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Fisherman's Wharf: Hydraulic Design of a Successful Harbor Project

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ABSTRACT

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Physical and numerical models were used to investigate the design of proposed breakwater configurations for wave protection in the Fisherman's Wharf area, San Francisco Bay, California. A 1:75 scale (undistorted) physical model was used to determine wave conditions in the harbor for locally generated short-period wind waves and swell conditions entering through the Golden Gate. A hybrid-finite element numerical model, capable of calculating forced harbor oscillations for harbors of arbitrary shape and variable depth, then was used to calculate harbor resonance at Fisherman's Wharf. In addition, a ship surge analysis was conducted for the historic vessels moored along or near Hyde Street Pier. An optimum plan of improvement was developed in the physical model considering wave protection afforded the harbor and entrance, ease of navigation, and economics. Numerical model test results and ship motion analysis indicated that the improvement plan would result in decreased wave amplification in the inner basins of the harbor and reduced ship response along the Hyde Street Pier. The breakwater plan was constructed at Fisherman's Wharf in 1986 and has functioned as intended to this point. In fact, the project recently won an Engineering Design Award of Merit in the U.S. Army Chief of Engineer's 20th Design and Environmental Awards Program.

ADDITIONAL INDEX WORDS: *Fisherman's Wharf (San Francisco Bay, California), hydraulic models, coastal engineering, physical and numerical modeling, breakwaters, wave action, harbor oscillation, ship motion.*

INTRODUCTION

The Fisherman's Wharf Area is located in San Francisco Bay near the Golden Gate (Figure 1) and is a well-defined segment of San Francisco's city waterfront. The area is bounded on the east by Pier 45 and on the west by the Municipal Pier. Development existing in 1985 consisted of a complex of commercial and recreational facilities (Figure 2). Fisherman's Wharf has been the center of the northern California commercial fishing industry for many years. Data from the California Department of Fish and Game indicate that about 16.8 million pounds of fish were landed at Fisherman's Wharf in 1979 and the amount was increasing by about 1 million pounds annually (U.S. ARMY CORPS OF ENGINEERS, 1982). About 170 berths are located in the area for commercial fishing boats.

The Fisherman's Wharf area is a world-famed tourist attraction with a complex of recreational activities that receives in the tens of millions of visitors annually. The San Francisco Maritime State Historic Park is located on the Hyde Street Pier where five historic antique ships are on display to the public. Custody of the historic fleet has been transferred to the Golden Gate National Recreation Area. Excursion vessels provide waterfront tours of the area. Sport fishing is popular, and numerous boats engage in regular for-hire trips. The area encompasses many commercial businesses, including curio shops, restaurants, parks, sidewalk cafes, fishing shops, hotels, marinas, museums, and shopping complexes, clustered about the central attraction of the Wharf and its commercial activities.

Although part of a densely developed, heavily populated area with a network of piers, wharves, and berthing areas, Fisherman's Wharf prior to 1986 essentially was unprotected from wave damage. Minimal protection provided by timber piers diminished with the removal of deteriorated sections. During winter

