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8201 & 8202 DISCUSSION

# Dubai Dry Dock: Planning, direction and design considerations

**R. J. DANIELS & B. N. SHARP**

# Design and construction

**G. H. COCHRANE, D. J. L. CHETWIN & W. HOGBIN**

### Mr Daniels

Although these two papers have been compiled separately, they might equally well have been written as one by the same authors, since we have all been closely involved, from planning the concepts to the detailed design and construction, over the past eight years. This period has seen significant changes and economic upheaval in the world, but nevertheless the pattern of distribution of oil supplies from the Middle East remains essentially the same, and is a major factor in maintaining the standard of living of all. The first report to the Client was submitted in 1971, when my firm established the feasibility of building a single dry dock at Dubai. In the ensuing development stages, however, The Ruler of Dubai, in his own right as Employer, decided on the scope of dock facilities which he required. The docks have been built to suit tankers from 100 000 to 1 million tonnes dwt. The growth in the size of tankers in recent years has been immense and continuous; the capacity of present vessels exceeds that of the standard 16 500 dwt T2 tanker of World War II by up to thirtyfold. Consequently, at all stages of design and construction of these unique facilities, we have been involved in the consideration of scale and design parameters virtually at the frontier of experience.

### Mr Cochrane

I would like to point out that the Contractor's design team had taken technical advice and obtained other assistance from many sources. It would be difficult to acknowledge them all at this time, but particular thanks are due to the following firms of consulting engineers:

- Ove Arup & Partners, who acted as geotechnical consultants to the joint venture throughout the project, and also undertook specialized computer work;
- T. F. Burns & Partners, who designed and detailed the dock gates;
- Babtie Shaw & Morton, who provided invaluable advice in the early stages of the project on ship characteristics and dock design parameters.

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DISCUSSION

**Mr K. R. Sturrock,** Babtie Shaw & Morton

Although the Ruler took the major decisions on the overall scope of this project, there were many thousands of detailed requirements within the overall specification which had to be planned, designed and constructed. In most cases in a ship repairing facility of this nature there is an operator appointed at the time of the conception of the scheme who can give advice as to exactly what is required. But in this case the Authors had the added problem of taking all those decisions upon themselves before they got down to the other more usual engineering problems.

4. Some explanation would be helpful concerning some of the matters which were decided in the planning stages. The first relates to the main breakwaters which protect the docks from the prevailing north-west wind. There is also a long lee breakwater which faces north-north-east. It would appear from Figs 2 and 3 of Paper 8201 that equal protection to the docks could have been provided by extending the main breakwater in a north-easterly direction, and that this would have given a larger protected area. Perhaps the lee breakwater might still have been necessary, but it could have been shorter and moved perhaps further towards the north. The lee breakwater appears to be a potential hazard on the lee side of ships entering the harbour. Concerning the model tests which were carried out to observe the effectiveness of the breakwaters, I should be interested if the Authors could indicate how well the models predicted the reduction in wave height within the protected harbour. Do they have any information on observed wave heights outside and inside the harbour? Another interesting question is whether there were any resonance effects within the harbour.

5. The second matter that I should like to raise concerns the decision to use caissons for the dock walls. The use of this type of construction has an obvious advantage in that the permanent structure is used for the cofferdams to protect the works from inundation. The use of caissons, however, appears to be in some ways inhibiting, particularly where the width of the piers between the docks is provided by one caisson: this has the effect of reducing the working space and access space between the docks. It also appears to me that dewatering and access to the floor of the dock might have been achieved earlier had the use of caissons been confined to the outside ring of caissons around the outer docks; perhaps then a greater freedom would have been gained in layout of the docks in relation to one another, and perhaps also some benefit might have been gained in providing a longer time within the total programme for construction of the dock floor.

6. The caissons themselves are massive structures and their design was no easy matter. It was interesting to read about the design methods, and the investigation which was made into the pressure of infill material, and perhaps it might be possible to get some more information as to the pressure measurements which were taken, and whether in fact the results of these investigations were used in producing some economy in the design of the caissons themselves in the later stages.

7. A matter which gave great concern in the initial stages was the dewatering of the dock area. At the time that I was involved, the permeability of the underlying strata was being investigated, and it was thought that it might be necessary to drill wells below the general floor level of the docks to relieve pressure gradients underneath the caissons. Could the Authors indicate whether such wells were found to be necessary?

8. The Authors mention an anticipated total inflow into the drained area of the docks of $\frac{1}{2}$–$1\frac{1}{2}$ $m^3/s$. Perhaps if there are figures available we can be told what the actual inflow is. That might be with the dock empty. There is another important matter here where leakage through joints in the dock floor can have an appreciable effect on the amount of water to be pumped from the underfloor systems. Perhaps the Authors could describe the methods and measures taken to minimize such inflows, and what increase, if any, was observed when the dock was flooded.

