CHAPTER 149

SEA-LEVEL MEASUREMENTS IN THE WASH BAY

1. Introduction

A report (Binnie and Partners, 1965) on the water resources of the Great Ouse Basin put forward proposals for storage in the Wash of fresh water from the four rivers draining into the bay. The scheme suggested was to take the form of a barrage, enclosing about a third of the area of the bay, behind which fresh water would be stored in raised impoundments. Four years later (Binnie and Partners, 1970) this proposal was superseded by a scheme for storage in bunded reservoirs built on the foreshore at the head of the bay. The current Wash Feasibility Study (commenced in 1971) is expected to highlight the most suitable scheme of this sort following a programme which includes field data collection, hydraulic and mathematical model testing and site investigations. The scheme as currently envisaged would take the form of bunded reservoirs built (largely from dredged sea bed material) on the foreshore close to the outfall of the river Great Ouse and connected by tunnel to intakes on that river, and later on the river Nene. To meet increasing demand further impoundments could be built along the foreshore to store water drawn from the other rivers draining into the Wash. Figure 1 shows a possible reservoir scheme which is among those being considered. Continuous sea level observations have been made at 4 points in the Wash bay (figure 1) using automatic level recorders. The purpose was to provide information on tides and surges in connection with the feasibility study.

2. Description of the Wash

The Wash is a bay on the east coast of England facing the North Sea. Almost all the drainage into the bay is carried by the four principal rivers (Figure 1) which debouch at its head. Nearly one sixth of the catchment area of these rivers lies below high water of ordinary spring tides and consists of alluvial deposits resulting from successive reclamation works dating from Roman times, and from settlement of suspended solids in the bay water. All the four rivers are navigable for a considerable distance inland from their outfalls but virtually all marine commercial traffic now goes to King's Lynn on the Great Ouse, Boston on the Witham or Wisbech on the Nene.

Apart from a few kilometers of cliffs on the north-east shore, the Wash is almost entirely bounded by man-made coastal defence works. Extensive sand and mud flats have formed on the foreshores and from time to time new land is reclaimed to agriculture by construction of a new sea defence bank.

The bay is about 28 km long and 25 km wide. It narrows at the mouth to about 20 km. The volume of sea water entering past the mouth is about 3500 million m^3 on a mean spring tide (whose range at the mouth is almost 6m). Spring ranges of 8 m or more occur from time to time.

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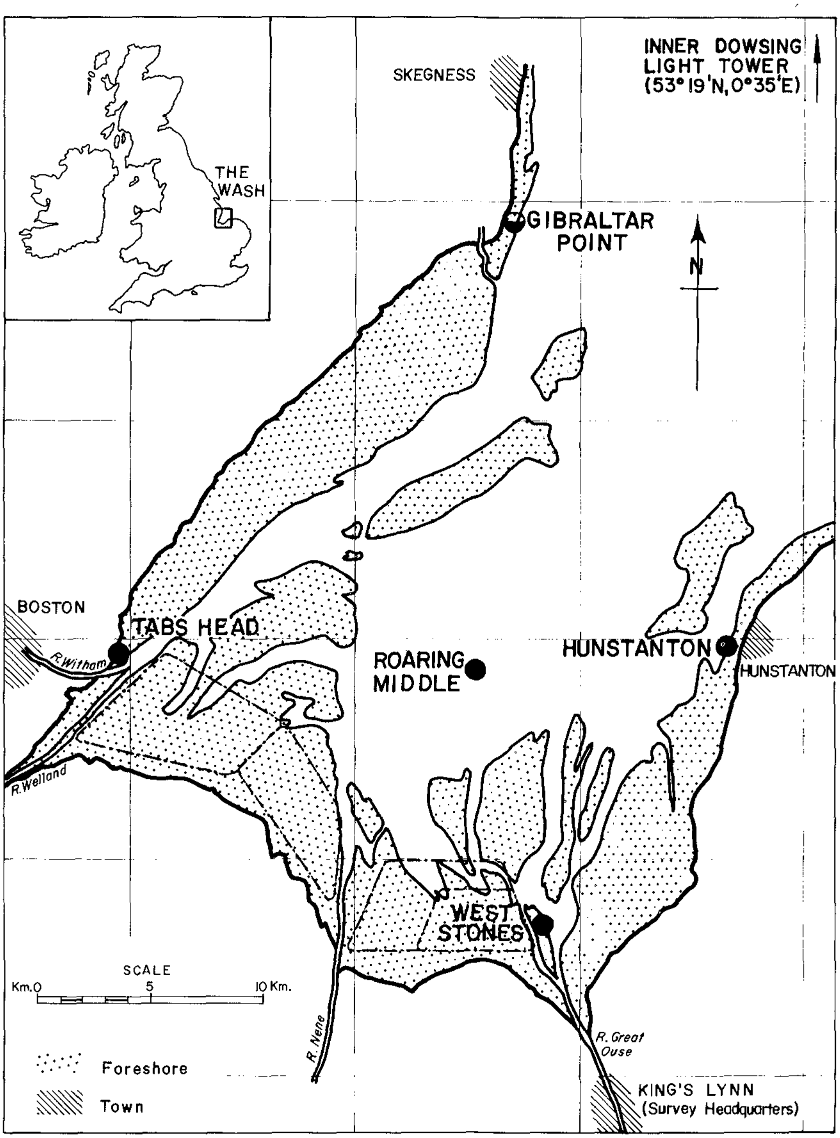
2. Binnie & Partners, Artillery House, Artillery Row, Westminster, London, England.



