EARTHQUAKE RESISTANCE OF DRYDOCKS

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SUMMARY

This paper investigates the earthquake resistance of a typical drydock to earthquake motions. Psuedo-static earthquake forces and finite element methods are used to investigate the problem. Stress distribution on the cold joints is investigated. The normal stress distribution across a horizontal section is not linear. The computer results show that the overall stress levels in concrete are below 500 psi in compression and about 180 psi in tension. The analysis from this paper shows that the drydock appears to be safer from the predicted pseudo static earthquake force than results from the simplified conventional stress analysis.

INTRODUCTION

Graving drydocks are massive concrete structures used for the repair of ships and are of critical importance to the commercial and defense needs of the country. Many of these drydocks exist on the West Coast of the USA and other parts of the world where earthquake occurrence is highly probable. The conventional design practice of these drydocks is based on simple beam theory which assumes that the strain distribution is linear across the section and also neglects the tension in the concrete. The bottom slab of the drydock is designed on the basis of "Beams on Elastic Foundations." The walls of the drydock are lightly reinforced. The drydock selected for analysis was originally designed in 1937 with little attention paid to earthquake forces. The present paper describes a pseudo-static earthquake analysis using refined finite element analysis and current field data on material properties. Effects due to weakness across horizontal construction joints are also discussed.

DESCRIPTION OF GRAVING DRYDOCK DD3

The graving drydock DD3 used in this study was designed in 1937 by the U.S. Naval Facilities Engineering Command (NAVFACENGCOM) (formerly the Navy Bureau of Yards and Docks) and constructed in 1940. It is 693 feet long. The drydock floor and walls are supported by many rows of wooden piles driven into stiff clay. Each row consists of 39 piles and are spaced longitudinally at 2.5-foot centers. In the middle section, the piles are spaced at 4-foot centers, while beneath the drydock walls, the spacing is 2.75-foot centers. The middle five piles of each row have special keys (notches) in the top of the piles and are embedded in the concrete to resist uplift. During the latter part of 1981, the thickness of the drydock floor was increased by 1.5 to 2 feet. The original design was based on equivalent fluid pressure of 85 psi acting on the side walls. The minimum specified strength of concrete is given by $f_c' = 2{,}500$ psi.

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FINITE ELEMENT ANALYSIS OF DD3

The finite element analysis is based on the present condition of DD3 with increased floor thickness.

FEM Model and Physical Parameters

Figure 1 shows the details of FEM model of the drydock and appropriate dimensions. There is 4' x 4' flooding tunnel on one side of the wall and horizontal construction (cold) joints at three levels. The top of the drydock is connected to the foundation of the crane rails through concrete ties.

EASE2 (Ref. 1) finite element program was used to analyze DD3 for a number of loading conditions and parameteric variations. The finite element mesh of the drydock was generated, using computer graphics and a software program called UNISTRUC II (Ref. 2). The drydock was considered as a plane strain problem and with linear, elastic, isotropic material. Reinforcement steel is not included in the model.

Material Properties

Since the drydock is a massive concrete structure, it is very important to use the appropriate concrete properties for the analysis. Reference 3 discussed the type of concrete property values to be used for computer models of massive structures similar to mass concrete dams.

Tests have been conducted on the concrete cores from DD3 (Ref. 4). Cores have been taken from various locations and across the construction joints. Tests on these cores show an average strength of 5,879 psi with two high values at 7,200 psi and one very low value of 2,950 psi. This seems to agree with the general trends observed in Reference 3. For this study the following values are used:

$$\begin{aligned} f'_c &= 4{,}800 \text{ psi} = \text{low} \\ &= 5{,}800 \text{ psi} = \text{average} \\ &= 6{,}800 \text{ psi} = \text{high} \end{aligned}$$

A concrete density of $w = 150$ pcf was used in the earlier studies and for this report.

