Synoptic Wave Height and Pattern Measurements in Laboratory Wave Basins Using Close-Range Photogrammetry

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ABSTRACT: An application of high-precision close-range photogrammetry for the measurement of wave heights and patterns in laboratory wave basins is described. A literature review of previous related field and laboratory work is followed by a detailed account of the various stereo-photographic problems which have to be overcome in the laboratory. The stereopairs are analyzed using the theory of Projective Transformations. The wave height analysis procedure for a typical model harbor configuration (for regular sinusoidal waves), from the taking of the stereopairs to the computer generation of wave height and pattern contour plots and three-dimensional views, is then described. Various applications, such as an investigation of breakwater gap wave diffraction and a study of the bow and stern waves generated by ships, are illustrated. It is concluded that the photogrammetric technique overcomes some of the limitations inherent in the use of standard wave probes. For example, compared with data from a wave probe array, a single stereopair contains a vast amount of synoptic water surface elevation data and there is no instrumental interference in the wave processes being observed. Furthermore, the photogrammetric technique allows the simulation of infinitely large harbor basins in the laboratory because stereopairs can be taken before wave energy is reflected from the basin walls.

INTRODUCTION

MODEL HARBORS are used by coastal engineers as an aid in optimizing harbor designs. The models predict wave heights in full scale harbors, the results being used to reduce these wave heights to a minimum in order to prevent damage to moored ships, to the wharf structure, and to the mooring systems. Two main limitations in experimental procedures are encountered, however, when attempting to measure accurately the wave height distributions within model harbors. These are

- Wave heights in model harbors are commonly measured using parallel wire resistance or capacitance wave probes. A number of these probes are usually mounted on a moveable instrument carriage which can traverse the wave basin to measure the wave heights. Such a configuration was used by Harms (1976). The disadvantage of this system is that the wave height at only a limited number of discrete locations can be measured at any one time. The system is also time consuming, because the instrument carriage has to be moved within the wave basin until the entire water surface has been scanned. Furthermore, excessive spacing of these wave probes may result in points of maximum wave heights being overlooked.
- Wave measurements using the above system necessitate (in most cases) that the wave paddle must run continuously. This allows secondary effects (such as wave reflections, basin oscillations, cross waves, etc.) to develop and distort the generated wave, thus causing marked anomalous wave height variations along the generated incident wave crests and troughs. These problems are discussed in depth by Harms (1976) and Pos (1984).

The afore-mentioned problems make it difficult to achieve accurate wave height and pattern measurement in model harbors. This paper summarizes the results of a PhD project undertaken by Pos (1984) at the University of Cape Town (UCT) and aimed at solving these problems by using stereophotogrammetry. The photogrammetric technique described makes it possible to obtain an instantaneous, synoptic, and permanent three-dimensional record of the deformed water surface in a model harbor. A procedure (for regular sinusoidal waves) for obtaining a computer-generated contour plot of the experimental wave height distributions in a wave basin is also described.

PREVIOUS WAVE HEIGHT AND PATTERN MEASUREMENT USING PHOTOGRAMMETRY

The earliest photogrammetric wave height and pattern measurements were made in Germany just after the turn of the century. These early attempts have been described by Schumacher (1952). The first useful photogrammetric wave height measurements were taken during the Atlantic cruise of the German research vessel "Meteor" in 1925 (Schumacher, 1939) using two main measurement cameras rigidly mounted on the ship with their axes parallel.

A more recent application of horizontal photography from ships is described by Monahan (1969) who undertook a study of fresh water whitecapping on the large North American lakes. Wave crest elevations have also been measured using horizontal stereophotography techniques with cameras mounted along the sea shore. This technique has been used by researchers such as Dickerson (1950), Maresca and Seibel (1976), and Adams (1978).

Marks and Ronne (1955) addressed the problem of the measurement of the two-dimensional wave energy spectrum at sea. They reasoned that high altitude stereophotography could provide a wealth of information about the two-dimensional wave energy spectrum at sea without appeal to any theoretical concepts. In order to capture enough of the sea surface for the purpose of analysis, two airplanes were used. The two airplanes flew in tandem 2000 ft (610 m) apart (one behind the other) and at an elevation of 3000 ft (914 m). Each plane was equipped with a CA-8 mapping camera, and the cameras were triggered simultaneously from the forward (master) plane by an FM radio link. The planes flew directly into the wind. The distance between the two planes was maintained nearly constant (at about 2000 ft) by means of a rangefinder located in the slave plane and by utilizing the wing span of the master plane as a base line. To help establish some sort of ground control in the area

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of operation, a target raft was towed 500 ft (152 m) behind the research vessel "Atlantis." The analysis procedure was as follows. From the stereopairs, elevations were read at discrete points, where the spacing of the points depended upon the properties of the sea surface and the resolution of the spectrum desired. The information was then fed into a computer which produced a two-dimensional energy spectrum of the waves.