Automatic tide recorders

Visual observations

—·—·–Reservoir banks
(Typical scheme)

FIG.1: LOCATIONS OF TIDE RECORDING STATIONS

High water is almost simultaneous throughout the Wash bay, being about 10 minutes earlier at Gibraltar Point than at West Stones and Hunstanton. The difference between high water levels measured at the head of the bay and those at its mouth is typically about $\frac{1}{2}$m (springs) or $\frac{1}{4}$m (neaps).

3. Requirements for tidal recording

The level recording instruments were chosen and sited to provide information relevant to several aspects of the scheme including the following:-

i. mathematical models of the Wash bay and of the tidal portion of the river Great Ouse

ii. hydraulic model (1:100V, 1:1250H) of the Wash bay

iii. sea bed survey relating to design and construction

iv. design and construction of the enclosing bunds from dredged sea-bed material with the highest possible use of local materials for surface protection

v. measurement of the effect on water levels in the Wash of local wind set-up and of North Sea surges

vi. programming of the final closure of each reservoir bund against the tide

vii. prediction of sea-bed changes in the bay consequent upon construction operations and reservoir location.

The nearest permanent gauge on the North Sea coast is at Immingham, about 70 km north of the Wash entrance. There are automatic recording gauges at King's Lynn, Boston and Sutton Bridge but they are not well placed for the purposes of study. The King's Lynn record has, however, helped in analysing the progress of certain North Sea surges, including that of 1953 which was associated with disasters in both England and the Netherlands. Tides are predicted from Immingham predictions, for certain points within the bay on the basis of observations lasting about a month. The most recent series of such observations was carried out by the Hydrographer to the Navy in 1968 at Skegness, Hunstanton and Tabs Head. The resulting predictions are accepted as adequate for navigation purposes but were not good enough for the feasibility study.

In order to understand the existing tidal circulation in the bay and obtain sufficient information about predicted tides and surges at the most important points, there was a need for accurate records at the mouth of the Wash bay, along its coasts and at the proposed construction sites. At least one year's record from each of these places was needed to evaluate the main tidal constants, to analyse the incidence of storm surges, and to judge the local effects of the sea bed shape on both tide and surge. Initial proposals were based on a single deep-water recording gauge at a site in the Wash mouth with two more gauges on the edge of the bay but considerations of cost, accessibility and operation resulted in the choice of West Stones, Tabs Head, Hunstanton and Roaring Middle as automatic recorder sites.

At Gibraltar Point, which is on the North Sea coast adjacent to the Wash entrance, sea levels were observed against a line of six tide poles at 15 minute intervals continuously for a month by a team of six and completed the geographical coverage of simultaneous observations.

The accuracy required in measurement of levels was determined by the hydraulic model and was of the order of $\pm$ 0.025 m. While this is not difficult in calm conditions, it is very demanding in a stormy area such as the Wash and was an important consideration in the choice of instrument.

4. Selection of instrument type and recorder sites

The principal considerations which governed the type of instrument chosen are listed in table 1 which shows how each of the commercially available types compared.

The Wash is an area of intense inshore fishing activity and the main river outfall channels are important seaways for vessels up to 3000 tons. The areas of greatest interest in engineering terms are dry or covered to only shallow depths during most of each tide. Any deep water channel which might have seemed attractive as a site for a pile-mounted recorder of the stilling-well type was inevitably part of a channel on which inshore fishermen depended at low water. Accordingly, there would have been strong opposition to any system dependent on piles in deep water. It was an important factor leading to selection of a pneumatic instrument which can be mounted out of the deep channels and needs only a very small and innocuous sensor below the low-water mark.

Apart from the navigational considerations, any solution which involved a pile in water deep enough to allow the whole tidal cycle to be monitored was bound to be much more expensive to support than one on a sand bank, because of the greater unsupported length in water. This cost penalty would be even greater if a mechanical system were used so that verticality of the pile became important. There was a reluctance too, in the light of experience in similar waters elsewhere, to rely on any form of electrical or rigid mechanical link between sensor and recorder. Repairs to such links can be costly and time-consuming as would be the initial installation. A gas-filled tube, on the other hand, although no less vulnerable, offered the following advantages:-

a cut or leak in the tube would merely cause the pen to move to zero on the chart with no serious damage,

a replacement tube length would be both cheap and easily stored with the recorder,

replacement or reconnection could be carried out even in moderately choppy weather provided access could be had to the severed part attached to the sensor; once the tube link was restored, the system could be quickly brought back into service by purging the tube with gas.

Feature	Type of instrument		
	Stilling Well	Seabed mounted	Pneumatic
Accuracy	Good if carefully designed & maintained	Unknown	Good - but system parameters
Cost	Relatively low but pile expensive	High	High but accurate alignment unnecessary
Navigational obstacle	Yes	No	No
Vulnerability	Fairly High	Fairly High	High (tube and sensor only)
Repair costs	High	Very High	Low
Accessibility	Boat need at all locations		Boat needed at only two of four locations
Degree of Development (in 1971)	High	High (overseas model). Well advanced but not commercially available (UK)	Basic design well established but relatively untried at remote coastal location
Dependent on density of water	Yes (Lennon, 1971)	Yes	Yes

