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DIRECT COMPUTATION OF PERMANENT SEISMIC DEFORMATIONS

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SUMMARY

The direct computation of permanent seismic deformations using the computer program TARA-3 is described. Examples include seismic foundation settlements and the 2-D deformation fields of soil structures. A detailed example from practice is presented involving the estimation of the seismic permanent deformations of the proposed Lukwi tailings dam in Papua New Guinea.

INTRODUCTION

Seismically induced permanent deformations are crucial to the damage potential and stability of structures. The computer program TARA-3 developed by Finn et al. (Ref. 1) allows the direct computation of permanent deformations. This program contains a nonlinear hysteretic effective stress constitutive model (Ref. 2) and its capability has been verified by simulated earthquake tests on centrifuged models (Refs. 3,4,5). Typical results from a centrifuge test are given in Fig. 1 which shows the measured and computed settlements of a surface footing on dry sand due to strong shaking.

In this paper attention will be focussed on the use of TARA-3 in estimating seismically induced permanent deformations in embankment dams.

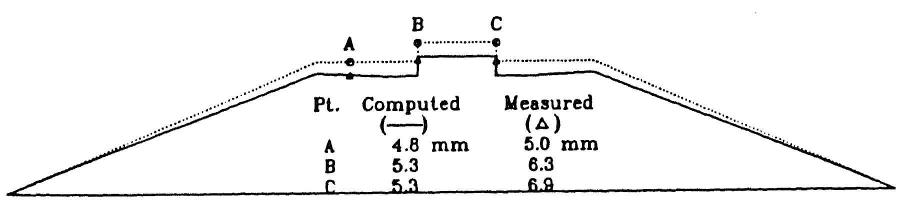

Fig. 1. Measured and Computed Settlements of Surface Structure in Dry Sand.

APPLICATION OF TARA-3 TO ANALYSIS OF DAMS

TARA-3 conducts both static and dynamic analysis. A static analysis is first carried out to determine the stress and strain fields throughout the cross-section of the dam at the end of construction. The program can simulate the gradual construction of the dam.

Dynamic analysis in each element of the dam starts from the static stress-strain condition. This leads to accumulating permanent deformations in the direction of the smallest residual resistance to deformation. Methods of dynamic analysis commonly used in practice ignore the static strains in the dam and start from the origin of the stress-strain curve in all elements even in those which carry higher shear stresses. TARA-3 also allows the analysis to start from the zero stress-strain condition, if it is desired to follow current practice.

As shaking proceeds, two phenomena occur; porewater pressures develop in saturated portions of the embankment and, in the unsaturated regions, volumetric strains and associated settlements develop. The program, by taking the effects of the porewater pressures on moduli and shear strengths into account can estimate the additional deformations due to gravity acting on the softening structure. At the end of the earthquake, additional settlements occur due to consolidation as the seismically induced residual porewater pressures dissipate. The final deformed shape of the dam results from the sum of permanent deformations due to the hysteretic dynamic stress-strain response, constant volume deformations in saturated portions and deformations due to consolidation as the seismic porewater pressures dissipate.

The post-earthquake deformed shape of an embankment with a central core is shown in Fig. 2. The water table is about 1.7 m below the crest. Only the

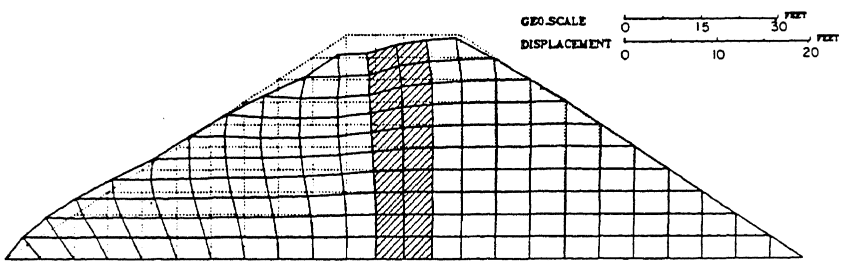

Fig. 2. Deformed Shape of Central Core Embankment After Earthquake.

upstream segment to the left of the core is saturated and generates high porewater pressure during earthquake shaking. Large deformations occur upstream and the core is strongly deformed towards the upstream side. Although the deformations in this case are contained, they are sufficient to cause severe cracking around the core.

LUKWI TAILINGS DAM

The seismic design of the proposed Lukwi tailings dam in Papua New Guinea posed some interesting problems because of the presence of siltstone, with low residual strength, below the downstream portion of the dam (Ref. 6). There was concern that the downstream slope might experience damaging deformations due to large movements in the siltstone during strong shaking. In order to explore the extent of the potential problem, a nonlinear dynamic effective stress analysis of dam and foundation was conducted using the computer program TARA-3.