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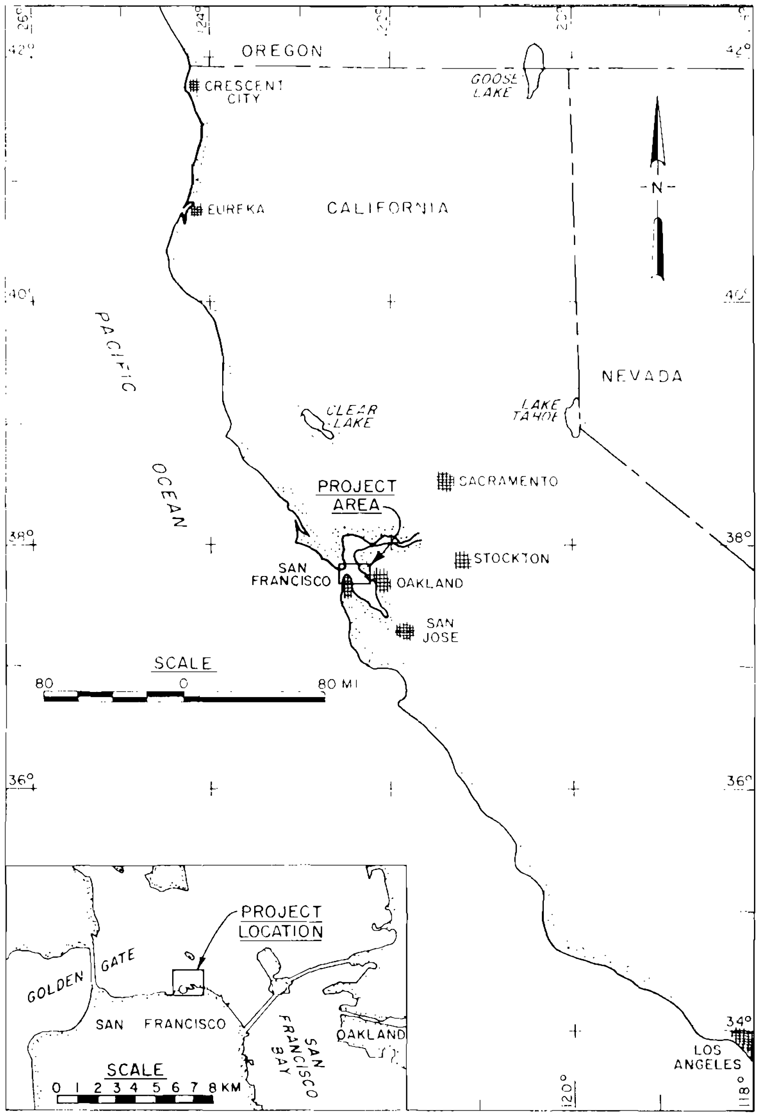

Figure 1. Project location.

storms, wave energy from the open ocean (entering through the Golden Gate) and local storms (waves generated by winds across the extensive water surface of the bay), resulted in continual damage to fishing vessels and mooring facilities. Many fishermen abandoned the harbor due to recurring boat damage. Waves also damaged historic vessels berthed in the area. Wave activity was relatively mild compared with the open coastline, but Fisherman's Wharf was the most exposed and vulnerable of small-craft harbors within San Francisco Bay with wave heights ranging up to 1.7 m in the area (ASSISTANT SECRETARY OF THE ARMY, 1983). Recreational berthing within the city of San Francisco is limited with only about 700 berths available, all of which are fully occupied.