The modulus of elasticity of concrete was computed by using the following empirical equation:

$$E_c = w^{1.5}\ 33 \sqrt{f'_c}$$

Using the above formula, the following three values are obtained for the modulus of elasticity of concrete using the three f'_c values given earlier.

$$E_c = 4{,}200{,}000 \text{ psi}; \quad 4{,}600{,}000 \text{ psi}; \quad 5{,}000{,}000 \text{ psi}$$

For the computer model, a value of $E_c = 4{,}600{,}000$ psi and a value of Poisson's Ratio $\nu = 0.2$ are used.

Pile Supports

In DD3 there are 39 piles in each row and each row of piles is at 2.5-foot centers along with longitudinal axis of the drydock (Figure 1). Each timber pile is about 52 feet long and 13 to 14 inches in diameter at the top, and 9 to 10 inches in diameter at the bottom, and an average diameter of 11 inches in the middle. The allowable load on each pile is 50 kips. For each pile, the average stiffness value is 1,200,000 lb/ft width of dock. The stiffnesses of crane girder ties are shown in Figure 2.

Lateral Soil Stiffness on Drydock Walls

For the earthquake loading, the inertial forces of the wall push into the soil on one side (passive pressure) and the inertial force of the wall and some amount of soil will act on the other side (active pressure). As far as the soil stiffness on the active side is concerned, the additional soil acts as a load on the wall and no stiffness of the soil is assumed. However, on the passive side, the wall will push into the soil and the spring stiffness of the soil needs to be considered. In the FEM the soil springs are attached to each exterior node of the drydock. The stiffness of the soil near the top of the dock will be very small and is assumed to increase linearly with depth.

Considering the very small movements of the wall, it is judged adequate to use an equivalent K_s = 300,000 pcf at the bottom of the wall to K_s = 0 pcf at the top. Using a computer program, this linearly varying stiffness is converted to discrete spring stiffness at each nodal point.

Load on the Drydock

For the FEM analysis, the full hydrostatic uplift pressure of 3,250 lb/ft^2 of dock is used.

The lateral pressure on the walls due to saturated soil is assumed to vary linearly using the conventional procedures and is equal to 131,800 lbs/ft of wall.

When the dock is empty, the net upward force on the full hydrostatic pressure is equal to 77,600 pounds. Part of this uplift force will be resisted by the tensile capacity of the piles embedded into the floor, and the remaining forces will be resisted by the friction on the drydock wall.

For the FEM model study of the dock, it is assumed that 50% of net uplift forces are resisted by 50% friction on walls with piles providing the remaining 50% resistance.

The FEM model used 780 psf of additional lateral pressure on drydock walls due to soil effects. This pressure is uniformly distributed along the height of the wall and acts on one side only. In addition, the program automatically used a 0.2g inertial load generated due to the mass of drydock.

Effect of Construction Joints

Construction joints are used during the construction of massive structures between various pours and stages of construction. Figure 1 shows DD3 with construction joints at several places; in the vertical wall there are three construction joints. From the earlier calculations, the section at the construction joint, near the flooding tunnel, is the most critical of the horizontal joints. There are also two shear keys at this joint.

The intent of the construction joint is to make the two pours (at different times) integral as much as possible, but nonetheless these are weak spots. The Army Waterways Experiment Station (WES) (Ref. 5) has studied some of these aspects in great detail by performing static tests. Using this information and the field tests (Ref. 4), the following values are judgementally estimated for the direct tensile, shear, and flexural strength:

Direct tension = 200 psi
Split cylinder tensile strength = 450 psi
Flexural tensile strength = 500 psi

For the approximate study made for the stability analysis of the drydock wall, a very conservative value of 100 psi is assumed for the flexural tensile strength.

Discussion of Results of Finite Element Analysis for a Typical Case

A total of 14 computer runs were made on the finite element model. Run 11 studies the FEM model with parameters shown in Figure 2. The movement of the wall at the top is around 0.012 feet or 0.15 inches. Figure 3 shows the stress distribution across critical sections. The maximum compressive stress is about 300 psi, and the maximum shear stress is about 150 psi. The maximum tensile stresses are in the range of 60 psi.

