SEISMIC RESPONSE OF CAISSON-RETAINED AND TANKER ISLANDS

W.D. Liam Finn (I)
R. Siddharthan (II)
Presenting Author: W.D. Liam Finn

SUMMARY

A new method for non-linear dynamic effective stress analysis is introduced which is applicable to the soil-structure interaction problems associated with offshore drilling islands in the Beaufort Sea. Its scope is demonstrated by analysis of a drilling island consisting of a ballasted modified tanker sitting on a submerged sand berm. Full interaction including potential slip between tanker and berm is taken into account. Verification is provided by data from simulated earthquake tests on a centrifuged model.

INTRODUCTION

Man-made islands of cohesionless soils have been used extensively as drilling platforms for oil and gas exploration in the Beaufort Sea. As exploration moves to deep waters more complex forms of drilling islands are evolving to minimize the amount of fill required for construction. Two of the newer types currently in use are the caisson-retained island (Ref. 1) and the tanker island (Fig. 1). The distinguishing characteristic of this type of island is a steel structure filled with sand resting on a submerged berm of dredged fill. When drilling is completed the steel structure can be de-ballasted and floated away to a new location. Since the island berms are constructed by dumping dredged sand on the seafloor, the berm sand is rarely very dense and, therefore, the deformation, stability and liquefaction potential of the island berm may be a major concern in seismic environments.

The predominant motions of the caissons and tankers are sliding and rocking. High porewater pressures may develop in the saturated berm under strong shaking and as these pressures increase the stiffness of the berm decreases. Under sufficiently strong shaking and, especially if high porewater pressures develop, slip may occur between the berm and the upper structure. The propagation of seismic motions through the island and the structure must be modelled taking all these factors into account in order to provide reliable estimates of deformations and settlements in the island berm and of input accelerations to drilling equipment mounted on the upper structure. Clearly, the determination of the seismic response of these islands is a complex problem in soil-structure interaction.

(I) Professor of Civil Engineering, University of British Columbia, Canada and Overseas Churchill Fellow, Cambridge University, England.

(II) Graduate Student, Dept. of Civil Engineering, University of British Columbia, Vancouver, Canada.

METHOD OF ANALYSIS

Siddharthan and Finn (Ref. 2) developed a method of dynamic non-linear effective stress analysis for determining the response of these drilling islands and incorporated it in the finite element computer program, TARA-2. The program includes slip elements to allow relative motion of structure and sand berm in both sliding and rocking modes during strong shaking. Both dynamic and permanent displacements, consolidation settlements, porewater pressures, accelerations and velocities are computed. The program continuously modifies soil properties for the effects of porewater pressures and dynamic strains.

Only a very general description of the basis of the method of analysis is possible here. Soil response is modelled by combining the effects of shear and mean-normal stresses. In shear, the soil is treated as a non-linear hysteretic material exhibiting Masing behaviour (Ref. 3). The stress-strain relationship is characterised by a tangent modulus in shear which depends on strain level and the current state of effective stress. This model of shear behaviour has been developed extensively by Finn et al (Ref. 4) and has been thoroughly tested in both laboratory tests (Ref. 5) and by field data (Ref. 6).

Soil behaviour under changes in mean-normal stresses is taken to be non-linear stress-dependent but essentially elastic compared to shear behaviour.

Porewater pressures are generated during analyses using an extended version of the Martin-Finn-Seed (Ref. 7) porewater pressure model which can include the effects of initial static shear stresses on the development of porewater pressure (Ref. 8).

SEISMIC RESPONSE OF A TANKER ISLAND

The seismic response of the typical tanker island illustrated in Fig. 1 was analysed using TARA-2. The properties of the rockfill and sand were selected corresponding to relative densities, D_r = 50%, to be consistent with those of dumped material. The steel tanker with plan dimensions 170 m x 60 m and 21 m high weighs 200,000 tonnes when fully ballasted. Both the tanker and the island were modelled by finite elements.

Dynamic analyses were performed on the island berm without the tanker in place and on the berm with the tanker in place, with and without slip elements. These analyses were designed to illustrate the effects on accelerations, displacements and porewater pressures of both soil-structure interaction and slip between island and tanker.

The S00E acceleration component of the Imperial Valley Earthquake of May 18, 1940, scaled to a maximum value of 0.1 g, was used as input motion for all analyses. The properties of the slip elements for this example were selected to allow some slip to occur under the specified excitation.

