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Numerical simulations of sandy soil deposit liquefaction during earthquakes

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ABSTRACT: Numerical constitutive laws have been proposed by researchers for expressing the behavior of sand as an elastoplastic material in analyses of liquefaction which occurs in sandy soil deposits during earthquakes. Sophisticated engineering judgment is often necessary in defining the required material constitutive parameters for such analyses. The finite element program "DYNAFLOW" developed by Prevost (1981) is based on the three dimensional multi-yield surface plasticity theory and the required material parameters could be obtained from standard soil tests.

In this paper, the basic components of the analysis procedure are presented, together with its validation. As a validation test of DYNAFLOW, three liquefaction experiments using a large shaking table performed by Prevost et al. (1991), were simulated. Computed excess pore water pressure and acceleration are discussed and compared to the recorded values.

1 INTRODUCTION

DYNAFLOW is a finite element computer program for nonlinear seismic site response analysis. Dry and saturated deposits can be analyzed. DYNAFLOW has been developed to allow site response analyses to be performed taking into account : (1) the nonlinear, anisotropic and hysteretic stress strain behavior of the soil material and (2) the effects of the transient flow of pore water through the soil strata. The soil and fluid coupled field equations proposed by Biot (1962) and constitutive equations proposed by Prevost (1985, 1977, 1982) are general and applicable to multi-dimensional situations. Required material constitutive parameters are identified in terms of "classical" soil mechanics parameters (e.g. elastic moduli, friction angels, permeability, etc.) and do not require user's familiarity with the constitutive model nor sophisticated soil test data.
The multi-yield surface model implemented in DYNAFLOW was validated in the past for liquefaction analysis using laboratory and in situ recorded pore pressures and accelerations presented by Ohbo et al. (1990) and Kean and Prevost (1989).

In this paper, validation is provided by simulating shaking table tests. Measured and computed pore pressures and accelerations are presented and compared.

2 LIQUEFACTION EXPERIMENT

2.1 Outline of Experiment

The tests were performed at Kajima Technical Research Institute using a large shaking table. A shear box was used for obtaining simple shear deformation in the model ground and its size is 2.5m length, by 1.0m width, by 1.0m depth. The shear box is composed of nine shear frames, each joined to prevent friction in the shaking direction and to reduce the movements in the other two directions. The grain size of Fujigawa sand used in the experiment is shown in Figure 1. The sand was compacted with a vibroplate (compaction stress=6.0 kPa) to obtain a relative density of 60%. The model ground was then saturated with water.

Three different models were studied : a layered soil, a layered soil with a rigid structure (for short : structure model) and a layered soil with an embankment (for short : embankment model). Acceleration meters, pore water pressure meters and displacement meter were installed mainly in vertical section a-a, b-b of three models shown in Figure 2, 3, 4 respectively.

Dynamic excitation was provided using sinusoidal 4Hz waves indicated in Figure 5. The input acceleration amplitude is 200gal for the layered soil model and the structure model, 300gal for the embankment model.

2.2 EXPERIMENTAL RESULTS

The excess pore water pressure ratios at one second intervals for section a-a in the layered soil model are presented in Figure 6. The excess pore water pressure ratio is negative throughout the depth for the first 3 seconds of shaking. After 10 seconds of excitation, the excess pore water pressure ratio has risen to 1.0, signifying the occurrence of liquefaction, at depths between 40 and 60cm.

Recorded excess pore fluid pressure ratio at the end of the shaking in two vertical sections are presented in Figure 7, for the three models. In the layered soil model, the distributions of the maximum excess pore water pressure ratio at the two cross sections were in good agreement. This confirmed that the excess pore water pressure had risen uniformly throughout the soil deposit.

The distributions of the three models were in good agreement for two vertical sections. However, the presence of the structure and embankment leads to slightly lower values of the excess pore water pressure ratio, especially in the central section a-a.

3 MATHEMATICAL MODEL

The multi-yield surface kinematic hardening model is based on a relatively simple plasticity theory proposed by Prevost(1985) and is applicable to both cohesive and cohesiveless soil.
A non-associative flow rule is used for the dilatational component of the plastic potential. The model has been tailored: (1) to retain the extreme versatility and accuracy of the simple multi-surface J2-theory presented by Prevost (1977) in describing observed shear nonlinear hysteretic behavior and shear stress-induced anisotropic effects; (2) to reflect the strong dependency of the shear dilatancy on the effective stress ratio in both cohesionless and cohesive soils. Nested conical yield surfaces are used for that purpose.