Table 1 - Considerations governing choice of instrument

Location	West Stones	Roaring Middle
Design wind speed (m/s)	46	46
Design wave height (m)	3.5	4.0
Design tidal velocity (m/s)	2.5	1.7
(kts)	4.5	3.0
Pile diameter (mm)	353	406
Wall thickness (mm)	9.5	9.5
Depth (m) to which jetted	10 (ie. ½m into clay stratum underlying sand)	10½ (into sand: driven by hammer for last 3m)
Sea bed level (m O.D.) at site	-1.0	-2.5
Lengths (m) of pile sections		
Upper	9.5	14.0
Lower	9.0	

Table 2 - Pile Design

Having established that a pneumatic instrument might be suitable for local acceptability at any site combined with accuracy and ease of installation and access, there remained the limitation that the maximum length of tubing ruled out any site not close to a sandbank or an existing firm structure on which to mount the recorder. In all cases but one it proved possible to select a site at which a manageable tube length could be combined with a useful sea level record; the exception was Hunstanton, where the problem of friction loss in the bubbler tube was overcome by using two tubes, one to carry the gas and the other to feed back the pressure signal (see Section 5). Table 4 summarises the essential physical details of each of the selected sites shown on figure 1.

All five stations contributed data to the physical and mathematical models of the Wash and certain served other functions as follows:-

West Stones : Monitored sea levels in the area in which construction would probably commence and which was therefore also the scene of related studies such as trial bank construction, site investigation and wave recording. This site was also the most seaward of a chain of 10 stations on the river Great Ouse which provided tidal data for a mathematical model of the river.

Hunstanton : as work on the R. Great Ouse mathematical model proceeded, the decision was made to site the seaward origin of the model further out than West Stones, it having been established by this time that the fluvial outflow passing West Stones was largely contained between drying sandbanks for another 8-10 km. The commercial entertainment pier at Hunstanton afforded the only location of the S.E. shore of the Wash at which a record could be obtained without the expense of a third offshore pile-mounted recorder.

Roaring Middle : this site was the closest approach practicable to a "deep water" record at the Wash mouth. Roaring Middle is a sandbank which dries about $\frac{1}{2}$m at low water springs. The recorder was mounted on a pile near the southern extremity of the bank where survey showed the sand to be most stable and the length of tubing would be shortest.

Use of the Roaring Middle site enabled monitoring of the full tidal range at a site in deep water away from fluvial effect.

Tabs Head : monitored sea levels in the SW corner of the Wash into which later stages of the water storage scheme could extend.

5. Principles of pneumatic gauge design

The physics of pneumatic pressure tide gauges has been discussed in detail elsewhere (Pugh, 1971, 1972); in this section we summarise the essential theory and present formulae for determining basic system parameters for coastal installations. In the bubbling system compressed gas from a cylinder is reduced in pressure through one or two valves so that there is a small

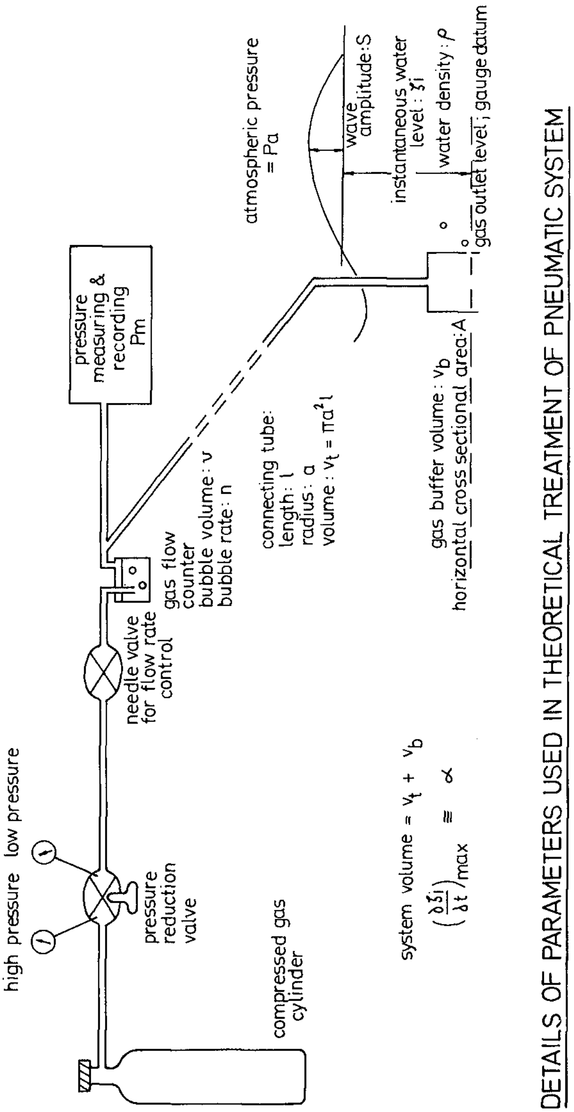


FIG 2: PNEUMATIC GAUGE SYSTEM THEORETICAL PARAMETERS

steady flow down a connecting tube to escape through an orifice in an underwater canister or 'pressure point', (figure 3). At this underwater outlet, for low rates of gas escape the gas pressure is equal to the water pressure. The pressure of gas in the system is measured and recorded at the shore end so that, apart from small pressure gradients in the connecting tube, the measured pressure, P_m is related to the water level above the outlet by the elementary hydrostatic relationship:

$$P_m = \rho g \xi_i + P_a \qquad (1)$$

where P_a is the atmospheric pressure at the water surface, g is the gravitational acceleration, ρ is the mean water density and ξ_i the instantaneous water level above the outlet. The flow of gas along the tube will be driven by a pressure gradient so that the measured pressure is higher than the true water pressure by an amount which depends upon the tube dimensions and the rate of gas flow. This flow rate, which is usually monitored through a liquid filled bubble counter as illustrated, should therefore be kept low to minimise the pressure gradient error and to conserve the supply of gas. However, if the rate of supply of gas is too low, the pressure in the system may be unable to increase as rapidly as pressure change at the outlet due to increasing water depth. Consequently water will be forced into the system until the pressure balance and the recorded pressure is not then related to the bubbler outlet datum.