Polderman (1976) employed a pair of Hasselblad cameras, initially fixed on outrigers built on a helicopter, but then progressed to the use of cameras in two separate helicopters flying in formation, with auxillary photographic recordings of the position of each helicopter in relation to the other at the moment of the (simultaneous) exposure of each of the downward facing cameras. The water surface was recorded by the use of flash photography. Polderman's research work was essentially very similar to that of Holthuijsen (1979, 1983).

Holthuijsen (1979, 1983) used stereophotographic techniques to estimate the two-dimensional spectrum of ocean waves and thus to determine the distribution of wave energy over wave lengths and directions. He used three Hasselblad cameras which were mounted in two helicopters. One camera in each helicopter pointed vertically downwards and was used to take the stereopairs. The third camera was mounted in one of the helicopters with the other helicopter in its field of view through an open window. This camera was used to compute the distance between the helicopters. Photographs were taken at flight speeds of approximately 10 m/s at altitudes ranging from 200 to 500 m with the two helicopters flying side by side.

The results were analyzed using a stereoplotter. A Cartesian system of x, y, and z coordinates was defined in the three-dimensional space created in the stereoscopic viewing device. The x and y axes defined the horizontal plane and the z axis was pointing upwards. The mode of operation was a profiling method. Every time the horizontal position of the floating point crossed a grid point, the three coordinates of that point were recorded on tape. These data were used to generate a two-dimensional wave energy spectrum.

Holthuijsen set out to achieve a maximum time difference of 5 ms between the firing of both cameras. This was based on observations of other researchers, namely, Cote *et al.* (1960) and Cruset (1952), and on the fact that the significant wave phase speed was 10 m/s. Holthuijsen used a novel approach to the synchronization of the firing of the two cameras. Each camera was provided with an electronic unit to generate an additional delay for each camera, such that the total average delays for both cameras were equal within acceptable narrow limits.

Szczechowski and Mucha (1980) used stereophotogrammetry to map the wave patterns around various model hydraulic structures in a wave basin. An area of the basin of 10 m by 10 m was utilized for these experiments. Pairs of stereophotographs were taken using two Zeiss UMK FF 10/1318 photogrammetric cameras situated 10 to 12 m above the water surface. Illumination was by means of flashes which could be triggered by the wave generator. The water surface was identified by using aluminum powder.

The resultant water surface patterns were plotted using two methods:

- The direct plotting of the water surface image with a stereoplotter.
- Creating a numerical model of the water surface.

The numerical model technique involved using a stereocomparator and observing up to 1000 points on each plate, that is, approximately 10 points per 1 m^2 of model surface. These results were then processed on a digital computer to produce three-dimensional field coordinates of the points observed. A map of the water surface was then plotted. The accuracy of the stereoplotter results was found to be $\pm$ 2 mm in the x and y directions and $\pm$ 4 mm vertically. Wave heights measured were as high as 120 mm.

Szczechowski and Mucha maintained that the camera shutters must be synchronized within 0.001 sec or 1 ms of each other. Their method of overcoming this problem was very novel. By using a flash, they not only solved the synchronization problem, but also effectively froze the water surface (in the $<$ 1 ms duration of the flash, the water surface waves would move less than a millimetre or two).

STEREOPHOTOGRAPHY OF A DYNAMIC WATER SURFACE

WATER PENETRATION

Two basic approaches have been adopted in the past to signal or define the water surface for photographic purposes, namely:

- Discoloring the water in some way so that the light penetration of its surface is minimal. A white solution is favored.
- Creating a thin flexible opaque film of some substance on the water surface.

The first approach was used by Döhler (1965) and later by Faig (1972) and Jaggi (1975) for the photogrammetric analysis of laboratory hydraulic models of river retainment structures. They found that the addition of small quantities of fluorescein (1 part per 100,000) to the water in conjunction with ultraviolet illumination was effective in signaling the water surface.

The second approach has been used with success by Szczechowski and Mucha (1980). They sprayed fine aluminum powder on the water surface directly before photography. This approach was also adopted by Moffitt (1968) for the mapping of the wake of a ship model in a test basin. He sprinkled confetti over the water surface before each run of the ship model. Both materials were tested at UCT and were found to be inconvenient and ineffective when compared with the method which was finally adopted.

The first approach was adopted at UCT and initially three solutes were used, namely: starch, PVA white paint, and water soluble cutting oil, all dissolved in water. The first two solutes tended to settle out within a few hours after mixing while the cutting oil solution remained stable for days. A thorough light penetration versus cutting-oil concentration test was then carried out and, as a result, an oil/water concentration of 0.7 mℓ/litre (which ensured light penetration of less than 1 mm) was adopted. Tests with a Brookfield Synchro-Electric Viscometer showed no significant difference in viscosity between the above oil/water solution and pure water.