The Coastal Engineering Research Center (CERC) completed physical and numerical

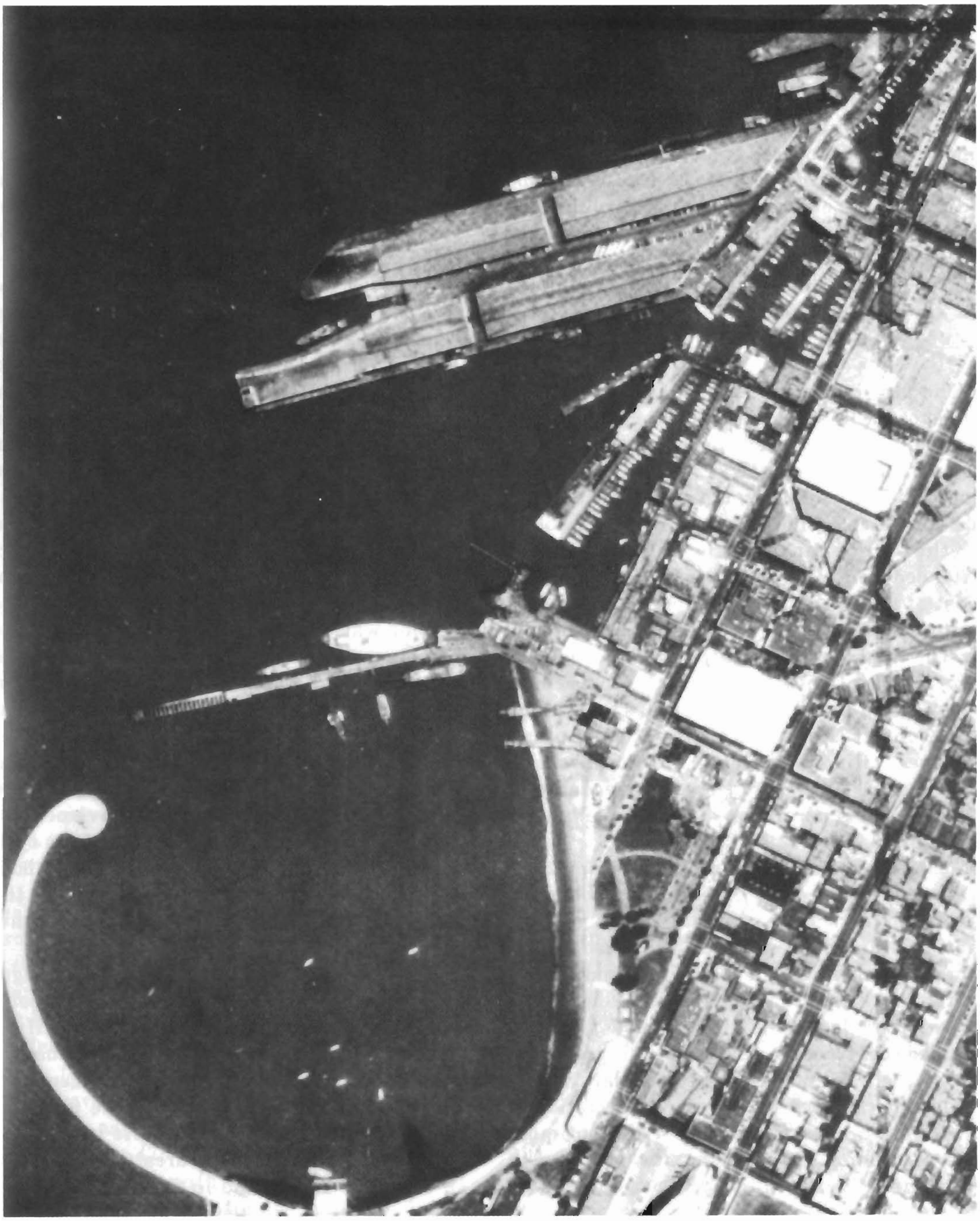

Figure 2. Aerial view of Fisherman's Wharf area.

model investigations at Fisherman's Wharf to determine (1) the most economical breakwater configuration that would provide adequate wave protection for small-craft in the area from short-period waves, (2) the impact of reflections from the proposed breakwater with regard to erosion of the beach at Aquatic Park, (3) the impact of the proposed structure in relation to harbor response due to wave excitation for long period wave energy entering through the Golden Gate, and (4) the impact of the proposed breakwater on the motions of historic vessels moored along or near the Hyde Street Pier.

THE PHYSICAL MODEL

The physical model was constructed to an undistorted linear scale of 1:75, model to prototype, and operated in accordance with Froude's model law (STEVENS, 1942). It reproduced the entire Fisherman's Wharf area (Figure 3), which included approximately 1,950 m of the San Francisco Bay shoreline that extended from a point east of Pier 45 to a point west of the Municipal Pier, and underwater contours in the bay to an offshore depth of 18.3 m. The total area reproduced in the model was approximately 557 sq m, which represented about 2.8 sq km in the prototype. The existing area consisted of a complex system of piers, wharves, pilings, firewalls, wave baffles, and solid landfills, all of which were reproduced in the model. A general view of the model is shown in Figure 4.

Test waves from six directions of approach were generated by a 12.2-m-long movable wave generator with a trapezoidal-shaped vertical motion plunger. Resistance-type wave gages and an automated data acquisition and control system were used to measure wave height data at selected locations in the model, and a crushed coal tracer material (specific gravity = 1.3, D_{50} = 0.58 mm) was used to qualitatively determine the degree of erosion or accretion at the Aquatic Park shoreline for the optimum improvement plan. The tracer was chosen in accordance with the scaling relations of (NODA, 1972). Previous studies at the U.S. Army Engineer Waterways Experiment Station (BOTTIN and CHATHAM, 1975) indicate that crushed coal in a physical model can be used as a tracer and satisfactorily reproduce aspects of the movement of prototype sand.

