Proceedings of Ninth World Conference on Earthquake Engineering
August 2-9, 1988, Tokyo-Kyoto, JAPAN (Vol.VIII)

SI-2

VERIFICATION OF DYNAMIC EFFECTIVE STRESS ANALYSIS BY CENTRIFUGED MODEL IN SATURATED SAND

W.D. Liam FINN[1], M. YOGENDRAKUMAR[1] and N. YOSHIDA[2]

[1]Department of Civil Engineering, University of British Columbia, Vancouver, B.C., Canada
[2]Engineering Research Institute, Sato Kogyo Co., Ltd., Atsugi, Kanagawa, Japan

SUMMARY

Centrifuged model tests were conducted to verify the capability of the computer program TARA-3 to perform nonlinear dynamic effective stress analysis of soil-structure systems. In one test described in this paper, a model structure embedded in a saturated sand foundation was subjected to simulated earthquake loading. Horizontal and vertical accelerations and porewater pressures were recorded at many locations during the test. Model response was computed by TARA-3. Recorded and computed accelerations and porewater pressures agreed very closely.

INTRODUCTION

A 2-D method for nonlinear dynamic effective stress analysis is incorporated in the computer program TARA-3 developed by Finn et al. (Ref. 1). In TARA-3, response in shear is assumed to be nonlinear and hysteretic with unloading and reloading stress-strain paths defined by the Masing criterion (Ref. 2). The response of the soil to uniform all round pressure is assumed to be nonlinearly elastic and dependent on the mean normal effective stress. Residual porewater pressures during shaking are computed using the Martin-Finn-Seed porewater pressure model (Ref. 3), modified to take into account the effects of initial static shear stresses. These residual porewater pressures affect stiffness and stability. Transient porewater pressures due to transient changes in total mean normal stresses are not modelled as they do not alter the effective stress regime and therefore do not affect stability. Computed time-histories of porewater pressure will, therefore, not show the fluctuations about the residual pressure typical of recorded data. Moduli and shear strengths are continuously updated during analysis to reflect changes in the effective stress regime. A detailed description of the constitutive relations in TARA-3 is given by Finn (Ref. 4).

The United States Nuclear Regulatory Commission (USNRC) through the U.S. Army Corps of Engineers sponsored a series of simulated earthquake loading tests on centrifuged models to verify the nonlinear dynamic effective stress method of analysis incorporated in TARA-3. The tests were conducted on the large geotechnical centrifuge at Cambridge University in the United Kingdom. The models included dry and saturated embankments with and without surface supported and embedded structures. The capability of TARA-3 will be demonstrated by simulating the dynamic response in one of the more complex tests involving a massive structure embedded in a saturated sand foundation (Ref. 5).

EXPERIMENTAL SET-UP

A schematic view of a saturated embankment with an embedded structure is shown in Fig. 1. The structure is made from a solid piece of aluminum alloy and has dimensions 150 mm wide by 108 mm high in the plane of shaking. The length perpendicular to the plane of shaking is 470 mm and spans the width of the model container. The structure is embedded a depth of 25 mm in the sand foundation. Sand was glued to the base of the structure to prevent slip between structure and sand. During the test the model experienced a nominal centrifugal acceleration of 80 g. The model therefore simulated a structure approximately 8.6 m high by 12 m wide embedded 2 m in the foundation sand.

The foundation was constructed of Leighton Buzzard Sand passing BSS No. 52 and retained on BSS No. 100. The mean grain size is 0.225 mm. The sand was placed as uniformly as possible to a nominal relative density $D_r = 52\%$. De-aired silicon oil with a viscosity of 80 centistokes was used as a pore fluid. In the gravitational field of 80 g, the structure underwent consolidation settlement which led to a significant increase in density under the structure compared to that in the free field. This change in density was taken into account in the analysis.

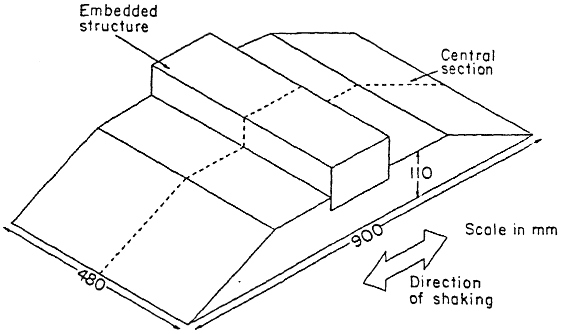

Fig. 1. Model Structure Embedded in Saturated Sand Embankment.