RESULTS OF DYNAMIC ANALYSES

Deformations and porewater pressures, u, in the cohesionless soils comprising the sand berm are controlled by the ratio of the dynamic horizontal shear stress, τ_{dy}, to the initial vertical effective stress, σ'_{vo}. The distribution of τ_{dy}/σ'_{vo} along the centreline of the island is shown in Fig. 2. Larger values of this ratio are generated in the island berm without the tanker than when the tanker is in place. The increased normal stresses under the ballasted tanker more than compensate for the higher shear stresses generated by the inertia of the tanker. Since smaller stress ratios, τ_{dy}/σ'_{vo}, are generated with the tanker in place, smaller porewater pressures are expected. This is confirmed by the distribution of maximum residual porewater pressures shown in Fig. 3.

The porewater pressure model used to generate the residual porewater pressure during analysis is based on a function of the dynamic shear strain (Ref. 7). The maximum dynamic shear strains for all three analyses are shown in Fig. 4. Clearly, the pattern of seismically-induced porewater pressures follows closely that of the maximum dynamic shear strains.

The patterns of maximum dynamic horizontal displacements are shown in Fig. 5. The displacements are much smaller with the tanker in place. As an example of permanent deformations the computed post-earthquake displacements in the vertical direction are shown in Fig. 6.

VERIFICATION

As discussed earlier, elements of TARA-2 have been checked by both laboratory and field data. Recently, a program of simulated earthquake loading on centrifuged models has been initiated at Cambridge University to verify the predictive capability of TARA-2 directly. The model set-up is somewhat similar to that used by Lee (Ref. 9) and shown in Fig. 7. One of Lee's tests has been analysed using TARA-2 with very encouraging results. The most difficult prediction in dynamic effective stress analysis is the time history of residual porewater pressures because it demands both adequate stress-strain relations and an adequate porewater pressure generation model. The history of porewater pressure recorded in Lee's test and that predicted by TARA-2 are shown in Fig. 8. The correlation is quite good and is typical of the agreement between computed and recorded pressures at all transducers for two different earthquakes. The accelerations were predicted within 10% of the recorded accelerations except for transducers directly under the plate when slip occurred. In this case, the computed accelerations are within 20% of the recorded values. The conclusion is that the properties of the slip elements need more precise definition.

The preliminary results are quite encouraging and it is hoped that the detailed centrifuge studies will result in further improvement of the method.

ACKNOWLEDGEMENTS

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REFERENCES

1. De Jong, J.J.A. and Bruce, J.C. (1978), "Design and Construction of a Caisson-Retained Island Drilling Platform for the Beaufort Sea", Proceedings, 10th Annual Offshore Technology Conference, Houston, Texas, May 8-11, OTC Paper 3294.

2. Siddharthan, R. and Finn, W.D. Liam (1982), "TARA-2, Two-dimensional Non-linear Static and Dynamic Response Analysis", Soil Dynamics Group, University of British Columbia, Vancouver, Canada, November.

3. Masing, G. (1926), "Eigenspannungen und Verfestigung beim Messing", Proceedings, 2nd International Congress of Applied Mechanics, Zurich, Switzerland.

4. Finn, W.D. Liam, Lee, K.W. and Martin, G.R. (1976), "An Effective Stress Model for Liquefaction", Journal of the Geotechnical Engineering Division, ASCE, Vol. 103, No. GT6, Proc. Paper 13008, June, pp. 517-533.

5. Finn, W.D. Liam and Bhatia, Shobha K. (1980), "Verification of Non-linear Effective Stress Model in Simple Shear", In Application of Plasticity and Generalized Stress-Strain in Geotechnical Engineering, ASCE, Editors, R.N. Yong and E.T. Selig, pp. 241-252.

6. Finn, W.D. Liam, Iai, S. and Ishihara, K. (1982), "Performance of Artificial Offshore Islands under Wave and Earthquake Loading: Field Data Analyses", Proceedings, 14th Annual Offshore Technology Conference, Houston, Texas, May 3-6, Vol. 1, OTC Paper 4220, pp. 661-672.

7. Martin, G.R., Finn, W.D. Liam and Seed, H.B. (1975), "Fundamental of Liquefaction under Cyclic Loading", Journal of the Geotechnical Engineering Division, ASCE, Vol. 101, No. GT5, Proc. Paper 11284, May, pp. 423-438.

