V - 489

DYNAMIC NONLINEAR INTERACTION OF RC/SOIL SYSTEM UNDER SEISMIC EXCITATION

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1. INTRODUCTION

In the frame of seismic design, dynamic inertial forces as equivalent static loads are determined with reference to seismicity of construction cites, ground characteristics, structural ductility and an associated limit state of reinforced concrete. This simplified way of design works well for particular types of structures but is no longer versatile for complex structures having interaction with surrounding media. Dynamic forces which arise in underground RC have much to do with deformation of soil. At the same time, dynamic soil pressure applied to RC is also affected by the stiffness reduction of RC members, ductility of structures and hysteresis damping characteristics. Thus, the entire system of RC/soil foundation has to be treated as being coupled for rationalization of design. Here, simplified design methods, as stated above, have to be specified based on these full model analysis.

The kinematic nonlinear interaction of RC and foundation is a main concern and dynamically induced damage of underground RC is investigated. Full path-dependent constitutive laws of RC, soil and their interfacial zones are of interest in a dynamic FEM named "WCOMRSJ"[1] developed in The University of Tokyo. Consequently, RC/soil hysteresis damping and energy absorption, which are identified with seismic structural excitation, are taken into account with corresponding states of damage and plasticity regarding concrete and reinforcement.

2. DESCRIPTION OF THE PROBLEM.

For discussing kinematic interaction under seismic loads, full RC/soil nonlinear dynamic analysis was conducted. The dimension and finite element mesh of target structure, which is a simple model of RC underground tank with a square section, are shown in Fig.1. The thickness of the wall is variable in sensitivity of analysis. Mixed mode artificial boundary of reflection was put at both extreme sides of soil foundation in order to dissipate energy from FE analysis domain to far field[3]. Based on the acceleration phase record of TAFT earthquake (East-West), created was the design seismic base rock acceleration whose response spectrum and the exact wave used in time are shown in Fig.1. Magnitude of seismicity used is close to level S2 regarded as the most strong for nuclear power plant facilities. The limit state specifies that yield of reinforcement is allowed but still load carrying mechanism have to be maintained.

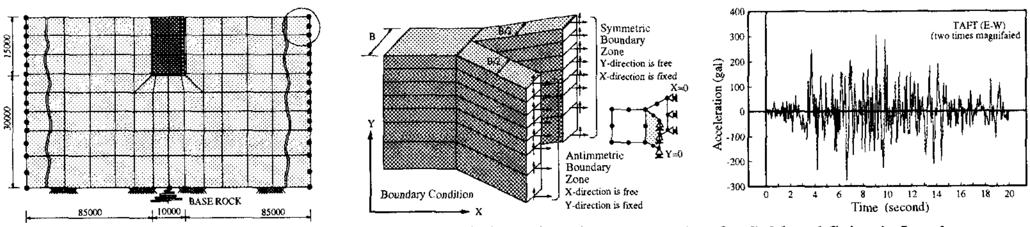
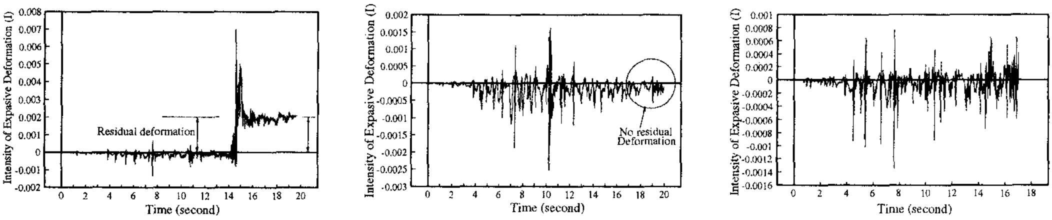


Fig.1 Finite element mesh, mixed mode boundary for representing far field and Seismic Load.

3. DAMAGE INDUCED TO RC IN TIME DOMAIN

Since the discussion of static kinematic interaction[2] reveals that underground RC possesses higher safety if sufficient ductility would be obtained, severe situations were intentionally assumed to reproduce high damage. Accordingly, very thin wall (thickness/wall span = 1/36: approximately minimum allowable thickness specified in JSCE code) and low reinforcement (0.5%) were detailed. Initial stiffness of ground (26MPa: soft foundation and equivalent to N-value = 2~4) was herein selected so that much shear deformation can be excited by seismic action. In Fig.2 shown are induced damages to RC ,indicated by in-plane mean strain. For comparison, three cases are reported here. One is full nonlinear dynamic analysis of RC/soil system with interfacial elements, and the second is that RC is assumed elastic, and the third is full elasticity of RC and soil. Nonlinearity of RC/soil interface was taken into account in all cases.