Still-water levels of 0.0 m (mean lower low water) and +1.74 m (mean higher high water) were used during model testing. Test waves with periods ranging from 3.6 to 4.9 sec and heights ranging from 0.61 to 1.77 m were selected by the application of hindcasting techniques from (CERC, 1977) and (VINCENT and LOCKHART, 1983) to wind data acquired at the Oakland Airport and the Alameda Naval Air Station. In addition, 10-sec, 0.6 m waves were selected for model testing based on prototype wave gage data obtained in 1983 at Hyde Street Pier. These conditions were representative of swell entering through the Golden Gate.

Prior to testing various improvement plans, comprehensive tests were conducted for existing conditions (1985) to establish a base from which to evaluate the breakwater plans. Wave heights, sediment tracer patterns, wave pattern photographs, and videotape footage were obtained for test waves from all six incident wave directions. Wave height tests indicated rough and turbulent wave conditions in the various mooring areas of the harbor for storm waves from all incident wave directions. The harbor was virtually unprotected and wave heights were measured in excess of 1.2 m in the proposed small-craft harbor area, greater than 0.9 m in the existing fishing boat mooring area, and greater than 1.5 m along Hyde Street Pier in the historical vessel mooring area. Typical wave patterns for existing (1985) conditions are shown in Figure 5. Sediment movement in Aquatic Park for existing conditions was typical of a pocket beach. Material moved in both directions (east and west) depending on the incident wave direction with no sediment leaving the system.

The originally proposed breakwater configuration consisted of a 442-m-long curved solid breakwater enclosing the area between Hyde Street Pier and Pier 45. A 117-m-long baffled breakwater also was attached to the center of Pier 45 at its bayward end (Figure 6). Tests revealed excessive wave heights in the proposed small-craft mooring area (wave heights in excess of 1.4 m) and in the historic vessel mooring area (wave heights exceeding 0.9 m). For an improvement plan to be acceptable, the U.S. Army Engineer Districts of Los Angeles and San Francisco specified that, maximum wave heights in the small-craft and fishing vessel mooring areas should not exceed 0.3 m; and