The finite element representation of the Lukwi tailings dam is shown in Fig. 3. The sloping line in the foundation is a plane between two foundation

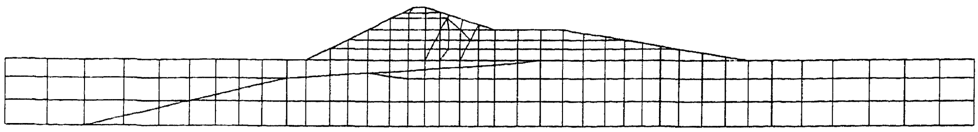

Fig. 3. Finite Element Idealization of Lukwi Tailings Dam.

materials. Upstream to the left is a limestone with shear modulus $G = 6.4 \times 10^6$ kPa and a shear strength defined by $c' = 700$ kPa and $\phi' = 45°$. The material to the right is a siltstone with a low shearing resistance given by $c' = 0$ and $\phi' = 12°$. The shear modulus is approximately $G = 2.7 \times 10^6$ kPa. The difference in strength between the foundation soils is reflected in the dam construction. The upstream slope on the limestone is steep whereas the downstream slope on the weaker foundation is much flatter and has a large berm to ensure stability.

DYNAMIC RESPONSE

The dam was subjected to strong shaking with a peak acceleration of 0.33 g (Fig. 4). The shear stress-shear strain response of the limestone foundation is almost elastic as shown in Fig. 5.

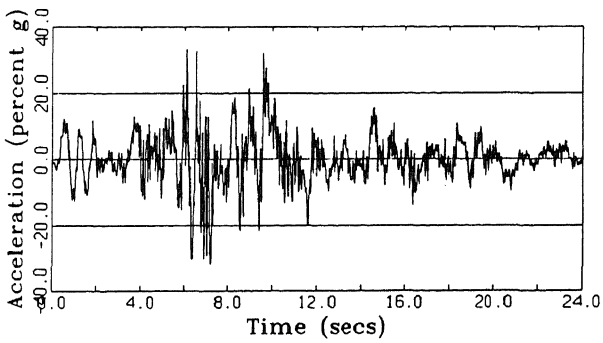

Fig. 4. Input Motions for Dynamic Analysis of Dam.

The response of the siltstone foundation is strongly nonlinear. The deformations increase progressively in the direction of the initial static shear stresses as shown in Fig. 6. Since the analysis starts from the initial post-construction stress-strain condition, subsequent large dynamic stress impulses move the response close to the highly nonlinear part of the stress-strain curve. It may be noted that the hysteretic stress-strain loops all reach the very flat part of the stress-strain curve, thereby ensuring successively large plastic deformations.

An element in the berm also shows strong nonlinear response with considerable hysteretic damping (Fig. 7).

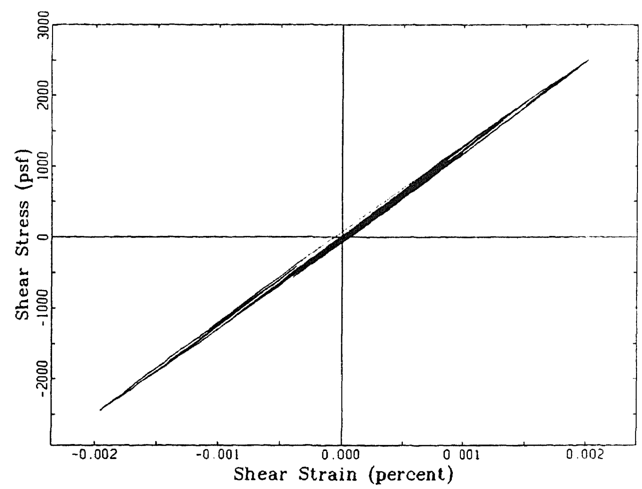

Fig. 5. Shear Stress - Shear Strain Response of Limestone Foundation.

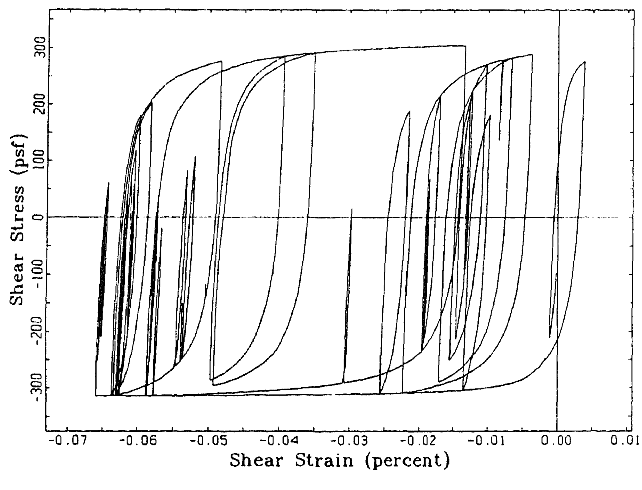

Fig. 6. Shear Stress - Shear Strain Response of Siltstone Foundation.