The locations of the accelerometers (ACC) and pressure transducers (PPT) are shown in Fig. 2.

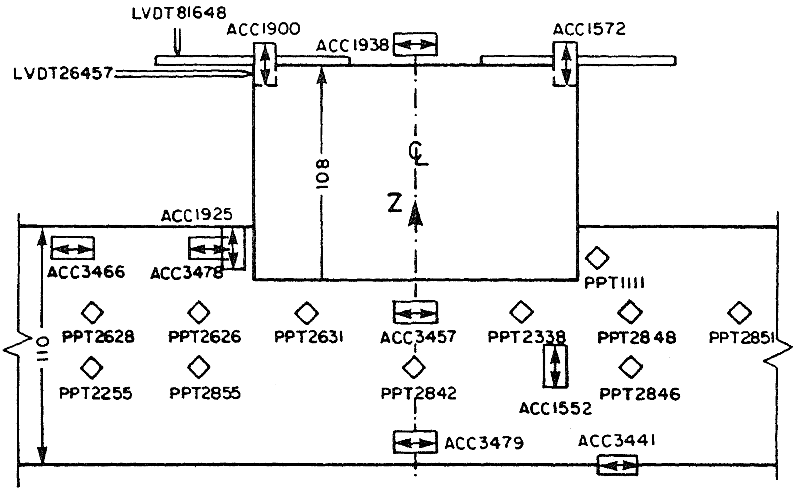

Fig. 2. Instrumentation of Model Structure.

The porewater pressure records from all transducers, shown in Fig. 3, give the sum of the transient and residual porewater pressures. The peak residual pressure may be observed when the excitation has ceased at about 95 milliseconds. The pressures recorded at corresponding points on opposite sides of the centre line such as PPT 2631 and PPT 2338 are quite similar indicating the sand properties are symmetrical about the centre line of the model.

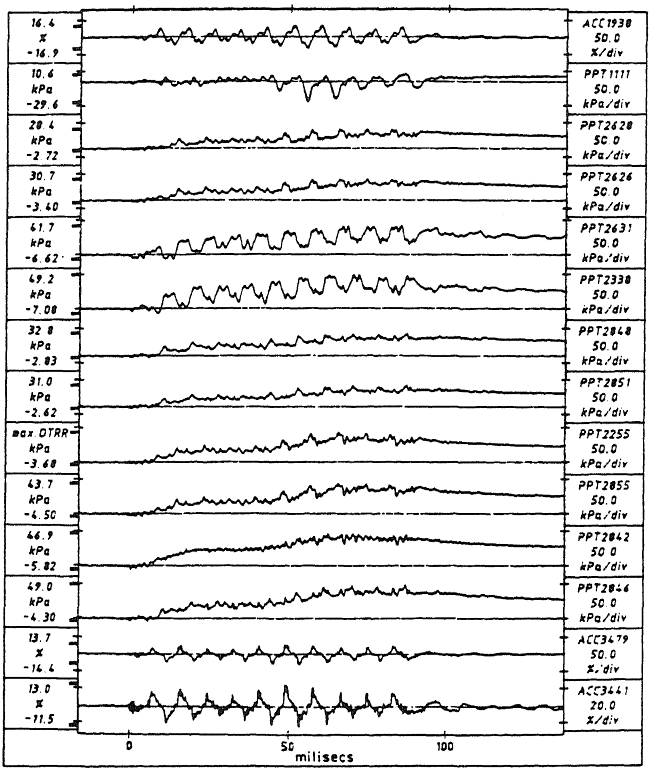

Fig. 3. Porewater Pressure Data from Centrifuge Test.