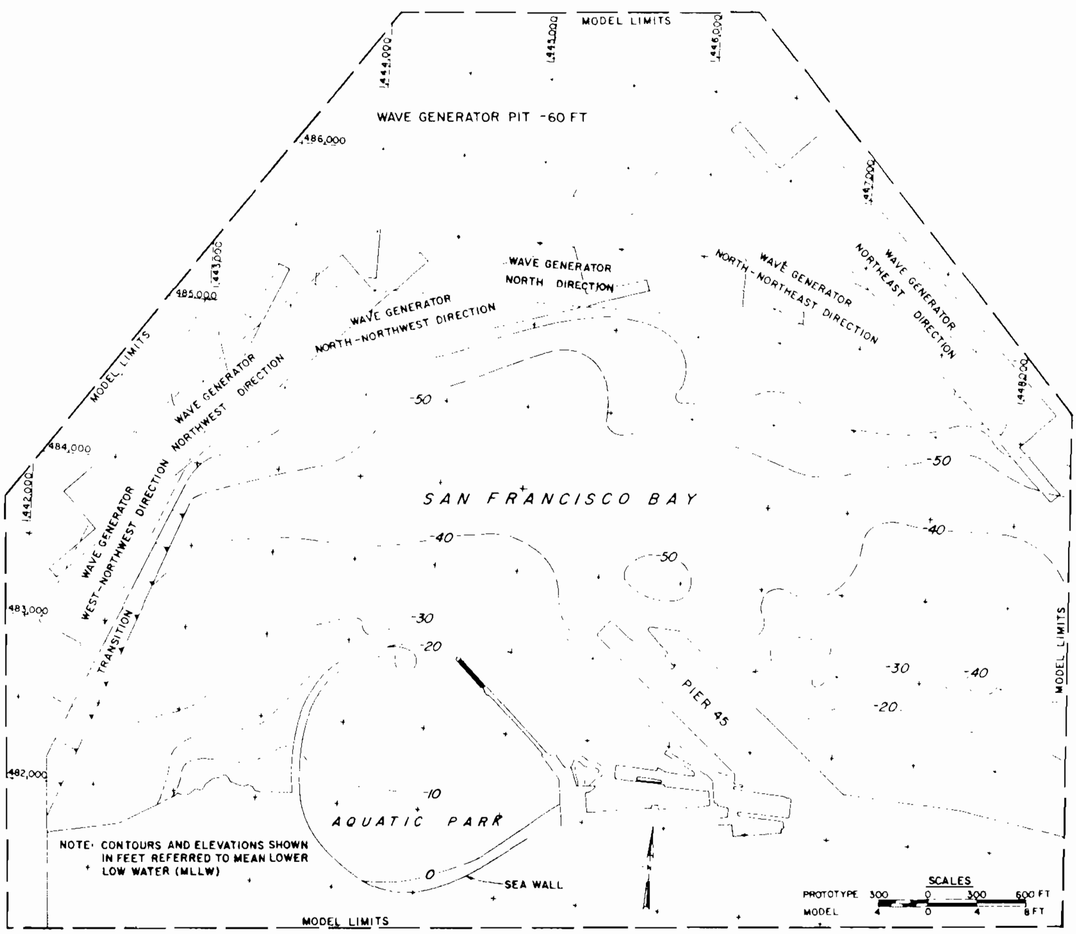

Figure 3. Model layout.

maximum wave heights in the mooring area provided for the historic fleet should not exceed 0.46 m. Model tests were conducted for 90 test-plan variations which consisted of changes in the lengths, alignments, and locations of solid, baffled, and/or segmented breakwater structures. The optimum improvement plan, considering wave protection afforded the harbor and entrance, ease of navigation, and economics, consisted of a 475-m-long outer solid breakwater configuration with a 46-m-long segmented breakwater (8.5-m solid sections and 1.8-m openings) installed diagonally between the fingers of the bayward end of Pier 45 and a 76-m-long segmented breakwater installed adjacent to the west side of the west finger of Pier 45. A view of the optimum improvement plan is shown in Figure 7. Sediment tracer tests for this plan indicated that reflections off the new outer breakwater would result in no adverse impacts on sediment movement (such as erosion) in the Aquatic Park area.

THE NUMERICAL HARBOR OSCILLATION MODEL

A numerical model was used to study harbor response to long-period wave energy. The model was originally developed by (CHEN and MEI, 1974) and uses a hybrid finite element solution to the generalized Hemholtz equation in shallow water. The model has been modified to incorporate variable depth bathymetry and the dispersion relationship from linear wave theory

