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THIRD ORDER HYDROSTATIC LEVELLING

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ABSTRACT

The paper reports on the Australian Survey Office's experience in using a hydrostatic levelling technique in the tidal mangrove swamps of Hinchinbrook Island, Queensland where conditions precluded the economical use of spirit levelling or trigonometrical heighting for proposed third order results. The technique employs repeated 300-metre bays with change points, along the banks of a watercourse. The watercourse is the means of transportation and provides the necessary temperature stability for the hydrostatic tube. The equipment used is cheap and readily available anywhere at short notice. Experiments performed in Brisbane to test accuracy are described.

The Australian Institute of Marine Science is conducting an inshore productivity research programme in the tidal mangrove areas of northern Queensland. The initial and largest intensive study area (fig. 1) is at Missionary Bay, Hinchinbrook Island (north of Townsville) and it is here that much survey assistance is being provided by the Australian Survey Office. A basic mapping programme for the production of 1 : 5 000 orthophotomaps and contour sheets has been undertaken, and this included the establishment for two months of an automatic tide gauge to determine Mean Sea Level.

Scientists have a need to understand tidal movements and depths through the mangrove system because biological productivity is presumed to be closely related to events associated with these water movements. To this end the Australian Survey Office has established a series of tide boards (fig. 2) spaced at one kilometre along two of the creeks which penetrate the mangroves, and has established bench marks throughout the area to act as level control points for the hydrographic contour survey of the mangrove system. Owing to the massive interwoven root system and dense

