Dynamic Measurement of Undulating Water Surfaces in a Lock Fill

Clive S. Fraser and Richard G. McGee

Abstract

One of the principal concerns in lock operation is the question of how the dynamics of the water surface during the fill (or emptying) cycle translate to forces on vessels in the lock. Drift forces are greatly influenced by water surface oscillations, and, thus, their modeling is considerably enhanced by the mapping of the undulating water surface at frequent intervals during the fill cycle. Close-range photogrammetry offers a practical and accurate means for water surface mapping. This paper reports on a project in which an array of 71 floating targets, distributed throughout the 160- by 33-m surface area of the Bay Springs Lock in Mississippi, were monitored photogrammetrically. Two synchronized large-format CRC-1 cameras were employed in a convergent imaging configuration to record XYZ coordinate data to better than 2-cm accuracy, at 8-second intervals over several 8-minute, 26-metre lift cycles. Automatic image coordinate mensuration was then used for the 100 or so photographs taken at each fill/empty cycle. From the resulting time-tagged digital elevation model, data-pertinent hydraulic parameters were computed and graphics visualization sequences were generated to illustrate water surface oscillation harmonics.

Introduction

Efficiency is the primary goal in navigation lock design. Basically, optimum lock efficiency involves a balance among the parameters of (1) filling and emptying times for a given lift, (2) lock chamber water surface performance, and (3) the approach conditions for vessels entering a lock. The primary objective is to maximize capacity, reduce processing and queuing times, and reduce traffic delays; all without adversely affecting the lock chamber performance.

Lock chamber water surface performance can be characterized in terms of turbulence and low-order harmonic oscillations. Both of these are related directly to the rate of fill and the distribution of flow delivered to the lock chamber through the filling and emptying (F&E) system. An optimal F&E system would be one that provided a balanced delivery of flow to the lock chamber, irrespective of valve operations

Water surface harmonic oscillations, particularly in the longitudinal direction, are important in lock design due to the possible generation of high drift forces on vessels in the lock. These forces can give rise to undesirable safety conditions. Figure 1 indicates longitudinal modes of oscillation which might occur, depending on lock design and operation. The vertical differential along the length of the chamber that could cause significant problems might be less than 8 to 10 cm over 200 m.

A primary objective in lock testing and evaluation has been to accurately and efficiently assess lock chamber performance, i.e., to quantify the dynamics of the water surface during operation. Traditional direct measurement techniques utilizing hydrostatic pressure transducers, acoustic water level sensors, or float-type water surface instrumentation provide virtually no quantitative measure of the total chamber surface performance. The most desirable measurement technique would be one that provided a comprehensive surface map of high accuracy at desired instants of time throughout the F&E cycle.

To meet this need, a new technique had to be found. It would have to be noninstrusive, rapid, provide as much surface measurement continuity as possible, and display accuracies at the 1-cm level in the vertical dimension. Close-range photogrammetry seemed to offer a practical measurement approach which would meet test requirements, for it provided the means to construct a comprehensive, field-measured digital elevation model (DEM) of a lock chamber water surface during operation. In order to evaluate the photogrammetric approach for lock performance assessment, a number of full-scale tests were performed at the Bay Springs Lock which is situated on the Tennessee-Tombigbee Waterway in Mississippi. The lock, which is shown in Figure 2, has nominal chamber dimensions of 180 m (length) by 34 m (width), and a lift at normal upper and lower pool levels of 26 m. The Bay Springs Lock, with its culvert manifold F&E system and high lift, is considered a state-of-the-art facility and was chosen for testing because of its rapid fill rate of less than 8 minutes over the full 26-m lift.