For any pneumatic system the three primary design constraints are: the required accuracy, the tidal range to be measured and the maximum rate of water level increase, $\alpha \equiv (\delta\xi_i/\delta t)$ max. For the Wash measurements the required accuracy, γ , was 0.025 m, the range to be measured allowing two metres for surges on a tidal range of less than 8.0 m was 10.0 m with a maximum rate of water level increase of 2.4 metres per hour. The two remaining design constraints, which may be optimised by suitable site selection are the maximum wave amplitude, and the length of the connecting tube from the shore installation to the underwater outlet. It is important to select a site which requires as short a connecting tube as possible. The maximum expected wave amplitude may be reduced by picking a sheltered site, but care should be taken to ensure that the site chosen is well connected hydraulically to the location for which the measurements are to be representative. In practice, as shown by the previous discussion of site selection in the Wash, the choice is limited, particularly when suitable recorder housing and access are considered.

As the system pressure increases, the bubbling rate usually drops. The minimum rate, n_0 , at which gas should be supplied from the high pressure source through the bubble counting chamber at zero water head to avoid water entering the system is:-

$$n_0 v \geqslant \frac{V}{600}\alpha \qquad (2)$$

where v is the volume of each bubble passing through the counter (given approximately by $^4/_3 \pi c^3$, assuming spherical bubbles of radius equal to the radius, c, of the submerged orifice in the counter), and V is the total system of volume including both the tube and wave buffer volume, α is in metres per hour and n_0 in bubbles per minute.

When the maximum wave amplitudes are represented by:-

$$\xi_s + s(1 + \sin \omega t) \qquad (3)$$

where s is the maximum wave amplitude in metres, the period is $\frac{2\pi}{\omega}$ secs, ξ_s is the height (m) of the wave trough above the gauge outlet and the atmospheric pressure is taken as 10 m of water head equivalent to sufficient accuracy the minimum wave buffer volume is:-

$$V_b = \beta V_t \qquad (4)$$

where $\beta = \dfrac{2s}{\xi_s + 10}$ and V_t is the tube volume.

The gas volume in the measuring system is considered negligible and, for design purposes, the time constant of the tube is ignored. Because water enters the buffer volume during the wave cycle, the recorded pressure differs from the mean water head pressure by:-

$$\frac{V}{A} \frac{\beta}{2} \qquad (5)$$

where A is the horizontal cross sectional area of the buffer volume which should therefore be sufficiently large to satisfy the accuracy requirements - note that using an unbuffered open ended tube gives very large wave corrections. Since (5) is independent of wave period it may also be applied for tidal changes of level if the tidal amplitude is substituted for and the buffer volume is sufficiently large: if this is done, then the flow of gas is not necessary and the gauge operates in a non-bubbling mode so that the pressure drop is substantially reduced - see Pugh (1972) for further details.

When the minimum gas flow rate and wave buffer volume are applied, the maximum water head equivalent pressure drop across the connecting tube is:-

$$\Delta\xi = \frac{1}{\rho g} \quad \frac{8\eta}{10} \quad \frac{\alpha \cdot}{3600} \quad \left(\frac{\ell}{a}\right)^2 \quad \phi \qquad (6)$$

where η is the gas viscosity at the system temperature ($\eta = 17{\cdot}5 \times 10^{-6} NM^{-2}$ for air at $10^{\circ}C$) and a is the tube radius.

$$\phi = \beta + {^3/_2} \qquad \text{for bubbler gauge}$$

$$\phi = {^1/_2} \qquad \text{for non - bubbler gauge}$$

This shows that the error due to tube pressure gradient increases as the square of the tube length; for lengths less than about 200 metres the error is small but for greater lengths careful design is necessary.

Where the pressure point is mounted near the sea bed the optimum design parameters for the straightforward bubbler system may be estimated using the following formulae:-

cylindrical buffer volume radius $= 0.4a \, (\ell/\Upsilon)^{\frac{1}{2}} \times 10^{-3}$m

depth $= 1.6 \; \Upsilon$ m

minimum flow rate $n_0 v = 0.0065[\alpha a^2 \ell]$ cc/minute

maximum total head loss (in tube) $= 0.7 \times \left(\ell/a\right)^2 \times 10^{-6}$ metres

where the tube length ℓ is in metres, the internal radius a is in mm, the design accuracy Υ is in metres, and the maximum rate of water level increase is in metres per hour. This assumes a value of 0.25 for β.

For installations where the gauge is mounted more than 20 m above the underwater gas outlet, for example on an oil rig, a correction for the static pressure head in the tube may be required, but this was not necessary in the Wash.

It is possible to design a system which has the low tube head loss of the non-bubbler gauge, yet avoids the necessity of the non-bubbler correction. This is done by using two tubes from the shore to the underwater outlet: air is forced along one tube so that the buffer volume is full of air, while the outlet pressure is transmitted through the second tube, in which there is no net flow of gas, to the recorder. This system was used for the Hunstanton gauge because the outlet was 440 m from the recorder.