8. Finn, W.D. Liam, Lee, K.W., Maartman, C.H. and Lo, R. (1978), "Cyclic Porewater Pressures under Anisotropic Conditions", Proceedings, ASCE Specialty Conference on Earthquake Engineering and Soil Dynamics, Pasadena, California, June 19-21, Vol. 1, pp. 457-471.

9. Lee, F.H. (1983), "Partial Liquefaction in a Centrifuge Model Embankment in an Earthquake", M.Phil. Thesis, Engineering Department, Cambridge University, July.

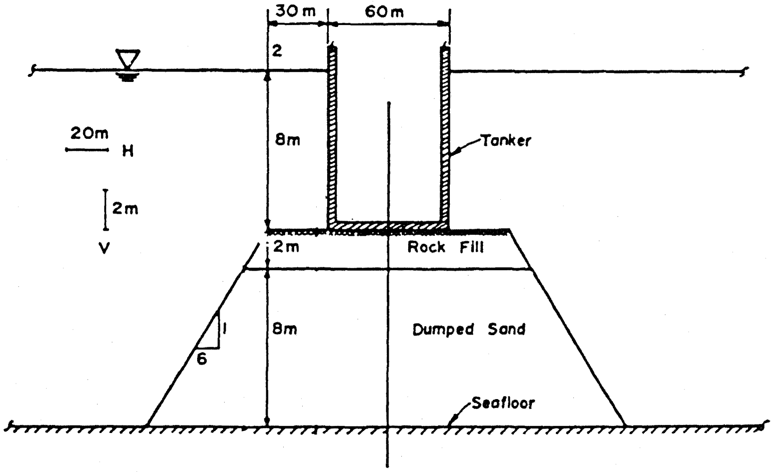

FIG. 1 Schematic Drawing of a Typical Tanker Island.

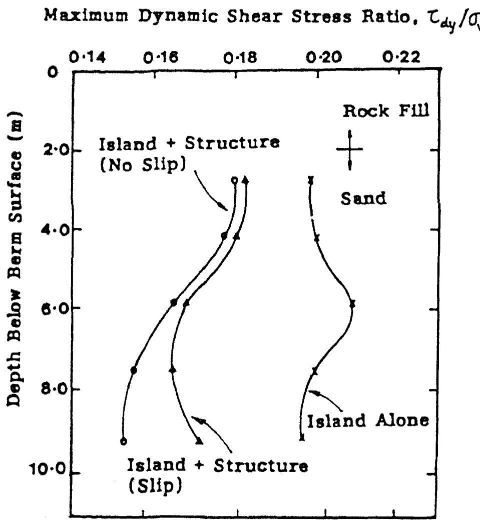

FIG. 2 Distribution of the Stress Ratio, τ_{dy}/σ'_{vo}.

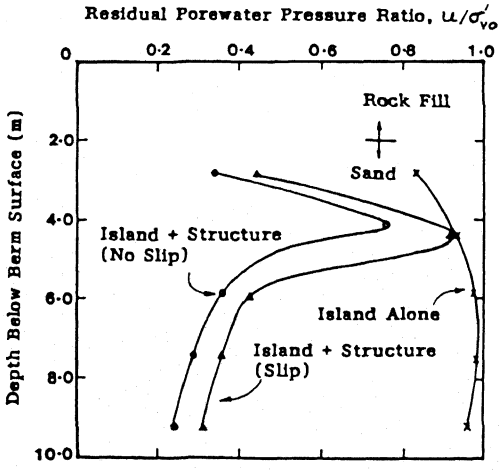

FIG. 3 Distribution of Residual Porewater Pressure Ratio, u/σ'_{vo}.

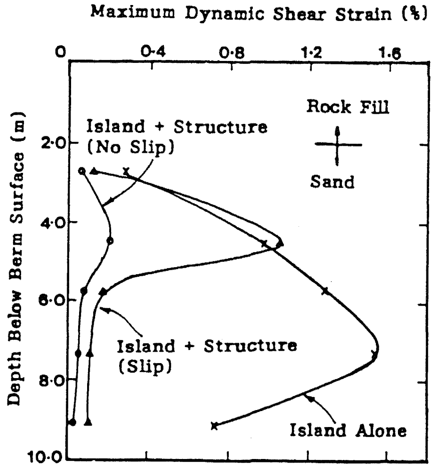

FIG. 4 Distribution of Maximum Dynamic Shear Strain.