COMPUTED AND MEASURED RESPONSES

Accelerations The computed and measured horizontal accelerations at the top of the structure at the location of ACC 1938 are shown in Fig. 4. They are very similar in frequency content, each corresponding to the frequency of the input motion given by ACC 3441 (Fig. 3). The peak accelerations agree fairly closely. The vertical accelerations due to rocking as recorded by ACC 1900 and computed by TARA-3 are shown in Fig. 5. Once again, the computed accelerations closely match the recorded accelerations in both peak values and frequency content.

Porewater Pressures The porewater pressures in the free field recorded by PPT 2851 are shown in Fig. 6. A fairly reliable estimate of the peak residual pressure is given by the record between 7 and 7.5 seconds when significant shaking has ceased. The overall agreement between measured and computed pressures is quite good. As the structure is approached, the recorded porewater pressures show the increasing influence of soil-structure interaction (PPT 2846) having larger oscillations in pressure than those recorded in the free field (Fig. 7). This location is close enough to the structure to be affected by the cyclic normal stresses caused by rocking. Computed and recorded values agree closely.

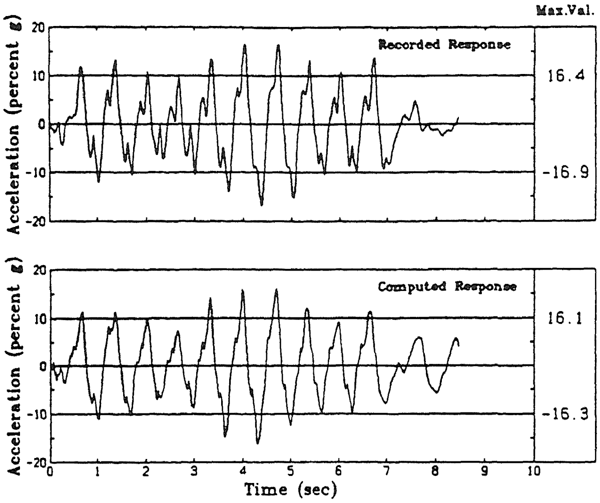

Fig. 4. Recorded and Computed Horizontal Accelerations at ACC 1938.

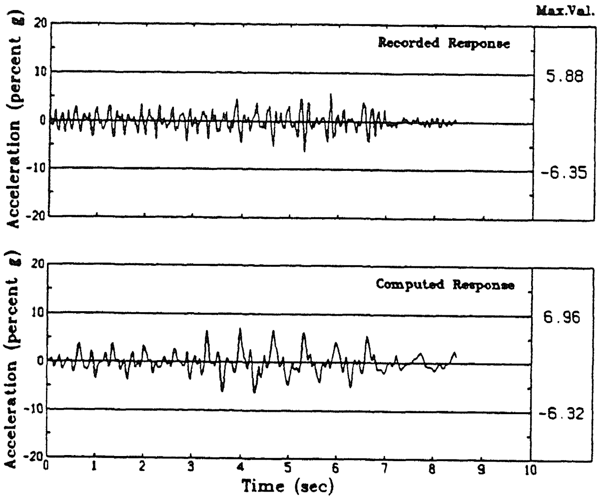

Fig. 5. Recorded and Computed Vertical Accelerations at ACC 1900.

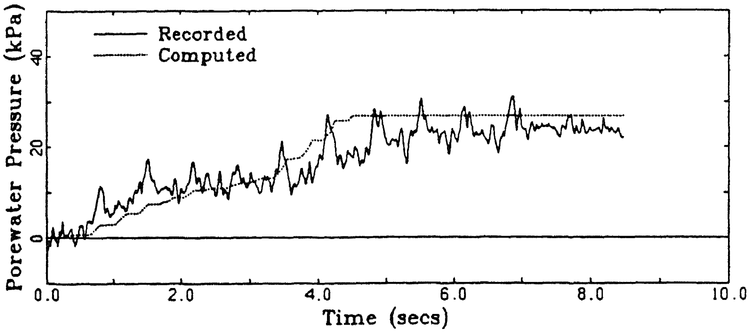

Fig. 6. Recorded and Computed Porewater Pressures at PPT 2851.

