SEISMIC DESIGN OF PORT OF LOS ANGELES' PIER 400: A GEOTECHNICAL ENGINEERING PERSPECTIVE

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SUMMARY

The recently completed Pier 400 landfill project within Port of Los Angeles, a high seismic area, produced 235 ha of new land and posed unique design challenges. Pier 400 design team effectively combined centrifuge model tests, analyses using a fully coupled dynamic finite element computer code, DYSAC2, and traditional pseudo-static slope stability analyses, and Newmark's sliding block method to produce a safe and economic design in a timely manner. Centrifuge model tests results were used to validate the DYSAC2 predictions and to study the deformation mechanisms. Centrifuge model tests and DYSAC2 predictions indicated that the primary movement of the dike would be a rigid body motion with majority of the displacements occurring in the foundation layer immediately below the dike. This predicted rigid body motion allowed the design team to utilize Newmark's sliding block method to calculate the lateral deformations. However, DYSAC2 predicted average excess pore pressures were still used in the pseudo-static slope stability analyses to calculate the yield accelerations for the sliding block method.

INTRODUCTION

To accommodate the projected increase in Pacific-rim trade, Port of Los Angeles (POLA) has recently created 235 ha of new land called Pier 400 by dredging and landfilling behind approximately 6 km of rock dikes (Fig. 1). The POLA is situated in a high seismic area. The proposed facilities to be developed on the Pier 400 include container handling terminals and liquid bulk facilities which may handle crude oil and petroleum products. These facilities, if damaged during seismic events, could cause severe disruption to the flow of goods and products into and out of POLA with major consequences to the economy (Wittkop, 1993). The threats of fire and explosion during an earthquake are also of concern. Therefore, the dikes and landfill utilized for Pier 400 must be designed to safely withstand earthquake-induced loads. On the other hand, the dikes and landfill cannot be over-designed due to cost considerations. In order to ensure safety and economy, POLA wanted to use the most advanced analyses and design methods available. Accordingly, POLA chose a fully coupled, elastoplastic, dynamic finite element code DYSAC2 (Muraleetharan et al., 1988, 1997b) and centrifuge model testing to validate DYSAC2 for the analysis of rock dike retaining structures. Centrifuge testing was also used to provide potential deformation mechanisms for Pier 400 during earthquake loadings. The results from DYSAC2 together with traditional embankment analysis techniques and engineering judgement based on experience were used to produce a viable and safe seismic design of Pier 400 dikes and landfill.

This paper first, briefly describes the POLA's seismic design criteria consisting of two levels of earthquakes, namely, an Operational Level Earthquake (OLE) and a Contingency Level Earthquake (CLE). Centrifuge testing program is then summarized and key conclusions are discussed. Next, computer code DYSAC2 is described. DYSAC2 analysis performed on a cross-section of Pier 400 is then described in detail. Finally, how the results obtained from DYSAC2 analyses were incorporated into the traditional embankment analysis techniques in the design of Pier 400 is discussed.

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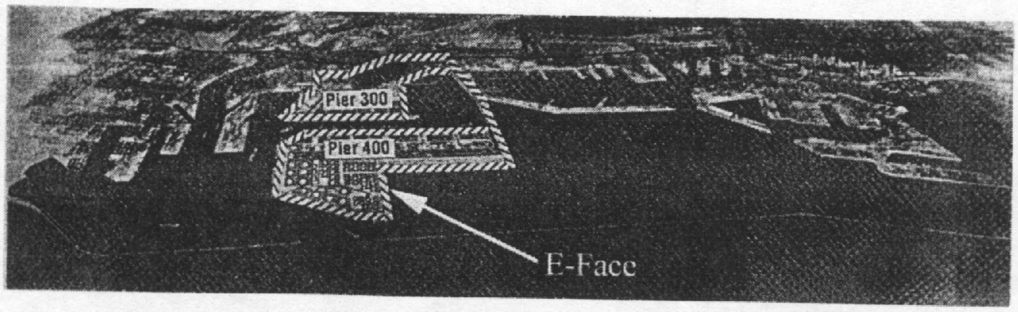