Fourteen runs were made to study the effect of various parameters and to determine the stress conditions under various loading conditions, including static earth pressure, earthquake, and ship loads. Run 14, similar to run 11 but with the spring resistance of concrete ties at the top of the dock walls removed, had a maximum compression stress of 320 psi, and a maximum tensile stress of 180 psi across the construction joint. The analysis showed that the zone near the flooding tunnel with a construction joint was the most critical of all the sections (Ref. 6).

CONCLUSIONS

The finite element study indicated that the overall stresses in the dock are very low. Even in the most severe case - earthquake occurrence when the dock is empty, with no assistance from concrete ties - the maximum tensile stresses across the construction joint are around 180 psi and maximum compressive stresses are less than 320 psi. For these low stresses, it is judged that concrete in the tensile regions will not crack, and the dock walls will not overturn. The test data showed that the average strength of concrete in the dock is 5,879 psi, and thus the average direct tensile strength of concrete is 226 psi.

The lateral displacements of the walls at the top are very small, and in the most severe case it is less than 0.3 inch. This displacement is not adequate to generate large failure planes.

In summary, the finite element analysis showed that the stresses generated by earthquake forces are within the capacity of the drydock.

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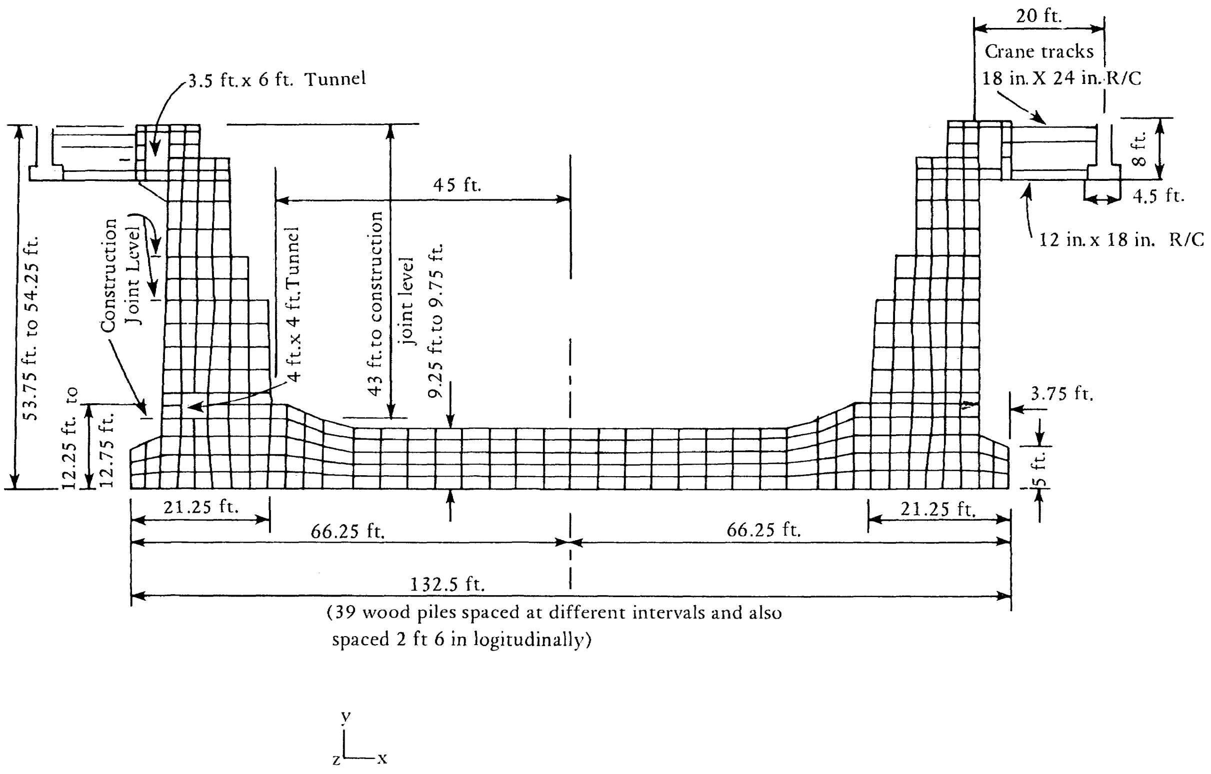

Figure 1. Drydock DD3 model dimensions.