6. Description of gauges : installation

For these measurements the commercially available Neyrpic 'Telimnip' gauge was selected because it has the required datum stability since it records pressure using a mercury manometer - the necessary stability was not possible using electronic transducers. Another advantage of this instrument is the automatic elimination of atmospheric pressure and its variations by leaving one side of the manometer open to the atmosphere, and applying the pressure in the pneumatic system (equation (1)) to the other side. In effect a column of mercury is balanced against the column of water to be measured. A chart speed of 20 mm per hour was adopted as compatible with the required accuracy and operating range of 10 m. The scaling of the recorder gave nearly 25 mm of chart for each metre of water head. Each instrument was calibrated against a dead weight pressure standard.

Table 3 gives the design parameters calculated for the four gauges. A tube radius of 1.9 mm was adopted as standard as larger tubes used too much gas. Only at Hunstanton was the length of tube great enough to make these parameters critical; Hunstanton values are given for the single tube bubbler, the non-bubbler and two tube systems: it was eventually decided to use the two-tube system for direct accurate logging of water head pressures.

PARAMETER	* Maximum rate of water level increase α	* Tube length ℓ	Tube radius a	Tube volume $V_t = \pi a^2 \ell$	Wave maximum amplitude factor $\left(\beta = \frac{2s}{\mathcal{J}s + 10}\right)$	† Minimum buffer volume $V_b = \beta V_t$	† Minimum cross sectional area of buffer volume $A = \frac{V\beta}{2 \times \text{accuracy}}$ from (5)	Total system volume $V = V_t + V_b$	† Minimum flow rate $n_0 v$ from (2)	Approximate life of scuba cylinder containing 1.5 m^3	ϕ^n from (7)	† Maximum tube pressure drop error: $\Delta\xi$ max from (6)
West Stones bubbler	2.4 m/hr	25 m	1.9 mm	.00028 m	$4/15$ = .27	.00008 m^3	.00194 m^2	.00036 m^3	1.5 cu/min	694 days	1.77	.001 m
Roaring Middle bubbler	2.0	50	1.9	.00068	$4/18$ = .22	.00015	.00365	.00083	2.8	372	1.72	.001
Tabs Head bubbler	2.4	50	1.9	.00056	$4/18$ = .22	.00012	.00308	.00070	2.8	372	1.72	.001
Hunstanton bubbler	2.2	440	1.9	.00499	$4/15$ = .27	.00134	.03180	.00633	23.2	45	1.77	.081
non-bubbler	2.2	440	1.9	.00499	$12/10$ = 1.2	.00599	not strictly applicable .06 m^2 gives suitable V/A	.01098	not required	–	0.5	.023
2-tube system	2.2	440 + 440	1.9	.00998	.27	.00268	.06360	.01266	46.4	22.5	0.5	.023

Table 3 Imposed (*) and computed (†) design parameters for pneumatic gauges in the Wash. (Design accuracy τ is 0.025 m)

The recorders at Tabs Head and Hunstanton were easily mounted in small huts erected on a sea defence bank and on an entertainment pier respectively. Those at Roaring Middle and West Stones were mounted in steel cabins on circular steel piles. The principal design details at these sites are listed in table 2. The steel cabins each weighed nearly half a ton; there would clearly be advantages in design modifications to reduce the weight without sacrifice of protection from the weather and wave attack. At both sites the piles were installed in two sections, the lower of these being jetted into the sea bed; sea water was pumped through two 1 inch pipes welded inside the pile. The two sections were connected by bolt-and-flange joints. Before installation, while still in the work-shops, the piles and cabins were coated with an epoxy resin and sacrificial zinc anodes were attached, one below the joint and one above; these measures proved adequate to prevent corrosion during the period of record. The cabins in which the recorders were mounted were in each case about a metre square and nearly two metres high. They provided sufficient space for routine work on the instruments but it was sometimes found a little inconvenient to have the entrance in the form of a trapdoor in the floor, particularly when renewing the gas cylinders. The pile designs were chosen to avoid vibration due to tidal streams of up to 4-5 knots, with reference to the work of Sainsbury and King (1971).

The sensors were in every case attached to screw pickets which were screwed $\frac{1}{2}$ to 1 m into the sea bed. In each case it was possible to do this by hand at a time of low water springs, but at Hunstanton divers were used.

After inserting a picket the sensor, already linked to its tube, was attached to the picket by a clamp and wing nuts. The tube was purged by compressed gas when the recorder had been installed. In the case of Hunstanton the twin tubes had to be purged separately and divers were used to operate valves at the seaward end of the system. A marker buoy was attached to each picket. The bubbler tubes were attached at frequent intervals to a chain laid on the sea bed. As a result of sea action, these chains were buried to a depth of 5 - 10 cm. quite quickly and thus hid the tubes from view while at the same time protecting them from tensional loads in rough sea conditions.

At West Stones and Tabs Head, the effects of river discharge on water density were significant. At West Stones the density varied between 1003 kg m^{-3} at low water to 1024 kg m^{-3} at high water. For subsequent calculation of water head from the recorded pressures, the required accuracy was maintained by expressing water density as a function of the water head. Because the error introduced by incorrect density is proportional to the water level being determined (e.g. 0.025 m accuracy requires the density to be within 2.5% at 1.0 m but within 0.3% at 7.5 m) the linear elevation/density relationship was weighted to give the best fit at the higher water levels.