Figure 1: Port of Los Angeles Outer Harbor Area and Pier 400

SEISMIC CRITERIA

POLA's seismic design criteria call for evaluating all the structures for two levels of earthquakes. The two levels of earthquakes are namely, Operating Level Earthquake (OLE) and the Contingency Level Earthquake (CLE). During an OLE event, wharf structures are to sustain only minor non-structural damage and should remain in service following the event. During a CLE event, some damage to wharf structures is expected but still total collapse should be prevented. Container cranes should be operational after repairs to support systems following a CLE event. For POLA, OLE and CLE are earthquakes having return periods of 72 years and 475 years, respectively. Primary seismic hazard to POLA facilities comes from the Palos Verdes fault. The contribution from the Newport-Inglewood fault virtually accounts for all non-Palos Verdes fault related seismic hazard at POLA (Earth Mechanics, 1993). The infamous San Andreas fault is some distance away from POLA to contribute meaningfully to the seismic hazard. Earth Mechanics (1993) performed a probabilistic seismic hazard analysis for the Pier 400 project. The details of this analysis are beyond the scope of this paper. Earth Mechanics (1993) also determined that the peak ground acceleration (PGA) for an OLE event is 0.24 g and for a CLE event is 0.45 g. These accelerations were later revised upwards to 0.28 g and 0.52 g, respectively, for OLE and CLE events (Earth Mechanics, 1996). Together with these PGA values and spectral acceleration considerations, Earth Mechanics chose a number of acceleration-time histories for the design purposes. The acceleration-time histories selected through the seismic hazard analyses were considered as firm-ground outcrop motions in the subsequent deformation analyses.

CENTRIFUGE MODELING

The use of dynamic centrifuge modelling in providing insights into dynamic behaviour of geotechnical models has been widely accepted. In the absence of data from instrumented sites during actual earthquakes, centrifuge modeling is a valuable tool in providing data for the validation of computer codes as well as insights into the deformation/failure mechanisms of similar prototypes (Arulanandan and Scott, 1993).

As a part of the Pier 400 project, several dynamic centrifuge tests were performed in the centrifuge facilities available at the University of California, Davis (UCD), and the California Institute of Technology (Caltech). These tests were performed by the researchers from UCD (Arulanandan and Zeng, 1993) and Caltech (Scott et al., 1993) in general accordance with the specifications provided by the Pier 400 design team (Earth Technology, 1993). The centrifuge configurations were selected to broadly represent the general features expected at the Pier 400 site. No attempt was made, nor was it practical, to exactly model the configurations of the Pier 400 site and the dike retaining structure in centrifuge experiments. Some of the essential features that are common to the centrifuge configurations and the Pier 400 sections are the stratified nature of the foundation soils and a coarse-grained dike retaining a fine-grained sand backfill. Nevada Sand and Bonnie Silt used in the VELACS project (Arulanandan and Scott 1993) and a fine gravel ($D50 = 5.5$ mm) were chosen as model soils for the centrifuge tests. The fine gravel used in the centrifuge tests was selected for two reasons: to retain the backfill and to act as a drainage boundary without generating any residual pore pressures within the dike. These are, in fact, two important features of a prototype rock dike.

More details of the centrifuge testing can be found elsewhere (Muraleetharan et al., 1997a). When the gravel dike alone was subjected to base shaking, very little deformations were observed. However, when the dikes were constructed on sand or silt foundations and were retaining backfill sand, substantial lateral movements were recorded. Virtually all the lateral displacements were concentrated within the first foundation layer whether it was sand or silt. Although some flattening of the dike was observed, predominant mode of movement of the dike was in rigid body motion dragging the first foundation layer with it. Sand backfills also showed substantial vertical settlement as expected since the models were tested in "as-placed" conditions. No excess pore pressures were recorded within the dikes.