The soil behavior is analysed by incorporating the effects of the transient flow of the pore-fluid through the voids. An extension of Biot's theory into the nonlinear domain is employed to analyze the transient response of the soil deposits.

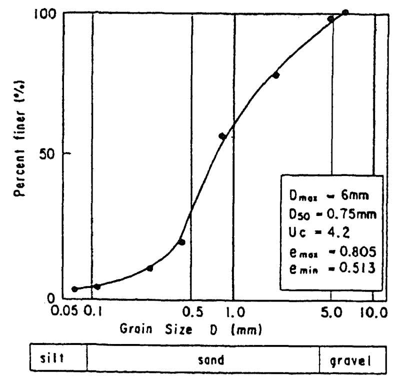


Figure-1 Grain Size Acceleration Curve of Fujigawa Sand

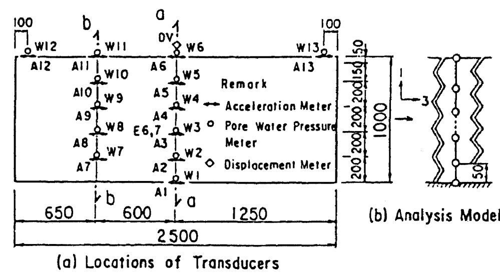


Figure-2 Layout and location of transducers for layered soil model

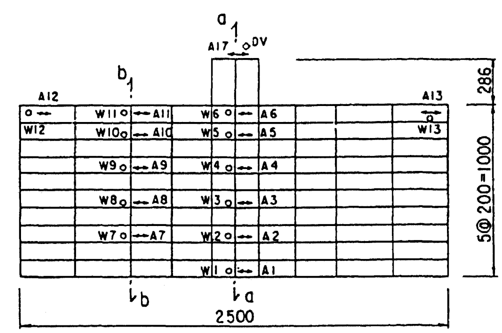


Figure-3 Layout and location of transducers for structure model

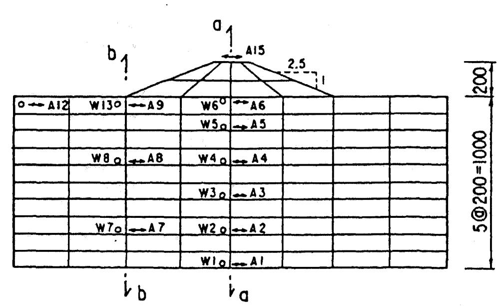


Figure-4 Layout and location of transducers for embankment model

The coupled field equations are presented by Prevost (1988). The time integration is accomplished by a finite difference time stepping algorithm, using the "split operator method".

The material parameters are obtained from the following laboratory and "in site" tests.

- Physical tests ---> Porosity, Mass density
- PS logging tests ---> Elastic moduli
- Monotonic and Cyclic triaxial tests ---> Dilatancy angle, Friction angle, Maximum shear strain in compression and extension, Dilatation parameter
- Permeability test ---> Permeability
- Method of setting up the specimen --->Ko value, Initial stress

4 SIMULATIONS

4.1 FINITE ELEMENT MODEL

Two dimensional analyses were performed, using 2 or 4 node linear elements. The sandy soil was idealized as two phase nonlinear porous medium with four nodal degrees of freedom (horizontal and vertical displacements for both solid and fluid phases). The compressiblity of water was considered. The structure and the embankment were modelled as elastic one phase media.

The layered soil model shown in Figure 2(b) was simulated assuming a semi-infinite horizontally layered soil deposit. The deformations and the stresses were assumed uniformly distributed over every horizontal section. For the strcuture and the embankment models, the plain strain behavior for the vertical plane containing the direction of excitation was assumed. The finite element meshes are presented in Fig. 3, 4, respectively.

The boundary conditions were prescribed as follows:

- prescribed acceleration for the solid phase horizontal d. o. f. of the base nodes;
- zero vertical displacement for both solid and fluid phases at the base nodes;
- same equation number for each nodal d. o. f. (i. e. both for the solid and fluid phases in the horizontal and vertical directions, respectively) for the lateral nodes on the same horizontal planes to simulate shear box condition.