7. Datum levels

All water levels were reduced to Ordnance Datum Newlyn (O.D.). In the Wash mean sea level is approximately 0.1 m above this datum. However, because the Roaring Middle gauge was sited more than 11 km from the nearest shore, conventional levelling techniques could not be used. Hydrostatic levelling using a liquid filled connecting tube was considered too expensive, so a technique of hydrodynamic levelling was developed for using simultaneous elevation measurements at Roaring Middle and Hunstanton and readings from intermediate internally recording current metres (Alcock and Pugh, 1974).

The water level difference terms fall into three groups:-

a. Those which depend on the dynamics of the intermediate water, i.e. acceleration gradients in time and space, and Coriolis effects,

b. those which depend on conditions at the two sites, i.e. kinetic energy, atmosphere pressure and water density,

and c. stress terms due to bottom friction and surface winds.

Average water levels at the two sites were estimated to differ by less than 0.04 m with the main uncertainty arising from determination of the advective and bottom stress terms. The datum level at Roaring Middle was determined by this means to be -3.43 m O.D.

8. Operating and maintenance experience : costs

During a period of 6 months the West Stones recorder was in operation alone and the experience gained was valuable in preparing for the more inaccessible and exposed location at Roaring Middle. Problems arising at West Stones and overcome during this period included:-

a. Wind vibration

The frequency was about 1-2 c/s. There is some likelihood that it amplified a troublesome chart-slippage problem. Flexible mountings were tried to insulate the recorder from the vibrating housing but ultimately it was found that adjustment of the chart guides cured the problem completely.

b. High temperatures

Apart from discomfort experienced during maintenance visits there was concern for the stability of the chart paper. Temperatures were monitored at West Stones and were found to range from 5 to 25°C typically. They were subsequently controlled within acceptable limits by painting the housing white, adding a hood mounted a few centimetres above the roof and coating the interior walls with insulating tiles.

Site	Sensor Location and Level	Recorder Location and Level	Means of access	Interval between maintenance visits		Installation cost	Approx. annual running cost	Physical reasons for choice of site	% acceptable data return from instrument
				Average	Maximum				
West Stones	In main Gt. Ouse navigation channel at toe of training wall. level −2.59 m OD ± 0.01 m	In steel housing on pile 9½ m high and jetted 10 m into sand at −1 m OD behind training wall. Pile diameter 356 mm and wall thickness 9.5 mm	By boat 1 hour from King's Lynn docks	7 days	23 days	£3,500 ($ 8,750)	£2,900 ($ 7,250)	Deep water with short run of tubing; also close to existing navigation beacon	89
Roaring Middle	On NW side of long sandbank. Level determined hydro-dynamically to be −3.43 m OD ± 0.05 m	In steel housing on pile 14 m high and jetted 10½ m into sand at −2.5 m OD (highest point of sand bank). Pile diameter 406 mm and wall thickness 9.5 mm	By boat 3-4 hours from King's Lynn docks	10 days	20 days	£4,700 ($ 11,750)	£4,200 ($ 10,500)	Most feasible "mid-Wash" site (in deep water). Site of pile just dries at lowest low waters	86
Tabs Head	In main Witham navigation channel at toe of stone pitching. level −3.01 m OD ±0.01 m	In concrete hut on top of levee at 7 m OD	By road and track ½ hour from Harbour Master's office at Boston	6 days	20 days	£1,500 ($ 3,750)	£1,700 ($ 4,250)	As West Stones: also close to existing staff gauge which forms basis of existing predictions	84
Hunstanton	½ km offshore of Hunstanton on line of pier at a level of −3.19 m OD	In wooden hut on concourse at end of entertainment pier at 9 m OD	Short walk along pier	4 days	16 days	£1,500 ($ 3,750)	£1,800 ($ 4,500)	Only practicable site on east side of Wash avoiding use of a third pile	69
Gibraltar Point	Line of 6 tide poles running out to springs low water mark from eastward–facing beach		———	Manned continuously for one month		£1,200*		Site previously used for observation of individual tides for model data collection	———

*cost of one-month exercise

Table 4 – The Wash: Details of Tide Recorder Sites

c. Humidity

Ventilation during maintenance visits was improved by cutting a 10 cm. diameter hole centrally in the roof below the hood to improve the flow of air.

The lowest parts of spring tide curves were lost at West Stones later in the study when sand began to accumulate in such a way as to retain a low-water "pool" around the sensor. Since dredging was not practical the loss (about 0.3 m at most) was overcome by sketching in the missing part of the curve with reference to complete curves for similar tides obtained earlier in the study.

Table 4 shows that the average data return from the four gauges was 82% over a period from July 1972 to November 1973. The below average return from Hunstanton was due to the vulnerability of the long length of tubing on a holiday beach and to the subsequent difficulty of purging water from a two-tube system: purging air tended to flow down the tube which was already free of water. Future two tube systems would avoid this by connecting each tube directly into the top of the underwater outlet canister and purging each line separately. Although some difficulty was experienced at West Stones and Roaring Middle due to irregular chart drive speeds and drive failure, it should be made clear that the gauges were not designed to operate in the relatively severe vibration conditions at the top of the piles.

On average the gauges were visited weekly, when standard checks for zero stability, elevation and timing accuracy were made. As the Roaring Middle gauge was difficult to reach, it was inspected less often than the others: the high data return from such an inaccessible site is very satisfactory.