COMPUTER CODE DYSAC2

The computer code DYSAC2 (Muraleetharan et al., 1988, 1997b) is based on fully coupled dynamic governing equations for a saturated porous media (soil skeleton and pore fluid). The details of this formulation and numerical implementation are given in Muraleetharan et al. (1994a). Nodal variables per node are two soil skeleton and two fluid displacements. In DYSAC2 stress-strain behaviour of the soil skeleton can be described by isotropic linear elastic model and bounding surface elastoplastic models. Two constitutive models based on the bounding surface plasticity theory are used in DYSAC2: one for cohesive soils (Dafalias and Herrmann 1986) and another for non-cohesive soils (Yogachandran 1991). Both the constitutive models were used in the design of Pier 400. Validation of DYSAC2 predictions for dike retaining structures using the above described centrifuge model tests results can be found elsewhere (Muraleetharan et al., 1994b; Wittkop 1993). DYSAC2 was able to successfully reproduce displacements, accelerations, and pore water pressures, including the rigid body type motions of the gravel dike described above.

DESIGN OF PIER 400

DYSAC2 Analysis of a Section Along the E-Face

An idealized cross section along the E-Face (see Fig. 1) of Pier 400, based on the information gathered during the geotechnical investigations for the project (Fugro-McClelland, 1992), is shown in Fig. 2. The foundation soils consist of Holocene Sands underlain by Undifferentiated Deposits, which in turn is underlain by Older Alluvial Deposits (Gaspur Formation). Undifferentiated Deposits are layered deposits of clay, sand and silt and Gaspur formation is a sand. For the DYSAC2 analyses, the Undifferentiated Deposit was considered to consist of equal thicknesses of clay, sand, and silt. The as-built (unimproved) landfill soils were assumed to be placed at approximately 45% relative density. For the operational conditions, the landfill soil behind the dike was assumed to have been improved to a relative density of about 75% over a distance of 45.7 m from the centreline of the dike and to about 60% beyond that distance. Soil that is trapped under the tails of the lower dike lifts is assumed to be unimproved. External loads corresponding to container operations were considered for operational conditions.

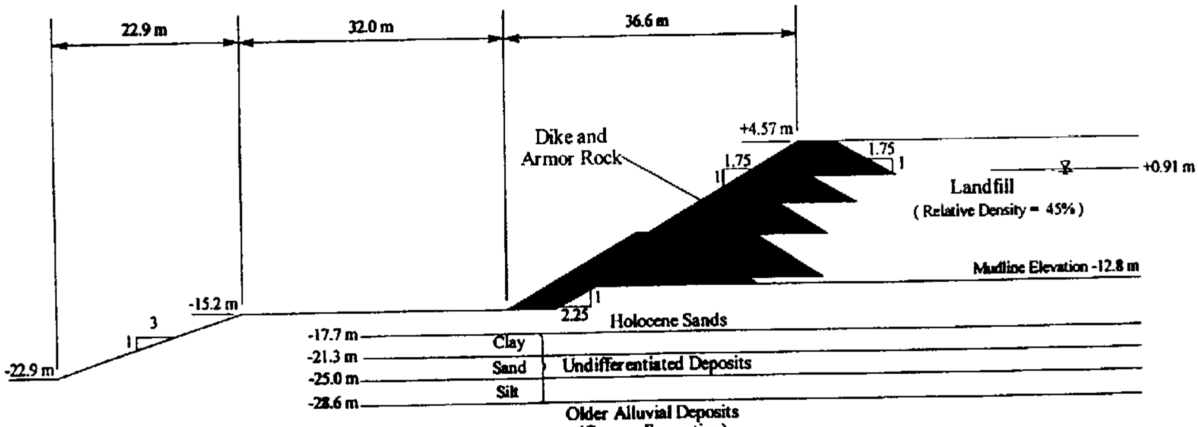

Figure 2: An Idealized Cross Section Along the E-face of Pier 400

The bounding surface constitutive model for non-cohesive soils was used for landfill soils, Holocene Sands, sand and silt in the Undifferentiated Deposits, and Gaspur Formation. The bounding surface model for cohesive soils was used to represent the clay in the Undifferentiated Deposits. The constitutive model parameters were calibrated using laboratory triaxial tests results and liquefaction strength curves obtained from field data.