PHOTOGRAPHIC CONTRAST

Although soluble cutting oil solves the problem of water penetration, it introduces serious photographic contrast problems because the water surface takes on the appearance of a large white projection screen.

Adams (1980) overcame the problem of lack of photographic contrast in the stereogrammetric study of white skeletal remains by projecting a grid onto the surface of the object. This method was used with the aid of overhead projectors to solve the water surface contrast problem. However, the use of a regular grid pattern in water surface studies, although successful from a photographic contrast point of view, introduced serious problems in the stereoscopic study of resulting stereograms, because depth perception is continually frustrated by the incorrect fusion of repeated similar grid intersections. This problem was overcome by using projector transparencies of concentric circles.

The use of overhead transparencies of concentric circles overcame the problem of false stereoscopic fusion but the unnatural regular pattern, when viewed as a stereogram, introduced stereoplotting problems from the stereo-operator's point of view. The concentric circles have an almost mesmeric effect on the operator, appreciably increasing the mental effort required in plotting the wave crests. It was due to this optically disturbing effect caused by a regular pattern that a series of irregular random patterns were tested for their photographic contrast qualities.

It was found that Letraset patterns of random stars and arrows applied to a transparent plastic sheet gave the best photographic contrast. The patterns were projected onto the water surface by means of four conventional lecture room type overhead projectors placed 4 m above the water surface in the plan positions shown in Figure 1.

Illumination and Image Movement

Following water penetration and photographic contrast, adequate illumination is the next serious problem in model harbor studies because the models are normally located inside a laboratory building. As was the case in the Szczechowski and Mucha (1980) studies, it was found to be more satisfactory to work at night when the available illumination could be concentrated on the water surface and the effects on the photography of stray surrounding light could be eliminated.

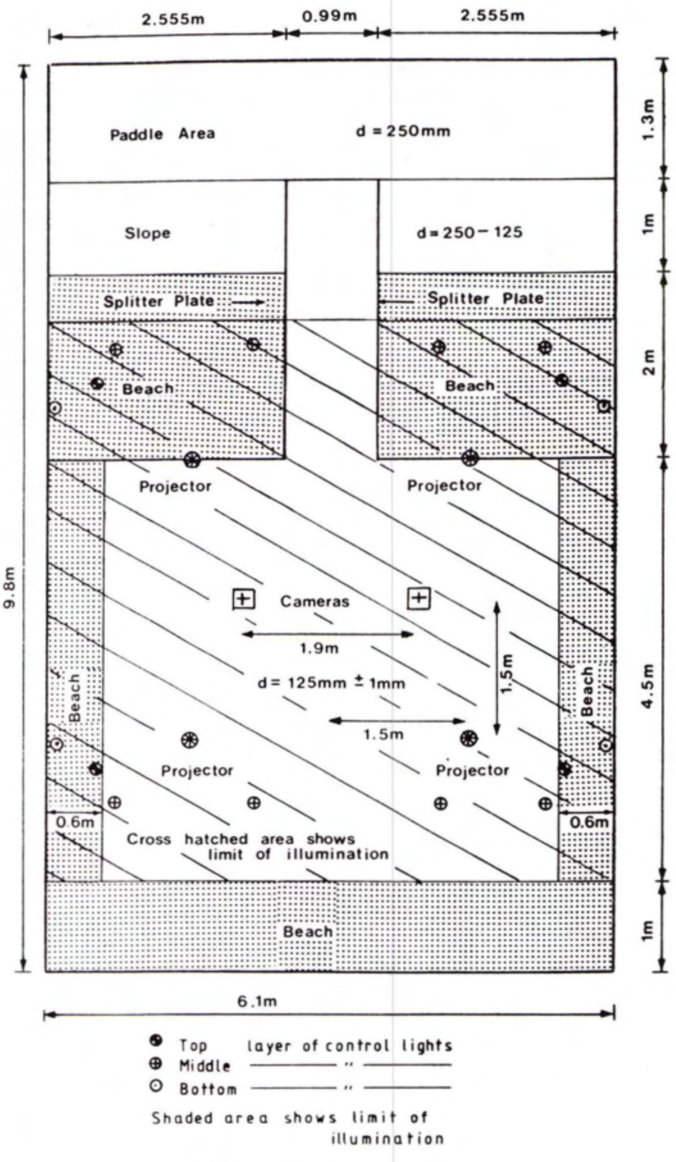

FIG. 1. Wave basin configuration.

At UCT stereophotography of the deformed water surface was undertaken with two Zeiss (Jena) UMK 10/1318 metric survey cameras mounted 1.9 m apart at an elevation of about 5 m above the water surface (Figure 1). Initial stereopairs were taken using the existing overhead projector lamps as an illuminating medium at the maximum camera aperture setting of *f*/8 and an exposure time of 1/30 s. It was found that this exposure time was too long because on average the laboratory waves could move approximately 32 mm in this time-interval. The problem was overcome by replacing the standard 250 W incandescent projector bulbs with powerful flash bulbs, placed at the focal points of the focusing lenses, and fired by a common capacitance.