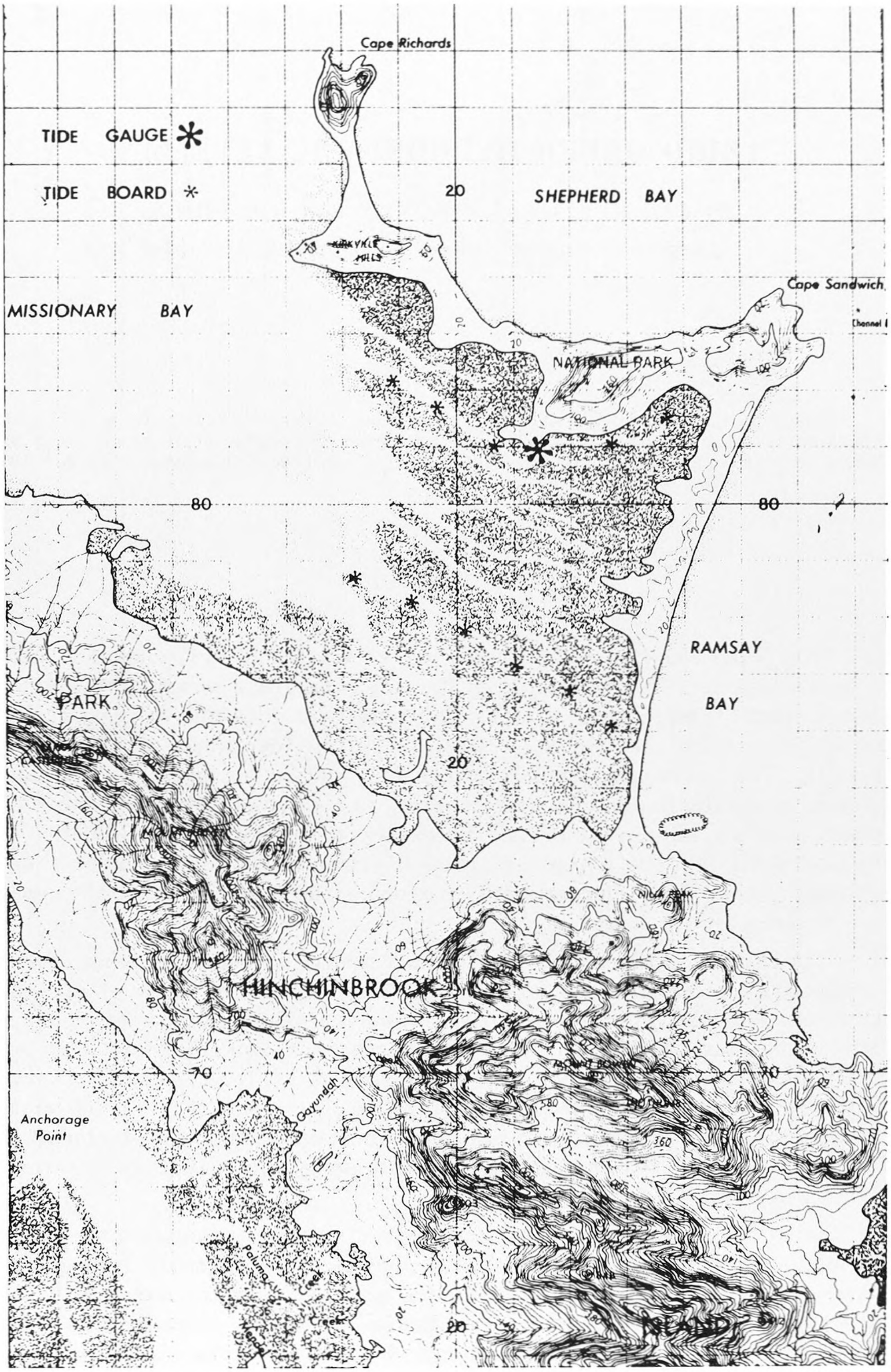

Fig. 1. — Tidal mangrove swamps, Hinchinbrook Island.

FIG. 2. — Taking the level with a measuring tape. Note the G-clamp, the length of plastic tubing and the wetted bandage on the main hose.

canopy, photogrammetry was unable to provide the 0.25 metre contours required within the mangroves. Instead, high tide inundation of the area is being utilized for surveyors to wade or swim through the mangroves with waterproof watches, field books, compasses, tagged measuring rope and offset tapes (to measure " soundings "). Photo identification and scaling from the orthophotomaps is used to control the terminals of these hydrographic mangrove traverses.

Levelling on to a common datum of the tide boards and hydrographic survey bench marks (temporary tide board stations) presented a problem.

Spirit levelling is impossible and trigonometric heighting was discarded in most cases, owing to inaccuracy and the difficulty and expense of setting up observing towers in the mud and above the canopy. Trigonometric heighting has been used as a check, where possible, and in a few short-distance cases where a photo control point could be seen from a stable position on the creek/mangrove edge. The method of transfer of tidal datum by simultaneous tide watch was not employed, because of the large number of bench marks required and because of lack of knowledge of the Mean Sea Level (tidal) gradient.

Hydrostatic levelling offered the only economic alternative. It could be carried out regardless of tide height ; the cost of equipment was low ; and expected accuracy was third order.

CHOICE OF EQUIPMENT

Time restrictions at the outset of the project dictated that equipment must be already available on the market. There was no possibility of calling tenders for special equipment.

SNEDDON [1] indicates the desirable relationship between reading-glass tube diameter and hydrostatic tube diameter for critical damping conditions ; i.e. conditions which will give the most rapid settling time without undesirable oscillation of the meniscus.

Ten-millimetre diameter glass tubing is readily available and fits easily into eleven millimetre diameter reinforced garden hose. This was chosen, with 200 m of hydrostatic tube in mind, as being a practical compromise. We have found that, following a large disturbance of the water level (blowing hard into one end), a 300 m garden hose, with 10 mm glass tubes, gives a rapid — 2 to 3 seconds — damping to small amplitude oscillations, and that settling sufficient for reading has occurred after 30 to 40 seconds.

Glass reading tubes have been used to date, but use of an unbreakable substitute would save on time lost due to breakages. On average, one glass tube has been broken per working day with about 20 to 30 minutes required to replace it.