One of the DYSAC2 input motion used in the analyses is shown in Fig. 3. The outcrop motion corresponding to the DYSAC2 input motion shown in Fig. 3 is the 1933 Long Beach Earthquake, Public Utility Building, North component record scaled to a PGA of 0.45 g (referred to as Long Beach Motion). This particular value of PGA corresponds to the PGA of a CLE event used in the initial stages of the design as described previously. The input motion for DYSAC2 was obtained by assuming that the top of the Gaspur Formation (Fig. 2) is the outcropping layer and using the 1-D computer code SHAKE (Scanabel et al., 1972) to obtain the motion at 6.1 meters below the top of the Gaspur Formation (base for the DYSAC2 analysis). A layer of Gaspur Formation, with a thickness of 6.1 meters, was also considered in the analysis to take into account the possible drainage into this formation. Soil below 6.1 meters of Gaspur Formation is assumed rigid in the DYSAC2 analysis.

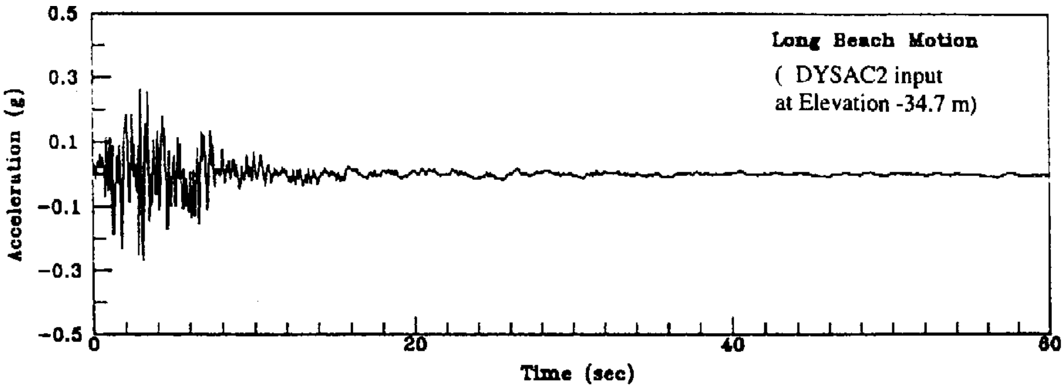

Figure 3: A DYSAC2 Input Motion Used in the Analyses

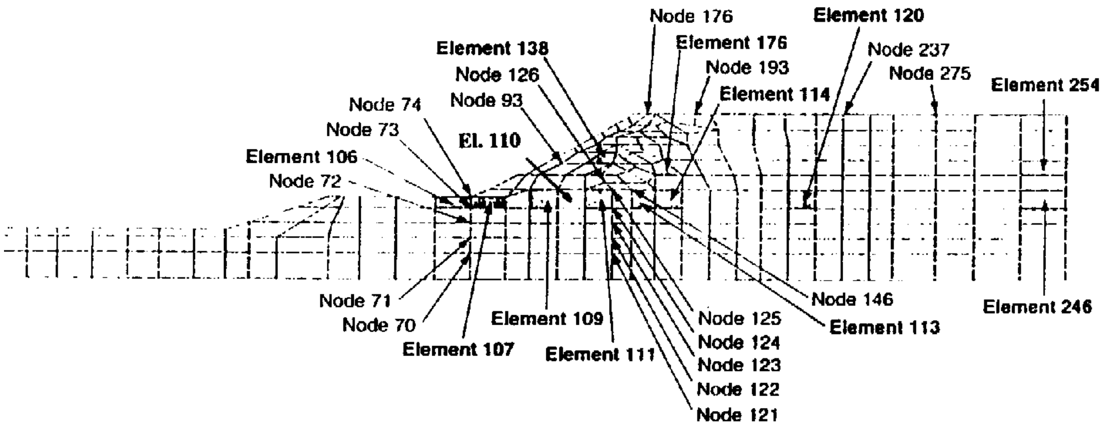

Figure 4: Finite Element Mesh Used in the DYSAC2 Analysis of the E-Face

The finite element mesh used in the DYSAC2 analysis is shown in Fig. 4. Also shown in this figure are numbers of key elements and nodes. The analysis described in this section was performed for the operational conditions. Prior to performing the dynamic analysis, a static analysis was performed to obtain the initial stresses required for the dynamic analysis. The dynamic analysis was performed up to 45.0 seconds. The horizontal displacement-time histories at the crest and toe of the dike, and at approximately mid-point on the dike slope are shown in Fig. 5. Final displacements at various points within the dike and landfill are given in Table 1. Based on Fig. 5 and Table 1, it can be concluded that, similar to centrifuge models, the dike moves as a rigid body with primary contributions to lateral deformations coming from the first foundation layer, the Holocene Sand. Excess pore pressure-time histories within the Holocene