9. The dock gates are of very interesting design, and the consulting engineers and contractors are to be congratulated in adopting this new approach to the closure of a very wide dock entrance. It is my impression that this type of gate should produce a

structural weight saving of some 50% for dock entrances of 70 m or more. I think there is some penalty, however, in the cost of a more complicated fabrication which, to some extent, must offset the saving in weight. Perhaps the Authors could confirm that weight savings of this order were in fact possible, and could indicate whether the penalty in higher fabrication cost was not sufficiently large to overcome the saving in weight through careful design.

10. I understand that provision has been made for an intermediate gate, but that such a gate has not been installed. I should like to have some brief description of the proposed gate and its method of operation.

**Mr J. W. Dagleish,** Scott Lithgow Drydocks Ltd

The most vulnerable part of a dry dock is its gate and most dry dock owners have a separate insurance policy for their gates because of this. Box type gates and single membrane gates with bouyancy tanks, such as are fitted at Dubai, submerge quickly. After the first minute there is no visual sign of the position of the gate: a warning light system should be fitted so that a tug will not move into the dock until the gate is in its lowest, housed, position.

12. Vessels to be drydocked at Dubai can be divided into two groups. In the first group, the beam of a vessel will be such that the vessel can be towed straight into the dry dock by the tugs and berthed at one side, leaving adequate room to allow the tugs to leave. The vessel will then be centred for drydocking. In the second group, the beam of a vessel relative to the dock will be such that a towing-in carriage must be used. The sequence of operations is that the vessel approaches the dry dock with two bow tugs; the tugs pull the vessel as close to the entrance as possible, moving port and starboard on to the roundheads; launches pick up port and starboard bow lines lowered to them from the vessel; these lines are taken ashore and dropped on to bollards; the vessel releases the bow tugs and heaves on the bow ropes, drawing the bow into the dock entrance; the vessel sends away port and starboard towing-in lines by launch; the towing-in lines are lifted on to the towing carriage hooks; the bow ropes are transferred from the bollards on to the second hooks on the towing-in carriage; and the vessel is towed into the dry dock with the shore equipment, the stern tugs being used to hold the stern central and to check the vessel when required.

13. Tugs require tow lines as short as possible for control of a vessel in shallow restricted waters. The tug's tow line consists of a towing junk 12 m long and a wire 38 m long, giving a 50 m length of tow.

14. The pilot or captain on a VLCC or a ULCC is so far aft and so far above the dock cope level that there is difficulty in assessing the position of the bow tugs and the dock entrance. There is a requirement for leading lights on the centre-line of each dock as a guide for lining the ship up with the dock while manoeuvring in the harbour and for the run in.

15. For manoeuvres into and out of the outer docks the dolphins are a navigational hazard and should be removed. A vessel approaching the outer docks with the dolphins fitted will be towed in clear of the dolphins and will not be lined up with dock centre-line. In this situation, if there is too much way on the vessel or too much wind, or if the stern tugs do not check quickly enough, the bow tugs could be caught and squeezed or could ram the gate of the 1 million ton dock.

**Mr J. M. Thomas,** John Howard & Co. Ltd

As one of the joint venture team involved in many of the design and construction decisions, I should like to highlight two points.

17. The first is the use of caissons for the walls. The decision to build the dockyard adjacent to Port Rashid meant that much of the shore land was already developed, and so a seaward development involving breakwaters was required. The whole of the constructional programme was conditioned by the wave protection given by the breakwaters. The caissons were particularly suitable for this purpose. First, the setting-up