For the case of full elasticity, in-plane mean strain fluctuates around zero because no mechanical damage is assumed, and when seismic action goes out, this index returns to the initial value. As no energy dissipation and reduction of stiffness are expected, the induced shear force to RC becomes large. If nonlinear characteristics of soil is assumed but no plasticity or damage, the induced shear force is much reduced much. At the same time, the mean strain is also diminished. Within this material, the kinematic interaction of dynamics has the same tendency as that of the static cases[2]. In the full nonlinear case, the mean strain is similarly small and varying in compression side because of the isotropic confinement by soil pressure and small numbers of cracking at the initial stage. But, positive large mean strain was introduced and remaining at the final stage of seismicity. This plasticity is much associated with yielding of reinforcement. The residual deformation can be evaluated only with the full path-dependent constitutive models and in fact, this is one of advantages of this analysis method. It is found that this damage is caused by the dynamic shear force increased so much when the base acceleration of 200gal with a frequency close to the natural harmonic one of the ground takes place.



(a) RC - nonlinear, soil - nonlinear, (b) RC - elasticity, soil - elasticity (c) RC -elasticity, Soil - nonlinear

Fig.2 Damage of RC underground vertical duct in time domain

4. NONLINEAR RESPONSE SPECTRUM.

It will be advisable to examine some parameters of RC concerning the damage level and corresponding shear forces in view of design for underground reinforced concrete. For this purpose, the maximum shear forces and residual mean deformation are picked up from the time history as shown in Fig.3. Here, total amount of reinforcement is kept constant and only the thickness of walls varies. The reason why these set of parameters are selected is that high capacity with smaller reinforcement ratio tends to be decided in accordance with present design codes. In the case of large thickness (d/L=1/6, p=0.15%) having high capacity but low ductility, induced shear force is very high owing to the large stiffness of RC. But, when the thickness is reduced one half with increasing reinforcement ratio, the shear force drastically decreases. Furthermore, the damage level indicated by the mean strain is accompanied. Consequently, it can be said that the reduced stiffness with ductility brings about safer structures.

The dimension of wall thickness is assumed smaller (d/L=1/10 - 1/36). The shear force hardly varies and the residual deformation goes up. Within this range, no failure is found. Here, reinforcement ratio is a minor factor for failure. This sensitivity is the same as in the case of static parametric study[2]. Therefore, reinforcement ratio similarly can be treated as a control parameter of cracking on the line of deformation based limit state.

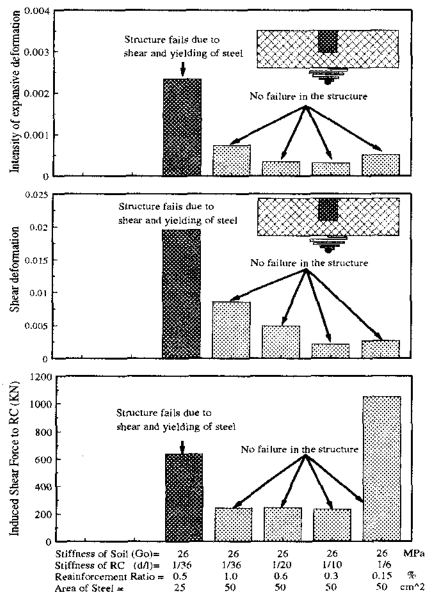


Fig.22 Effect of reinforcement and dimension on the response of RC

7. CONCLUSIONS

It is well known that the seismic earth pressure to underground structures predominantly influences on the practical design. However, its dependency on RC structural ductility has been neglected or simply idealized in practical design. Nonlinear characteristic of soil foundation has been of main concern and investigated in view of geotechnical problems. As a matter of fact, dynamic analysis serving practical design is conducted mostly in consideration of nonlinear soil but elasticity of underground RC structures. Based on these recent background, it was clarified that nonlinear characteristics of both RC and soil cannot be ignored for simplicity. The degrading stiffness of RC will tend to lessen the shear force under large strain. In most cases, owing to coupled nonlinear kinematics, structural safety will be sustained. From parametric studies, reinforcement ratio was understood as crack control agent but it does not sensitively influence on the dynamic force of section.

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