Sand are shown in Fig. 6. It can be seen from Fig. 6 that while Holocene Sand elements just outside the dike (El. #106 and #114) dilates during shaking, the element underneath the dike (El. #110) liquefies (excess pore water pressure = initial effective vertical stress). Holocene sand element underneath the landfill (El. #120) generates an excess pore pressure ratio of about 75%. Higher excess pore pressure ratios underneath the dike than in the free field were also observed in some centrifuge tests and for another outcrop motion (Orion Boulevard Motion: 1971 San Fernando Earthquake, Orion Boulevard, N00W component) used in the Pier 400 design. However, for a third outcrop motion (El Centro Motion: 1940 Imperial

Valley Earthquake, El Centro Station, S00E component), more pore pressures were generated outside the dike than underneath the dike. For the El Centro Motion, lateral displacements were very well distributed among the foundation layers, rather than being concentrated in the Holocene Sands. The lateral displacement of the toe of the dike was 1.01 m compared 1.43 m for the Long Beach Motion. Therefore, it was concluded that the excess pore pressure generated underneath the dike is the primary cause of lateral displacements. These excess pore pressures were also expected to exhibit some dependence on the base motions.

Table 1: Displacements within the Dike and the Foundation Predicted by DYSAC2 Using the Long Beach Motion for E-Face Operational Conditions

Displacement of Dike Slope (m)						Horizontal Displacement at Top of Different Foundation Soil Layers Below the Toe of the Dike (m)				
Crest		Toe		Middle						
Hor.	Ver.	Hor.	Ver.	Hor.	Ver.	Gaspur	Un. Diff. Deposit - Silt	Un. Diff. Deposit - Sand	Un. Diff. Deposit - Clay	Holocene Sand
1.43	0.58	1.43	0.27	1.62	0.24	0.03	0.09	0.15	0.42	1.43

Following the initial analyses of Pier 400 cross sections, several soil-structure interaction analyses were later performed (Muraleetharan 1998) to take advantage of the reinforcing effects of piles along container terminals in restricting the lateral displacement of the dikes.