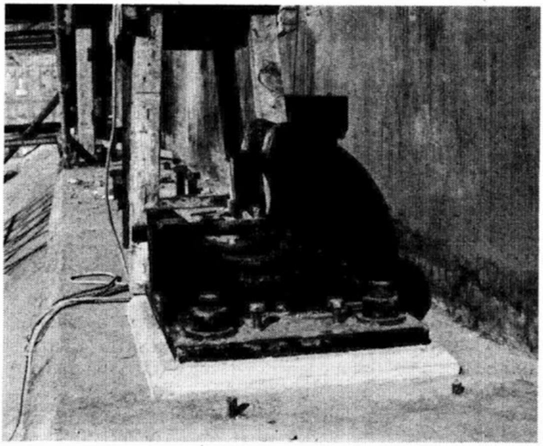

Fig. 1. One of the hinge bearings on dock sill

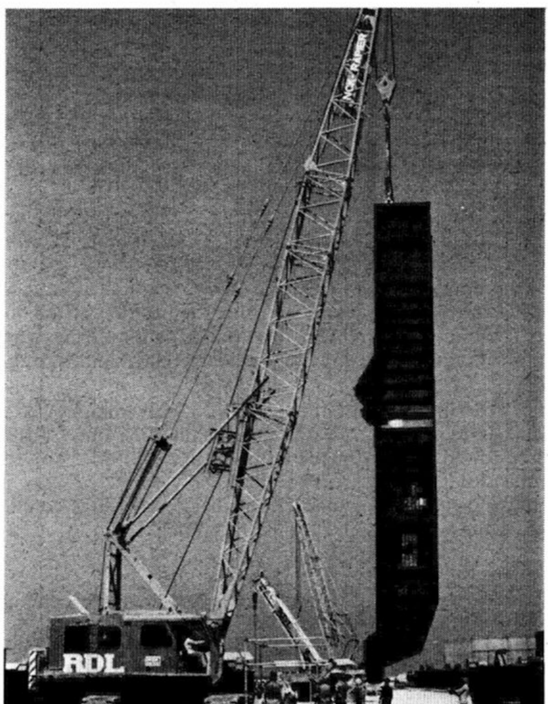


Fig. 2. Up-ending of buoyancy unit

of the caisson yard, the building of the first caissons and the fine tuning of the system could be done in the early months of the contract. Secondly, the forming of the foundations trench by means of a drill on a jack-up platform meant that this could be done ahead of wave protection. Thirdly, the short time from the launching of the caisson to its sinking in position meant that this could be done in periods of calm weather. Thus a large amount of the dock walls could be built before the wave shadow of the breakwaters was established, and by putting the concrete work on the walls earlier in the programme, resources were available for the floors and decks in the later part of the contract.

18. Secondly, I should like to refer to innovation. Innovation is the condiment of engineering design, and there is quite a fair amount of innovation in this contract. I refer, of course, to the forming of the foundations or caissons and also to the dock gate. Another innovation is the rubber-tyred lead-in trolley working on a quite small kerb on the cope of the dock; this eliminated the requirement for a massive steel beam with its associated obstruction to access.

19. A proposal which was made but which did not find favour was for the dock cranes to have a transverse crane rail across the head of the docks, and to have the cranes supplied with swivelling bogies and power-pack diesel electric generators. This would have meant that if necessary all the cranes could be concentrated on one berth.

20. I should like to ask the Authors whether they consider that the use of the conventional UK power supply by reeled cable is suitable for docks of this great length.

**Mr T. J. Upstone,** Redpath Dorman Long International Ltd

The dock gates were supplied and erected by a consortium of Redpath Dorman Long International Ltd and NEI Clark Chapman Ltd, Sir William Arrol Branch.

22. The exterior of the steelwork was shot blasted and painted on the site in a purpose-made blasting and painting complex.

23. The lower half of the hinge bearings (Fig. 1) were set on the dock sill. These bearings had to be set very precisely to preserve the gate alignment when opening. The bouyancy modules, weighing 37 t each, were up-ended and lifted into the hinge bearings (Fig. 2). They were maintained in position by the raking struts which were held at top and bottom by temporary tension bolts.

24. When the bouyancy modules had been erected in one dock they were all aligned and the main thrust bearing pads, under the lip of the dock sill, were set using each module as a template and grouted with epoxy mortar.

25. The raker struts were designed with flat end bearings at both ends. It was necessary during the setting of these bearings to prestress the struts by bending them so that the strut and bearing had the attitude during grouting that they would have subsequently when loaded with water pressure on the outside of the gate. This operation was time-consuming and had an adverse effect on the sequence of erection of components of the gates. A simple line contact type of bearing would have been more satisfactory and would accommodate more readily any future misalignments of the bearings.

26. The infill stiffened skin plates were erected between the bouyancy modules (Fig. 3). The joints between the skin plating and the bouyancy modules were made in a predetermined sequence. This sequence was arranged to reduce the effects of the expansion and contraction of the steelwork which was exposed to a temperature range from 5°C to 60°C during the erection period. When in service the gates always have sea water on at least one side and the temperature range is reduced to 10°C.

27. The rubber seals between the gate and the concrete sill and between the gate and the quoins were placed, precompressed and grouted with epoxy grout.

28. With all three gates completed the temporary cofferdam was flooded, subjecting the gates to their full hydrostatic pressure. A check inside each dock showed there were no significant leaks.