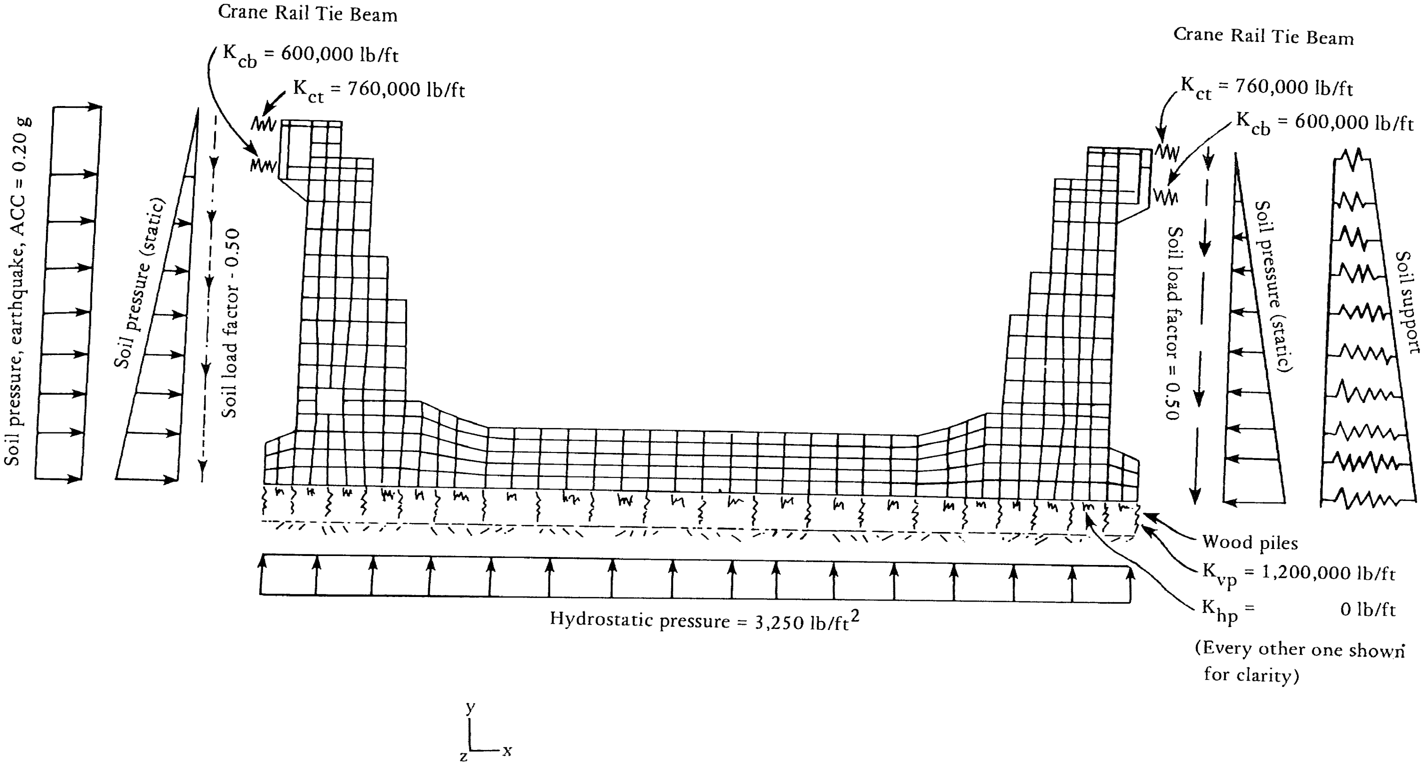

Figure 2. Drydock DD3 model showing conditions for run 11.