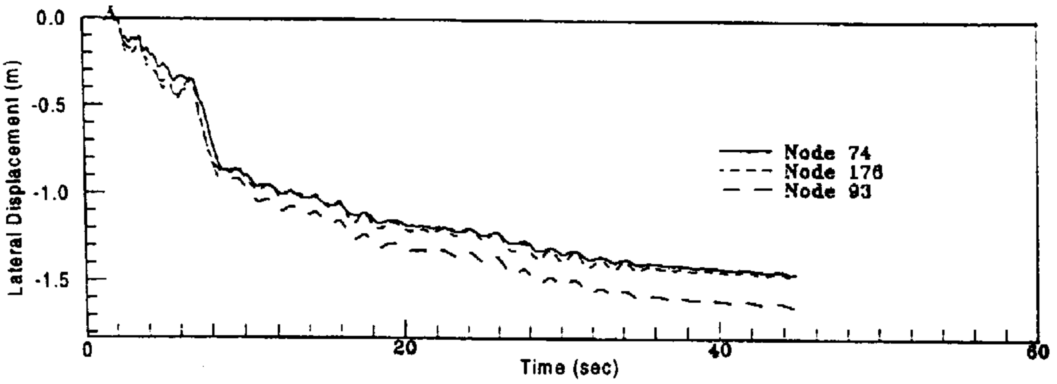

Figure 5: Displacement-Time Histories within the Dike Predicted by DYSAC2

Combination of DYSAC2 Results and Traditional Embankment Analysis Techniques

Rigid body motion of the dikes seen in centrifuge tests and DYSAC2 analysis of Pier 400 cross sections presented an opportunity to use simplified Newmark's sliding block analysis to predict the lateral movement of the dikes. Lateral displacement of the crest of the dike for E-Face predicted by DYSAC2 for the Orion Boulevard Motion and unimproved conditions is compared with the a Newmark's analysis using an yield acceleration of 0.04 g and the outcrop motion in Fig. 7. It can be seen that Newmark's sliding block analysis matches the DYSAC2 displacements fairly accurately. However, the difficult task is to find the correct yield acceleration using a pseudo-static slope stability analysis. The Pier 400 design team decided to use average pore water pressures predicted by DYSAC2 underneath the dike and landfills in the slope stability analyses to calculate the yield accelerations of various Pier 400 cross sections. Accordingly, all the unimproved landfill sands were assumed to liquefy during shaking and a residual strength of 9.6 kPa was used in the pseudo-static slope stability analyses. No excess pore pressures were assumed for the rock dike and landfill material above the water level. Holocene Sands lying outside the toe of the dike are expected to undergo dilation during shaking and no excess pore pressures were assumed for these sands. For Holocene Sands lying underneath the dike and the landfill, and the improved landfill excess pore water pressures were varied according to PGA values. For example, for a PGA of 0.45 g, 40% and 50% excess pore pressure ratios were used in Holocene Sands and improved landfill, respectively.

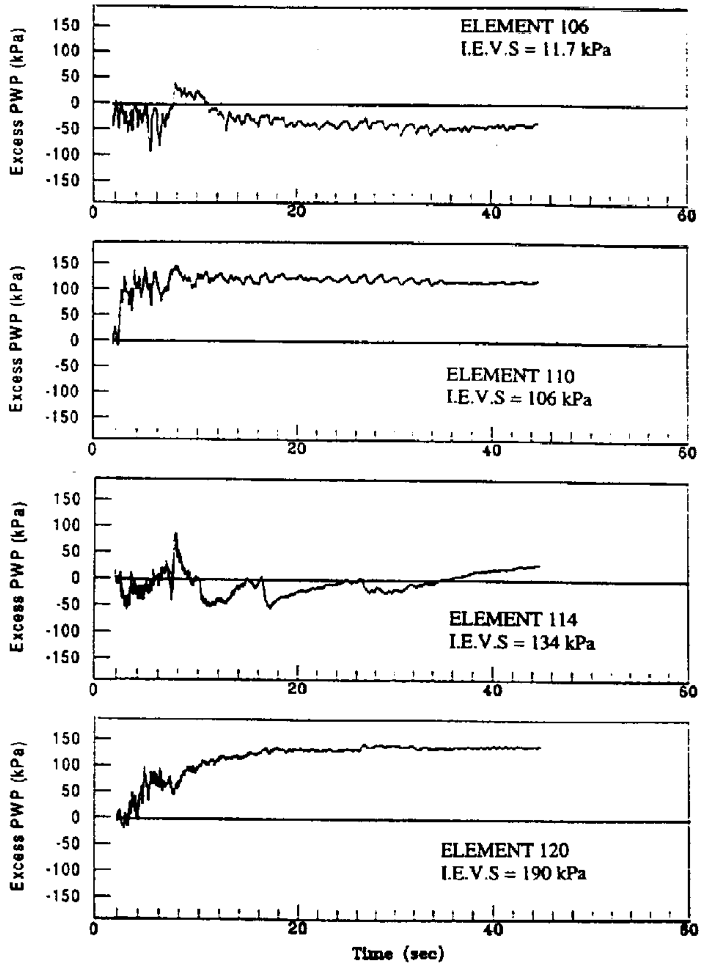

Figure 6: Excess Pore Water Pressure-Time Histories within the Holocene Sand Predicted by DYSAC2 (I.E.V.S. = Initial Effective Vertical Stress)