Measurement Requirements

The proposed water surface mapping called for the monitoring of an array of 71 points distributed throughout the 160-m by 33-m surface area of the lock. Target points were required to be accurately positioned at time intervals of less than 10 seconds, over the entire 8-minute lift cycle. The proposed grid layout for the surface points was based on criteria for determining longitudinal and lateral water-surface oscillations, and targets were located to facilitate contouring to the desired resolution. The targeting scheme is detailed in the

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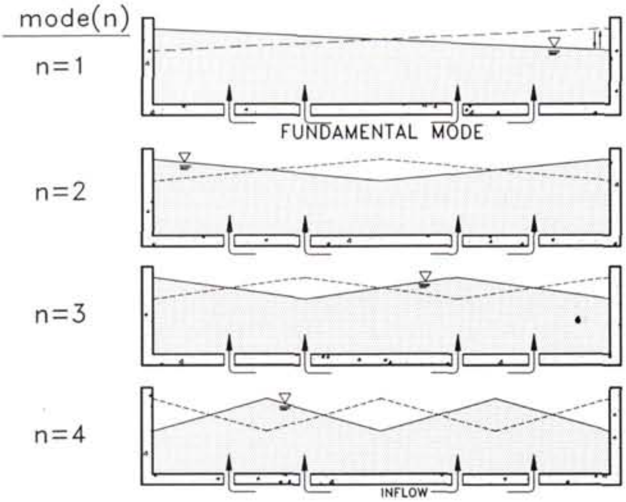

Figure 1. Longitudinal modes of oscillation.

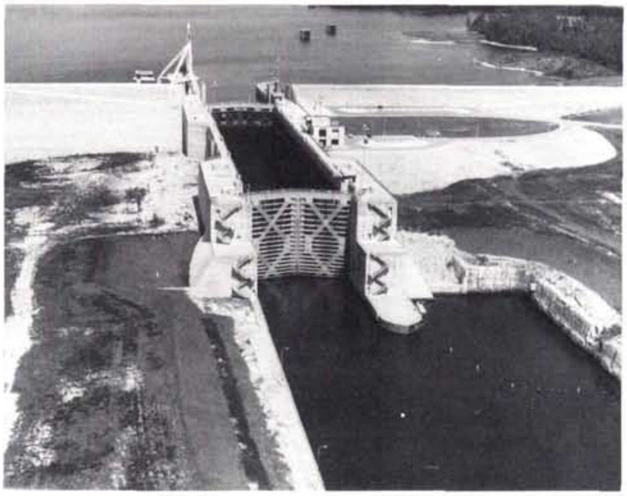
Figure 2. The Bay Springs lock.

following section. Water-surface oscillations of the largest magnitude can be expected to occur during periods of rapid flow acceleration, i.e., when the water surface rate of rise (or fall) is near maximum value. This takes place around the time the filling valves reach full open, when the natural periods of longitudinal and lateral oscillations of the lock chamber reach a maximum, which ranges from 10 to 60 seconds depending on the mode number. The choice of the rate of photography is governed by the need to isolate harmonic parameters of the various periods of water surface oscillations. The fast data acquisition rate of close-range photogrammetry is of considerable benefit in this regard. Application of photogrammetry to the dynamic mapping of water surfaces is not without its practical difficulties, however, and in the next section we look at how the principal photogrammetric difficulties were overcome

Photogrammetric Considerations

The monitoring of a dynamic event by photogrammetry requires the use of either dual or multiple synchronized cameras. At the preliminary design stage of the lock project, it was planned to adopt an imaging configuration of two large-format Geodetic Services, Inc. (GSI) CRC-1 cameras (Brown, 1984), each with a wide-angle lens of 120 mm focal length. When positioned on opposite lock walls, adjacent to the upstream gates, these two cameras, which have an 85° field of view, could image the entire water surface area over the full lift of the lock. Thus, stereo coverage of the event to be monitored was possible. Figure 3 gives a basic illustration of the mildly convergent stereo geometry of the photogrammetric network.

Targeting

The first aspect which required special attention was targeting. Of the 71 monitoring positions, 16 were at approximately 10.5-m intervals along each lock wall, 16 were at the same interval down the lock centerline, and there were five rows of seven points (including three from the longitudinal lines) which were positioned transverse to the lock at intervals of 40 m. These positions can be seen in the simulated CRC-1 photograph shown in Figure 4. Photographic distances ranged from approximately 15 m (an image scale of 1:125) to close to 175 m (1:1400), and the artificial targets to be used therefore needed to be of variable size to accommodate the 11-fold image scale variation between points in the near and