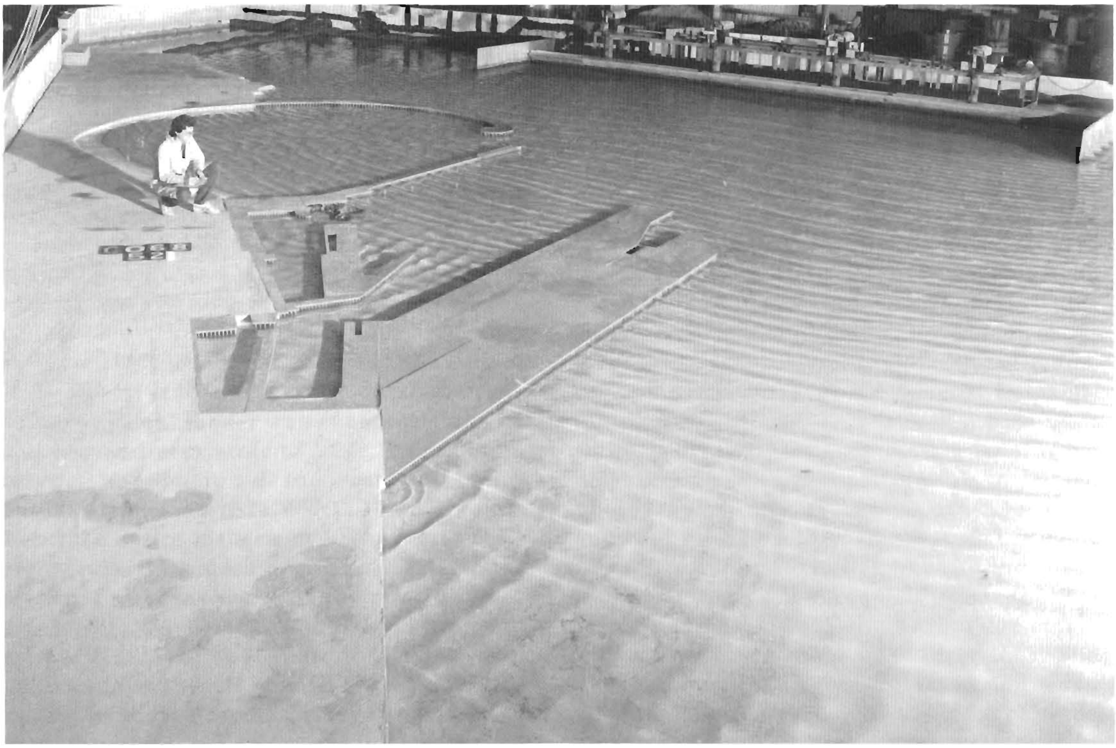

Figure 4. General view of model.

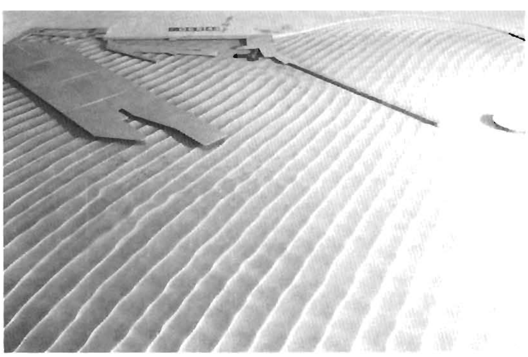

Figure 5. Waves approaching from west-northwest for existing conditions.

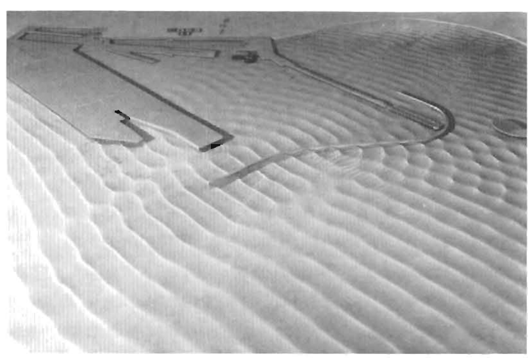

Figure 6. View of originally proposed breakwater plan with waves approaching from northeast.

(HOUSTON, 1976). The effects of bottom friction and boundary absorption on harbor resonant response also have been incorporated into the model (CHEN, 1986). These modifications more accurately reproduce conditions seen in prototype data and physical model testing.

Harbor oscillation tests were conducted for existing conditions (1985) and the optimum

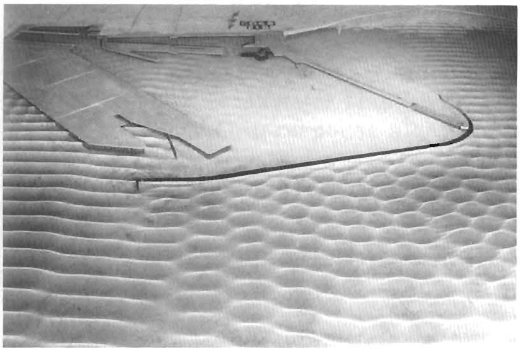

Figure 7. View of optimum breakwater plan with waves approaching from north.

breakwater plan (as determined in the physical model) for wave periods ranging from 30 to 600 seconds. Frequency response curves, contours of wave height amplification, and vector plots of normalized maximum current velocities were obtained for both conditions. The finite element grid used for existing conditions (1985) is shown in Figure 8. The size of the grid was based primarily on the proposed breakwater and harbor complex.

Frequency response curves of wave height amplification in the harbor identified resonant peaks for existing conditions at 34.5-, 54-, 79.5-, 115.5-, 135-, and 228-sec wave periods. For the breakwater plan, resonant peaks were identified at 63-, 81-, 115.5-, 147-, and 228-sec wave periods. Long-period prototype wave data obtained at the site indicated that long period wave energy was generally present at periods of 171 sec or greater, and that wave energy at periods of less than 171 sec was not observed (wave energy is not present to excite resonant oscillations at periods less than 171 sec). Based on the results of the harbor oscillation evaluation, the optimum breakwater plan will result