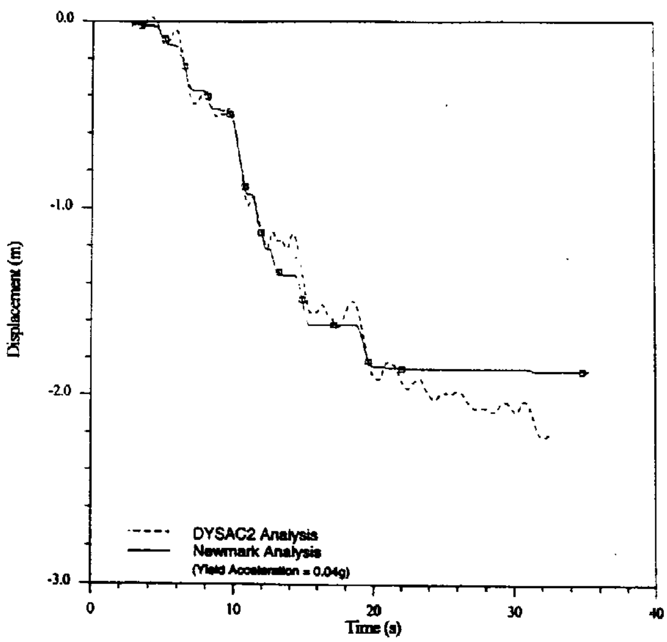

Figure 7: Comparison of Horizontal Displacement-Time Histories Obtained by DYSAC2 Analysis and Newmark's Method.

With the above mentioned pore pressure parameters, for a trial E-Face cross section (comparable to Fig. 2) a yield acceleration value of 0.039 g was calculated using a slope stability analysis and a block type failure. With sufficiently accurate comparisons between Newmark's sliding block analysis and DYSAC2 predicted lateral displacements of dikes, Newmark's sliding block analysis with the above mentioned pore pressure parameters were extensively used in designing various cross sections along the perimeter of Pier 400. This approach was efficient in minimizing the computational cost and the time taken for the design.

CONCLUSIONS

The recently completed Pier 400 landfill project within Port of Los Angeles (POLA) produced 235 ha of new land by dredging and landfilling behind rock dikes and posed unique design challenges in a highly seismic region. Pier 400 design team effectively combined centrifuge model tests, analyses using a fully coupled dynamic finite element computer code, DYSAC2, and traditional pseudo-static slope stability analyses, and Newmark's sliding block method to produce a safe and economic design in a timely manner. Centrifuge model tests results were used to validate the DYSAC2 predictions for the dike retaining structures. With the confidence gained through validating DYSAC2 predictions against centrifuge model test results, DYSAC2 was utilized to predict the behavior of various Pier 400 cross sections. Centrifuge models and DYSAC2 predictions of Pier 400 cross sections indicated that the dikes might move as a rigid body with most of the contributions to lateral deformations coming from the top most foundation layer. Large excess pore pressures generated within the top foundation layer were found to be the cause of the lateral deformations. For certain base motions, excess pore pressures were found to be larger underneath the landfill than underneath the dike pointing to the possibility of base motion dependence of pore pressure response. When the pore pressures were low underneath the dike lateral displacements were well distributed within the foundation rather than being concentrated in the top layer. Rigid body motion of the dike predicted by DYSAC2 and observed in centrifuge models allowed the design team to utilize Newmark's sliding block analysis for calculating the lateral displacement of the dike. However, average excess pore pressures predicted in DYSAC2 analyses were still used to calculate yield accelerations for the Newmark's method. The average excess pore pressures used are site and project specific and for other projects or sites additional fully coupled analyses should be performed before this simplified design procedure can be used to calculate the lateral deformations during seismic loading.

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