A shutter speed setting of 1/30 second (in conjunction with an aperture setting of *f*/8) was adopted to allow both shutters to be open long enough to encompass the flash duration (allowing for the variation in shutter speeds between the cameras and their lack of synchronization) and to ensure that the illuminated control points were adequately exposed. All photography took place at night. Because of the very short flash duration of less than a millisecond, the water surface detail was effectively "frozen" (that is, very little image movement) in the stereopairs. Flash photography simultaneously solved the problems of sufficient illumination, image movement, and non-synchronization of shutter openings of both cameras.

Camera Triggering for Wave Height Measurement

The next concern is to consider how the photographs are to be interpreted to yield information about wave heights at points in the field of view. Bearing in mind that a wave height is the vertical distance between a crest at a selected point and a subsequent (or preceding) trough at that point, it is clear that for regular sinusoidal waves two stereopairs are needed, and these were arranged to be taken such that the waves imaged in the second stereopair are 180° out of phase relative to the waves imaged in the first stereopair, making use of two electronic micro-switches triggered by the wave paddle mechanism. Algebraic subtraction of the two resulting deformed water surfaces gave the wave heights at all points where a crest or trough appeared in either stereopair. In the earlier stages of the investigation a Zeiss (Jena) Topocart stereoplotter was used to analyze the photographic plates and was found capable of measuring the wave heights with an average error of 2 mm. However, because this method requires the use of very expensive metric survey cameras in addition to the very expensive stereoplotter (plus a specially trained operator), a cheaper and more accurate alternative approach was adopted. These earlier stages of the investigation are described by Pos (1984). Detailed technical information about the experimental equipment, such as the camera's firing device and the flash circuitry is given by Adams and Pos (1981) and Pos (1984).

MEASUREMENT OF WATER SURFACE ELEVATIONS AND PLAN POSITIONS

The photographic plates were measured in stereoscopic mode using a Zeiss (Jena) stereocomparator. The algorithms selected to derive the three-dimensional space coordinates of the water surface points were developed through the method of projective transformations (Adams, 1979, 1981). Although metric cameras were used in this project and a knowledge of the elements of interior orientation would permit the use of the traditional algorithms of relative orientation to compute space coordinates, the method of direct solution using projective transformations has numerous advantages with the added attraction that it allows for the possibility of using much less expensive non-metric or semi-metric cameras to produce the stereo photography.

PROJECTIVE TRANSFORMATIONS

There is a deal of debate regarding the origin of the practical use of the mathematics of projective transformations in the theory of stereophotogrammetry. Felix Klein, the great German mathematician, at the beginning of the century in a series of lectures (see Klein, 1939) entitiled "Elementary mathematics from an advanced standpoint," devoted time to the theory of projective transformations and to the mapping of space upon a plane using homogeneous coordinates. He mentions that the mapping of space upon a plane can be a central projection and he describes photography as an example of a central projection.

In photogrammetry the practical difficulties of calculating the large number of unknowns present in the algorithms of projective transformations led to the development of analog solutions or approximate solution analytical methods for deriving space coordinates from stereoscopic pairs, and it was not until the advent of digital computers and the more recent micro and personal computers that the practical possibility of using projective transformation solution methods in photogrammetry were explored.

Thompson (1971), in a paper entitled "space resection without interior orientation," expanded on ideas previously reported (Thompson, 1968) and used the method of projective transformations and homogeneous coordinates to solve for the elements of interior orientation and, in particular, to solve for the space coordinates of the vertex (perspective center) of a single photograph.

Using essentially the algorithms of projective transformations, Abdel-Aziz and Karara (1971) proposed their Direct Linear Transformation (DLT) method which used comparator coordinates of stereoscopic pairs of photographs to calculate object space coordinates. Bopp and Krauss (1978) extended Thompson's ideas to calculate the position of object points in space using a stereopair of pictures. Their method is generally referred to as the 11 parameter solution. Also based on Thompson's ideas, Adams (1979) suggested a modified 11 parameter solution.

The usefulness of the method or projective transformations in close-range photogrammetry to derive object space coordinates has been widley recognised and reported in the literature. See, for example, Hadem (1981) and Shih and Faig (1987).

For this project the modified 11 parameter solution method was adopted to calculate the space coordinates of water surface points. For the purpose of determining the 11 transformation parameters of each of the photographic plates making up the stereoscopic pair, the images of a minimum of six suitably sited control points must appear on each of the photographs. Each control point must be coordinated in three dimensions to high precision using traditional ground survey methods. It is important that the type of signals used to mark the control points must produce photographic images which will ensure an unambiguous identification and pointing of the measuring mark.