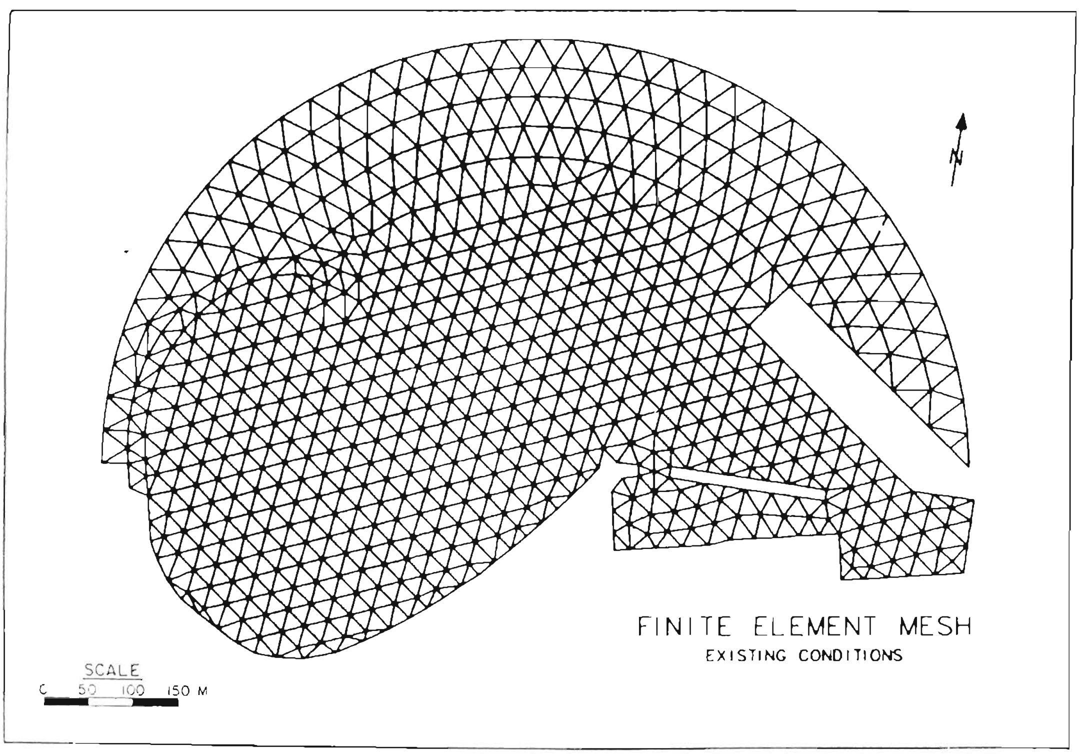

Figure 8. Finite element grid used for existing conditions.

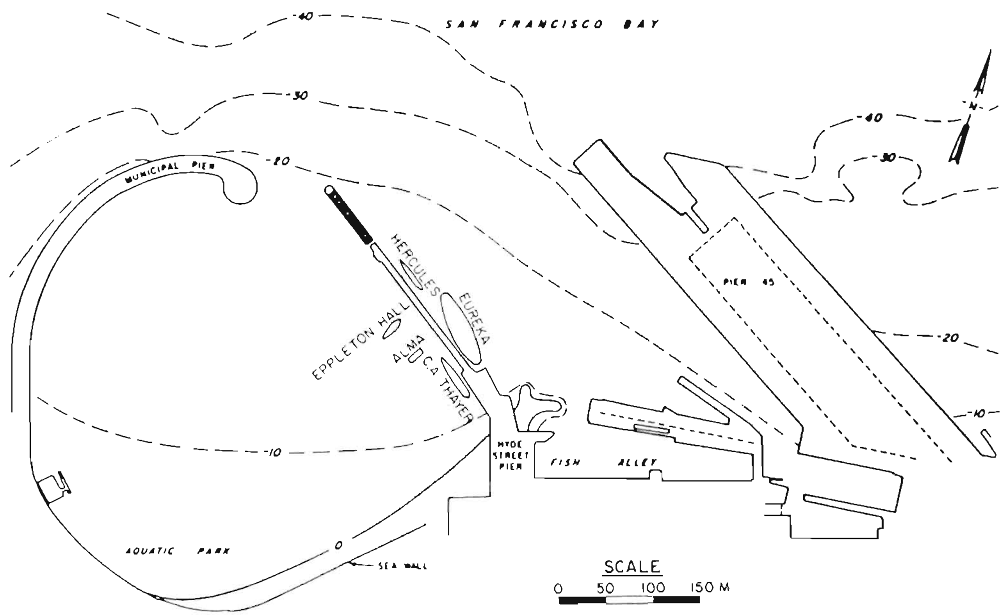

Figure 9. Historic fleet mooring locations around Hyde Street Pier.