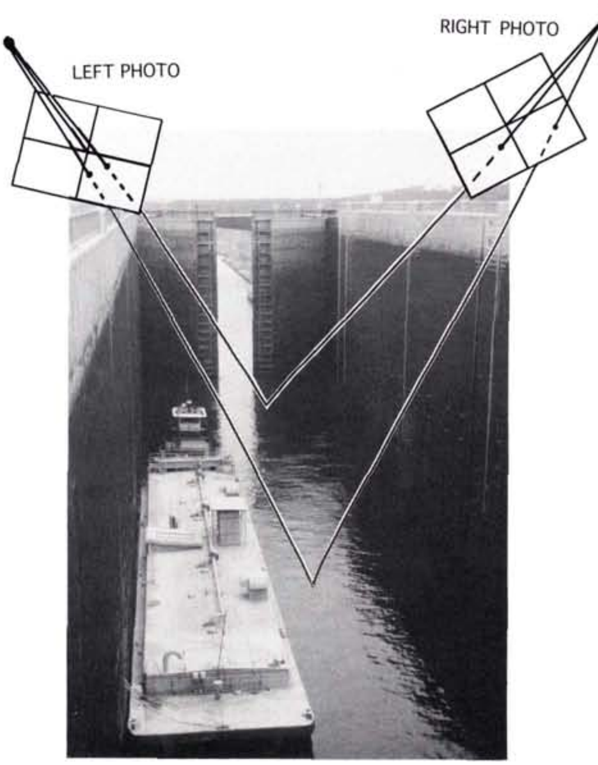

Figure 3. Convergent stereo geometry of the photogrammetric network.

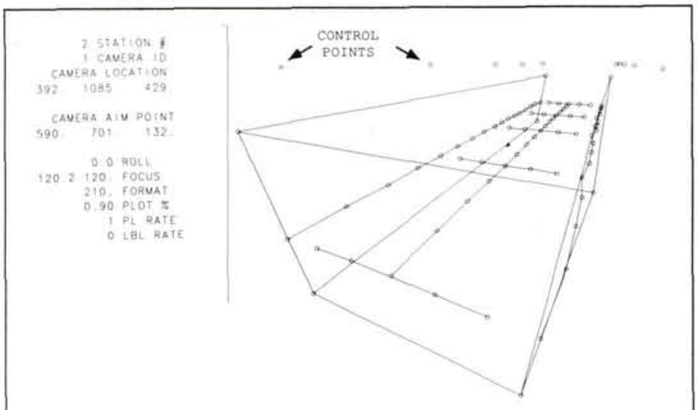

Figure 4. "Simulated photo" from the right-hand camera station, showing target and control point layout.

far fields. An optimum target image size for automatic photo mensuration on the GSI AutoSet video-scanning film reader, which measures image coordinates to accuracies surpassing 0.5 micrometres, is about 100 µm (Brown, 1987). This implied the need for targets ranging in size from just over a centimetre in the foreground to 14 cm for the points farthest from the cameras.

After some investigation of suitable targeting approaches, the one finally adopted involved the use of balls coated with retroreflective paint. These balls, which ranged in diameter from 2 to 15 cm, were then each mounted on a black 45-cm square piece of plywood which in turn was positioned on an inflated innertube. A lattice-like tethering scheme, which made use of the lock mooring bitts, was developed in order for the target array to freely rise and fall with the changing water surface.

The use of retroreflective targets is nowadays standard throughout industrial photogrammetry (e.g., Fraser and Brown, 1986; Fraser, 1993). In this case, "retrotargets" would provide a means to image the far distant points with only a modest amount of strobe light, even though the photography was to be taken at night.

Photography

For each fill cycle, 50 epochs of surface data were required, with the time interval between epochs being 6 to 8 seconds. This interval was the shortest possible due to the 6-second recycling time of the CRC-1 cameras. Between epochs, the water level would move up or down by a maximum of about 0.5 m. With the surface changing at such a rapid rate, it was critical to ensure that the two cameras were perfectly synchronized. Synchronization was achieved by means of a closed-loop shutter firing system which operated as follows: (1) as the shutter for the first camera was actuated by cable release, a shutter synchronization signal was sent to electronically activate the shutter of the second camera; (2) with the opening of the second shutter, the strobe for that camera was fired; and (3) a photosensitive "slave-tripper" then fired the strobe system at the first camera. The photo-electric coupling of the two strobe units ensured perfect synchronization for the photography.