CONTROL POINT CONFIGURATION

To determine the transformation parameters for photographs of a stereopair, a number of accurately surveyed control points are required within the stereoscopic overlap area. Karara and Abdel-Aziz (1974) conducted tests using non-metric cameras to determine the optimum number of object-space control points. A similar investigation was also carried out by Welham (1982). Both investigations showed that there is a relatively rapid increase in measurement accuracy with an increasing number of control points for between 6 and 16 control points. For 16 and more control points, however, there is a much slower increase in accuracy with increase in number of control points.

The plan positions of the 16 control points used are shown in Figure 1. The control points were situated in the basin in three planes. The bottom plane of control points was situated at a level approximately 50 mm below the water surface (at the bottom of dry surface-piercing cylindrical canisters), the central plane was situated approximately 220 mm above the water surface, and the top plane approximately 660 mm above the water surface. The control points were coordinated by a combination of trilateration and spirit leveling to an accuracy of better than 1 mm. All control point targets were individually illuminated.

MODEL HARBOR CONFIGURATION ANALYZED USING "INFINITE" BASIN TECHNIQUE

An analysis of the steady state results coupled with visual observations of the deterioration of the wave field in the basin after a very short period of wave paddle action led to the development and adoption of the infinite basin technique. It was observed that, when the wave paddle was subsequently stopped and the main wave train had traversed the basin, a marked reflection and resonance mode was evident in the basin, which took a few minutes to dissipate. This reflection and resonance mode was obviously superimposed upon the wave field in the basin under steady state conditions.

It was hypothesized that it would be possible to simulate the steady state situation of a continuous wave train entering an infinite basin by sending a wave train into a model basin of still water and taking a stereopair of the water surface just as the wave energy front reached the peripheral beaches. To test this hypothesis, two stereopairs were taken of the wave energy front region of a typical wave train entering an open basin of initially still water. On analysis it was found that the wave heights of the crests immediately behind the wave energy front were closely equal to the mean wave height between the front and the generator. The experimental configuration analyzed and the results obtained are described by Pos and Kilner (1982).

To illustrate the procedure, the analysis of a typical model harbor configuration will be briefly described. The stereopairs in Figure 2 show waves entering the model harbor basin shown in Figure 1. The incident wave train has the following characteristics: wave period 0.67 seconds, mean wave height 55.5 mm, and wave length (calculated using Airy wave theory) 604 mm. The gap to wave-length ratio (that is, B/L ratio) is 1.64. The water depth is 125 mm $\pm$ 1mm. The stereopairs shown were taken approximately 14.5 seconds after starting the wave paddle, at which stage the wave energy front was at the toe of the back wall beach. The second stereopair was taken with the waves in the basin 180° out of phase relative to the waves imaged in the first stereopair. This means that the troughs imaged in the second stereopair occupy the positions of the crests imaged in the first stereopair. If one subtracts the crest and trough elevations of the first stereopair from their corresponding elevations in the second stereopair, one will achieve a plot of wave-height distribution within the basin. As the harbor configuration is symmetrical about the center line, only the left hand side of the basin is shown in Figure 2.

WAVE HEIGHT MEASUREMENT PROCEDURE

The process of achieving a plot of wave-height distributions within the model basin is summarized from Pos (1982, 1984) and Pos and Kilner (1982). The analysis procedure is as follows: the control points and crests imaged in the first stereopair and the control points imaged in the second stereopair are observed using the stereocomparator. The observed data are then analyzed using the program WAVEHEIGHT, based on projective transformation theory, to yield the inner orientation elements and projective transformation parameters for the first and second stereopairs, the crest elevation data (crest XYZ data) for the first stereopair, and the positions at which the troughs must be observed on the second stereopair. The troughs imaged in