29. The docks were each then flooded in turn and the respective gates were taken

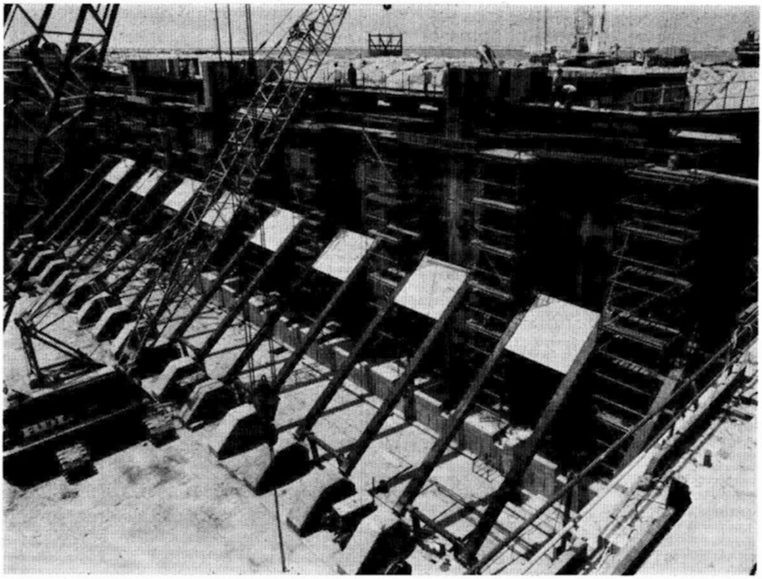


Fig. 3. Dock side of gate showing raking struts

Fig. 4. Trial opening of dock gate

through a sequence of lowering and raising (Fig. 4). The mains electric or the standby diesel motor were used for power supply.

**Mr R. Freer,** Babtie Shaw & Morton

This project has introduced into major dockworks overseas the concept of using large precast caissons for constructing sea walls, and the strategy in which design is done by those who have contracted to build the works, a method which has been successful in other branches of engineering.

31. Dubai is a good place to build a dry dock. Tankers, wherever they are bound, load in the Gulf so most of the world's VLCC traffic goes past Dubai and it offers minimum deviation from the tanker routes.

32. In the seven years during which this work has been carried out the maximum beam width of new VLCCs has not exceeded 71 m (except for one ship launched in October 1978 with a beam of 79 m) and the 80 m wide dock will be adequate for all these ships.

33. Rapid emptying of a dock is generally necessary but here the circumstances may be different. Most large tankers are driven by steam turbines and require to be moored in a sheltered anchorage until their turbines are cooled and they can be towed into dock. *In this scheme there does not seem to be within the space enclosed by the break-*waters room for ships to moor where they will be both clear of the turning circle and clear of the approaches to the tank cleaning berth.

34. I assume it is therefore intended that tankers will be towed into the dry docks and the dock water circulated through the ship until the turbines are cooled. A rapid rate of dewatering of the dock would appear to be less necessary at this installation and the capital cost of the pumping equipment might have been reduced.

35. How closely did the model tests predict the cut-off point of the main pumps in the full-scale tests and what depth of water was then remaining at the head of the dock?

36. The strutted cantilever gate has become necessary for wide docks because the conventional Box gate is uneconomic for large spans. Could the Authors say how the speed of the rising gate was controlled so that the gate did not accelerate too quickly to the vertical position?

37. The height of the blocks supporting the ship is usually arranged so that the capping pieces can be set in position on the blocks by hand without the need for staging. This reduces the time required for preparing the dock to receive a ship. A height of 1·5 m is a conventional and convenient height as it is about 0·15 m below average eye level. My height is 1·76 m so if I was working on the top of the 1·8 m high blocks at Dubai I should need to stand on a staging to see what I was doing. Could the Authors indicate what extra time they have estimated for the setting up of a pattern of 1·8 m high blocks in a dock to receive a VLCC compared with the time for blocks 1·5 m high?

38. The loading on the walls of the caisson due to the filling material is an important contribution. Could the Authors give details of the location and measurement of these pressures and the method of loading?

39. The tank cleaning installation is reported to produce a product with an oil content of 5 ppm. An oil effluent consistently of this quality would be difficult to achieve and to measure. Would the Authors give details of the acceptance trials and commissioning tests of the oil cleaning and measuring equipment which produced a product of this quality?

**Dr B. Simpson,** Ove Arup & Partners

Ove Arup & Partners have been the joint venture's geotechnical consultants, and my comments arise from two features of the project that I was involved in on site.

41. The caissons which formed the piers were floated into position and filled with water and then with sand tipped into the water. It was not surprising to find that the sand tipped into the water was extremely loose. It had been envisaged that this fill

would carry quite substantial loads, particularly the service roads along the piers. So it became necessary to compact the sand, and this was done using a Muller vibrator attached to the end of a long length of pipe pile. This proved to be very effective as a means of compaction: the surface level dropped by about 1 m and water flowed out of the cells. But it was a messy operation. We had to mount a trial rather rapidly to try and determine whether it might be damaging the caissons by building up too large a pressure inside them during compaction. Apart from being messy, the operation caused some minor delays. I wonder whether the Authors could comment in retrospect and say whether they would prefer to have loads sitting on the fill on these caissons, or whether they would prefer to have a structural slab on which they could set the surface loading.