A single diaphragm marine hand pump has been found to be the most suitable device for filling the hose.

Two-way radios should be as water resistant as possible, and protected from salt spray during use.

Aluminium punts or rubber boats provided with outboard motors of 10-35 HP have proved much more stable than conventionally shaped hulls. The rubber boats are expensive, but pay off in terms of transportability and extremely good stability and seaworthiness. Two such boats are adequate for transporting 300 m of hose. The lead boat tows the second boat, using the hose as the tow line. Experience at Hinchinbrook Island indicates that more than 400 m of hose would be unmanageable by small boats.

WAALEWIJN [2] advocates the use of pure boiled water. However, at Hinchinbrook, with proposed third order results in mind, it was decided to use local sea water. This saved much time filling, refilling and topping up during the work.

Waterproof field books and washable clutch-pencil leads have been used with much success. They can be used underwater.

FILLING THE HOSE

About 0.6 m of clear plastic tubing is attached to the top of the 0.5 m glass reading tubes. The plastic tubing is used to clamp off the hose at each end during transportation and to connect to the outlet of the filling pump. An adaptor is required to connect the pump outlet hose to the plastic tubing. All connections are suitably clamped.

Other methods have been tried, but the following has been found to be the most successful and efficient. The pump is held vertically underwater (outlet hose upwards) and slowly pumped. This fills the pump inlet hose, pump body and outlet hose completely with water and ensures the complete elimination of air bubbles. The outlet hose is connected underwater to the clear plastic tubing which is already attached to the glass reading tube and full hose length. A few pump strokes are then given (with the pump still underwater) to fill the first few metres of hose. The pump is then brought out of water to a more convenient position and pumping continued. The filling is carefully monitored by watching the glass tubes at each end of the hose. When bubble-free water is seen emerging from the hose, pumping is continued for another five minutes to ensure the dislodgement of any residual bubbles. The filling operation from commencement to final clamping-off of each end takes about 20 to 25 minutes for 300 m of hose.

Hose position during filling has, so far, been either stretched out on land or between two boats in the water. No attempt has been made to fill the hose whilst still rolled up on its storage reel. It is clearly essential to have perfect seals at all connections and on the pump itself.

An initial test of a fill can be made by bringing both ends together and comparing heights in the glass tubes. Any substantial difference in height indicates the presence of air in the system. A gross temperature effect can be observed by allowing half the hose to lie for a time in strong sunlight.

HOSE POSITION AND CHANGE POINTS

Change points are established along the banks of the watercourse at hose length intervals. On the Brisbane test base, change points are star pickets driven deep into the mud banks of a canal. At Hinchinbrook a stable mangrove root is chosen within 0.5 m of approximate high water mark, and a tack driven into a side surface of the root. A large G-clamp is then used to clamp the hose to the root so that the glass reading tube is near vertical and very close to the change point tack. The hose clamp which secures the hose to the glass reading tube provides a suitable strong point at which a G-clamp may be applied (fig. 2).

SNEDDON [1] indicates that, for minimisation of errors due to temperature variation within the hose, the hose should lie in an equipotential plane throughout its length. Supporting the hose throughout its length with floats apparently solves this problem, but causes constant and large (up to 0.1 m) oscillations of the meniscus due to wave action on the watercourse surface. Allowing the hose to rest on the bottom is the closest workable solution to the problem. In order to keep most of the hose on the bottom (and thus in approximately the same equipotential plane) the rising sections at each end should be as vertical as possible and thus be as short as possible.

When observing with the hose in a fast flowing current, care must be taken not to allow a loop to be formed in the hose by the current at the downstream end : such a loop will cause severe oscillation of the meniscus as the loop is buffeted about. Stability of the rising section of the hose is achieved by tying it to a mangrove root below surface level with a small piece of rope.