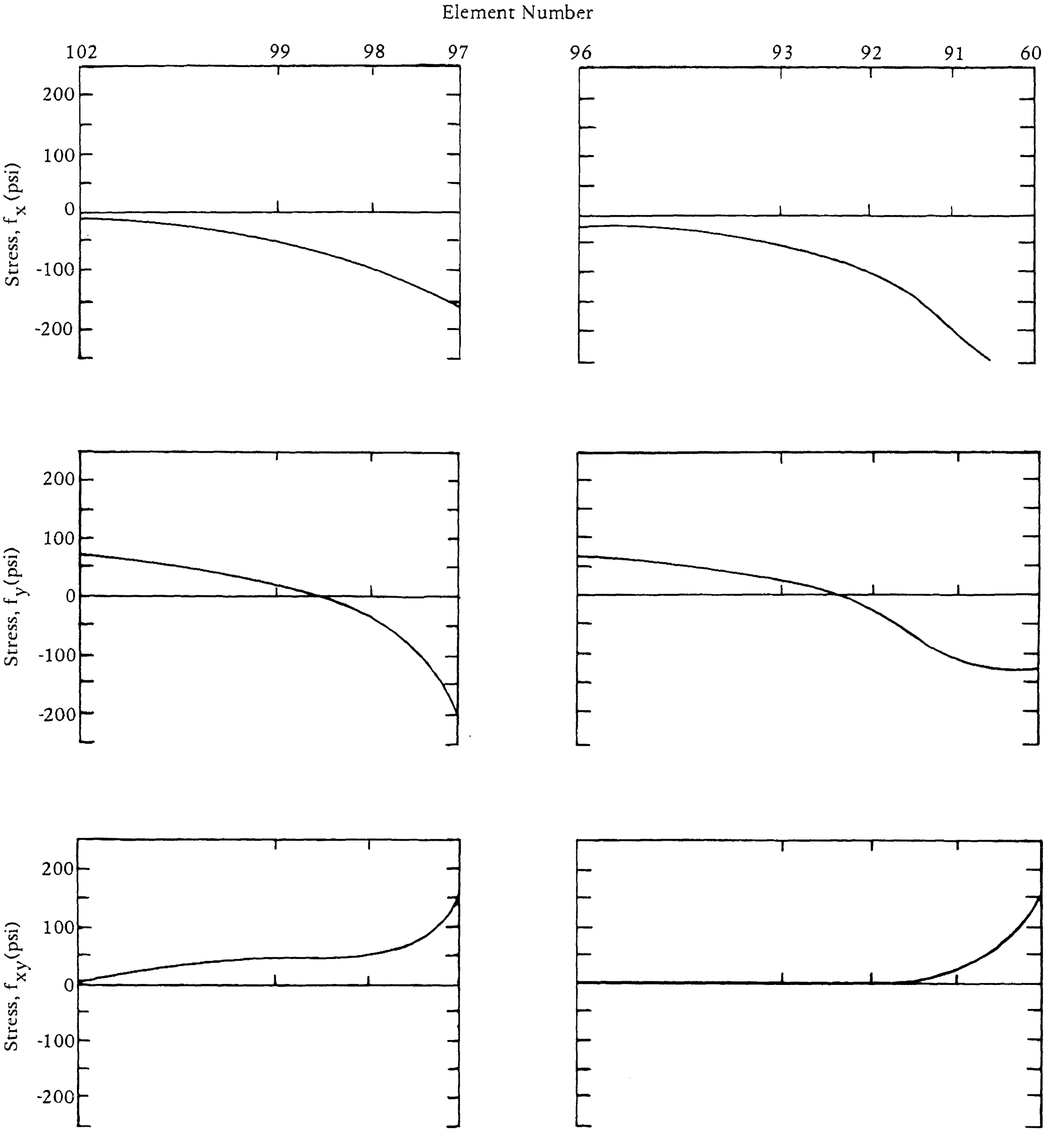

Figure 3. Drydock DD3 Model, stresses at centroid of element, showing results of Run 11.