42. Figure 5 shows the cofferdam that was used to allow construction of the dock floor and gates. Cellular cofferdams were used to connect the piers to an earth bund which was a mound of sand placed in the sea by dredger. The cellular cofferdam worked extremely well, whereas the bund again meant some delay because it was impossible to control its grading internally, and perhaps not suprisingly some seepages arose, particularly during the first dewatering, which meant that the rate of drawdown had to be slowed down.

43. Initially only two docks were dewatered, but the figure shows a later stage when all three docks were dry and an intermediate section of cellular cofferdam was redundant. An attempt was made to withdraw some of the sheet piles which connected the redundant cells to the sheet pile core of the bund, and when this was done damp patches started to appear on this section of the cofferdam, slumping of surface layers occurred and its stability was in question. I should like to ask the Authors whether in retrospect they would have preferred perhaps to use a cellular cofferdam the whole way round, which seems to be neater and cleaner. Both types of cofferdam have recently been removed, and I should be interested to know how difficult they were to remove, and whether that has affected the Authors' view on which type of cofferdam they prefer.

Fig. 5

**Dr L. A. Clark,** University of Birmingham

In § 12 of Paper 8202, it is stated that each wall of the caisson was analysed as a two-dimensional structure and that Nielsen's equations were used to design the reinforcement. Am I correct in assuming that the two-dimensional analysis was a plane stress analysis? Although it is not stated, I presume that Nielsen's equations were also used to check that the minor principal stresses in the concrete were within a specified limit. When applying Nielsen's equations to the design, at the ultimate limit state, of slab elements under in-plane forces it is usual[1,2] to limit the minor principal stresses in the concrete to 40% of the characteristic strength of the concrete because this is the value that CP110 implies should be adopted. I should be interested to know whether the Authors adopted this or some other value.

45. Also in § 12, it is stated that in retrospect a three-dimensional analysis would have been preferable. Could the Authors say whether they mean a coupled bending plus in-plane analysis or a full three-dimensional analysis? Could they also indicate how they would have used the output from such an analysis to design the reinforcement and to check the concrete stresses? I ask this question because it is a problem which is exercising the minds of a number of engineers in a variety of fields—bridges and offshore structures are examples.

46. In § 24 it is suggested that, in the design of the pump-house, difficulties were encountered in relating the principal stresses from the STARDYNE program to reinforcement placed only horizontally or vertically. I am not familiar with the STARDYNE program and thus do not know in what form the output is produced. However, if it is a plane stress program then Nielsen's equations could have been used in the same manner as for the caisson walls; alternatively if it is a program which considers bending effects or is of a three-dimensional nature then the problem of designing against combined stresses arises. If the latter is the case, I should be interested to hear how the calculations were carried out.

**Mr A. W. Shilston,** Consulting Engineer

The Council of the Institution has enjoined the membership to be more controversial. Seeking to distil essences for possible application to other classes of civil engineering work carried out under similar Middle East conditions, I did find controversial the observation that the contractual framework on which this scheme was mounted was simple in concept. No doubt, like beauty, simplicity in the design of contractual mechanisms (which are an important part of total design) lies in the eyes of the beholder. My feeling is that the reason why disaster was averted on this scheme is because

(*a*) either explicitly or implicitly the legal backcloth to the contract could only have been common law and not local law;
(*b*) the staff of both the consulting engineers and the contractors were from the UK.

Had the contractors not been deeply familiar with English contractual traditions and nuances, and not been good communicators, both orally and in writing, in the English language, it is almost impossible to believe that this scheme within the adopted procedural contractual framework could have reached timely fruition.

48. The foregoing remarks do not imply that on an *ad hoc* basis the unusual procedural and contractual arrangements adopted at Dubai were not appropriate in all the prevailing surrounding circumstances.

**Mr D. A. Rodger,** NEI Clarke Chapman Cranes Ltd, Sir William Arrol Branch

May I make the following comments as a representative of the fabricator of the gates, and designer and supplier of the winches for the operation of the gates.

50. Contrary to Mr Cochrane's statement, all detail design and drawings of the gate structure, rakers etc. were carried out by the Sir Wm Arrol unit of NEI Clarke Chapman

Cranes Ltd, to the design and arrangement drawings provided by T. F. Burns & Partners. In addition, the complete design and detail drawings of the operating winches were carried out by Arrols, with the company manufacturing the six winches, one of which was load-tested at our Mossend unit before despatch.

51. Arrol, together with Redpath Dorman Long, who were to be responsible for site assembly, carried out stringent tests on inter-unit seals and on the main gate seals to ensure that, with the agreed fabrication tolerances, the gates would be watertight at both inter-unit joints (there are 30 in the largest gate) and around the outer periphery to the sill and jambs. RDL's site agent was complimentary on the accuracy of Arrol's fabrications, which made site assembly relatively simple.