Network Geometry

Design options for a suitable network geometry were very limited. The positioning of the two CRC-1 cameras on each side of the lock gave rise to a photogrammetric base of 33 m, and to "base/height" ratios in the convergent stereo network ranging from a favorable value of 2 for near-field targets to a less than ideal 0.2 in the far field. The associated range of standard errors for the photogrammetric triangulation was then 0.3 cm for targets closest to the cameras to 6 cm for points at the far end of the lock. In the latter case, the triangulation precision is weakest in the "depth" direction, i.e., along the lock. Of principal concern to the surface mapping, however, was the vertical coordinate, and here the standard errors of triangulation ranged from 0.2 to 1.2 cm. Thus, even at a distance of some 170 m from the cameras, the accuracy of water level determination would readily surpass the 2.5-cm tolerance specified.

Standard errors of object point triangulation were estimated based on an overall image coordinate measurement accuracy of 2 µm. To ensure that such accuracy would be achieved, it was imperative to pay close attention to the subject of camera calibration. In order to calibrate the two CRC-1 cameras a self-calibration procedure was adopted whereby a supplementary 12-photo, two-camera network was established using the object point target field. The resulting camera calibration parameters were then applied in all subsequent two-photo bundle triangulation computations for the water surface mapping.

Control Considerations

The bundle triangulation performed at each measurement epoch amounted to an analytical relative orientation only; no account was taken of object point control coordinates. There was, nevertheless, a need to provide a stable datum for the *XYZ* reference system in order to quantify epoch-to-epoch

Figure 5. CRC-1 camera.

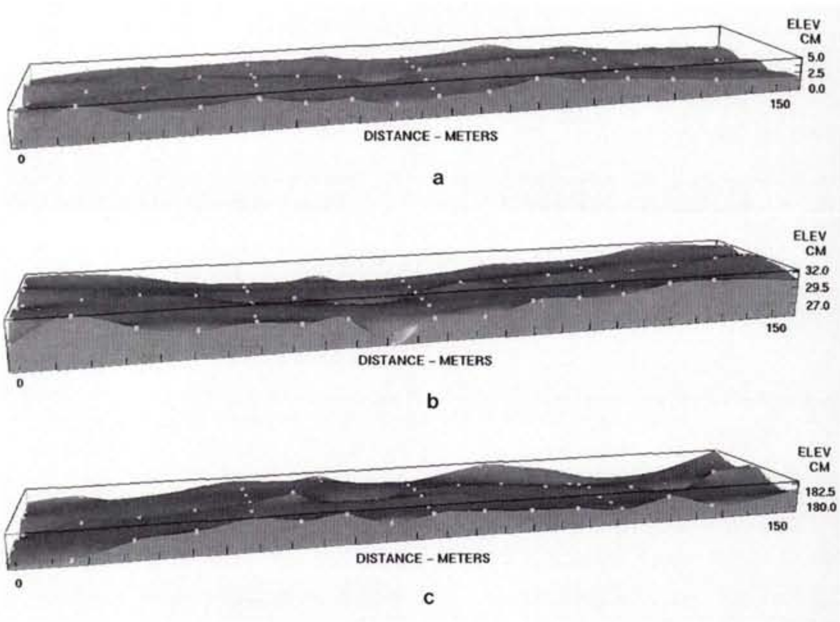

Figure 6. Measured water surface DEM at (a) Epoch 2, b) Epoch 5, and (c) Epoch 10.

point movements. Moreover, because surface slope information was to be derived, it was important that the *Z*-coordinate be truly aligned to the local vertical.

To provide a stable datum, ten targeted control points were established along the walls of the lock. These targets, which are indicated in the simulated photograph (Figure 4), were also balls coated with retroreflective paint. Following the final photography session, the *XYZ* coordinates of these control points were surveyed using theodolites and levelling to an accuracy of a few millimetres. The resulting *XYZ* coordinates provided the stable reference system to which all coordinate data would refer. Through a 3D similarity transformation, the object point coordinates of the relatively oriented photogrammetric networks were transformed into the control system, thus providing the necessary absolute orientation. The provision of ten common points in the coordinate transformation would provide a degree of quality assurance for the photogrammetric triangulation process, because coordinate residuals resulting from the least-squares fit could be evaluated against the positional standard errors from both the photogrammetry and the ground survey of the control points.