After removal from the gauges, records were sent to the Institute of Oceanographic Sciences for quality examination and reduction to hourly values. Chart readings were processed by computer to allow for gauge calibration and water density. For two periods of detailed study the records were processed every quarter hour. Output was on cards and line printer. Some preliminary filtering to distinguish tidal and non-tidal variations of levels was also effected, and these results could be plotted, if required.

The costs of the different installations at the four sites are listed in Table 4.

9. Derivation of design data from output

Full details of the observations will be included in the final report of the Consulting Engineers, but we include here examples of the kind of treatment proposed.

Figure 3 shows a plotted output from Tabs Head separating the tidal and non-tidal components using the Doodson Xo filter. To see how surge residuals compared at sites in the Wash and in the open North Sea, results from measurements using a similar gauge on the Inner Dowsing light tower were plotted (figure 4).

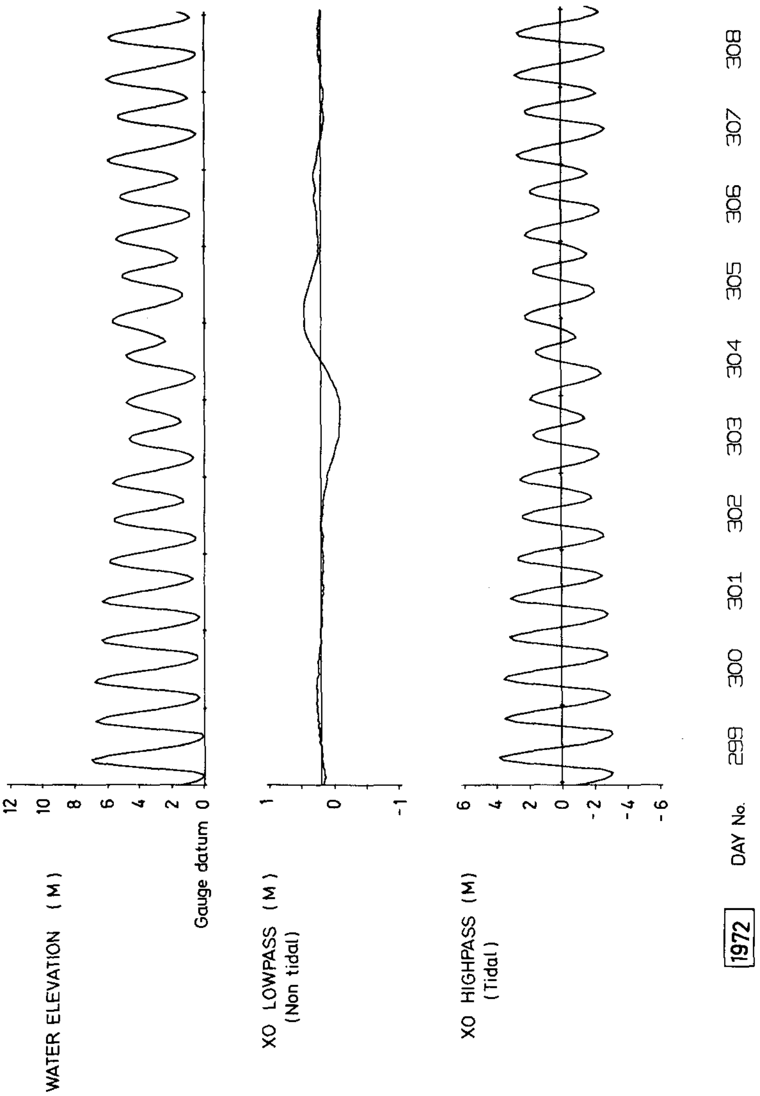


FIG.3: TIDAL AND NON-TIDAL COMPONENTS AT TABS HEAD

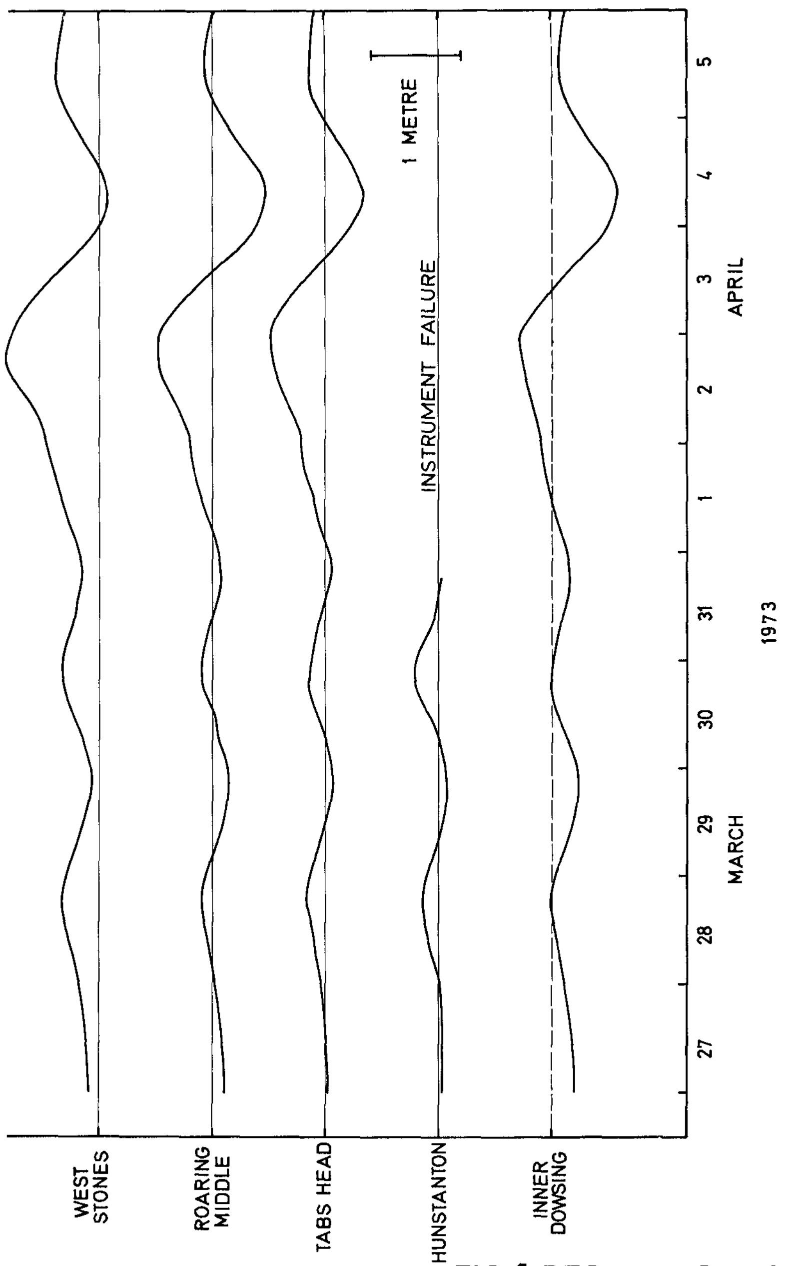


FIG.4: RESIDUALS AT WASH STATIONS AND IN NORTH SEA

The surge levels are very similar showing not only that there is a similar response throughout the area, but also how well the gauges reproduce the finer detail. The characteristic quasi-periodicity of the surges is concentrated in the 40 to 50 hour and 70 to 80 hour parts of the long period spectrum (Pugh and Vassie 1974). The residuals obtained from the Wash recorder will be used to assist in estimating, e.g. for survey purposes, the probability that during a planned exercise the high and/or low water levels (whichever are relevant to the particular case) will be within an acceptable margin of the predicted levels.

Other work undertaken in the feasibility study is supplying details of tidal velocities prevailing at the construction sites. By relating these measured velocities to the measured level record at one or more sites, "predicted" velocities and probable variations in them can be produced for a year in which construction is planned. To do this a knowledge of tidal constituents is required and these are to be generated from the record at Roaring Middle in the first instance; that at West Stones could be similarly analysed in order to predict tides for a year in which construction is to proceed. From the prediction can be selected the optimum period for tidal closure of embankments when a series of particularly low high waters can be expected over a period of several days.