52. In view of the co-operation between RDL and Clarke Chapman and the perfection of the completed contract, it can be seen that the order was awarded to the companies most capable of doing the work. When anyone who has attempted to construct a three-hinged door considers that on the largest gate there are 31 vertical portions which had to be relatively straight in line under the top gangway girder, and that all 30 hinges had also to be relatively truly aligned (some bearing clearance was built into the design), the magnitude of the task and accuracy required both in the shops and on site will be appreciated.

## Mr Hogbin

My comments are confined to matters relating to construction.

54. **Mr Sturrock** raises an interesting point concerning the validity of the dock pier construction method, intimating that a more economic solution might have resulted from a combination of different techniques. **Mr Thomas** goes part way to providing an answer to this but the matter warrants further elaboration. In the pre-contract planning phase numerous dock wall schemes were considered and among them were derivatives of the scheme proposed by Mr Sturrock (i.e., outer piers formed with caissons, inner piers cast in situ).

55. Two major considerations influenced the choice. The first was the speed of construction necessary to meet the overall programme requirements and the second was the location of the main dewatering pump-houses. The programme required concurrent construction of breakwaters, dock walls and pump-houses while dredging and sea bed preparation work in the dock area was carried out. A precast caisson scheme permitted this.

56. The pump-houses were large, complex units, and as they were located at the ends of the inner piers their completion to the state of being ready to sink in position determined the earliest date at which dock dewatering could be contemplated. Detailed study of the construction programme showed that, even with 24 h working throughout, by the time these units were ready for sinking, 66% of all dock wall caissons would already have been cast and the remainder could be completed within five months. This was considerably faster than the equivalent amount of work which could be carried out in situ after dewatering.

57. **Dr Simpson** raises several questions concerning the cofferdam and queries whether, with the benefit of hindsight, a different design would have been chosen. To answer his questions it is first necessary to understand the logic from which the chosen form derived. Dewatering of a dock opened up a large amount of work lying on the critical path to completion, and the first thoughts were to dewater the docks individually by cofferdamming from the pier ends. The pump-houses, however, were founded deeper than the standard wall caissons to accommodate the intake culverts, and to have waited until enough internal work was completed for them to be capable of withstanding the hydrostatic head would have unacceptably delayed dock dewatering. Any cofferdam, therefore, had to include the pump-houses and connect with a standard wall caisson. With both pump-houses being constructed simultaneously, it was found that a cofferdam built into Dock 1 to include Docks 2 and 3 achieved the earliest

possible access to the dock floors. This portion of the cofferdam subsequently became redundant and was removed as soon as the last dock was dewatered.

58. Dr Simpson's suggestion, to have constructed the whole cofferdam from straight web sheet pile cells, was given serious consideration but was discarded for economic reasons. Cells were used for the arms leading out from the piers, because they could be constructed concurrently with nearby caisson placing operations and pump-house foundation preparation works, but for the main length of cofferdam a dredger-placed bund was used since both the plant and material necessary were readily available. This latter method also had the all-important benefit of speed, even though commencement had to await substantial completion of adjacent caisson placing and underwater work.

59. No major problems were encountered in constructing the cofferdam; although, in seeking to guarantee free drainage of the bund by dumping a windrow of specially selected granular material along the inner toe line, exactly the opposite situation was inadvertently created. An impermeable blanket of fine silt developed along the inner face of the bund during dredger deposition of the main bund material and this inhibited drainage during drawdown. Only after much effort and experimentation was the entrapped water level reduced to an acceptable value.

60. A further problem was encountered while redundant sheet piles were being removed prior to flooding. During this operation the bund was disturbed and inflow increased. Exceptionally high tides and rough seas exacerbated problems at the time, but by careful monitoring and control of water levels within the bund, major slips were avoided. Removal of redundant cells that had stood dry for some time proved difficult. All conventional methods were tried with limited success and in the end the cells were cut up into panels, using driven chisels and burning gear. Extraction of the outer arms was much simpler due to the lubricating effect of the surrounding water. After relieving clutch tension by grabbing out fill and dumping this around the periphery of each cell, extraction was completed using Muller vibrators. Removal of the main bund by cutter suction dredger was speedy and straightforward.

61. Both forms of cofferdam proved satisfactory in practice and the combination of designs provided an effective solution to the particular requirements of this project.

**Mr Sharp**

On behalf of the Authors, I should like to reply to all the design topics raised.

63. **Mr Sturrock** suggests that the main breakwater could have been extended and so have reduced the need for the lee breakwater. Various configurations were studied but it was found that even with a longer main breakwater, involving the penalty of construction into deeper water, the lee breakwater was required to reduce wave activity within the harbour. The predominant north-westerly waves diffract around the head of the breakwater and are reflected against the existing Port Rashid breakwater. Protection is also necessary against the significant north-easterly wave climate. The configuration was designed to provide maximum protection to the docks and a direct approach from deep water to the reception berth.

64. Wave heights were observed both outside and within the harbour during the construction period and showed that the actual attenuation factor at the entrance to the docks was of the same order, approximately 10%, as measured in the model tests.