READING PROCEDURES

The following technique, for height difference determination between change points and for proving the validity of the result, has been adopted.

a) Clamp the glass tube to the mangrove root at a suitable height at each end.

b) With radio contact, unclamp the clear plastic tube, adjust water level, allow to settle, then read simultaneously the vertical height difference between change point and water level. Note that a slight want of verticality of the glass tube will not affect the measurement, by offset tape, of a vertical height difference.

c) Disturb by blowing hard into one end.

d) Allow to settle and read simultaneously.

e) Add seawater so that water level rises by about 0.1 metre. All adjustments of water level are done from the same end so as to maintain internal hose parameters.

f) Repeat steps b), c), d) and e) twice more so that three water level positions are observed over the length of the glass tubes, giving six sets of simultaneous readings.

The height differences obtained from each of these six sets of readings vary from the mean by about ± 0.003 m. Any height difference which varies from the mean by more than three standard deviations (calculated for a single observation), is rejected and further readings are taken. Radio contact is essential to ensure that the readings are simultaneous and for transferring observations to the master field book for immediate reduction.

See Table 1 for a typical set of readings. The sign convention is as in spirit levelling, the meniscus in the glass tube being regarded as the instrument and a positive reading being obtained to a change point below it.

Table 1

(figures in metres)

EXAMPLE 1

Forward readings

Time	1013	1014	1016	1018	1019	1020
Change point 76/04	– 0.024	– 0.012	+ 0.041	+ 0.022	+ 0.167	+0.145
C.P. 76/05	+ 0.160	+ 0.177	+ 0.226	+ 0.203	+ 0.352	+0.326
Diff. Ht.	– 0.184	– 0.189	– 0.185	– 0.181	– 0.185	– 0.181

Tide falling 12 March 1976
Mean forward reading = – 0.184
Standard deviation of single observation = ± 0.003
Standard deviation of mean = ± 0.001

Return readings (hose reversed)

Time	1028	1030	1032	1033	1034	1036
C.P. 76/05	+ 0.193	+ 0.184	+ 0.312	+ 0.299	+ 0.411	+ 0.395
C.P. 76/04	+ 0.016	+ 0.006	+ 0.135	+ 0.122	+ 0.239	+ 0.220
Diff. Ht.	+ 0.177	+ 0.178	+ 0.177	+ 0.177	+ 0.172	+ 0.175

Tide falling 13 March 1976
Mean return reading = + 0.176
Standard deviation of single observation = ± 0.002
Standard deviation of mean = ± 0.001
Adopted mean of forward and return runs = – 0.180

EXAMPLE 2

Forward readings

Time	1049	1050	1052	1053	1055	1056
C.P. 76/05	+ 0.067	+ 0.068	+ 0.155	+ 0.143	+0.273	+ 0.254
C.P. 76/06	+ 0.088	+ 0.086	+ 0.174	+ 0.162	+ 0.292	+ 0.269
Diff. Ht.	– 0.021	– 0.018	– 0.019	– 0.019	– 0.019	– 0.015

Tide falling 12 March 1976
Mean forward reading = – 0.019
Standard deviation of single observation = ± 0.002
Standard deviation of mean = ± 0.001

Return readings (hose reversed)

Time	0959	1000	1002	1003	1004	1006
C.P. 76/06	+ 0.032	+0.022	+ 0.157	+ 0.147	+ 0.328	+ 0.308
C.P. 76/05	+ 0.021	+ 0.011	+ 0.143	+ 0.134	+ 0.314	+ 0.295
Diff. Ht.	+ 0.011	+ 0.011	+ 0.014	+ 0.013	+ 0.014	+ 0.013

Tide falling 13 March 1976
Mean return reading = + 0.013
Standard deviation of single observation = ± 0.001
Standard deviation of mean = ± 0.001
Adopted mean of forward and return runs = – 0.016

The above technique will detect the accidental entry of air into the hose or a constriction caused by snagging. If a large air bubble is present in the hose when water is added, an error due to compression of the bubble is caused, resulting in a progressive change in height difference over a set of readings. On one occasion, when air was trapped in a loop in the hose, a difference of 0.03 m in reduced height difference from start to finish was observed. In the case of a complete constriction, the height difference will vary by the amount of water added at one end and by lesser amounts for partial constrictions. Both problems (air entry and constrictions) have proved rare in occurrence, but immediately detectable by the standard reading procedure adopted.

