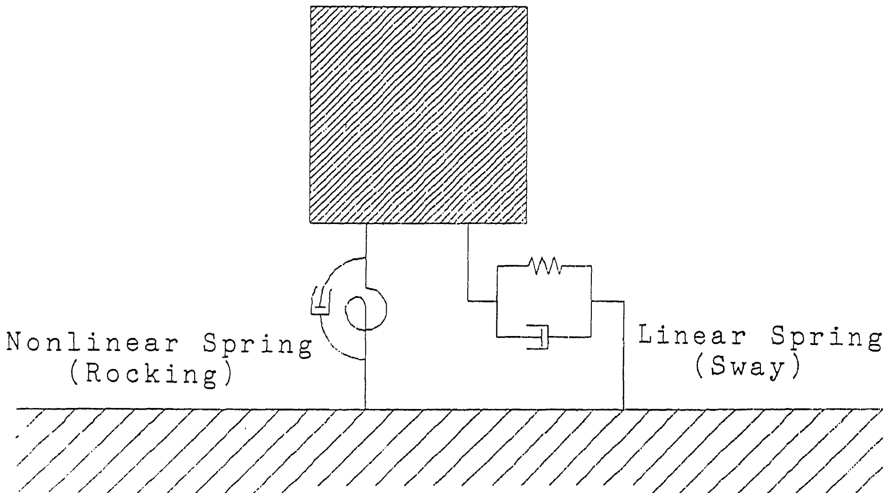

Fig.3 Lumped Mass System

This method is not so expensive as the FEM because of the smaller degree of freedom; in other words, it is not very useful for detailed analyses but is good for qualitative analyses.

Papers SC-11 and SC-12 use this method. Its future use will be to obtain approximate estimations of nonlinear responses.

DEM(Distinct Element Method) (Ref.20-22)

This method was introduced by Cundall in 1971, and has found increased use recently in Earthquake Engineering . It is a numerical simulation that is used to analyze the behavior of rock and is based on the assumption that individual rock elements satisfy the equation of motion. The response of a granular assembly model of a foundation subjected to a horizontal sinusoidal force (increasing amplitude, 2Hz) is shown in Fig.4. Uplifting of the foundation from its supporting ground is recognizable in this figure. The nonlinear angular displacement response of the foundation is shown in Fig.5, and Fig.6 gives the relation between the applied moment and the angular response; linearity under the small moment and nonlinearity with a large hysteresis loop under the great moment. Figs.7 and 8 show other DEM results for soil-structure interaction. Both of a structure and soil are made of circular particles. Only a structure was subjected to a horizontal monotonically increasing force. In Fig.7 of the begining stage of a fracture of soil, a tension crack occurred at the right foot of the structure and a separation of soil from the structure occurred at the right foot.