65. The reasoning behind **Mr Dagleish**'s objections to the dolphins is appreciated. Dolphins were originally to be located on all four pier lines, in connection with the handling of the original choice of caisson gate. The outer dolphins contribute to the length of the wet berths. The change to a flap gate, however, enabled the inner dolphins to be removed. Throughout the design, every effort was made to maximize area available for ship movements.

66. Leading lights are provided on each of the dock centre-lines, and the main approach is served by a sector light.

67. Both **Mr Sturrock** and **Mr Freer** refer to the instrumented caisson tests.

Mr Sturrock asks whether they have enabled economy to be realized in the later caissons. Impetus was indeed given to the instrumentation programme by the need to confirm the design of the large number of similar structures and, where possible, reduce reinforcement in congested areas as caisson production progressed. The information was considered to be particularly important in the event that it became necessary to analyse any additional load case, or if any unforeseen behaviour occurred which might affect sensitive design aspects of a thin-walled structure, such as bond anchorage between walls.

68. However, the task of completing and interpreting the results throughout the complete loading history, compounded by problems experienced in gaining response from the associated strain gauges, could not keep pace with construction. Caisson casting eventually advanced well ahead of programme and consequently the opportunity to refine the design was limited in practice. The most useful direct outcome of the testing was in establishing the acceptability of conditions associated with the filling.

69. Three caissons were fitted with earth pressure cells, grouted into precast box-outs when in the casting yard. Associated strain gauges were fitted during casting, in these and in a fourth caisson which was not to be filled until later. This provided a control enabling ambient and early thermal movements to be separated from structural action. In general, the external walls of up to six caisson cells in each caisson were fitted with earth pressure cells at five levels. At one of these levels, three pressure cells were located in order to investigate the variation in pressure across the span of a wall.

70. As the caissons were sunk by water ballast, it was possible to make an accurate check of the recorded pressures. Measurements were continued during sand filling and compaction, and during and subsequent to the initial dewatering of the dock. The scatter of results was acceptable, being slightly higher in the upper zones, since the accuracy of readings reduces with lower pressures. Fig. 10 of Paper 8201 illustrates the average wall pressure results, and these and the interpretation of strain gauge readings could only be adequately expanded by reference to the results as a whole.

71. **Dr Simpson** refers to the choice of supporting deck loads on the fill as opposed to the use of a structural deck slab. The majority of the sand fill is needed for the stability of the caissons, and once there provides the simplest and most economic means of supporting load. Although a structural deck slab might be preferable for a simple pier deck carrying light loading, in this case a heavy complicated deck structure would have resulted from the heavy concentration of services and surface works on the piers. The flexibility required for design and construction of the services would have been lost, and the margin available for structural strength and safety would have been reduced.

72. **Dr Clark**'s questions can best be answered by summarizing the design approach for the various types of caisson. In essence the caissons are buried box structures in which the external walls are predominantly loaded by earth and water pressure normal to the walls, in conjunction with other externally applied loading. The primary in-plane shear load case arises from the unbalanced load when a caisson is retaining the full hydraulic head from a dewatered dock. Three types of computer analysis were utilized, and comparisons made with manual methods:

(*a*) A plane frame analysis was used to derive the horizontal moments, shears and axial loads for horizontal slices of the cellular dock wall caissons.

(*b*) A two-dimensional finite element program was used, for the pump-house caissons, to derive the vertical and horizontal moments, axial loads and shears from the interaction of normally loaded slabs joined in three dimensions.

(*c*) A dynamic relaxation analysis gave the in-plane shear and axial forces for the unbalanced loading cases. This was a plane stress analysis.

73. Nielsen's equations were used to derive the reinforcement areas and the concrete stresses in the in-plane shear condition. The minor principal compressive stresses in the concrete were within the implied limit of 40% of the characteristic concrete

strength and therefore the question of possible enhancement of this limit did not arise. The requirements for resisting in-plane shear and out-of-plane bending were considered separately, and then combined. The question of designing for simultaneous bending and in-plane stresses did not arise in respect of the primary load cases as they do not occur simultaneously.

74. The retrospective preference expressed for a three-dimensional analysis for the cellular dock wall caissons referred to the use of a two-dimensional finite element program as chosen for the pump-house caissons and not a full three-dimensional analysis. The reference to difficulties in the application of the STARDYNE analysis referred to the combination of bending and shear in two dimensions arising from loading normal to the wall, and did not relate to combination with in-plane stresses.

75. In answer to **Mr Sturrock**'s question about the pressure relief wells, these were indeed constructed as illustrated in Fig. 4 of Paper 8201 and Fig. 2 of Paper 8202. They were formed to limit the exit hydraulic gradients under the dock walls and minimize the build-up of excessive pressure in the formation below the dock floor. By diverting flow away from the central area of the dock they reduce potential for uplift of the dock floor arising from any local blockage of the drainage system.