Figure 10. Aerial view of completed breakwater project at Fisherman's Wharf, San Francisco Bay, California.

in decreased wave height amplification (15 to 20 percent) in the inner harbor area when compared to existing conditions.

SHIP MOORING ANALYSIS

A ship mooring analysis was conducted for the historic fleet to determine conditions under which significant long-period ship motions could occur, and the effect of the proposed breakwater on the motions of the vessels. Within the Fisherman's Wharf area, the historic fleet is moored on either side of Hyde Street Pier (Figure 9). The fleet consists of five vessels at present: the *C. A. Thayer, Eureka, Hercules, Eppleton Hall,* and *Alma* which are either listed or nominated for inclusion on the "National Register of Historic Places." On several occasions before the breakwater was constructed, significant ship motions caused anchor lines to move and mooring lines to part, which has resulted in damage to ships and piers.

The ship mooring numerical model used in this study can be used with limited ship characteristic data and has the ability to incorporate geometric asymmetries and nonlinear elastic properties of the mooring systems (RAICHLEN, 1968). In the model, the ship is idealized as a block body positioned in a standing wave field (linear wave theory is used), and the bow-to-stern axis of the vessel is perpendicular to the nodal lines. Thus, the motion considered in the analysis is the surging (horizontal motion) in the bow-to-stern direction. The standing wave acts as a dynamic force moving the ship from equilibrium while the mooring lines counteract this motion and act as a restoring force that holds the vessel in dynamic equilibrium.

Results of the ship motion analysis indicated that the proposed breakwater plan would substantially reduce ship response along Hyde Street Pier for short-period waves (reductions up to 74 percent). For long period wave activity, in general, ship response was not significantly altered by the breakwater plan.

DISCUSSION

Through the joint applications of physical and numerical models, an optimum breakwater configuration at Fisherman's Wharf was developed (with regard to short-period wave protection, harbor resonance due to long-period wave energy, and ship motions of the historic fleet). Construction of the recommended plan was completed in 1986 (Figure 10). Wave conditions within the harbor have been very calm, even during periods of storm wave attack, and the harbor has performed as intended. The Fisherman's Wharf project recently won an Engineering Design Award of Merit in the U.S. Army Chief of Engineer's 20th Design and Environmental Awards Program. The program recognizes excellence in design of recently completed Corps projects from around the world.

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□ RÉSUMÉ □

La forme d'une jetée de protection de la houle (zone du wharf de Fisherman, San Francisco, Californie) a été étudiée à partir d'un modèle physique et numérique. Le modèle physique à 1/75 (non déformé) a permis de déterminer les conditions de houle du port pour les houles à courte période générées localement par le vent et le clapot entrant par la Golden Gate. Un modèle numérique d'éléments hybrides finis, et permettant de calculer les oscillations forcées des ports de forme arbitraire et de profondeur variable a permis de calculer la résonance du port du wharf de Fisherman. De plus, le sillage des bateaux a été analysé pour les navires historiques ancrés le long ou à proximité de Hyde Street Pier. Un plan optimum a été établi, tenant compte de la protection accordée au port et à l'entrée, des facilités de navigation et de l'économie. Les résultats des tests du modèle numérique et les mouvements des navires indiquent que le plan d'amélioration entraînerait une diminution de l'amplification des vagues dans les bassins internes du port et des réponses atténuées des navires le long de Hyde Street Pier. Le plan de la jetée construit au wharf de Fisherman en 1986 a fonctionné selon l'attente. En fait, ce projet a récemment gagné l'Engineering Design Award of Merit de l'US Army Chief of Engineer.—*Catherine Bressolier-Bousquet, Géomorphologie EPHE, Montrouge, France.*