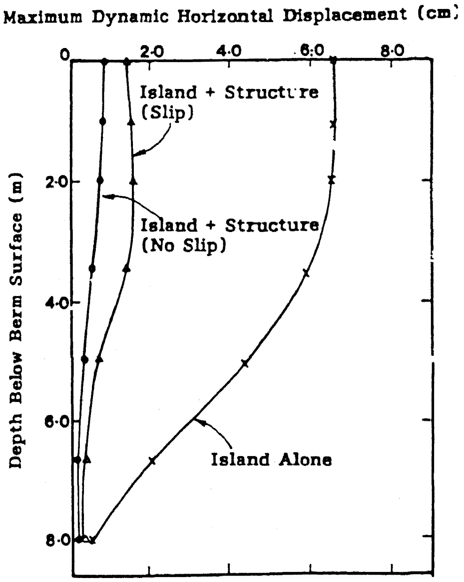

FIG. 5 Distribution of Maximum Dynamic Horizontal Displacement.

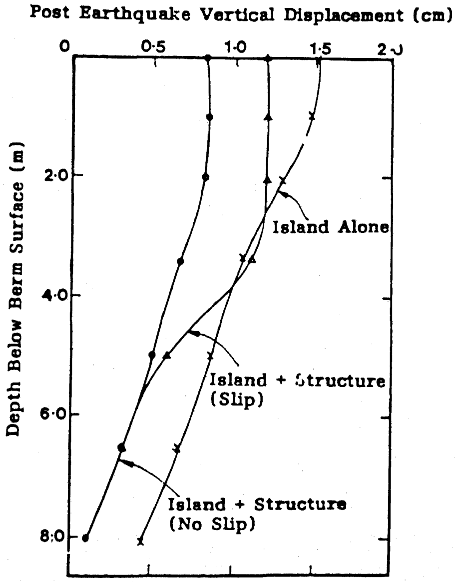

FIG. 6 Distribution of Vertical Post-Earthquake Displacement.

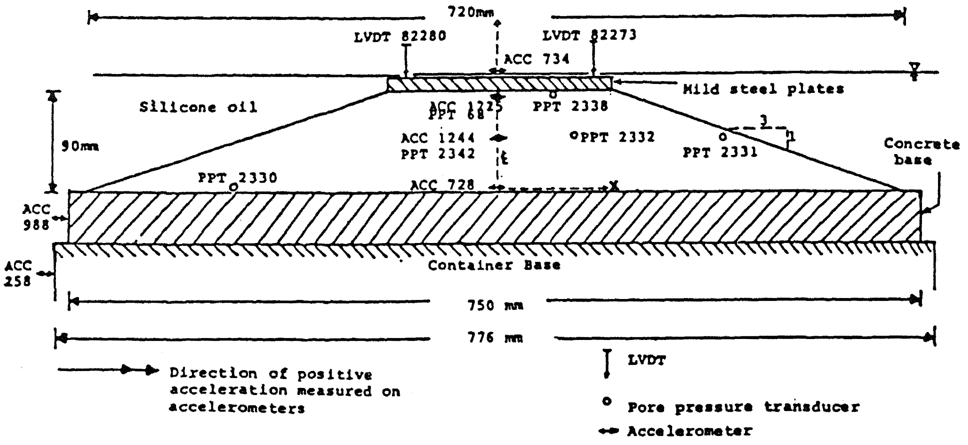

FIG. 7 Instrumented Centrifuge Model Embankment with Rigid Structure (after Lee, 1983).

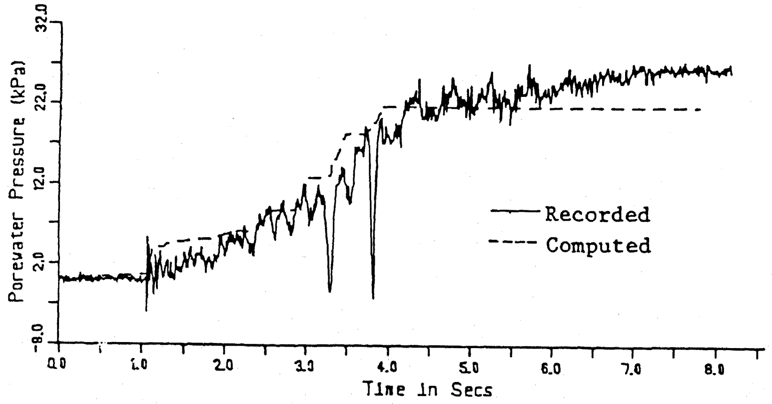

FIG. 8 Time Histories of Porewater Pressure Transducer 2342.