76. They consist of gravel-filled wells, 300 mm dia. by 10 m deep, drilled in the drainage trenches at 10 m centres. In practice it has been found that the wells adjacent to the two outer piers intercept some 50% of the total inflow into these trenches, while wells adjacent to the intermediate piers exhibit negligible flow. They gave the benefit of providing a drier floor during construction without noticeably increasing the total inflow.

77. The measured inflow into the docks stabilized at 0·5 $m^3/s$, which corresponded favourably with the minimum estimates made prior to the addition of contingency factors for design of the whole drainage system. Detectable leakage has not been observed at dock floor joints, expansion joints having been fitted with water bar and sealant, and construction joints made with prepared concrete surfaces. However, problems have been experienced in ensuring satisfactory seals to manholes against the head of the full dock.

78. **Mr Freer** observes that the call for rapid dock dewatering may be eased, and hence pumping capacity may be reduced, if pumping is halted while steam turbines are allowed to cool. However, just because they have to face delays of this nature, we found that operators insist on sufficient pumping capacity in order to recoup the lost time. They require dewatering times commensurate with those of existing docks, irrespective of the size of dock.

79. Formal pump testing and the setting of cut-off points for the main pumps is incomplete. However, the characteristics of the surface drainage system have proved to be considerably more efficient than predicted by the model tests. The dock water level can be drawn down completely by the main pumps and the dock floor is then entirely free of water.

80. In answer to **Mr Sturrock**, a structural weight saving of the order of 50% can be expected for the type of gate chosen, over that of conventional gate forms. The propped flap solution must show distinct advantages over any form of gate required to span entrances in excess of 70 m, with the added factor that the individual elements are statically determinate. A straightforward cost comparison is not reasonable in this case, as a prototype was under development. Fabrication of repetitive modular sections should, however, result in economy and incur the minimum site erection costs.

81. The intermediate gate, for which accommodation only was provided for eventual future installation, was anticipated as a sectional propped bulkhead. It would be of inverted Y form and be handled into position by dock crane. An outline design was prepared, sufficient for making suitable foundation provision.

82. **Mr Upstone** observes that a simple line contact bearing would have been more satisfactory for the raker props of the main gate. He presumably means a form of pin bearing in which the load is carried through the bearing. The prop bearings were

designed so that the props would rise simply and reliably into position and in the same place each time. In view of the requirement for reliability in service and the extremely corrosive environment, the choice of a bearing which separates the function of controlling rotation from that of taking thrust is surely preferable.

83. In answer to **Mr Freer,** the dock gate is hoisted up to the mean vertical position, where it strikes a limit switch which stops the hoist motion. Closure is then controlled by inching into final position with the seal slightly compressed.

84. The question of keel block height provides a continual source of controversy. Opinions vary from one extreme to the other, but quoted figures for large docks show a consensus close to 1·8 m high, with a geographic variation related to the human stature at the location! When one considers the extent of the area below these vessels, the climate, and the consequent requirements for access by mechanical equipment, anything less than 1·8 m would be unnecessarily restrictive.

85. It is agreed that the reduction of oil content to 5 ppm is difficult to achieve, and even more so to measure. The reduction is achieved in four stages. After settling, the water is passed through a preconditioning unit containing coalescing cartridges. It then flows through a tilted plate separator after which it passes through an emulsion breaker containing more cartridges.

86. There were no controller–analysers on the market capable of detecting oil to this accuracy. It was therefore necessary to promote the development of a prototype which reads depth of opacity over a broad band light frequency close to infra-red. The instrument was tested on a rig using calibrated quantities of oil–water mixture in small increments. Samples were taken after stable conditions had been established, and analysed in a laboratory using a Perkin–Elmer spectrophotometer, capable of reading down to 1 ppm of oil in water. Three controller–analysers, calibrated over coarse to fine ranges, are used to direct the flow of oily water through the process.

87. In answer to **Mr Thomas**, it is agreed that the abandoned system of the transfer track for interchanging cranes between piers had considerable advantages. With the greater travel and switching of cranes, independent drive would then have been a necessity. As to whether the use of electricity supply by reeled cable for docks of this length is practicable, the answer is definitely yes. The system is internationally recognized and adopted. A decision as to when to use cable supply as opposed to an underground bus-bar system is more difficult. This depends upon such factors as the load/voltage required, bus-bar availability for the system voltage and climatic conditions, and in Dubai was ruled out on account of ambient conditions.

88. It is somewhat surprising that more comment was not evoked by the contract arrangements. The comments from **Mr Shilston** are indeed appropriate and, in the opinion of the Authors, demonstrate the power of the British contract system and the need to oppose the tendency for it to be eroded by those unfamiliar with its evolvement and purpose.

## References

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