4.2 INPUT PARAMETERS

The constituitive model parameters were evaluated from the results of conventional laboratory and shear wave velocity tests. Parametric studies

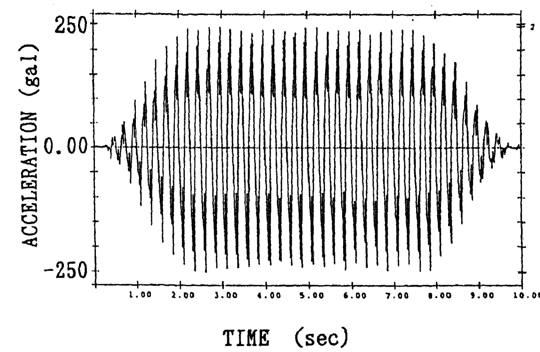


Figure-5 Input Acceleration Wave

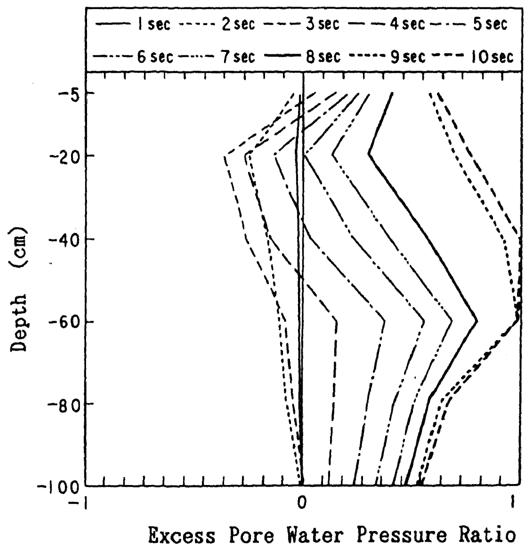
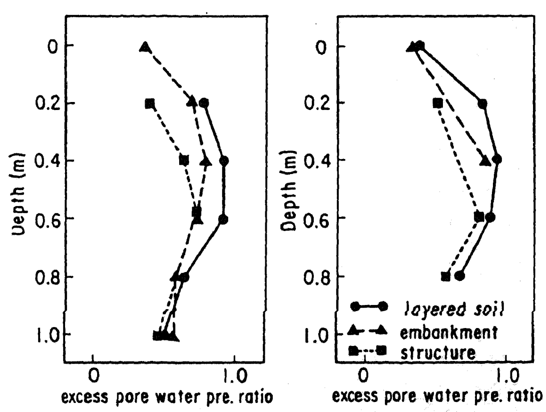


Figure-6 Excess Pore Water Pressure Ratio Distribution (layered soil model)



(a) central section a-a (b) lateral section b-b

Figure-7 Maximum Excess Pore Water Pressure Ratio concerned with initial stress induced by compaction and permeability were performed to derive the material properties dependent on the details of the specific sample preparation. These parameters were found to be slightly different from a model to another and variable in elevation.

Due to the flexibility of the shear box, two zones with slightly different material properties were identified: zone 1 corresponding to the first compaction layer, from the bottom to 0.8m depth, and zone 2 consisting from the other four layers. The material parameter values are presented in Table 1.

5. SIMULATION

5.1 EXCESS PORE WATER PRESSURE

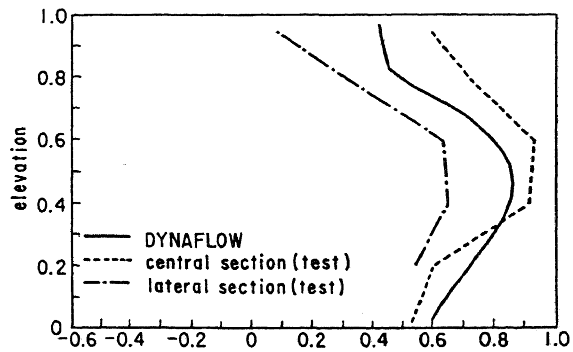
Computed and recorded excess pore pressures comparisons for the three models are presented in Figure 8, 9, 10, 11. Figure 8 shows the distribution at the end of shaking in two vertical sections. Figure 9, 10, 11 show the time histories for a location "W3" in the central section. A very good agreement between experimental and computed values was achieved for all the three models, excepting a general tendency of the numerical model to predict an excessive dilatancy in the early phases of the shaking (Fig. 9, 11).

5.2 ACCELERATION

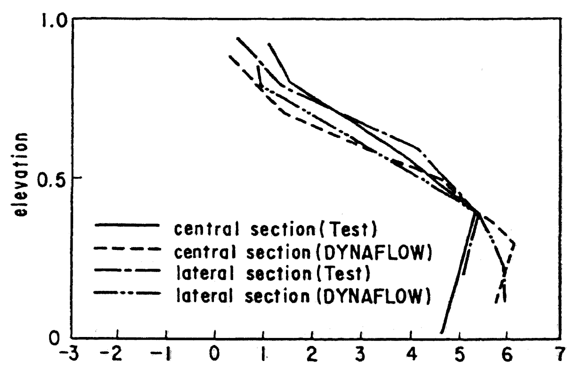
Acceration time histories at a location "A3" in the central section are presented in Figure 12, 13, 14. A good overall agreement is achieved during the first 4...5 sec. of the excitation period. After this, when the soil begins to gradually loose its stength, the recorded acceleration time histories become peak shaped, while the computed acceleration amplitudes are gradually decreasing, as expected.