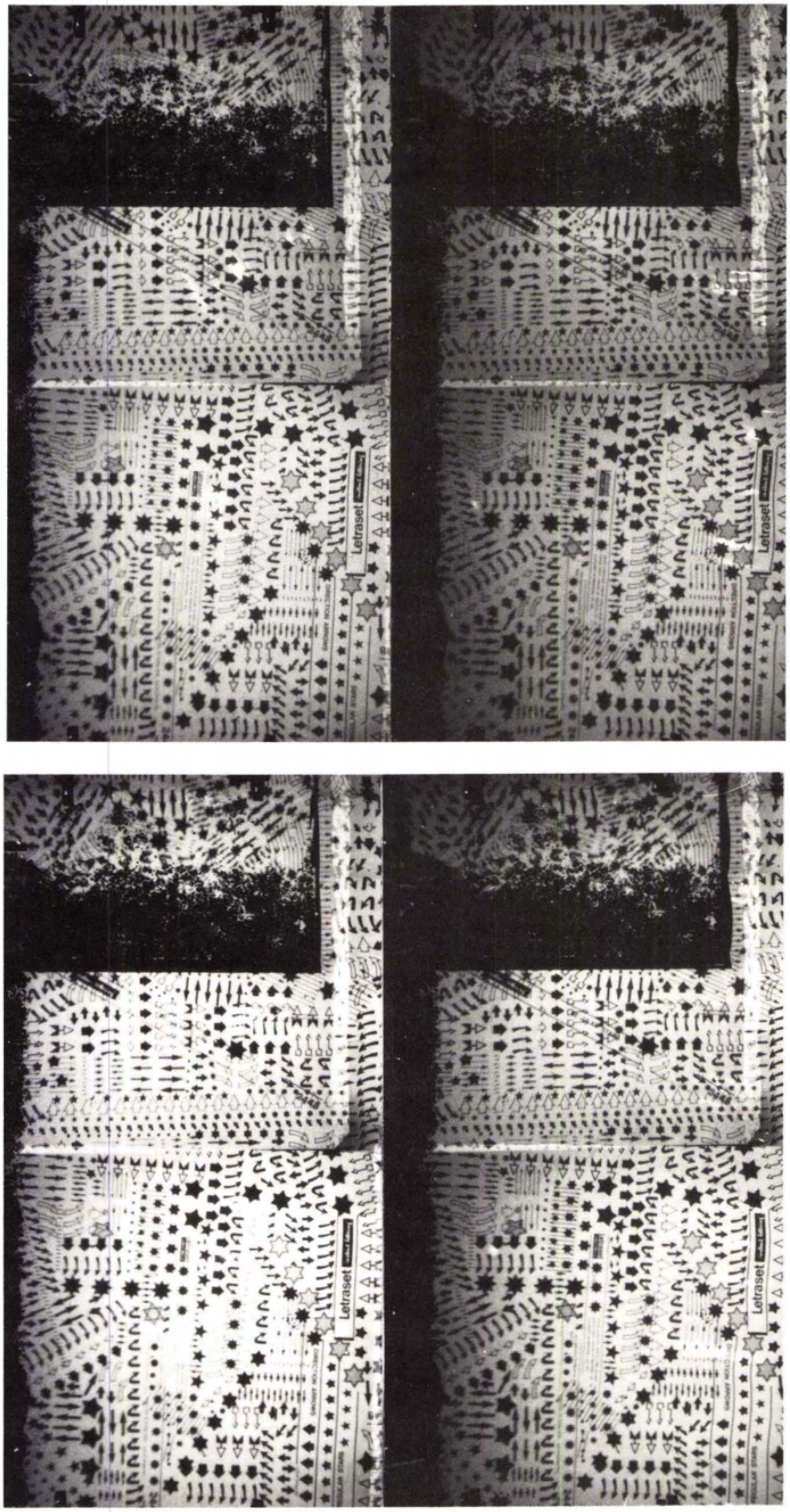

FIG. 2 Stereopairs of B/L = 1.64 breakwater gap configuration.

the second stereopair are then observed at the predetermined points, while the crests are observed at arbitrary points selected by the observer. The first stereopair is again placed in the stereocomparator and the imaged control points are observed. These observed data are analyzed using the program WAVEHEIGHT to yield trough and crest XYZ data for the second stereopair, inner orientation elements and projective transformation parameters for the first stereopair (second viewing), and the trough positions to be observed in the first stereopair (second viewing). The troughs imaged in the first stereopair are then observed at the predetermined points. The observed data are then analyzed using the program WAVEHEIGHT which yields the trough XYZ data for the first stereopair and the XYH values along the crest lines imaged in the first and second stereopairs, where H is the wave height at a point within the basin.

The *XYH* data are then used to plot a contour plot of the wave-height distributions within the model harbor basin. The stereopairs, shown in Figure 2, were analyzed using the procedure described above to yield the contour plot of wave heights within the basin, shown in Figure 3.