Measurement Operation

In most respects, the photogrammetric measurement operation proceeded as planned. A total of 12 tests consisting of 11 fills and one drain were performed. Unfortunately, a few of the tests had to be prematurely terminated because of heavy rain which presented the double adversities of poor visibility and the loss of reflectivity of retrotargets when they became very wet. Light rain persisted for most of the three-day test period, but fortunately it had limited impact on the data gathering phase. Figure 5 shows one of the CRC-1 cameras on its mount on the lock wall.

Of the photography gathered, only that for four tests has been measured to date. Film mensuration on the AutoSet monocomparator required a little more manual intervention than had originally been envisioned, due mostly to poor target images caused by the weaker than normal return of light from wet retrotargets. Nevertheless, the film reading process proceeded quite rapidly, with about six to eight photos being measured per hour. For any photograph in an image sequence, it was possible to predict accurately the position of target points based on an extrapolation from the two previous photographs. This *a priori* knowledge of image point positions assisted in speeding up the film measurement process. Again, because of the rain, one to three targets per epoch were typically unmeasurable, and, as anticipated, this problem was most pronounced for points in the far field.

The bundle triangulation adjustment for each epoch was carried out immediately after the associated pair of photographic negatives was measured. Closures of triangulation averaged about 2.2 μm, though *x*-image coordinate residuals (close to being within the epipolar plane) were typically under a micrometre due to the weak internal reliability exhibited by the network geometry. Perhaps a more reassuring quality control indicator was provided by the root-mean-square (RMS) values of *X*, *Y*, and *Z* coordinate residuals that arose in the transformation of the photogrammetrically measured coordinates to those of the ten-point control configuration. The resulting values of 2 cm in *X* and *Y* and 0.5 cm in *Z* were both within the bounds anticipated, and were very repeatable from epoch to epoch.

Analysis of Surface Mapping Data

With the time-tagged DEM for each of the 50 epochs of measurement within a fill or empty cycle, a first-of-a-kind prototype evaluation of the water surface performance of a lock chamber had become possible. The primary hydraulic parameters to be evaluated from the DEM data were water surface harmonic oscillations and F&E system discharge. Photogrammetry allowed the latter to be measured to hitherto unattainable levels of precision through a determination of volumetric changes between photo epochs. This afforded improved evaluation of various hydraulic coefficients such as those for valve loss, friction and form loss, and entrance and exit manifold loss.

The primary analysis objective focused on determining the harmonics of water surface oscillations. Figures 6a through 6c show the water surface DEMs for three photo epochs during the critical period of culvert valve movement. Figure 6a, Epoch 2, is just after the valve opening begins. The longitudinal water surface oscillation is generally at the fundamental mode ($n = 1$) as expected. (Note: The vertical exaggeration is approximately 134 times the horizontal scale.) Higher frequency transverse oscillations are also present. Approximately 30 seconds later, at Epoch 5, the longitudinal water surface oscillation is being driven predominantly around the second mode ($n = 2$) of oscillation. Figure 6b definitely shows higher elevations at the ends of the lock than at the midpoint. Forty seconds later, at Epoch 10 (Figure 6c), the case could be made for oscillations of $n = 2$ and $n = 4$. These modes of oscillation were not unexpected for the high lift, balanced-flow F&E system at Bay Springs. In terms of lock performance, however, the severity of the surface oscillations is not considered unacceptable. Vessels utilizing Bay Springs Lock have reported no difficulties during processing.

Concluding Remarks

The reported dynamic mapping of undulating water surfaces in a lock fill represented a first-of-a-kind application of close-range photogrammetry to lock chamber performance assessment. The Bay Springs lock project persuasively demonstrated that a photogrammetric approach employing synchronized large-format cameras and automated image mensuration was both a practical and economical means for providing water surface DEM data to the high measurement frequency required. Moreover, photogrammetry facilitated the recovery of harmonic oscillation data and associated hydraulic parameters to levels of accuracy which have been hitherto unattainable with traditional, direct measurement techniques.

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