Figure 5 shows the percentage of time for which different levels are covered by water and exposed, and also the percentage residence time of water levels within superimposed bands. Both of these are useful in the design of reservoir embankments; they also assist in understanding the formation and behaviour of salt marshes and other shore environments which could be altered by a water storage scheme (Gray, 1972).

10. Conclusions

Our experience of using pneumatic gauges in the unfavourable environment of the Wash has shown that if they are properly designed, as described, pneumatic systems are capable of an accuracy and versatility superior to those of conventional stilling well gauges. Not only may they be used in areas where measurements by conventional gauges or tide poles are impossible, but they are also cost-competitive for all projected installations.

Were we to plan a similar study with the benefit of the experience now gained, we would press for sufficient funds to cover the installation of a pneumatic recorder on a pile driven into the seabed at about -6m O.D. near the mouth of the Wash, since we are now confident that expenditure on such a gauge would yield satisfactory results and the gauge datum could be established by hydrodynamic methods rather than the expensive hydrostatic method used formerly.

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FIG. 5: ANALYSIS OF SEA LEVEL RECORD

Of the many individuals who have contributed greatly to the success of the level recording enterprise particular mention is made of D.H. Cowie of Binnie and Partners who coordinated the field work from King's Lynn; R.M. Young and A.P. Lane of the same firm who bore the brunt of the operation and maintenance work, often under very trying conditions; and Miss D.C.C. McDonald and Miss S.M. Brown of IOS who supervised the data reduction.

References

Alcock, G.A. and Pugh, D.T. (1974). Hydrodynamic levelling to an off-shore tide gauge. (Submitted to press, August 1974)

Binnie and Partners (1965). Report on the water resources of the Great Ouse Basin. Ministry of Housing and Local Government.

Binnie and Partners (1970) - in association with Rendel, Palmer and Tritton and with Lewis and Duvivier - Wash desk study report to the Water Resources Board. In, The Wash : Estuary Storage (Report on the Desk Study), HMSO, London.

Gray, A.J. (1972). The salt marshes of Morecambe Bay, Journal of Applied Ecology, 9, (1), 207-220.

Lennon, G.W. (1971). Sea level instrumentation, Int. hydrogr. Rev., 48(2), 129-148.

Pugh, D.T. (1971). Sea level measurements using the Neyrpic bubbler pressure gauge. Institute of Coastal Oceanography and Tides, Internal Report No. 22.

Pugh, D.T., (1972). The physics of pneumatic tide gauges. Int. hydrogr. Rev., 49(2), 71-97.

Pugh, D.T. and Vassie, J.M. A year of simultaneous off-shore current and elevation measurements in the North Sea (in preparation)

Sainsbury, R.N and King, D. (1971). The flow-induced oscillation of marine structures. Proc. Instn. civ. Engrs, 49, 269-302.