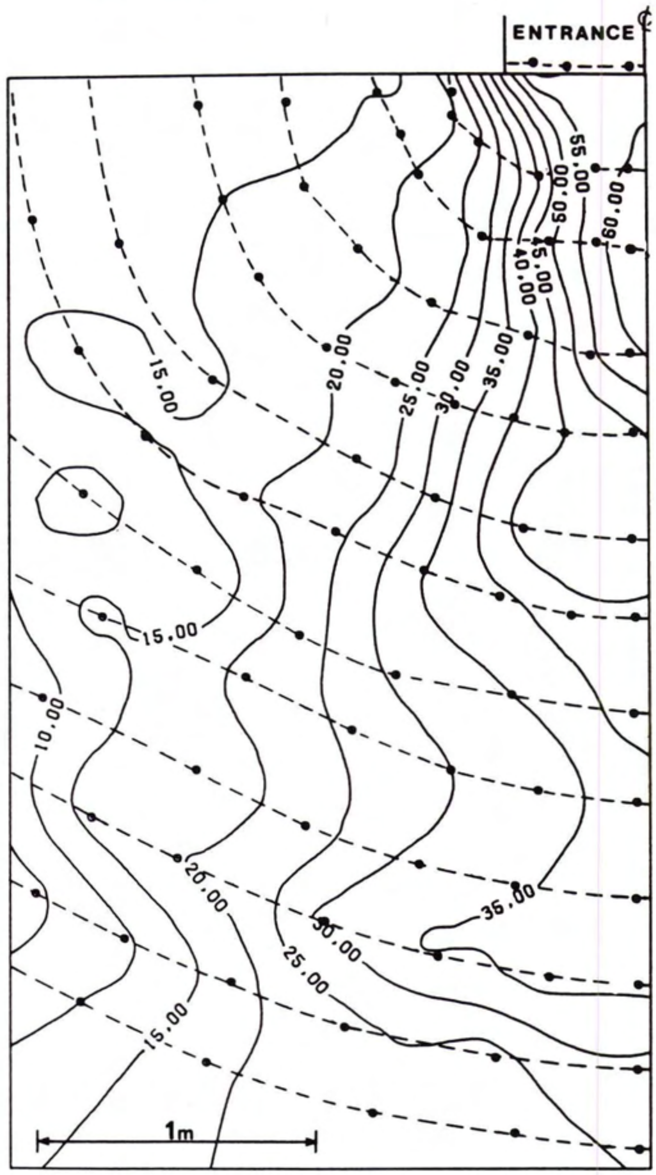

FIG. 3. Computer contour plot of wave heights in basin for $B/L = 1.64$ breakwater gap configuration (heights in mm).

Pos (1984) undertook a detailed statistical analysis to determine the potential wave-height measurement accuracy of the system. He found that the absolute average error and the standard deviation of the wave-height measurements were 1.2 mm and 1.6 mm respectively. The high accuracy of the system is due primarily to the use of high-precision metric cameras for the photography and a high-precision stereocomparator to analyze the glass plates.

Because the measurement accuracy of the system depends heavily on the precision of the cameras, it is advised that cameras with a precision equivalent to that of a metric camera should be used to take the stereopairs. The use of non-metric cameras for accurate photogrammetric measurement purposes has been investigated by Schwidefsky (1970), Faig (1972), Karara and Abdel-Aziz (1974), Kölbl (1976), and Adams (1981). A comparison between three different photogrammetric wave-height measurement techniques is given by Adams and Pos (1984).

APPLICATIONS

The above-water surface elevation and wave-height measurement technique has been used to analyze a number of experimental configurations. Pos (1983, 1984, 1985) and Pos and Kilner (1984, 1987) used the technique to analyse a range of breakwater gap configurations (see Figure 3). The experimental results were compared with corresponding numerical results (using finite elements) and also available analytical solutions. As an example, the experimental diffraction diagram for an asymmetrical breakwater gap configuration is shown in Figure 4. This diagram shows contours of equal diffraction coefficient K' where $K' = H/H_i$, H_i is the incident wave height (in the channel), and H is the wave height at a point in the basin. The gap-width to wave-length ratio for this configuration is 1.64. The black dots indicate the crest-line sampling points plotted from both stereopairs, while the dashed lines indicate the crest lines. In another application Pos *et al.* (1987) used the technique to experimentally analyze the refraction-diffraction of water waves around an island.

Most recently, Paterson (1984, 1986) has used the technique to analyze ship bow and stern wave profiles (a similar study was carried out by Moffitt (1968)). As an example, the experimental water surface elevation contour plot of the bow and stern waves generated by a model boat traveling with a forward speed of 1.15 m/s in still water is shown in Figure 5.

Proposed future applications of the technique are (1) the analysis of irregular wave diffraction and refraction-diffraction patterns in the laboratory using procedures developed by Holthuijsen (1979, 1983) and (2) the accurate measurement of laboratory-generated three-dimensional deterministic freak waves of the type described by Kjeldsen (1982).

CONCLUSIONS

The two major problems which prevent the accurate measurement of wave heights in model harbors using conventional techniques (as described in the introduction) can be successfully solved by using the photogrammetric technique. Problem (1) for monochromatic waves is solved because the two stereopairs of photographs can be taken in a much shorter period than is required for a scan using wave probes and because the information contained on the plates is permanent, synoptic, and detailed. Furthermore, there is no instrumental interference in wave processes being observed. Problem (2) can be overcome by using the infinite basin technique, that is, by photographing before the wave energy is reflected from internal walls, thus eliminating the distorting effects of wave reflections within a model basin. The infinite basin technique effectively enables the