The acceleration time history of a point near the crest in the steeper upstream slope is shown in Fig. 8. The displacement time history of the point is shown in Fig. 9. Note that the permanent deformation is of the order of 25 cm. Most of this was generated by a large permanent slip which occurred about 8 secs after the start of shaking. The deformed shape of the central portion of the dam is shown at an enlarged scale in Fig. 10.

CONCLUSIONS

The program TARA-3 can compute directly the permanent deformations of earth and rockfill dams under seismic loading. The utility of TARA-3 in practice was demonstrated by the analysis of Lukwi tailings dam. Computed stress - strain

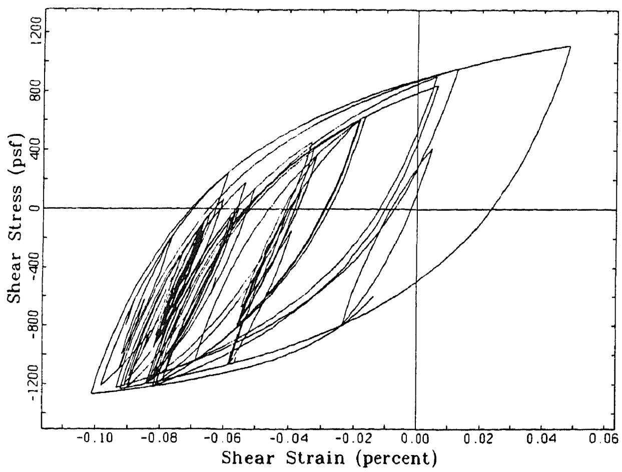

Fig. 7. Shear Stress - Shear Strain Response of Berm.

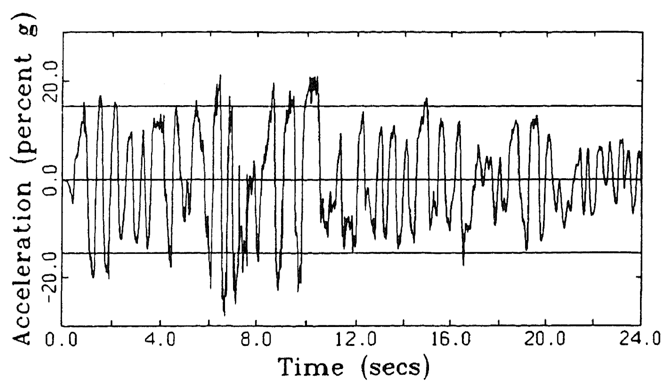

Fig. 8. Computed Accelerations of a Point Near the Crest.

responses in various parts of the dam show clearly the widely different response characteristics. The sound foundation rock under the upstream slope shows almost elastic response. The siltstone foundation with low residual strength under the downstream slope shows strongly nonlinear response to the design earthquake as does the rock fill in the dam embankment. Time histories of displacements including permanent displacements are provdied.

In this case nonlinear dynamic effective stress analyses provides the designer with a very clear overall picture of seismic response. In addition it gives all details necessary in zones of potential concern.

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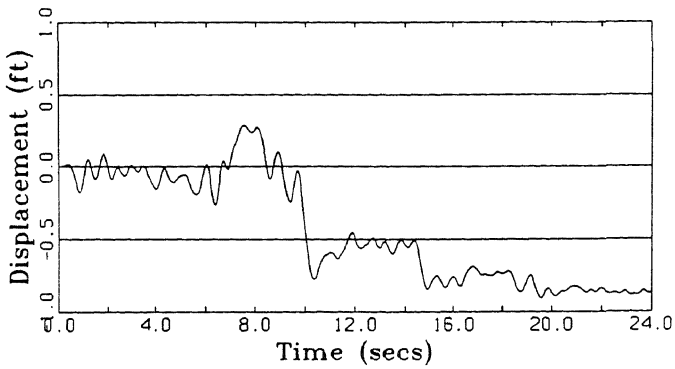

Fig. 9. Displacement History of Point Near the Crest.

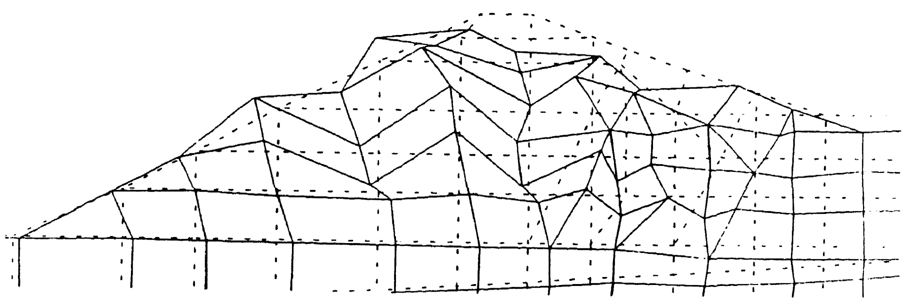

Fig. 10. Deformed Shape of the Dam After Earthquake to Enlarged Scale.

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