Good observations are possible with the meniscus fluctuating up to three or four millimetres, but attention must be paid to positioning of the hose if greater fluctuations are experienced.

The following two effects cause a gradual movement of water level at both ends in the same direction. The first effect is caused by compression or expansion of the hose as the tide rises or falls. Level changes in the glass tubes of up to one centimetre per minute are common. The second effect is caused by gradual shrinkage of the hose after it has been stretched during towing from one pair of change points on to the next. This second effect can sometimes be larger than the first, in which case it is possible for the water level to move in the opposite direction to that expected from a knowledge of tide direction. Simultaneous observation by radio contact eliminates possible errors due to the two effects.

When satisfied with the readings at a pair of change points, the hose is topped up (at the nominated end) with sea water, using a small funnel, and then clamped off ready for towing.

SYSTEMATIC ERROR

We expect that sea water in the hose will have an amount of dissolved gases in it at any time and that with changes in temperature and pressure these gases will be either in solution or in the form of minute air bubbles clinging to the inner walls of the hose. Presuming some of these bubbles to exist at all times and to vary in quantity throughout the hose, especially in the rising sections at each end, then a systematic error in reduced level will accumulate, due to varying compression of the air bubbles, as the hose is moved forward to successive pairs of change points. Consider the hose being reversed end-for-end and a second height determination made between change points. If the internal parameters of the hose remain unchanged, then the systematic error will tend to cancel out by adopting the mean of forward and reversed height difference determinations.

For one particular fill of the hose, we have found the systematic error to have values remaining constant at a difference in height between forward and reverse measurements of between one and five cm.

To prove this in absolute terms and to test real accuracy, a precise levelled base of four 300-metre measuring bays was established along the banks of a tidal canal at Eagle Farm in Brisbane. An analysis of the test base observations (see Table 2), together with all field results (where hose reversal was used), indicates that in 92 % of cases to date, systematic error has occurred and been monitored in the expected direction. The effect is masked by random error, and it is therefore impossible to calibrate a particular fill and to apply the value of the systematic error found to height differences determined from levelling in one direction only.

Table 2

Comparison of hydrostatic levelling (300 m sections) with precise spirit levelling.

Bay	Hydrostatic Levelling (metres)			Precise Levelling	Difference
	Forward	Return	Mean	(m)	(m)
1-2	+ 0.471	– 0.457	+ 0.464	+ 0.4656	+ 0.002
2-3	– 0.463	+ 0.469	– 0.466	– 0.4628	+ 0.003
3-4	+ 0.343	– 0.337	+ 0.340	+ 0.3410	+ 0.001
1-2	+ 0.456	– 0.464	– 0.460	+ 0.4640	+ 0.004
2-3	– 0.477	+ 0.460	– 0.468	– 0.4690	– 0.001
3-4	+ 0.340	– 0.357	– 0.349	+ 0.3460	– 0.003
4-5	– 0.180	+ 0.179	– 0.179	– 0.181	– 0.002
Standard Deviation for a single double-run bay = ± 0.0024 m					

It is desirable to remeasure with reversed hose between two change points with as short a delay as possible ; but we have found that a hose with one particular fill, and always depleted and topped up from the same end, will maintain its internal parameters fairly closely for two to three days.

Thus the procedure, in levelling between two bench marks, is to measure successive 300-metre bays in one direction ; then to reverse the hose in position and perform a return run. The mean height difference from forward and reverse runs is adopted for each pair of change points.