Table-1 Material parameters

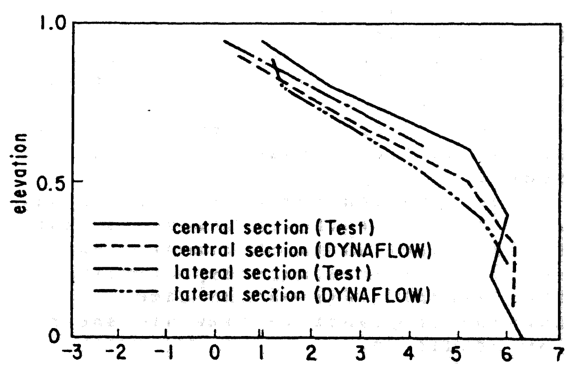
Property	Value
Mass density (Kg/m^3)	2708.0
Porosity	0.40
Low strain base shear modulus (MPa)	12.0 (16.8-zone 1)
Poisson s ratio	0.3
Fluid bulk modulus (MPa)	100.0
Cohesion	0.0
Reference mean normal stress(KPa)	10.0(11.2 embank. model)
Power exponent	0.5
Dilatation angle (compression and extension)	30° (25°-zone 1)
Dilatation parameter	0.02
Friction angle (compression and extension)	38°
Coefficient of lateral stress	1.0
Slpoe of stress path ($\Delta p/\Delta q$)	0.33
Maximum shear strain in compression	0.05
Maximum shear strain in extension	0.03
Permeability (m/s)	2×10^{-6}.. 10^{-5}
Initial stress (KPa)	5.0 ...12.0



(a)Layered soil model



(b)Structure model



(c)Embankment model

Figure-8 Maximum Excess Pore Water Pressure Distribution

6 CONCLUSION

The validity of the liquefaction analysis program DYNAFLOW has been studied for shaking table tests data and studied models were layered soil model, structure model and embankment model.

As a result, it was confirmed that DYNAFLOW is capable of closely simulating the details of the experimental shaking table liquefaction tests, such as : the excess pore water pressure time histories, the vertical distribution of maximum excess pore water pressures and acceleration time histories.

The reported study was conducted as a part of Kajima Corporation - Princeton University joint research.

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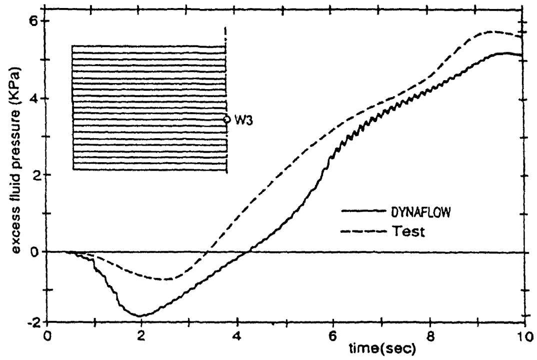


Figure-9 Excess Pore Water Pressure at Point W3 (Layered soil model)

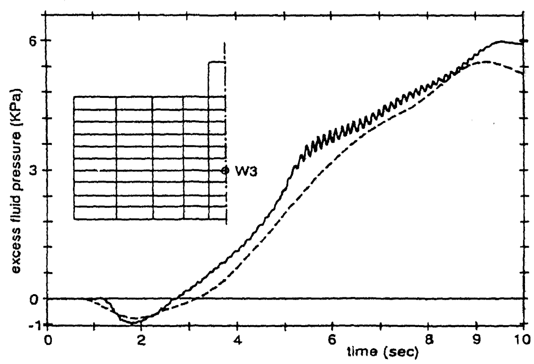


Figure-10 Excess Pore Water Pressure at Point W3 (Structure model)