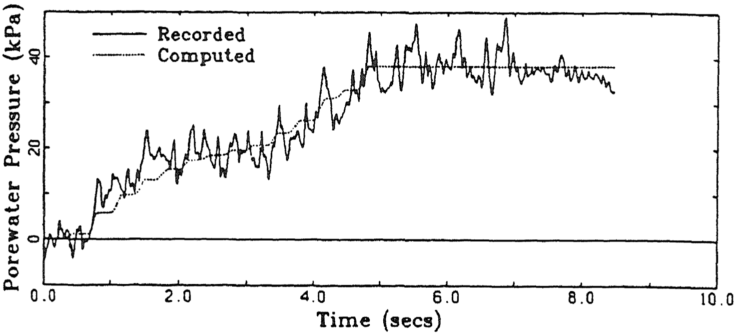

Fig. 7. Recorded and Computed Porewater Pressures at PPT 2846.

Stress-Strain Response The stress-strain response at the location of porewater pressure transducer PPT 2338 is shown in Fig. 8a. Hysteretic behaviour is evident but the response for the most part is not strongly nonlinear. This is not surprising as the initial effective stresses under the structure were high and the porewater pressures reached a level of only about 20% of the initial vertical effective stress. The response in the free field at the location of PPT 2851 (Fig. 8b) is strongly nonlinear with large hysteresis loops indicating considerable softening due to high porewater pressures and shear strain. At this location the porewater pressures reached about 80% of the initial vertical effective pressure.

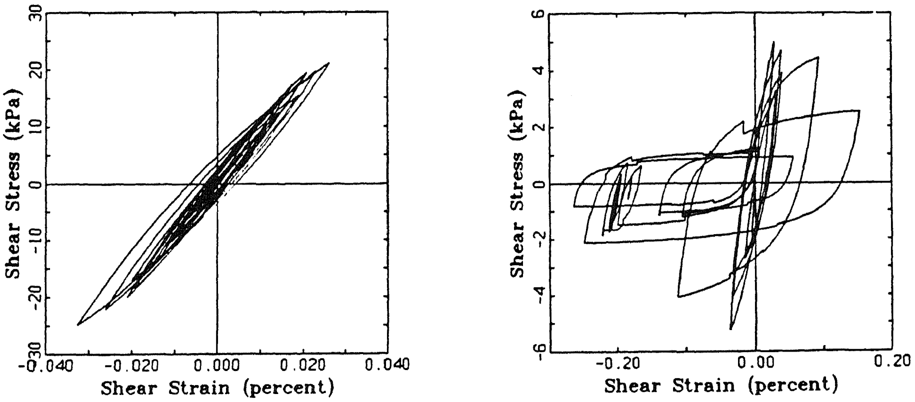

Fig. 8. Stress-Strain Response (a) Under the Structure and (b) in the Free Field.

CONCLUSION FROM VERIFICATION STUDIES OF TARA-3

The comparison between measured and computed responses for the centrifuge model of a structure embedded in a saturated sand foundation demonstrates the wide ranging capability of TARA-3 for performing complex effective stress soil-structure interaction analysis with acceptable accuracy for engineering purposes. Seismically induced residual porewater pressures are satisfactorily predicted even when there are significant effects of soil-structure interaction. Computed accelerations agree in magnitude, frequency content and distribution of peaks with those recorded. In particular, the program was able to model the high frequency rocking vibrations of the model structure. This is an especially difficult test of the ability of the program to model soil-structure interaction effects.

Other tests in the verification program were also simulated satisfactorily. Details of some of these simulations may be found in Finn et al. (Refs. 6,7,8) and Finn (Refs. 4,9).

ACKNOWLEDGEMENTS

This research was supported financially by the U.S. Government through the European Research Office of the U.S. Army and the National Science and Engineering Research Council of Canada under Grant No. 1498. The project was managed by W. Grabau and J.C. Comati of the European Research Office, U.S. Army London; R.H. Ledbetter of USAE Waterways Experiment Station, Vicksburg, Miss.; and L.L. Beratan, Office of Research, U.S. Nuclear Regulatory Commission. The centrifuge tests were conducted by R. Dean, F.H. Lee and R.S. Steedman of Cambridge Univerity, U.K., under a separate contract. The tests were under the general direction of A.N. Schofield, Cambridge University and were monitored by the first author on behalf of USAE. Description of model test and the related figures are used by permission of Cork Geotechnics Ltd., Ireland.

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