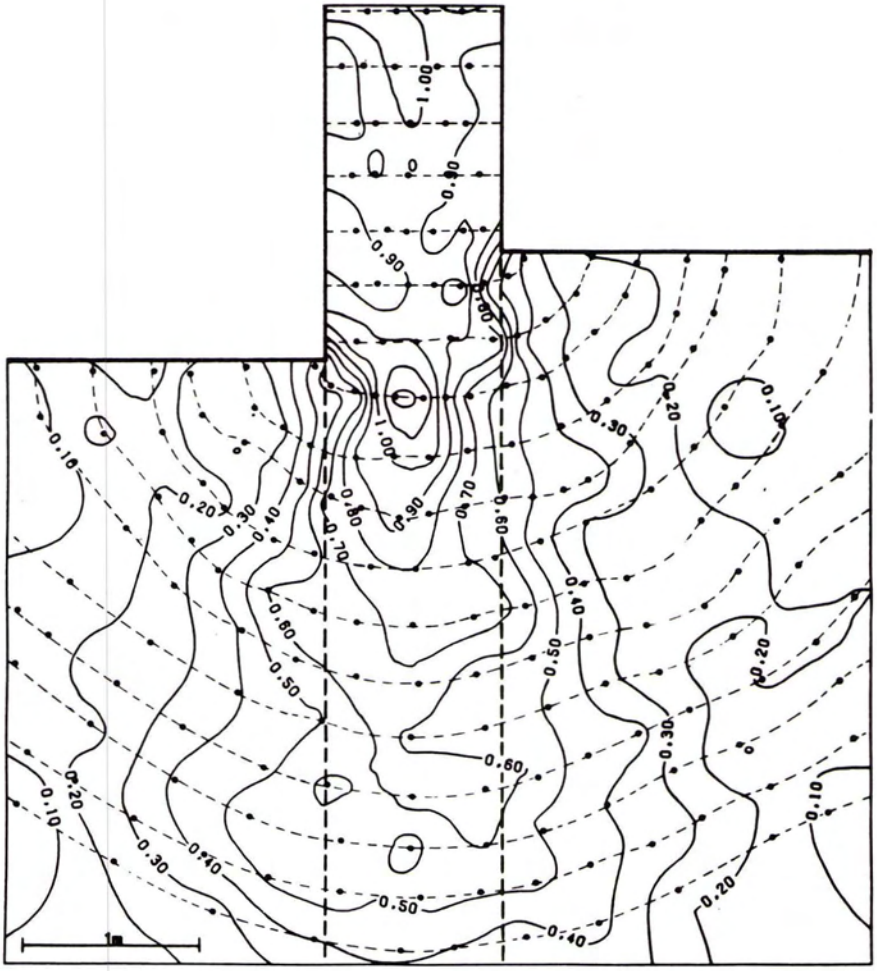

FIG. 4. Experimental diffraction diagram for the asymmetrical B/L = 1.64 breakwater gap configuration.

researcher to accurately model the situation of a continuous wave train entering a basin of infinite extent.

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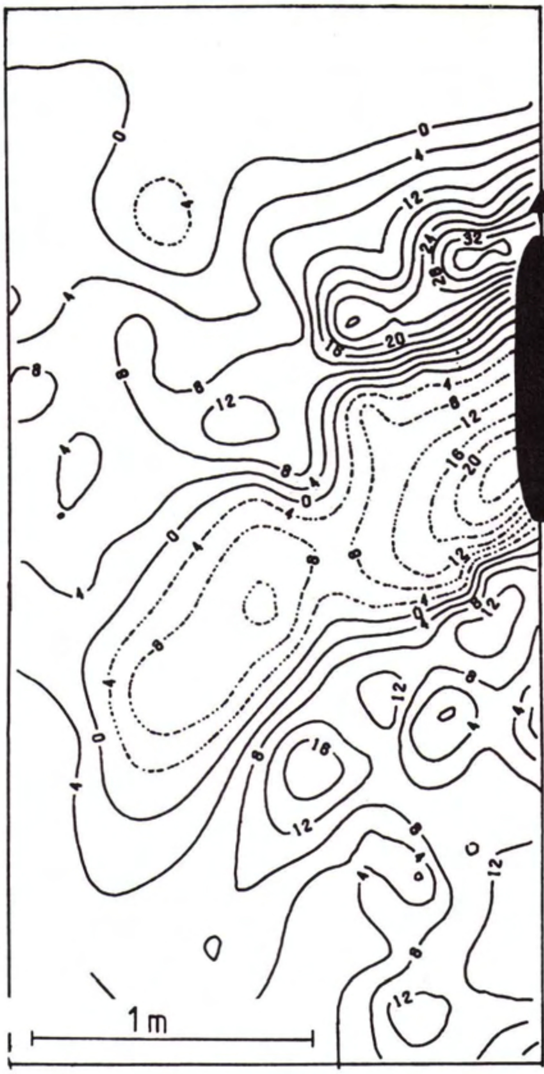

FIG. 5. Computer plot of bow and stern waves generated by a model boat.

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