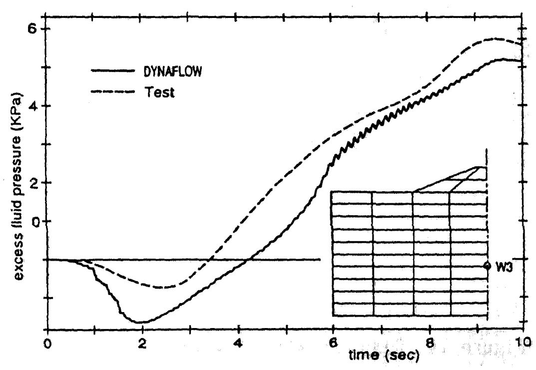
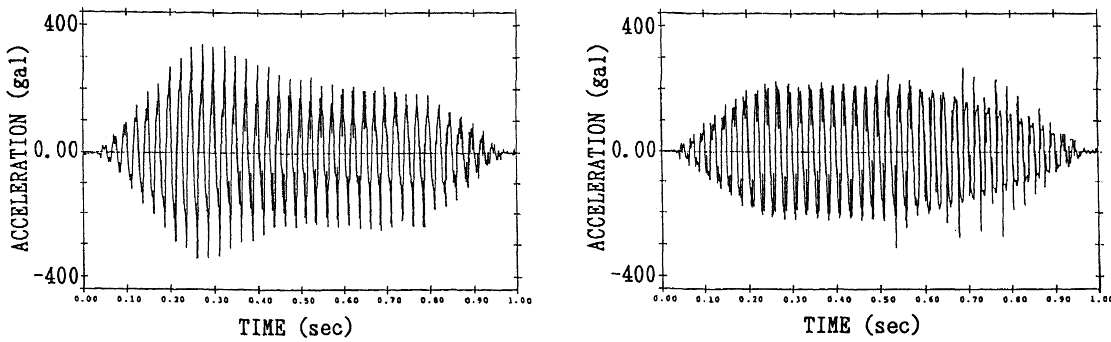


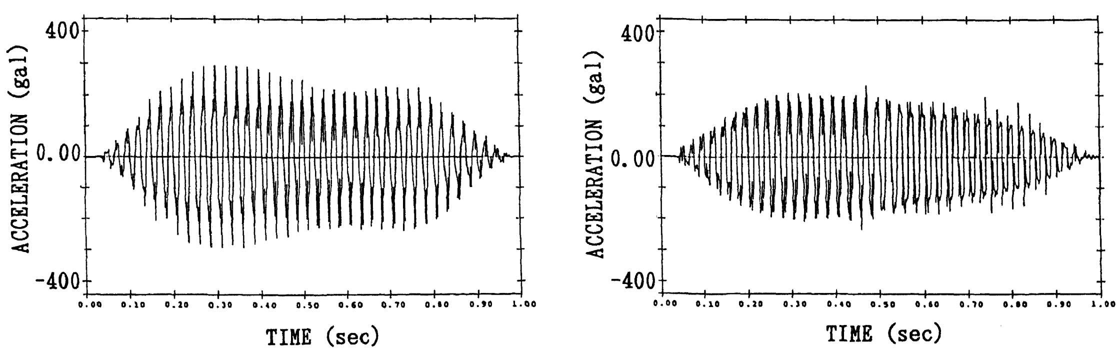
Figure-11 Excess Pore Water Pressure at Point W3 (Embankment model)



(a) Test

(b) DYNAFLOW

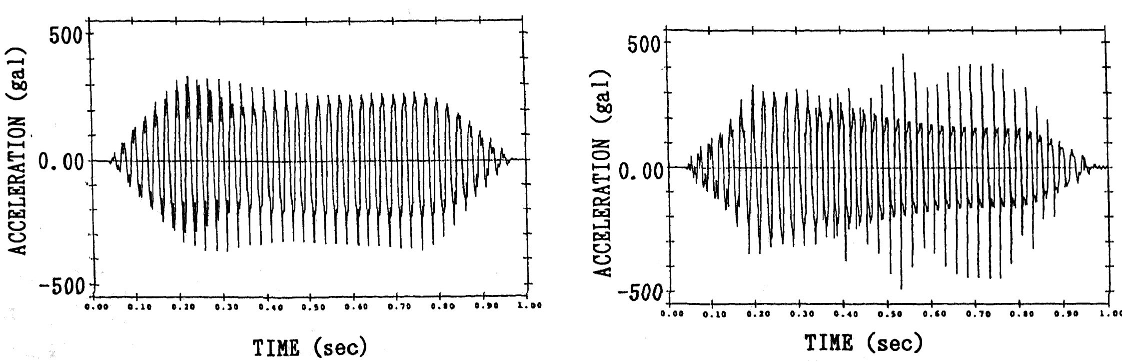
Figure-12 Computed and measured horizontal accelerations time histories at Point A3 (Layered soil model)



(a) Test

(b) DYNAFLOW

Figure-13 Computed and measured horizontal accelerations time histories at Point A3 (Structure model)



(a) Test

(b) DYNAFLOW

Figure-14 Computed and measured horizontal accelerations time histories at Point A3 (Embankment model)