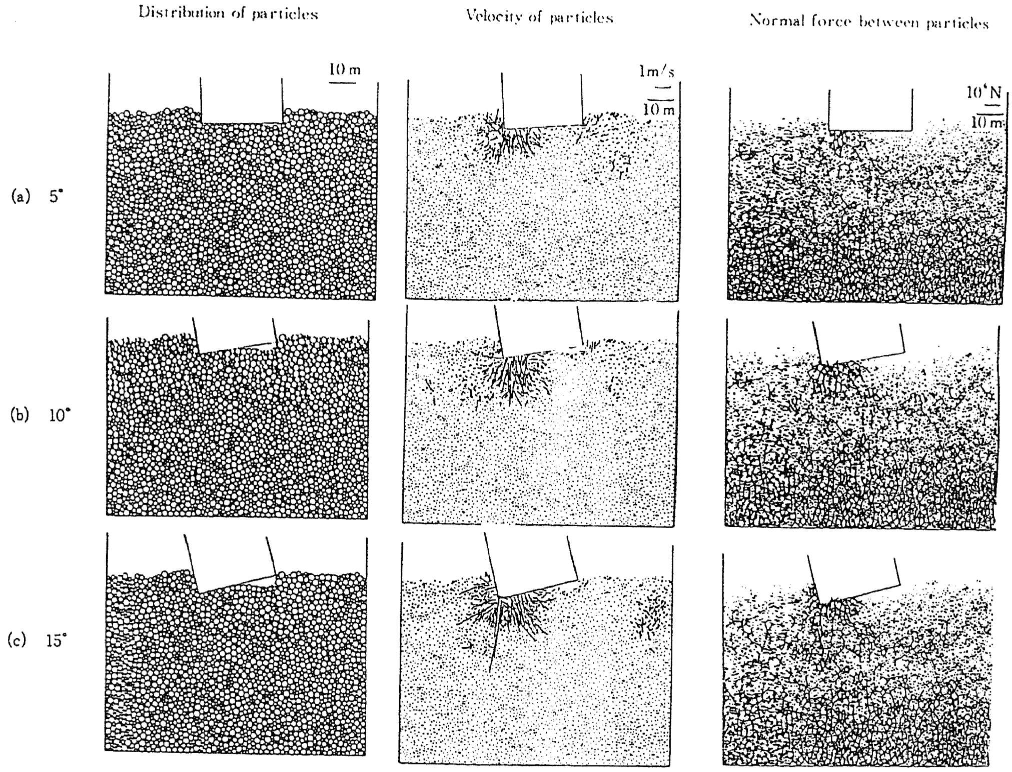

Fig.4 Nonlinear Soil-Structure Interaction

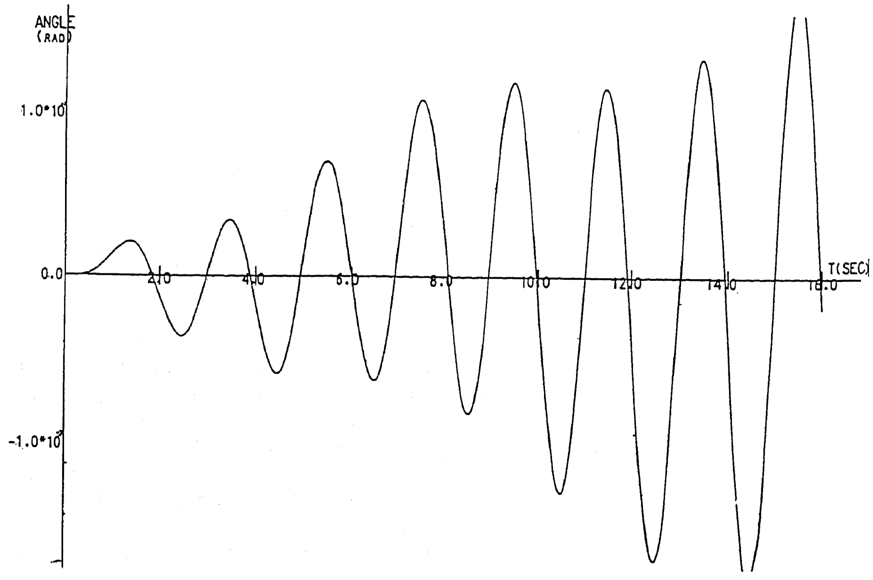

Fig.5 Rocking Response of a Foundation

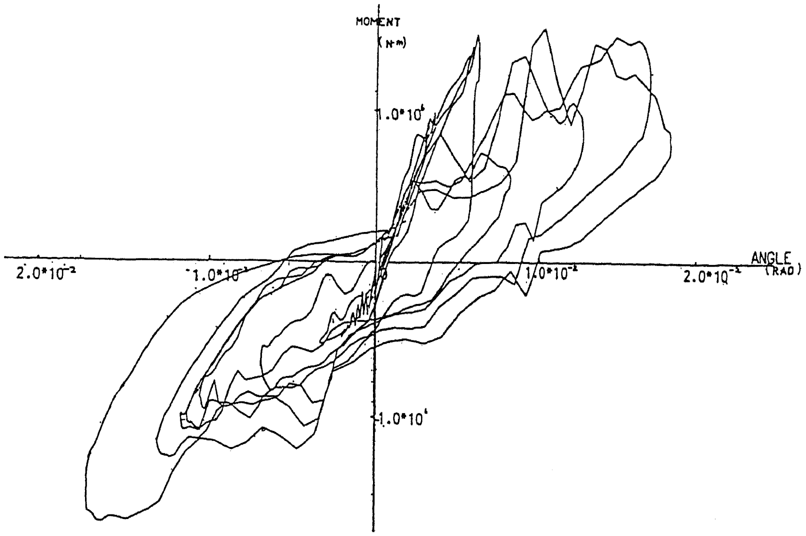

Fig.6 Moment-Angle Relationship

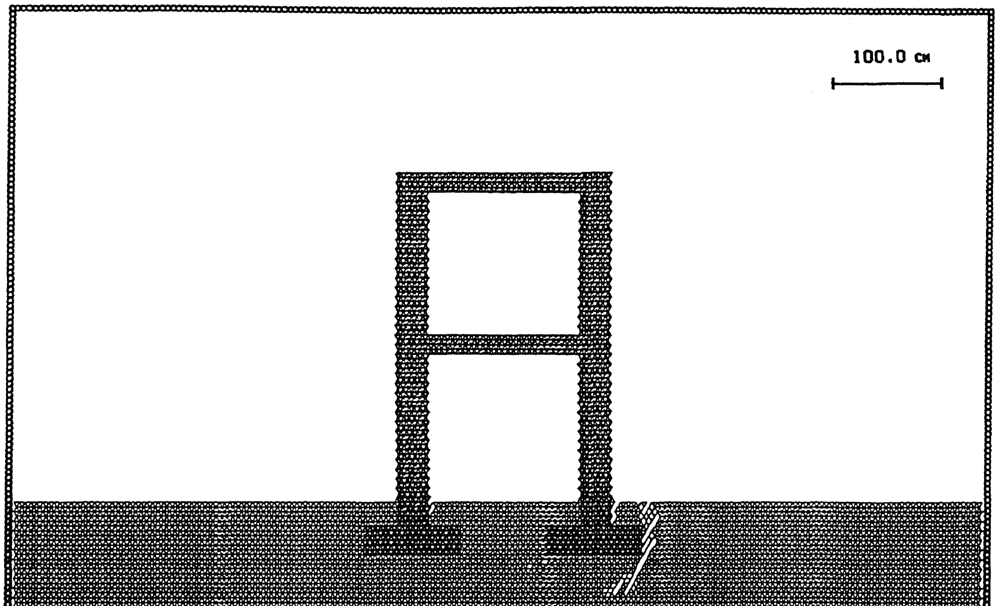

Fig.7 Nonlinear Soil-Structure Interaction (stage 1)

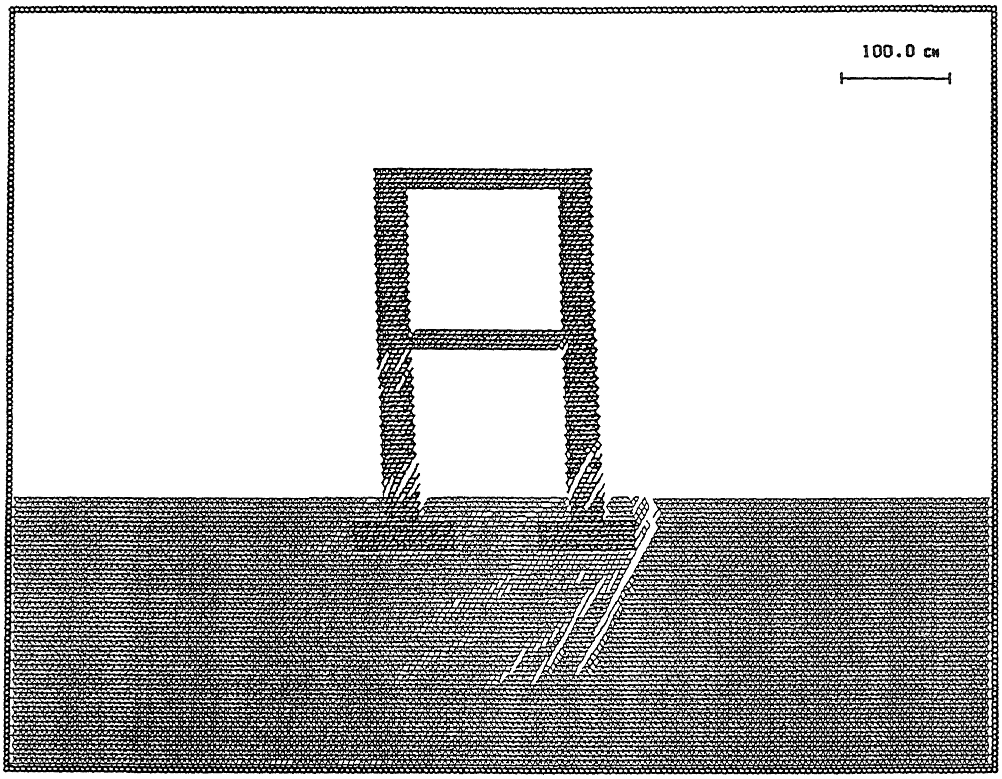

Fig.8 Nonlinear Soil-Structure Interaction (stage 2)

In Fig.8, the time passed and the tension crack advanced further and made branches, and shear cracks in soil started at the bottom of the right foot. Shear cracks occurred at both of structural feet.

The future uses of this method will be in making qualitative analyses of problems with large nonlinearities.

EXPERIMENTAL METHOD (Ref.23-27)

Both field and laboratory tests, provide powerful tools for nonlinear analyses. Papers SC-11,SC-12 given in this session report experimental results or describe actual experimental research.

Pseudo-dynamic-online test which has been broadly used in the experimental analysis of concrete and steel structures, is going to be used in the analysis of soil dynamics and soil-structure interaction.

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Note;

ASCE: American Society of Civil Engineers

JSCE: Japan Society of Civil Engineers

EESD: Earthquake Engineering and Structural Dynamics