TEMPERATURE AND ATMOSPHERIC EFFECTS

For temperature uniformity, it is important to keep any hose length out of water to a minimum, and change points and clamping of the tube should be chosen with this in mind. Conditions at each end of the hose may be different, e.g. sun and shade, or steep banks at one end and gently-sloping banks at the other end. These problems may be solved by making conditions similar (e.g. shading a sunny end or taking extra hose out of the water at a steep-banked end) or by minimising the effect. Minimisation is most easily achieved by lagging three metres of hose at each end with bandages and then keeping the bandages wet at all times.

In one experiment in Brisbane, both ends had 1.5 m of lagged wet hose exposed for a set of observations. The lagging was removed from one end and, after ten minutes exposure to strong sun, another set of readings was taken. A change of two millimetres in the height difference occurred in the expected direction. Owing to the masking effect of the random error (e.g. 0.003 m) in relation to the very small effect of temperature (e.g. 0.002 m for two metres of hose varying in temperature by 5 °C), we have been unable to produce reliable results from the tests. We can however, say that the effect must occur and that it is desirable to minimise any source of error. Lagging with wet bandages (fig. 2) has proved to be no trouble in use.

Atmospheric pressure and temperature differences between ends of the hose can be ignored over 300 m for third order work.

ACCURACY

Table 2 shows the difference between two-way hydrostatic levelling and precise-levelled values from the test base in Brisbane. The precise values are so accurate that differences from them may be treated as true errors for third order purposes. For a single height determination between 300 m-spaced change points (i.e. the mean of forward and hose-reversed sets of measurements), we can deduce a standard deviation (single observation) of ± 0.0024 m which can be extrapolated to ± 0.005 m over a kilometre. This is well inside the 0.012 m for a kilometre required by third order standards, and so third order accuracy is claimed for the method as outlined. Thus, for third order work, the earlier assumptions are justified, viz. : that temperature stability supplied by immersion in the watercourse and by wet lagging of exposed hose is adequate ; that the watercourse bed's approximation to an equipotential plane is sufficient ; that local water can be used instead of pure boiled water ; that atmospherics can be ignored ; that the filling and reading procedures adopted are acceptable ; and that the tidal tilt of the equipotential measuring plane over 300 m is insignificant.

ACCURACY WITHOUT SYSTEMATIC ERROR CANCELLATION

Reading-glass tube breakages can be rectified without a significant change in the overall internal hose parameters, but suppose the hose should part at a midway connection or air enters the hose, thus requiring a complete new fill. The systematic error of the new fill will be randomly different to the original fill. Thus part of a return levelling run may have to be completed with a different fill to the forward run. Field experience indicates that this may be a necessary economic expedient, and that the mean of two different-fill height determinations will approach third order accuracy. This is based on the knowledge that, in 70 % of cases, height differences obtained from one-way levelling will be within third order standards. It is also clear that a measurement should be fully repeated (i.e. both directions with the one fill) if third order results are to be guaranteed.

TIMES, FOR COSTING PURPOSES

On the most recent trip to Hinchinbrook, detailed times were recorded for analysis. Time taken to perform the actual observations ranged from five to sixteen minutes, with an average of seven minutes. The cycle time from unclamping the 300 m hose, moving it forward, completing a set of readings to unclamping again, averaged thirty-nine minutes, with a range of twenty-six to fifty-five minutes. The return run is slightly shorter, owing to change points having been selected and established on the forward run.

The average progress rate for (one-way) hydrostatic levelling with a 300 m hose is 2.2 km/day. This is based on an eight-hour working day. The best distance recorded was 3 km in one day. A basic hydrostatic levelling party consists of four persons (i.e. one party leader and assistant in each of two boats). The progress rate includes allowance for travel and the many problems which arise when working with boats.

CONCLUSION

We feel that we have evolved a successful third order levelling technique for use in difficult land/water border areas where conventional levelling is impractical ; also that the investigation into the existence and elimination of systematic error has been useful.

We wish to acknowledge the essential help of the Australian Survey Office in preparation of this paper.

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